Loss Prevention in the Process Industries

Volume 3
This book is dedicated to

Herbert Douglas Lees (1860–1944), gas engineer;
Frank Priestman Lees (1890–1916), gas engineer;
Herbert Douglas Lees (1897–1955), gas engineer;
David John Lees (1936–), agricultural engineer;
Frank Lyman MacCallum (1893–1955), mining engineer and missionary;
Vivien Clare Lees (1960–), plastic and hand surgeon

Harry Douglas Lees (1962–), restaurateur
and their families

‘They do not preach that their God will rouse them a little before
the nuts work loose.
They do not teach that His Pity allows them to drop their job when
they dam’-well choose.
As in the thronged and the lighted ways, so in the dark and the
desert they stand,
Wary and watchful all their days that their brethren’s days may be
long in the land.’

Rudyard Kipling (The Sons of Martha, 1907)

Wo einer kommt und saget an,
Er hat es allen recht getan,
So bitten wir diesen lieben Herrn,
Er will uns solche Kunste auch lehren

(Whoever is able to say to us
‘I have done everything right’,
We beg that honest gentleman
To show us how it is done)

Inscription over the ‘Zwischenbau’ adjoining the Rathaus in Brandenburg-on-the-Haven
(quoted by Prince B.H.M. von Bulow in Memoirs, 1932)

If the honeys that the bees gather out of so manye flour of herbes… that are growing in other
mennis medowes… may justly be called the bees’ honeys… so maye I call it that I have…
gathered of manye good autours… my booke.
William Turner (quoted by A. Scott-James in The Language of the Garden: A Personal Anthology)

By the same author:

A.W. Cox, F.P. Lees and M.L. Ang (1990): Classification of Hazardous Locations (Rugby: Institution of Chemical Engineers)


Loss Prevention in the Process Industries
Hazard Identification, Assessment and Control
Volume 3

Second edition

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Preface to Second Edition

The first edition of this book appeared in 1980, at the end of a decade of rapid growth and development in loss prevention. After another decade and a half the subject is more mature, although development continues apace. In preparing this second edition it has been even more difficult than before to decide what to put in and what to leave out.

The importance of loss prevention has been underlined by a number of disasters. Those at San Carlos, Mexico City, Bhopal and Pasadena are perhaps the best known, but there have been several others with death tolls exceeding 100. There have also been major incidents in related areas, such as those on the Piper Alpha oil platform and at the nuclear power stations at Three Mile Island and Chernobyl.

Apart from the human tragedy, it has become clear that a major accident can seriously damage even a large international company and may even threaten its existence, rendering it liable to severe damages and vulnerable to takeover.

Accidents in the process industries have given impetus to the creation of regulatory controls. In the UK the Advisory Committee on Major Hazards made its third and final report in 1983. At the same time the European Community was developing its own controls which appeared as the EC Directive on Major Accident Hazards. The resulting UK legislation is the NHH Regulations 1982 and the CIMAH Regulations 1984. Other members of the EC have brought in their own legislation to implement the Directive. There have been corresponding developments in planning controls...

An important tool for decision-making on hazards is hazard assessment. The application of quantitative methods has played a crucial role in the development of loss prevention, but there has been lively debate on the proper application of such assessment, and particularly on the estimation and evaluation of the risk to the public.

Hazard assessment involves the assessment both of the frequency and of the consequences of hazardous events. In frequency estimation progress has been made in the collection of data and creation of data banks and in fault tree synthesis and analysis, including computer aids. In consequence assessment there has been a high level of activity in developing physical models for emission, vaporization and gas dispersion, particularly dense gas dispersion; for pool fires, firesballs, jet flames and engulfing fires; for vapour cloud explosions; and for boiling liquid expanding vapour explosions (BLEVEs). Work has also been done on injury models for thermal radiation, explosion overpressure and toxic concentration, on models of the density and other characteristics of the exposed population, and on shelter and escape.

Some of these topics require experimental work on a large scale and involving international cooperation. Large scale tests have been carried out at several sites on dense gas dispersion and on vapour cloud fires and explosions. Another major cooperative research programme has been that of DIERS on venting of chemical reactors.

The basic approach developed for fixed installations on shore has also been increasingly applied in other fields. For transport in the UK the Transport Hazards Report of the Advisory Committee on Dangerous Substances represents an important landmark. Another application is in the offshore oil and gas industry, for which the report on the Piper Alpha disaster, the Cullen Report, constitutes a watershed.

As elsewhere in engineering, computers are in widespread use in the design of process plants, where computer aided design (CAD) covers physical properties, flowsheeting, piping and instrument diagrams, unit operations and plant layout. There is increasing use of computers for failure data retrieval and analysis, reliability and availability studies, fault tree synthesis and analysis and consequence modelling, while more elusive safety expertise is being captured by computer-based expert systems.

The subject of this book is the process industries, but the process aspects of related industries, notably nuclear power and oil and gas platforms are briefly touched on. The process industries themselves are continually changing. In the last decade one of the main changes has been increased emphasis on products such as pharmaceuticals and agrochemicals made by batch processes, which have their own particular hazards.

All this knowledge is of little use unless it reaches the right people. The institutions which educate the engineers who will be responsible for the design and operation of plants handling hazardous materials have a duty to make their students aware of the hazards and at least to make a start in gaining competence in handling them.

I would like again to thank for their encouragement the heads of the Department of Chemical Engineering at Loughborough, Professors D.C. Freshwater, B.W. Brooks and M. Streat; our Industrial Professors T.A. Kletz and H.A. Duxbury and Visiting Professor S.M. Richardson; my colleagues, past and present, in the Plant Engineering Group, Mr R.J. Aird, Dr P.K. Andow, Dr M.L. Ang, Dr P.W.H. Chung, Dr D.W. Edwards, Dr P. Rice and Dr A.G. Rushton – I owe a particular debt to the latter; the members of the ACHM, chaired by Professor B.H. Harvey; the sometime directors of Technica Ltd, Dr D.H. Slater, Mr P. Charsley, Dr P.J. Comer, Dr R.A. Cox, Mr T. Gjerstad, Dr M.A.F. Pyman, Mr C.G. Ramsay, Mr M.A. Seaman and Dr R. Whitehouse; the members of the IChemE Loss Prevention Panel; the IChemE’s former Loss Prevention Officer, Mr B.M. Hancock; the members of the IChemE Loss Prevention Study Group and of the Register of Safety Professionals; the editorial staff of the IChemE, in particular Mr B. Brammer; numerous members of the Health and Safety Executive, especially Dr A.C. Barrell, Mr J. Barton, Dr D.A. Carter, Mr K. Cassidy, Mr P.J.
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Frank P. Lees
Loughborough, 1994
Preface to First Edition

Within the past ten or fifteen years the chemical and petroleum industries have undergone considerable changes. Process conditions such as pressure and temperature have become more severe. The concentration of stored energy has increased. Plants have grown in size and are often single-stream. Storage has been reduced and interlinking with other plants has increased. The response of the process is often faster. The plant contains very large items of equipment. The scale of possible fire, explosion or toxic release has grown and so has the area which might be affected by such events, especially outside the works boundary.

These factors have greatly increased the potential for loss both in human and in economic terms. This is clear both from the increasing concern of the industry and its insurers and from the historical loss statistics.

The industry has always paid much attention to safety and has a relatively good record. But with the growing scale and complexity involved in modern plants the danger of serious large-scale incidents has been a source of increasing concern and the adequacy of existing procedures has been subjected to an increasingly critical examination.

Developments in other related areas have also had an influence. During the period considered there has been growing public concern about the various forms of pollution, including gaseous and liquid effluents and solid wastes and noise.

It is against this background that the loss prevention approach has developed. It is characteristic of this approach that it is primarily concerned with the problems caused by the depth of technology involved in modern processes and that it adopts essentially an engineering approach to them. As far as possible both the hazards and the protection are evaluated quantitatively.

The clear recognition by senior management of the importance of the loss prevention problem has been crucial to these developments. Progress has been made because management has been prepared to assign to this work many senior and capable personnel and to allocate the other resources necessary.

The management system is fundamental to loss prevention. This involves a clear management structure with well defined line and advisory responsibilities staffed by competent people. It requires the use of appropriate procedures, codes of practice and standards in the design and operation of plant. It provides for the identification, evaluation and reduction of hazards through all stages of a project from research to operation. It includes planning for emergencies.


Another indicator is the creation in 1973 by the Institution of Chemical Engineers Engineering Practice Committee of a Loss Prevention Panel under the chairmanship of Mr T.A. Kantyka.

In the United Kingdom the Health and Safety at Work etc. Act 1974 has given further impetus to loss prevention. The philosophy of the Robens Report (1972), which is embodied in the Act, is that of self-regulation by industry. It is the responsibility of industry to take all reasonable measures to assure safety. This philosophy is particularly appropriate to complex technological systems and the Act provides a flexible framework for the development of the loss prevention approach.

The disaster at Flixborough in 1974 has proved a turning point. This event has led to a much more widespread and intense concern with the loss prevention problem. It has also caused the government to set up in 1975 an Advisory Committee on Major Hazards. This committee has made far-reaching recommendations for the identification and control of major hazard installations.

It will be apparent that loss prevention differs somewhat from safety as traditionally conceived in the process industries. The essential difference is the much greater engineering content in loss prevention.

This is illustrated by the relative effectiveness of inspection in different processes. In fairly simple plants much can be done to improve safety by visual inspection. This approach is not adequate, however, for the more technological aspects of complex processes.

For the reasons given above loss prevention is currently a somewhat fashionable subject. It is as well to emphasize, therefore, that much of it is not new, but has been developed over many years by engineers whose patient work in an often apparently unrewarding but vital field is the mark of true professionalism.

It is appropriate to emphasize, moreover, that accidents arising from relatively mundane situations and activities are still responsible for many more deaths and injuries than those due to advanced technology.

Nevertheless, loss prevention has developed in response to the growth of a new problem, the hazard of high technology processes, and it does have a distinctive approach and some novel techniques. Particularly characteristic are the emphasis on matching the management system to the depth of technology in the installation, the techniques developed for identifying hazards, the principle and methods of quantifying hazards, the application of reliability assessment, the
practice of planning for emergencies and the critique of traditional practices or existing codes, standards or regulations where these are outdated by technological change.

There is an enormous, indeed intimidating, literature on safety and loss prevention. In addition to the symposia already referred to, mention may be made of the *Handbook of Safety and Accident Prevention in Chemical Operations* by Fawcett and Wood (1965); the *Handbook of Industrial Loss Prevention* by the Factory Mutual Engineering Corporation (1967); and the *Industrial Safety Handbook* by Handley (1969, 1977). These publications, which are by multiple authors, are invaluable source material.

There is a need, however, in the author’s view for a balanced and integrated textbook on loss prevention in the process industries which presents the basic elements of the subject, which covers the recent period of intense development and which gives a reasonably comprehensive bibliography. The present book is an attempt to meet this need.

The book is based on lectures given to undergraduate and postgraduate students at Loughborough over a period of years and the author gladly acknowledges their contribution.

Loss prevention is a wide and rapidly developing field and is therefore not an easy subject for a book. Nevertheless, it is precisely for these reasons that the engineer needs the assistance of a textbook and that the attempt has been considered justified.

The structure of the book is as follows. Chapter 1 deals with the background to the historical development of loss prevention, the problem of large, single-stream plants, and the differential between loss prevention and conventional safety and between loss prevention and total loss control; Chapter 2 with hazard, accident and loss, including historical statistics; Chapter 3 with the legislation and legal background; Chapter 4 with the control of major hazards; Chapter 5 with economic and insurance aspects; Chapter 6 with management systems, including management structure, competent persons, systems and procedures, standards and codes of practice, documentation and auditing arrangements; Chapter 7 with reliability engineering, including its application in the process industries; Chapter 8 with the spectrum of techniques for identifying hazards from research through to operation; Chapter 9 with the assessment of hazards, including the question of acceptable risk; Chapter 10 with the siting and layout of plant; Chapter 11 with process design, including application of principles such as limitation of inventory, consideration of known hazards associated with chemical reactors, unit processes, unit operations and equipments, operating conditions, utilities, particular chemicals and particular processes and plants, and checking of operational deviations; Chapter 12 with pressure system design, including properties of materials, design of pressure vessels and pipework, pressure vessel standards and codes, equipment such as heat exchangers, fired heaters and rotating machinery, pressure relief and blowdown arrangements, and failure in pressure systems; Chapter 13 with design of instrumentation and control systems, including regular instrumentation, process computers and protective systems; Chapter 14 with human factors in process control, process operators, computer aids and human error; Chapter 15 with loss of containment and dispersion of material; Chapter 16 with fire, flammability characteristics, ignition sources, flames and particular types of process fire, effects of fire and fire prevention, protection and control; Chapter 17 with explosion, explosives, explosion energy, particular types of process explosion such as confined explosions, unconfined vapour cloud explosions and dust explosions, effects of explosion and explosion prevention, protection and relief; Chapter 18 with toxicity of chemicals, toxic release and effects of toxic release; Chapter 19 with commissioning and inspection of plant; Chapter 20 with plant operation; Chapter 21 with plant maintenance and modification; Chapter 22 with storage; Chapter 23 with transport, particularly by road, rail and pipeline; Chapter 24 with emergency planning both for works and transport emergencies; Chapter 25 with various aspects of personal safety such as occupational health and industrial hygiene, dust and radiation hazards, machinery and electrical hazards, protective clothing and equipment, and rescue and first aid; Chapter 26 with accident research; Chapter 27 with feedback of information and learning from accidents; Chapter 28 with safety systems, including the roles of safety managers and safety committees and representatives. There are appendices on Flixborough, Seveso, case histories, standards and codes, institutional publications, information sources, laboratories and pilot plants, pollution and noise, failure and event data, Canvey, model licence conditions for certain hazardous plants, and units and unit coverings.

Many of the matters dealt with, such as pressure vessels or process control, are major subject areas in their own right. It is stressed, therefore, that the treatment given is strictly limited to loss prevention aspects. The emphasis is on deviations and faults which may give rise to loss.

In engineering in general and in loss prevention in particular there is a conflict between the demand for a statement of basic principles and that for detailed instructions. In general, the first of these approaches has been adopted, but the latter is extremely important in safety, and a considerable amount of detailed material is given and references are provided to further material.

The book is intended as a contribution to the academic education of professional chemical and other engineers. Both educational and professional institutions have long recognized the importance of education in safety. But until recently the rather qualitative, and indeed often exhortatory, nature of the subject frequently seemed to present difficulties in teaching at degree level. The recent quantitative development of the subject goes far towards removing these objections and to integrating it more closely with other topics such as engineering design.

In other words, loss prevention is capable of development as a subject of presenting intellectual challenge. This is all to the good, but a note of caution is appropriate. It remains true that safety and loss prevention depend primarily on the hard and usually unglamorous work of engineers with a strong sense of responsibility, and it is important that this central fact should not be obscured.

For this reason the book does not attempt to select particular topics merely because a quantitative treatment is possible or to give such a treatment as an academic
exercise. The subject is too important for such an approach. Rather the aim has been to give a balanced treatment of the different aspects and a lead in to further reading.

It is also hoped that the book will be useful to practising engineers in providing an orientation and entry to unfamiliar areas. It is emphasized, however, that in this subject above all others, the specialized texts should be consulted for detailed design work.

Certain topics which are often associated with loss prevention, for example included in loss prevention symposia, have not been treated in detail. These include, for example, pollution and noise. The book does not attempt to deal in detail with total loss control, but a brief account of this is given.

The treatment of loss prevention given is based mainly on the chemical, petrochemical and petroleum industries, but much of it is relevant to other process industries, such as electrical power generation (conventional and nuclear), iron and steel, gas, cement, glass, paper and food.

The book is written from the viewpoint of the United Kingdom and, where differences exist within the UK, of England. This point is relevant mainly to legislation.

Reference is made to a large number of procedures and techniques. These do not all have the same status. Some are well established and perhaps incorporated in standards or codes of practice. Others are more tentative. As far as possible the attempt has been made to give some indication of the extent to which particular items are generally accepted.

There are probably also some instances where there is a degree of contradiction between two approaches given. In particular, this may occur where one is based on engineering principles and the other on relatively arbitrary rules-of-thumb.

The book does not attempt to follow standards and codes of practice in drawing a distinction between the words should, shall and must in recommending particular practices and generally uses only the former. The distinction is important, however, in standards and codes of practice and it is described in Appendix 4.

An explanation of some of the terms used is in order at this point. Unfortunately there is at present no accepted terminology in this field. In general, the problems considered are those of loss, either of life or property. The term hazard is used to describe the object or situation which constitutes the threat of such loss. The consequences which might occur if the threat is realized are the hazard potential. Associated with the hazard there is a risk, which is the probability of the loss occurring. Such a risk is expressed as a probability or as a frequency. Probability is expressed as a number in the range 0 to 1 and is dimensionless; frequency is expressed in terms of events per unit time, or sometimes in other units such as events per cycle or per occasion. Rate is also used as an alternative to frequency and has the same units.

The analysis of hazards involves qualitative hazard identification and quantitative hazard assessment. The latter term is used to describe both the assessment of hazard potential and of risk. The assessment of risk only is described as risk assessment.

In accident statistics the term Fatal Accident Frequency Rate (FAFR) has some currency. The last two terms are tautologous and the quantity is here referred to as Fatal Accident Rate (FAR).

Further treatments of terminology in this field are given by BS 4200: 1967, by Green and Bourne (1962), by the Council for Science and Society (1977) and by Harvey (1979b).

Notation is defined for the particular chapter at the point where the symbols first occur. In general, a consistent notation is used, but well established equations from standards, codes and elsewhere are usually given in the original notation. A consolidated list of the notation is given at the end of chapters in which a large number of symbols is used.

The units used are in principle SI, but the exceptions are fairly numerous. These exceptions are dimensional equations, equations in standards and codes, and other equations and data given by other workers where conversion has seemed undesirable for some reason. In cases of conversion from a round number it is often not clear what degree of rounding off is appropriate. In cases of description of particular situations it appears pedantic to make the conversion where a writer has referred, for example, to a 1 inch pipe.

Notes on some of the units used are given in Appendix 12. For convenience a unit conversion table is included in this appendix. Numerical values given by other authors are generally quoted without change and numerical values arising from conversion of the units of data given by other authors are sometimes quoted with an additional significant figure in order to avoid excessive rounding of values.

Some cost data are quoted in the book. These are given in pounds or US dollars for the year quoted.

A particular feature of the book is a fairly extensive bibliography of some 5000 references. These references are consolidated at the end of the book rather than at the end of chapters, because many items are referred to in a number of chapters. Lists of selected references on particular topics are given in table form in the relevant chapters.

Certain institutions, however, have a rather large number of publications which it is more convenient to treat in a different manner. These are tabulated in Appendices 4 and 5, which contain some 2000 references. There is a cross-reference to the institution in the main reference list.

In many cases institutions and other organizations are referred to by their initials. In all cases the first reference in the book gives the full title of the organization. The initials may also be looked up in the Author Index, which gives the full title.

A reference is normally given by quoting the author and, in brackets, the date, e.g. Kletz (1971). Publications by the same author in the same year are denoted by letters of the alphabet a, b, c, etc., e.g. Allen (1977a), while publications by authors of the same surname and in the same year are indicated for convenience by an asterisk against the year in the list of references. In addition, the author's initials are given in the main text in cases where there may still be ambiguity. Where a date has not been determined this is indicated as n.d.
In the case of institutional publications listed in Appendices 4 and 5 the reference is given by quoting the institution and, in brackets, the date, the publication series, e.g. HSE (1965 HS2 Bklt 34) or the item number, e.g. IChemE (1971 Item 7). For institutional publications with a named author the reference is generally given by quoting the author and, in brackets, the initials of the institution, the date and the publication series or item number, e.g. Eames (UKAEA 1965 Item 4).

The field of loss prevention is currently subject to very rapid change. In particular, there is a continuous evolution of standards and codes of practice and legislation. It is important, therefore, that the reader should make any necessary checks on changes which may have occurred.

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Loughborough,
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The author would also like to acknowledge his use of material from Refining Process Safety Booklets of the Amoco Oil Company (formerly the American Oil
Company, Chicago), in particular Booklet No. 4, Safe Ups and Downs of Refinery Units, Copyright 1960 and 1963. The American Oil Company and Booklet No. 9, Safe Operation of Air, Ammonia and Ammonium Nitrate Plants, Copyright 1964 The American Oil Company. Quoted material is used with the permission of the copyright owner.

Professor H.A. Duxbury and Dr A.J. Wilday have been good enough comment on Chapter 17, Sections 17.16–17.21. Professor Duxbury has also contributed Appendix 13 on safety factors in simple relief systems.

The responsibility for the text is mine alone.
Terminology

Attention is drawn to the availability in the literature of a number of glossaries and other aids to terminology. Some British Standard glossaries are given in Appendix 27 and other glossaries are listed in Table 1.1.

Notation

In each chapter a given symbol is defined at the point where it is first introduced. The definition may be repeated if there has been a significant gap since it was last used. The definitions are summarized in the notation given at the end of the chapter. The notation is global to the chapter unless redefined for a section. Similarly, it is global to a section unless redefined for a subsection and global to a subsection unless redefined for a set of equations or a single equation. Where appropriate, the units are given, otherwise a consistent system of units should be used, SI being the preferred system. Generally the units of constants are not given; where this is the case it should not be assumed that a constant is dimensionless.
Use of References

The main list of references is given in the section entitled References, towards the end of the book. There are three other locations where references are to be found. These are Appendix 27 on standards and codes; Appendix 28 on institutional publications; and in the section entitled Loss Prevention Bulletin which follows the References.

The basic method of referencing an author is by surname and date, e.g. Beranek (1960). Where there would otherwise be ambiguity, or where there are numerous references to the same surname, e.g. Jones, the first author’s initials are included, e.g. A. Jones (1984). Further guidance on names is given at the head of the section References.

References in Appendices 27 and 28 are by institution or author. Some items in these appendices have a code number assigned by the institution itself, e.g. API (1990 Publ. 421), but where such a code number is lacking, use is generally made of an item number separated from the date by a slash, e.g. IChemE (1971/13). Thus typical entries are

API Std 2000: 1992 a standard, found in Appendix 27 under American Petroleum Institute

API (1990 Publ. 421) an institutional publication, found in Appendix 28 under American Petroleum Institute

HSE (1990 HS(G) 51) an institutional publication, found in Appendix 28 under Health and Safety Executive, Guidance Booklets, HS(G) series

Coward and Jones (1952 BM Bull. 503) an institutional publication, found in Appendix 28 under Bureau of Mines, Bulletins

Institutional acronyms are given in the section Acronyms which precedes the Author Index.

There are several points of detail which require mention concerning Appendix 28. (1) The first part of the appendix contains publications of a number of institutions and the second part those of the Nuclear Regulatory Commission. (2) The Fire Protection Association publications include a number of series which are collected in the Compendium of Fire Safety Data (CFSD). A typical reference to this is FPA (1989 CFSD FS 6011). (3) The entries for the Health and Safety Executive are quite extensive and care may be needed in locating the relevant series. (4) The publications of the Safety and Reliability Directorate appear under the UK Atomic Energy Authority, Safety and Reliability Directorate. A typical reference is Ramskill and Hunt (1987 SRD R354). These publications are immediately preceded by the publications of other bodies related to the UKAEA, such as the Health and Safety Branch, the Systems Reliability Service and the National Centre for Systems Reliability.

References to authors in the IChemE Loss Prevention Bulletin are in the style Eddershaw (1989 LPB 88), which refers to issue 88 of the bulletin.
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Loss Prevention Bulletin

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Appendix 1

Case Histories

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An essential feature of the learning process in safety and loss prevention is the study of case histories.

### A1.1 Incident Sources

Collections of case histories have been published in *Case Histories of Accidents in the Chemical Industry* by the Manufacturing Chemists Association (MCA) (1962–1974) and by Kier and Müller (1983). Specialized collections have been published on particular topics such as major hazards (Harvey, 1979; 1984; Carson and Mumford, 1979; Lees, 1980b; V.C. Marshall, 1987), fire and explosion (Vervalin, 1964a, 1973a; W.H. Doyle, 1969), vapour cloud explosions (Gugan, 1979; Slater, 1978a; D.J. Lewis, 1980d; Davenport, 1987; Lenoir and Davenport, 1993), LPG (L.N. Davis, 1979), instrumentation (W.H. Doyle 1972a, b; Lees, 1976b), transport (Haastrop and Brockhoff, 1990) and pipelines (Riley, 1979). The series Safety Digest of Lessons Learned by the API gives case histories with accompanying analyses. Another such series is that published by the American Oil Company (AOC) of which Hazards of Water and Hazards of Air are the best known. The Canvey Reports and the Rismond Report give information on certain incidents. The reports of the HSE provide case histories of investigations by a regulator as do those of the NTSB, which deal with rail, road, pipeline and marine accidents. Incidents involving large economic loss are described in the periodic review 100 Large Losses by Marsh and McLennan.

Case histories are also given in the Annual Report of HM Chief Inspector of Factories, the Chemical Safety Summary of the Chemical Industry Safety and Health Council (CISHC) and in journals such as Petroleum Review and NFPA Quarterly. In addition, the Loss Prevention Bulletin issued by the IChemE gives case histories. There are also numerous case histories described in much greater detail in various papers and reports. The disasters at Flixborough (R.J. Parker, 1975), at Bantry Bay (Costello, 1979) and on Piper Alpha (Cullen, 1990) are among the most thoroughly documented.


Selected references on case histories are given in Table A1.1. Some major incidents are listed in Table A1.2. A proportion of these are described in Section A1.10.

### Table A1.1 Selected references on case histories

<table>
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<td>Major hazard control</td>
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<td>Sellers (1988); Sellers and Piccioli (1988); Cullen (1990)</td>
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<td>Anon. (1992 LPB 107, p. 27)</td>
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<td>Chemical reactors</td>
<td>Anon. (1962a); Zielenksi (1967, 1973); Fowler and Spiegelman (1968); Batt (1970); Grewer (1970); Valpiana (1970b); Zehr (1970); Vincent (1971); Fire J. Staff (1973a, d); Bloore (1974); Gugan (1974b); HM Chief Inspector of Factories (1974); Anon. (1975 LPB 1, p. 10); Anon. (1975 LPB 3, p. 1); Anon. (1975 LPB 5, p. 16); Anon. (1977 LPB 13, p. 13); Tong, Seagrave and Wilderhorn (1977); Anon. (1979 LPB 28, 29, 30); Skinner (1981); Bond (1985 LPB 65); Anon. (1986 LPB 68, p. 33); Berkley and Workman (1987); Anon. (1989 LPB 90, p. 29); Levy and Penrod (1989); Anon. (1991 LPB 98, p. 7); Kotoyori (1991); Anon. (1993 LPB 113, p. 25); Anon. (1994 LPB 115, p. 1); Anon. (1994 LPB 117, p. 18); Anon. (1994 LPB 118, p. 8); Dixon-Jackson (1994)</td>
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<tr>
<td>Petrochemical plants</td>
<td>Britton (1994)</td>
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<td>Utilities</td>
<td>Dowell (1994a)</td>
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<td>Ammonia, urea and ammonium nitrate plants</td>
<td>R.W. James and Lawrence (1973); Anon. (1975b); Din (1975); Esrig, Ahmad and Mayo (1975); Henderson (1975); Lonsdale (1975); Osmani (1975); K. Wright (1975); Viswanathan (1976); Kusha (1977); P.C. Campbell (1981); Janssen, Sirra and Blanken (1981); Roney and Persson (1984); Anon. (1987 LPB 78, p. 11)</td>
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<td>LNG</td>
<td>FPC, Bureau of Natural Gas (1973); L.N. Davis (1979)</td>
</tr>
<tr>
<td>Pressure systems and components</td>
<td>Bohlken (1961); Saibel (1961a, b); Atteberry (1970); R.W. Miller and Caserta (1971); Banks (1973); Gupton and Kreisher (1973); R.W. James and Lawrence (1973); van der Horst and Sloan (1974); Appl (1975); Blanken (1975); Fuchs and Rubinstein (1975); Lonsdale (1975); Steele (1975); Ketz (1976b, 1987a); National Vulcan (1977); Kinsley (1978); Makhan and Honse (1978); Perkins</td>
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(1980 LPB 33); Anon. (1981 LPB 37, p. 23); Connaughton
(1981); Blanken and Groefsma (1983); Anon. (1984 LPB
56, p. 26); R.W. Clark and Connaughton (1984); NBS
(1986); Anon. (1988 LPB 83, p. 1, 3, p. 11, 15, 17 and 19);
Anon. (1989 LPB 86, p. 22 and 27); Anon. (1989 LPB 94,
p. 16); Droste and Mallon (1989); Anon. (1990 LPB 93, p.
23); Rademayer (1990); Anon. (1991 LPB 97, p. 9); Smith
(1991 LPB 102); Anon. (1992 LPB 104, p. 27); Anon.
(1992 LPB 107, p. 27); Crawley (1992 LPB 104); Anon.
(1993 LPB 111, p. 25); Anon. (1993 LPB 113, p. 13);
Anon. (1994 LPB 117, p. 24); Clayton and Griffin (1994)
Process machinery
OIA (n.d./7); Gibbs (1960); Rendos (1967); Shield (1967,
1972); Naughton (1968); North and Parr (1968);
Telesmanic (1968); Zech (1968); Zimmerman (1968); D.S.
Wilson et al. (1970); von Nimitz, Wachel and Szenasi
(1974); Anon. (1975f); Roney (1975); Novacek (1983);
Anon. (1985 LPB 62, p. 27); Anon. (1990 LPB 91, p. 16);
Anon. (1990 LPB 92, p. 15); Anon. (1994 LPB 116, p. 21)

(1986); McCoy, Dillenback and Truax (1986);
Steinbrecher (1986, 1989 LPB 88); Anon. (1987 LPB 77,
p. 11 and 27); V.C. Marshall (1987, 1990 LPB 95, 1994
LPB 116); Anon. (1988 LPB 79, p. 23); Anon. (1988 LPB
82, p. 19); Anon. (1988 LPB 83, p. 13); Anon. (1988 LPB
84, p. 19); Armstrong (1988 LPB 83); Schwab (1988a,
1988 LPB 83); Anon. (1989 LPB 87, p. 15); Anon. (1989
LPB 88, p. 19); B. Browning and Searson (1989); IMechE
(1989/111); Anon. (1990g); Anon. (1990 LPB 91, p. 22);
Anon. (1990 LPB 94, p. 26 and 30); Anon. (1990 LPB 95,
p. 19); Adelman and Adelman (1990 LPB 94); Perunicic
and Skotovic (1990 LPB 96); Anon. (1991 LPB 97, p. 12);
Anon. (1991 LPB 98, p. 9); Kohlbrand (1991); Anon.
(1991 LPB 102, p. 35); Anon. (1992 LPB 103, p. 24);
Anon. (1992 LPB 104, p. 7, 9 and 13); Anon. (1992 LPB
105, p. 15); Carson and Mumford (1992 LPB 108, 1993
LPB 109, 110); Kirk (1992 LPB 105); Prine (1992); Anon.
(1993 LPB 113, p. 27); Anon. (1993 LPB 114, p. 19);
Anon. (1994 LPB 115, p. 6); Anon. (1994 LPB 120, p. 10
and 19)

Instruments
MCA (1962-/1±4); W.H. Doyle (1969, 1972a,b); Fritz
(1969); H.D. Taylor and Redpath (1971, 1972); Kletz
(1974b,d); McLain (1975b); K. Wright (1975); Lees
(1976b); Anon. (1986 LPB 68, p. 35); anon. (1992 LPB
104, p. 11); Anon. (1994 LPB 116, p. 22); Griffin and
Garry (1984)

Fire: static electricity
Klinkenberg and van der Minne (1958); Bustin (1963);
Èller-Hillebrand (1963); van der Meer
Eichel (1967); Mu
(1971); Anon. (1979 LPB 29, p. 134); Anon. (1983 LPB
52, p. 19); H.R. Edwards (1983); M.R.O. Jones and Bond
È ttgens (1985); Anon. (1987 LPB 78, p. 9);
(1984, 1985); Lu
Owens (1988); Anon. (1994 LPB 118, p. 14);

Computer control systems
Nimmo, Nunns and Eddershaw (1987, 1993 LPB 111)
Human error
Speaker, Thompson and Luckas (1982); Anon. (1983i);
Anon. (1989b); Anon. (1990 LPB 92, p. 13)
Emissions, leaks, releases
25); Anon. (1982 LPB 43, p. 21); Edwards (1982 LPB 47);
Christiansen and Jorgensen (1983); Anon. (1986 LPB 70,
p. 1); Anon. (1989 LPB 85, p. 27); Anon. (1989 LPB 90, p.
13); Anon. (1990 LPB 91, p. 16); Anon. (1992 LPB 104, p.
27); Anon. (1994 LPB 117, p. 24)
Fire
OIA (Publ. 651, 1972 Publ. 302, 1973); Woodworth
(1958); Lamond (1962); MCA (1962-/1±4); Pinney (1962);
Rendos (1964); Vervalin (1964a,c, 1973a,b); Anon.
(1966d); Ashill (1966); Cowles (1966); McCarey (1966);
Darling (1967); Ostroot (1967, 1973); Zielinski (1967,
1973); Anon. (1968b); Leroy and Johnson (1969); Orey
(1972a); Searson (1972, 1990 LPB 94); Fire J. Staff
(1973b,e); Fowle (1973); Garrad (1973); NFPA (1973/10);
St. Clair (1973); Beausoleil, Phillips and Snell (1974);
Sharry and Walls (1974); Anon. (1975 LPB 0, p. 13);
McLain (1975b); Anon. (1976h,k); Kletz (1976g, 1979a,
1984 LPB 58, 1993 LPB 114); Saia (1976); Anon. (1978d);
HSE (1978c); Isman (1978); Lathrop (1979); Anon.
(1980u); Anon. (1981p); Crain (1981); Oosterling and
Orbons (1981); Anon. (1982 LPB 43, p. 2); Anon.
(1983m); Anon. (1983 LPB 51, p. 13); FM (1983); Anon.
(1984 LPB 57, p. 19); Mullier, Rustin and Hecke (1984);
Mumford (1984 LPB 57); Anon. (1985 LPB 64, p. 13);
Bond (1985 LPB 65, 1991); Carson, Mumford and Ward
(1985 LPB 65); KoÈhler (1985); Politz (1985); Anon. (1986
LPB 69, p. 17 and 33); Anon. (1986 LPB 71, p. 27); Lask

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Explosions
OIA (Publ. 651, 1973); Assheton (1930); Jacobs et al.
(1957); F.C. Price (1960); Matthews (1961); Popper
(1963); Alexander and Finigan (1964); Bateman (1964);
W.A. Mason (1964); Pipkin (1964); Sakai (1964); Schmitt
(1964); Thodos (1964); Walls (1964b); Sorrell (1965);
Anon. (1966c); W.L. Ball (1966a); Haseba et al. (1966);
Wilkinson (1966); Adcock and Weldon (1967b, 1973);
Dixon (1967); Dorsey (1967); Lorentz (1967, 1973); J.D.
Reed (1967); Bast (1970); Buehler et al. (1970); Fritsch
(1970); Grewer (1970); Kotzerke (1970); Valpiana
(1970a,b); Volpers (1970); Cracknell (1971); Dartnell and
Ventrone (1971); K.W. Sanders (1971); G.A. Campbell
and Rutledge (1972); Fire J. Staff (1973d); Freese (1973);
Gozzo and Carraro (1973); Jacobs et al. (1973); Meganck
(1973); de Oliviera (1973); W.W. Patterson (1973);
Vervalin (1973e); Bateman, Small and Snyder (1974);
Bloore (1974); Grimm (1974); Gugan (1974b); Hadas
(1974); Hartgerink (1974); Kletz (1974b, 1976b, f, x, 1984
LPB 56, 1988); Lockemann (1974); Ludford (1974);
Èro
Ès and Honti (1974); Anon. (1975
Tanimoto (1974); Vo
LPB 1, p. 3 and 15); Anon. (1975 LPB 5, p. 1); Anon.
(1975 LPB 6, p. 17); Dooyeweerd (1975); Henderson
(1975); Strehlow and Baker (1975, 1976); Anon. (1976
LPB 11, p. 2); Carver (1976); Kotoyori et al. (1976);
Rebsch (1976); Saia (1976); Anon. (1977d); Tong,
Seagraves and Wiederhorn (1977); Anon. (1978 LPB 19,
p. 24); Cremer and Warner (1978); Markham and Honse
(1978); Biasutti (1979); Anon. (1980y); Ramadorai (1980);
Edwards (1982 LPB 47); Anon. (1983a); Bond (1983 LPB
50); Anon. (1983 LPB 51, p. 9); Lloyd (1983); Ursenbach
(1983); Anon. (1984 LPB 54, p. 13); Anon. (1985c); HSE
(1985d); Schwab (1988a,b, LPB 83); Wrightson and
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13); Bond (1989 LPB 93); Cronin (1989 LPB 90); Ernst

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CASE HISTORIES

(1989); G.M. Lawrence (1989); MacDiarmid and North
(1989); Nightingale (1989a,b); Urben (1989 LPB 80);
Anon. (1990d,e,i); Anon. (1990 LPB 91, p. 15); Anon.
(1990 LPB 95, p. 15); de Haven and Dietsche (1990);
Segrave and Wilson (1990); Anon. (1991d,f.k,l); Anon.
(1991 LPB 97, p. 23); Anon. (1991 LPB 98, p. 1 and 18);
Anon. (1991 LPB 102, p. 7); Arendt and Lorenzo (1991);
Carson and Mumford (1991 LPB 102); Hempseed and
19); Anon. (1992 LPB 103, p. 31); Anon. (1992 LPB 107,
p. 17); S.E. Anderson, Dowell and Mynaugh (1992);
Moran (1992); Palazzi (1992); Raheja et al. (1992); Anon.
(1993 LPB 109, p. 7); Anon. (1993 LPB 109, p. 25 and
26); Anon. (1993 LPB 110, p. 25); Anon. (1993 LPB 112,
p. 21); Bergroth (1993 LPB 109); Bond (1993 LPB 101);
Wehrum (1993); Whitmore, Gladwell and Rutledge
9); Anon. (1994 LPB 116, p. 17)
BLEVEs
KoÈhler (1985); Selway (1988 SRD R492)
Dust explosions, dust fires
Morozzo (1795); D.J. Price and Brown (1922); NFPA
(1957/1); K.C. Brown and James (1962); Remirez (1967);
Yowell (1968); Noss (1971); O'Reilly (1972); Tonkin and
Berlemont (1972 FRS Fire Res. Note 942); K.N. Palmer
(1973a); Pollock (1975); Lathrop (1978); Anon. (1979e);
Braun (1979); Snow (1981); Anon. (1983 LPB 51, p. 9);
Anon (1989 LPB 90, p. 27); Skinner (1989); Anon. (1990
LPB 95, p. 1, 6 and 13); Kaiser (1991); Senecal (1991);
Anon. (1994 LPB 115, p. 9)
Toxic release
Chasis et al. (1947); Joyner and Durell (1962); Hoveid
(1966); Inkofer (1969); MacArthur (1972); Simmons,
Erdmann and Naft (1973, 1974); Eisenberg, Lynch and
Breeding (1975); Lonsdale (1975); Luddeke (1975);
Anon. (1976n,o); Hoyle and Melvin (1976); HSE (1978b);
Harvey (1979b); Shooter (1980); N.C. Harris (1981b);
Anon. (1982 LPB 48, p. 13); Prijatel (1983); Sweat (1983);
Anon. (1985 LPB 66, p. 23); HSE (1985 LPB 63); Anon.
(1987 LPB 75, p. 23); Anon. (1989 LPB 86, p. 22 and 27);
Anon. (1989 LPB 89, p. 27); Anon. (1990 LPB 91, p. 19);
Anon. (1990 LPB 92, p. 11, 15, 23 and 26); Duclos and
Binder (1990); Huvinen (1990 LPB 92); Pallen (1990);
M.P. Singh (1990); M.P. Singh, Kumari and Ghosh
(1990); Anon. (1991 LPB 97, p. 7); Anon. (1991 LPB 98,
p. 25); Anon. (1993 (LPB 113, p. 26); Anon. (1993 LPB
112, p. 22)
Plant commissioning
Dyess (1973); Parnell (1973); J.R. Robinson (1973);
Severa (1973); Arnot and Hirons (1974); Horsley (1974);
Jenkins and Crookston (1974); Butzert (1976); Anon.
(1977 LPB 18, p. 2); Bress and Packbier (1977); Gilbert
and Eagle (1977); Tandy and Thomas (1979); Kletz
(1984k); Grotz, Gosnell and Grisolia (1985); Ruziska et al.
(1985); Song (1986); W.K. Taylor and Pino (1987);
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Plant operation
MCA (1962-/1±4); W.H. Doyle (1972a); Kletz (1975b);
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LPB 77, p. 17); Anon. (1989 LPB 88, p. 1); Anon. (1989

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LPB 89, p. 9 and 18); T.O. Gibson (1989); Anon. (1990
LPB 92, p. 22); Anon. (1991 LPB 98, p. 19); Anon. (1992
LPB 106, p. 19); Anon. (1992 LPB 107, p. 17); Anon.
(1994 LPB 115, p. 7)
Plant maintenance
Simms (1965); Anon. (1978 LPB 24, p. 155); Anon. (1979
LP 27, p. 80); P.C. Campbell (1981); Roney and Persson
(1984); Deacon (1988); Anon. (1989 LPB 85, p. 1, 3 and
5); Anon. (1989 LPB 86, p. 17); Anon. (1990 LPB 92, p.
20); Anon. (1991 LPB 102, p. 27); Anon. (1991 LPB, p. 20
and 25); Anon. (1992 LPB 103, p. 24, 25 and 29); Anon.
(1992 LPB 104, p. 10); Anon. (1992 LPB 107, p. 21 and
22); Anon. (1993 LPB 112, p. 20); Anon. (1994 LPB 116,
p. 22); Anon. (1994 LPB 117, p. 17); Anon. (1994 LPB
119, p. 8); Bond (1994 LPB 117)
Construction
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Plant modification
Anon. (1975 LPB 1, p. 1); R.J. Parker (1975); Booth
(1976); Henderson and Kletz (1976); Heron (1976); W.W.
Russell (1976); Anon. (1978 LPB 22, p. 101)
Storage
OIA (Publ. 711, 1974 Loss Inf. Bull. 400-1); Vervalin
(1964a, 1973a); J.A. Lawrence (1966); Frank and Wardale
(1970); J.R. Hughes (1970); A. Nielsen (1971);
Litchenberg (1972, 1977); MacArthur (1972); Anon. (1975
LPB 0, p. 2); Henderson (1975); Lonsdale (1975); Anon.
(1976 LPB 12, p. 7); Hampson (1976); Anon. (1978 LPB
20, p. 55); Anon. (1979 LPB 26, p. 31); Anon. (1979 LPB
27, p. 68); Gustin and Novacek (1979); Anon. (1980 LPB
32, p. 13); Anon. (1980 LPB 36, p. 25); Anon. (1981 LPB
37, p. 7); Anon. (1981 LPB 41, p. 11); Morgenegg (1982);
Anon. (1984 LPB 57, p. 11); Anon. (1986 LPB 69, p. 29);
Badame (1986); NBS (1986, 1988); Anon. (1987 LPB 75,
p. 19); Anon. (1987 LPB 78, p. 26); Anon. (1988m);
Marshall (1988 LPB 82); Anon. (1989 LPB 88, p. 11);
(1988); Christiansen, Kakko and Koiviso (1993); Koivisto
and Nielsen (1994)
Transport
AGA (Appendix 28 Pipeline Accident Reports); NTSB
(annual reports); Engel (1969); Inkofer (1969); Medard
(1970); Cato and Dobbs (1971); A.W. Clarke (1971b);
Kogler (1971); Caserta (1972a); Ass. of Amer. Railroads
(1972); Hayes (1972); Fire J. Staff (1973); Lloyds List
(1974); Wilde (1974); DoE (1976/6); Anon. (1977 LPB
15, p. 33); Getty, Rickert and Trapp (1977); Merricks
(1977); Anon. (1978j); Anon. (1978 LPB 54, p. 7); Anon.
(1979g); Selikoff (1979); Egginton (1980); Anon. (1981m);
George (1981a,b); Kletz (1981b); Knife (1982±83); V.J.
Clancey (1983); van der Schaaf and Steunenberg (1983);
M. Griffitsh and Linklater (1984); Hymes (1985 LPB 61);
Kilmartin (1985 LPB 61); G.A. Gallagher (1986); G.A.
Gallagher and McCone (1986); D.J. Lewis (1986b);
Watson (1986 LPB 72); Anon. (1988 LPB 80, p. 3); Anon.
(1990 LPB 92, p. 25 and 26); Anon. (1990 LPB 93, p. 3);

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**Emergency planning**
Donovan (1973); R.J. Parker (1975); Ikeda (1982); Anon. (1986 LPB 70, p. 1); Anon. (1993 LPB 113, p. 26)

**Emergency planning: transport**
Dowell (1971); Kogler (1971); Burns (1974); Dektar (1974); Ellis (1974); Furey (1974); Eisenberg, Lynch and Breeding (1975); HSE (1978b); Zajic and Himmelman (1978); Anon. (1982b); Anon. (1983m)

**Personal health and safety**
Anon. (1988 LPB 88, p. 3 and 14 (x2))

**Environment**
E. Hughes (1973); Willman (1977); Anon. (1978 LPB 22, p. 114); Anon. (1982c); Kharbanda and Stallworthy (1982); Frisbie (1982); A. Shepherd (1982a); A. Smith (1982); Kier and Müller (1983); Cairns (1986); Goudray (1992); Anon. (1993a,f)

**Offshore**
Fischer (1982); Anon. (1991f)

**Other case histories**
Bakir et al. (1973); Anon. (1976 LPB 9, p. 5); Anon. (1976 LPB 11, p. 10); Vervain (1981, 1987); Anon. (1982 LPB 48, p. 27); Anon. (1982 LPB 49, p. 26); Kletz (1982 LPB 48, 49); Anon. (1984 LPB 54, p. 21); Anon. (1984 LPB 60, p. 1); Anon. (1985 LPB 61, p. 33); Anon. (1985 LPB 64, p. 27); Buhrow (1985, 1986); Lask (1986); Manuell (1986 LPB 71); Schillmoller (1986); Anon. (1987a); Plummer (1987 LPB 73); Robinson (1987 LPB 78); Anon. (1988h); Anon. (1988 LPB 81, p. 15); Anon. (1988 LPB 83, p. 25); Anon. (1989 LPB 88, p. 18); Anon. (1989 LPB 90, p. 15); Mansot (1989); Mooney (1991); Anon. (1993c); Davie, Nolan and Hoban (1994)

### A1.2 Incident Databases

There are a number of databases specifically dealing with case histories. They include the following:

- The incident databases Major Hazards Incident Data System (MHIDAS) and the corresponding explosives data system EIDAS are operated by SRD.
- TNO has developed the FACTS incident database.
- The JRC of the CEC at Ispra, Italy, runs the Major Accident Reporting System (MARS), described by Drogaris (1991, 1993).
- The FIRE incident database for chemical warehouse fires has been described by Koivisto and Nielsen (1994).
- An account of the offshore Hydrocarbon Release (HCR) database in the UK has been given by Bruce (1994).

### A1.3 Reporting of Incidents

The extent and accuracy of the reporting of incidents and injuries is variable and this creates problems particularly for attempts to perform statistical analysis of incident data.

Three distinct problems may be identified: (1) occurrence of an incident; (2) injuries associated with an incident; and (3) national injury statistics. These three cases are considered in this section and in the next two sections, respectively.

The awareness of the engineering community worldwide of incidents varies according to the country in which the incident has occurred and the size and impact of the incident. For example, in the recent past incidents in the USA have generally been reported in the technical press but reports of comparable incidents in the USSR have been relatively few.

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**Figure A1.1** Number of accidents reported (after Badoux, 1983): A, accidents actually reported; and B, total number of accidents (and ideal reporting curve)
With regard to the effects of scale and impact, the probability of world-wide reporting of an incident clearly increases with these factors. The probability that an accident of the magnitude of Bhopal is not reported in countries with a free press is negligible. However, as the size of the incident decreases, the probability that it is not reported or at least is not picked up in incident collections and databases increases. The problem has been discussed by Badoux (1983). Figure A1.1 shows schematically the probable extent of underreporting, curve A representing the actual reporting situation and curve B the ideal one.

### A1.4 Reporting of Injuries in Incidents

For various reasons, accounts of incidents tend to differ in the number of injuries and, to a lesser extent, fatalities which are reported. A discussion of this problem has been given by Haastrep and Brockhoff (1991).

There are a number of reasons for differences in the numbers quoted. One is that early reports of an incident tend not to be very accurate, but are sometimes quoted without sufficient qualification and the numbers then receive currency.

With regard to fatalities, a difference arises between

![Figure A1.2](image-url)  
*Figure A1.2* Hazardous Materials Accident Spill map: propane pipeline release, Ruff Creek, Pennsylvania, 1977 (National Transportation Safety Board, 1979)
immediate and delayed deaths. A case where a proportion of delayed deaths is fairly common is burn casualties.

The most frequent and large differences, however, are in ‘injuries’. Here much of the difference can usually be accounted for by differences in definition.

As an illustration, consider the injuries in the explosion at Laurel, Mississippi on 25 January 1969. The NTSB report on this incident (NTSB 1969 RAR) states that 2 persons died, 33 received treatment in hospital and numerous others were given first aid. Some authors have therefore quoted this as 2 dead, 33 injured. Eisenberg, Lynch and Breeding (1975) refer to the NTSB report but also to a private communication from a railroad source and state that 976 persons were injured, 17 being in hospital for more than a month. This incident is one of those quoted by Hastrup and Brockhoff as an example of the problem.

Another illustration is provided by the explosion at Silvertown, London, on 19 January 1917. The account given later in this Appendix states that 68 were killed, 98 seriously injured, 328 had slight injuries and about 600 are thought to have received treatment in the street or from private doctors. Thus this account gives three separate categories of injury, without even mentioning hospitals.

A1.5 Reporting of Injuries at National Level

It is normal for there to be a regulatory requirement for the reporting, as a minimum, of deaths and injuries. In the UK the relevant regulations are RIDDOR 1985. The information gathered in this way is published by the HSE in the series Health and Safety Statistics.

The reporting is incomplete. A study supplementary to the household-based Labour Force Survey 1990 in the UK showed that only approximately 30% of non-fatal injuries were reported to the HSE, but that the level of reporting varied significantly across industries (Kiernan, 1992). For the energy industry the proportion of such accidents reported was 75%, and it seems probable that the level of reporting in process industries such as oil refining, petrochemical and chemicals is similar.

A1.6 Incident Diagrams, Plans and Maps

Many accounts of incidents give diagrams, plans or maps showing features such as derailed tank cars, location of missiles, location of victims, etc. In particular, such diagrams are a feature of the accident reports by the HSE and the NTSB and of case histories described in the Loss Prevention Bulletin.

Typical diagrams showing injury effects at an accident from an HSE report are given in Figure A1.19. A typical diagram of the site of an accident from an NTSB report is shown in Figure A1.16.

The NTSB system of Hazardous Material Spill Maps, documents separate from the accident reports, is described by the NTSB (1979), Benner and Rote (1981) and Lasseigne (1984). One such map is shown in Figure A1.2.

A1.7 Incidents Involving Fire Fighting

A feature of some interest in incidents is the experience gained in fire fighting. Some minimal information about this is given for selected case histories in Series A. Further information may be found in the following accounts:

- Brindisi, 1977 (Mahoney, 1990)
- Milford Haven, 1983 (Dyfed County Fire Brigade, 1983; Mumford, 1984 LPB 57)
- Thessalonika, 1986 (B. Browning and Searson, 1989)
- Grangemouth, 1987 (HSE, 1989a)
- Fort Heriot, 1987 (Mansot, 1989)

A1.8 Incidents Involving Condensed Phase Explosives

A number of the incidents given in the following sections involve explosives. There have been, however, a large number of other explosives and munitions incidents which are of only marginal interest here.

An account of explosions up to 1930 is given in History of Explosions by Assheton (1930) and later treatments are Explosions in History by N.B. Wilkinson (1966) and Darkest Hours by J.R. Nash (1976). Some principal explosions are listed by Nash. His list gives death tolls which in some cases differ from those given elsewhere. The incidents in which the number of deaths is quoted as 200 or more are

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Type</th>
<th>No. of deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1916</td>
<td>Nov. 16</td>
<td>La Satannaya, Belgium</td>
<td>Munitions</td>
</tr>
<tr>
<td>1917</td>
<td>Jan. 19</td>
<td>Silvertown, London</td>
<td>Munitions factory</td>
</tr>
<tr>
<td></td>
<td>Feb. 20</td>
<td>Archangel, Russia</td>
<td>Munitions ship</td>
</tr>
<tr>
<td></td>
<td>Jun. 23</td>
<td>Bloeweg, Belgium</td>
<td>Munitions factory</td>
</tr>
<tr>
<td></td>
<td>Aug. 6</td>
<td>Henningsdorf, Germany</td>
<td>Munitions factory</td>
</tr>
<tr>
<td></td>
<td>Dec. 6</td>
<td>Halifax, Nova Scotia</td>
<td>Munitions ship</td>
</tr>
<tr>
<td>1918</td>
<td>Aug. 3</td>
<td>Hamont Station, Belgium</td>
<td>Munitions ship</td>
</tr>
<tr>
<td></td>
<td>Sept. 22</td>
<td>Woellerdorf, Austria</td>
<td>Munitions factory</td>
</tr>
<tr>
<td>1925</td>
<td>May 25</td>
<td>Peking, China</td>
<td>Munitions store</td>
</tr>
<tr>
<td>1934</td>
<td>Mar. 14</td>
<td>La Libertad, Salvador</td>
<td>Explosives store</td>
</tr>
<tr>
<td>1935</td>
<td>Oct. 30</td>
<td>Lanchow, China</td>
<td>Munitions store</td>
</tr>
<tr>
<td>1941</td>
<td>Jan. 9</td>
<td>Fort Smederovo, Yugoslavia</td>
<td>Munitions store</td>
</tr>
<tr>
<td>1944</td>
<td>Apr. 14</td>
<td>Bombay, India</td>
<td>Munitions ship</td>
</tr>
<tr>
<td></td>
<td>Jul. 17</td>
<td>Port Chicago, CA</td>
<td>Munitions ship</td>
</tr>
<tr>
<td>1956</td>
<td>Aug. 27</td>
<td>Cali, Columbia</td>
<td>Munitions ship</td>
</tr>
</tbody>
</table>

* The death tolls given in the account in Section A1.10 are as follows: Silvertown 69; Halifax 1800; and Bombay Docks 350 (early reports)
This list does not include incidents involving primarily ammonium nitrate.
Other incidents given by Nash, with death tolls shown in brackets, are

**Munitions, explosives, powder factories**
1915 Oct. 20 Paris, France (52); Nov. 31 Eimmington, Delaware (31); Dec. 11 Havre, Belgium (110); 1916 Apr. 4 Kent, England (170); Dec. 6 Kent, England (26); 1917 Apr. 10 Chester, PA (133); Oct. 4 Morgan, NJ (64); 1924 Mar. 1 Nixon, NJ (26); 1925 Mar. 1 Kharpur, Turkey (160); 1926 Apr. 7 Mannheim, Germany (40); Aug. 12 Csepel, Hungary (24); 1929 Sep. 5 Brescia, Italy (22); 1931 Apr. 30 Nichteroy, Brazil (100); 1935 Jun. 13 Reinsdorf, Germany (52); Jul. 28 Taio, Italy (33); 1936 Jun. 15 Tallinn, Estonia (40); 1937 Jul. 17 Chungking, China (110); 1940 Aug. 29 Bologna, Italy (38); 1941 Jan. 10 Polichka, Czechoslovakia (80); 1943 Dec. 11 Grenoble, France (73); 1947 Aug. 18 Cadiz, Spain (149)

**Munitions, explosives stores and arsenals**
1916 Feb. 6 Skoda, Austria (185); Feb. 20 Nish, Serbia (43); Mar. 4 Fort Double Coronne, France (30); 1926 Jul. 19 Lake Denmark, NJ (30); 1928 Sep. 26 Ft Cabergeriza, Morocco (38); 1929 Mar. 4 Sofia, Bulgaria (28); 1931 May 5 Yuchu, China (100); Aug. 13 Macao, China (26); 1932 Jul. 10 Nanking, China (100); 1935 Oct. 23 Shanghai, China (190); 1944 Nov. 28 Fauld, England (175); 1945 Feb. 26 Paris, France (20); Jul. 7 Saragossa, Spain (30); Oct. 25 Ansier-en-Bessin, France (33); Dec. 29 Codroipo, Italy (23); 1946 Apr. 8 Saigon, Vietnam (23); 1949 Jul. 26 Tarancon, Spain (25); 1953 Apr. 6 Nantosce, Formosa (54); 1956 May 17 Takoradi, Africa (25); 1963 Aug. 13 Gauhati, India (32)

**Munitions, explosives shipments**
1916 Aug. 8 Koenigsberg, Germany (50); 1919 Feb. 1 Longwy, France (64); 1924 Dec. 27 Otaru, Japan (120); 1930 Dec. 3 Mida Garaa, Brazil (36); 1955 Sep. 23 Gomex Palacio, Mexico (40); 1960 Mar. 4 Havana, Cuba (100); 1964 Jul. 23 Bone, Algeria (85)

**Munitions, explosives (otherwise unspecified)**
1925 Nov. 22 Ahwaz, Persia (70); 1933 Jan. 20 Morelia, Mexico (23); 1934 Aug. 4 Nakang, Japan (25); 1953 Aug. 18 Benghazi, Libya (50); Sep. 12 Wiensdorf, Germany (20)

*The death toll given in the account in Section A1.10 is 68.

**A1.9 Case Histories: Some Principal Incidents**

Two series of case histories are given below. Series A consists of case histories chosen according to one or more of the following criteria: (1) the incident is well known, generally by name; (2) it involved major loss of life and/or property; and (3) the physical events and the escalation are of interest.

Series B consists of case histories of incidents which have not been selected for the A series and where in general the loss of life or property damage was less, but which are considered instructive, particularly in respect of the cause.

Generally, in the A series mention is made of deaths and injuries, but the cost of property damage is not given. However, many of the incidents figure in the thirteenth edition of *Large Property Damage Losses in the Hydrocarbon-Chemical Industries. A Thirty Year Review* by Marsh and McLennan (M&M), edited by Mahoney (1990), which gives the 100 largest losses. For these incidents, the cost is shown in Table A1.2.

**A1.10 Case Histories: A Series**

**A1 San Antonio, Texas, 1912**
On 18 March 1912 at San Antonio, Texas, workers were carrying out repairs on the boiler of a large locomotive. Steam pressure was being raised when something went wrong and the boiler exploded violently. One 1600 lb fragment travelled 1200 ft and a 900 lb one fetched up 2000 ft away. Twenty-six workers and residents were killed and another 32 were injured.

J.R. Nash (1976)

**A2 Ashton, Manchester, 1917**
On 13 June 1917 a nitrat in an explosives works at Ashton, Manchester, went out of control and ‘boiled’ over, releasing hot acid onto the wooden staging and starting a fire. The fire took hold in the nitrat house. Spectators were attracted, including children. Soon after there was a large explosion, involving some 5 tons of TNT. The explosion ruptured two gasholders nearby, setting them on fire. The flames were described as half a mile high.

Some 100 houses were demolished. 46 persons died, including 24 employees and 11 children. More than 120 were injured sufficiently to need hospital treatment. The explosion made two craters, one at the location of the TNT drums and one at that of the drier and setting trays. The former was 90 ft × 36 ft × 5 ft deep and the latter 30 ft × 15 ft and relatively shallow. Some 12 000 ft² of glass was replaced.

Billings and Copland (1992)

**A3 Halifax, Nova Scotia, 1917**
At about 8.48 am on 6 December 1917 the French ammunition ship *Mont Blanc* was rammed by the Belgian relief ship *Imo* in Halifax Harbor, Nova Scotia. The *Mont Blanc* was carrying in her hold some 4 661 794 lb of picric acid, 450 000 lb of TNT and 122 980 lb of guncotton as well as 486 762 lb of benzol on deck. The *Mont Blanc* burst into flame and at 9.05 am there was a massive explosion. The inhabitants heard a ‘thundering crash’ and many ran to their windows to see what had happened. The noise was heard 191 miles away and some windows broke at a distance of 61 miles.

The explosion tore the ship apart and hurled fragments all over the city. The anchor shank fetched up 3–4 miles away. The blast caused almost complete destruction within a radius of about three-quarters of a mile. There was severe structural damage at distances ranging from 1 to 1.75 miles. It was estimated that 95% of the glass in the city was broken. Fires caused by overturned stoves broke out in many parts.

Many people were killed when buildings were demolished. Large numbers suffered injury from flying glass and at least 500 people were totally blinded. In round figures, the death toll was put at 1800 and the number of registered wounded was 8000.

Assheton (1950); J.R. Nash (1976)
<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Location</th>
<th>Plant/transport</th>
<th>Chemical</th>
<th>Event</th>
<th>Deaths/injuries</th>
<th>Cost (million US$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1911</td>
<td>Glasgow, UK</td>
<td></td>
<td>DEX</td>
<td>5d, 8i</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1912</td>
<td>Liverpool, UK</td>
<td>Loco boiler</td>
<td>DEX</td>
<td>37d, 100i</td>
<td></td>
<td>9</td>
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</tr>
<tr>
<td>3</td>
<td>1914</td>
<td>Manchester, UK</td>
<td></td>
<td>Chlorine</td>
<td>3d, 5i</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1915 Sep. 27</td>
<td>Chrome, NJ</td>
<td>Rail tank car</td>
<td>DEX</td>
<td></td>
<td></td>
<td>3</td>
<td></td>
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<tr>
<td>5</td>
<td>1916 Jul. 30</td>
<td>Ardmore, OK</td>
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<td>Chlorine</td>
<td></td>
<td></td>
<td>10</td>
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<td>6</td>
<td>1917</td>
<td>Black Tom Island, NY</td>
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<td>7</td>
<td>Dec. 6</td>
<td>Ashton, UK</td>
<td>Chemical works</td>
<td>Chlorine</td>
<td>5d, many injured</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Jan. 19</td>
<td>Halifax, Nova Scotia</td>
<td>Ship</td>
<td>Muniitions</td>
<td>1963d, ≈8000i</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Wyandotte, MI</td>
<td>Morgan, NJ</td>
<td>Starch tank</td>
<td>Chlorine</td>
<td>1d</td>
<td></td>
<td>3, 7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1919</td>
<td>Cedar Rapids, IA</td>
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<td>64d</td>
<td></td>
<td>4</td>
<td></td>
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<td>11</td>
<td>1920</td>
<td>Niagara Falls, NY</td>
<td>Gas cylinder</td>
<td>Ammonium nitrate</td>
<td>3d</td>
<td></td>
<td>9</td>
<td></td>
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<td>12</td>
<td>1921 Aug. 24</td>
<td>Hull, UK</td>
<td>Storage tank</td>
<td>Ammonium nitrate</td>
<td>561d</td>
<td></td>
<td>6, 8, 14</td>
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<td>13</td>
<td>1922</td>
<td>Kriewald, Germany</td>
<td>Rail cars</td>
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<td>42d</td>
<td></td>
<td>4</td>
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<td>1923 Oct.</td>
<td>Oppau, Germany</td>
<td>Chemical works</td>
<td>Ammonium nitrate</td>
<td>2d</td>
<td></td>
<td>7</td>
<td></td>
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<tr>
<td>15</td>
<td>1924</td>
<td>Peking, IL</td>
<td>Starch plant</td>
<td>Ammonium nitrate</td>
<td>19d</td>
<td></td>
<td>10</td>
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<td>1925</td>
<td>De Noya, OK</td>
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<td>1d</td>
<td></td>
<td>3</td>
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<td>1926 Dec. 13</td>
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<td>1d</td>
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<td>3</td>
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<td>1927 Jul. 7, 13</td>
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<td>Phosgene</td>
<td>1d</td>
<td></td>
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<td>1928 May 20</td>
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<td>Syracuse, NY</td>
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<td>Chlorine</td>
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<td>21</td>
<td>1930</td>
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<td>Fuel plant</td>
<td>Hydrogen fluoride,</td>
<td>11d, 32i</td>
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<td>1930 Dec.</td>
<td>Lüttich, Belgium</td>
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<td>Sulphur dioxide</td>
<td>63d</td>
<td></td>
<td>9</td>
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<td>23</td>
<td>1932 Dec.</td>
<td>Detroit, MI</td>
<td>Storage</td>
<td>LPG</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
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<tr>
<td>24</td>
<td>1933 Feb. 10</td>
<td>Neunkirchen, Germany</td>
<td>Gasholder</td>
<td>EX</td>
<td></td>
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<td>6</td>
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<td>1934 Mar.</td>
<td>Hongkong</td>
<td>Gasholder</td>
<td>EX</td>
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<td>26</td>
<td>1934 Oct.</td>
<td>Niagara Falls, NY</td>
<td>Rail tank car</td>
<td>EX</td>
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<td>27</td>
<td>1935 Mar. 13</td>
<td>Griffith, IN</td>
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<tr>
<td>28</td>
<td>1936 Nov. 12</td>
<td>Johnsonburg, NY</td>
<td>Pipeline</td>
<td>Chlorine</td>
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<td>1939 Jan. 2</td>
<td>Newark, NJ</td>
<td>Pipeline</td>
<td>Oil film</td>
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<td>1940 Dec. 12</td>
<td>Wichita Falls, TX</td>
<td>Pipeline</td>
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<td>1941</td>
<td>Zarsn, Roumania</td>
<td>Storage tank</td>
<td>Chlorine</td>
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<td>32</td>
<td>1942 Jan. 26</td>
<td>Mjodalen, Norway</td>
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<td>33</td>
<td>1943 Dec. 24</td>
<td>Liverpool, UK</td>
<td>Chemical works</td>
<td>Ammonium nitrate</td>
<td>120d</td>
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<td>34</td>
<td>1944 Jan. 18</td>
<td>Los Angeles, CA</td>
<td>Road tanker</td>
<td>Butane</td>
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<tr>
<td>No.</td>
<td>Date</td>
<td>Location</td>
<td>Plant/transport</td>
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<td>Event</td>
<td>Deaths/injuries</td>
<td>Cost (million US$)</td>
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<td>40</td>
<td>Jul. 29</td>
<td>Ludwigshafen, Germany</td>
<td>Rail tank car</td>
<td>Butadiene</td>
<td>VCE</td>
<td>57d, 439i</td>
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<td>1944 Apr.</td>
<td>Bombay, India</td>
<td>Ship</td>
<td>Munitions</td>
<td>EX</td>
<td>&gt; 350, 1800i</td>
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<td>Gas cylinder</td>
<td>Chlorine</td>
<td>TOX</td>
<td>0d, 208i</td>
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<td>43</td>
<td>Oct. 20</td>
<td>Cleveland, OH</td>
<td>Storage</td>
<td>LNG</td>
<td>F</td>
<td>128d, 200-400i</td>
<td>3, 6, 7, 8, 10, 11</td>
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<td>44</td>
<td>Nov. 21</td>
<td>Denison, TX</td>
<td>Tank</td>
<td>LPG</td>
<td>F(?)</td>
<td>10d</td>
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<td>Nov. 27</td>
<td>Fauld, UK</td>
<td>Munitions store</td>
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<td>HEX</td>
<td>68d, 22i</td>
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<td>Corn mill</td>
<td>DEX</td>
<td>4d, 20i</td>
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<td>47</td>
<td>Jul. 17</td>
<td>Port Chicago, CA</td>
<td>Ships</td>
<td>Explosives</td>
<td>EX</td>
<td>321</td>
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<td>48</td>
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<td>Butane</td>
<td>VCE</td>
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<td>49</td>
<td>1947 Apr.</td>
<td>Brest, France</td>
<td>Ship</td>
<td>Ammonium nitrate</td>
<td>ANEX</td>
<td>21d</td>
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<td>Feb. 4</td>
<td>Chicago, IL</td>
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<td>Acetic anhydride, etc.</td>
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<td>17d, 130i</td>
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<td>TOX</td>
<td>2d</td>
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<td>Rauma, Finland</td>
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<td>19d</td>
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<td>Texas City, TX</td>
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<td>552d, ≥3000i</td>
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<td>207d, ≥3818 i</td>
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<td>1949 Dec.</td>
<td>Detroit, IL</td>
<td>Cat cracker</td>
<td>Propane, butane</td>
<td>VCE</td>
<td>5d</td>
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<td>Sep. 1</td>
<td>Freeport, TX</td>
<td>Pipeline</td>
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<td>Jun.</td>
<td>Nitro, WV</td>
<td>Reactor</td>
<td>TCDD</td>
<td>TOX</td>
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<td>HC5</td>
<td>EX</td>
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<td>63</td>
<td>Feb. 16</td>
<td>Midland, MI</td>
<td>Synthetic rubber plant</td>
<td>Butadiene, styrene</td>
<td>VEEB</td>
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<td>Plant</td>
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<td>Aug.</td>
<td>Wray, CO</td>
<td>Road tanker</td>
<td>Propane</td>
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<td>66</td>
<td>1951 Sep.</td>
<td>Avonmouth, Bristol, UK</td>
<td>Storage tank</td>
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<td>Aug. 16</td>
<td>Baton Rouge, LA</td>
<td>Naphtha treating</td>
<td>HCs</td>
<td>VCE</td>
<td>2d</td>
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<td>Port Newark, NJ</td>
<td>Storage</td>
<td>Propane</td>
<td>VCF</td>
<td>0d, 14i</td>
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<td>Dec. 22</td>
<td>Bound Brook, NJ</td>
<td>Phenolic resin plant</td>
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<td>5d, 21i</td>
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<td>VCE</td>
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<td>1957 Jan. 8</td>
<td>Montreal, Quebec</td>
<td>Turbogenerator</td>
<td>Chlorine</td>
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<td>BLEVE</td>
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<td>Ardmore, OK</td>
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<td>Augusta, GA</td>
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<td>VCE</td>
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<td>1959 Jan. 2</td>
<td>Deer Lake, PA</td>
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<td>1959 May 22</td>
<td>Signal Hill, CA</td>
<td>Tank farm</td>
<td>Oil froth</td>
<td>BLEVE</td>
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<td>1960 Dec. 17</td>
<td>Freeport, TX</td>
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<td>1960 Oct. 14</td>
<td>Kingsport, TN</td>
<td>Nitrobenzene plant</td>
<td>Reaction mixture</td>
<td>DET</td>
<td>15d, 60i</td>
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<td>1961 Feb. 23</td>
<td>Billingham, UK</td>
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<td>1961 Dec. 17</td>
<td>Freeport, TX</td>
<td>Caprolactam plant</td>
<td>Cyclohexane</td>
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<td>1962 Jan. 31</td>
<td>La Barre, LA</td>
<td>Air separation plant</td>
<td>Oxygen</td>
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<td>No.</td>
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<td>Location</td>
<td>Plant/transport</td>
<td>Chemical</td>
<td>Event</td>
<td>Deaths/injuries</td>
<td>Cost (million USS)</td>
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<td>114</td>
<td>Aug. 2014</td>
<td>Lake Charles, LA</td>
<td>Alkylation unit</td>
<td>Butane</td>
<td>VCE</td>
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<td>VCM</td>
<td>VEEB</td>
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<td>Berlin, NY</td>
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<td>118</td>
<td>Nov. 30</td>
<td>Cornwall, Ont.</td>
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<td>IE, VCE</td>
<td>89i</td>
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<td>Apr. 17</td>
<td>Doe Run, KY</td>
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<td>Fawley, UK</td>
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<td>Houston, TX</td>
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<td>Ras Tanura, Saudi Arabia</td>
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<td>2d, 34i</td>
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<td>Toledo, OH</td>
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<td>Acrylic polymer reaction</td>
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<td>Amsterdam, Netherlands</td>
<td>Trichlorophenol plant</td>
<td>Reaction mixture, including TCDD</td>
<td>IE, TOX</td>
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<td>Reactor</td>
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<td>Bay City, TX</td>
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<td>VCE</td>
<td>15.3</td>
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*Notes:*
- F: Fatal
- EX: Exposed
- REL: Respiratory symptoms
- VCE: Visual problems
- 7d: 7 days
- 2d: 2 days
- 3d: 3 days
- 1d: 1 day
- ≈: Approximately
- HUR: Hospitalization
- IE: Immediate exposure
- VCF: Visual complaints
- LPG: Liquid petroleum gas
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<th>Date</th>
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<td>North Blenheim, NY</td>
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<td>Porto de Leixhos, Portugal</td>
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<td>Ras Tanura, Saudi Arabia</td>
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<td>Aug 21</td>
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Alternative names

Abbreviations: FCC = fluid catalytic cracker; HC = hydrocarbon; HM = hazardous material; VCM = vinyl chloride monomer

Event abbreviations: ANEX = ammonium nitrate explosion; BLEVE = boiling liquid expanding vapour explosion; CD = criminal damage caused by vandalism, sabotage, etc.; DEL = delayed; DET = detonation (internal explosions only); DEX = dust explosion; EQK = earthquake damage; EX = explosion; F = fire; FB = fireball; HEX = high explosive explosion; HUR = hurricane damage; IE = internal explosion; POL = pollution; REL = release; TOX = toxic release; VCE = vapour cloud explosion; VCF = vapour cloud fire; VEEB = vapour escape into, and explosion in, building
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Costs are in US dollars and are taken from the M&M compilations. The great majority are the trended costs as given in the thirteenth, 1990 edition by Mahoney
(1990) and are thus in 1990 US dollars. Some values not included in the 1990 edition but given in the eleventh edition by Garrison (1988) have been converted to
1990 values, using a factor of 1.1; these are marked with an asterisk. Values for incidents in 1990 and 1991 given in the fourteenth 1992 edition by M&M (1992) are in
Principal references

Additional references

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LEES ± Loss Prevention in the Process Industries
Appendix 1

1; 2; 3; 4 J. R. Nash (1976); 5; 6; 7; 8 Assheton (1930); 9 Billings and Copland (1992); 10 Assheton (1930); J. R. Nash (1976); 11 Anon. (n. d. b); Ministry of Home
Security (n. d. a); Sainsbury (1977); 12; 13; 14; 15; 16 Slater (1978b); 17; 18 BASF (1921); Commentz et al. (1921); NBFU (1948); 19; 20; 21; 22; 23 Anon. (1928); N. C.
Èmcke and Evensen (1940); 37; 38 NBFU (1948); J.
Harris (1981b); 24; 25; 26; 27; 28 Anon. (1933a, b); 29; 30; 31; 32; 33; 34 P. Reed (1939); Armistead (1959); 35; 36 Ro
R. Nash (1976); 39 Slater (1978b); Strehlow (1973b); 40 Stahl, Strassman and Richard (1949); J. R. Nash (1976); Giesbrecht et al. (1981); D. J. Lewis (1983); 41 J. R.
Nash (1976); Patience (1989); 42 Chasis et al. (1947); 43 Moulton (1944); Coroner (1945); Elliott et al. (1946 BM RI 3867); Burgoyne (1965b); Strehlow (1973b); J. R.
Nash (1976); Marshall (1983 LPB 52); 44 Anon. (1952-53); 45 J. Reed (1977); Anon. (1992 LPB 103); V. C. Marshall (1992 LPB 105); 46; 47 J. R. Nash (1976); 48; 49 J.
R. Nash (1976); 50; 51; 52; 53; 54 Kintz, Jones and Carpenter (1948 BM RI 4245); NBFU (1948); Wheaton (1948); Blocker (1949); Blocker and Blocker (1949); J. R.
Nash (1976); 55 BASF (1948); Stahl, Strassman and Richard (1949); Giesbrecht et al. (1981); D. J. Lewis (1983); 56; 57; 58; 59; 60 Anon. (1949-50); 61; 62; 63; 64; 65;
66 H. E. Watts (1951); Anon. (1952); Kletz (1983 LPB 52); 67; 68 NBFU and FIRONT (1952); 69; 70 Jenkins and Oakshott (1955); Strehlow (1973b); D. J. Lewis
(1980): Alderson (1982 SRD R246); 71 NFPA (1957); 72; 73; 74; 75; 76; 77; 78; 79; 80; 81; 82; 83 Woodworth (1955); R.B. Jacobs et al. (1957, 1973); Randall et al.
(1957); 84; 85; 86; 87 Walker (1973); J. R. Nash (1976); 88; 89; 90; 91; 92 Lindley and Brown (1958); 93 Selway (1988 SRD 492); 94; 95; 96; 97; 98; 99; 100 Anon.
(1959a); Woodworth (1958); 101; 102; 103 Anon. (1960-61); Slater (1978b); Strehlow (1973b); Hymes (1985 LPB 65); 104 Schmitt (1964); 105; 106 Cronan (1960c); 107
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117 Walls (1963-64, 1964a); Strehlow (1973b); Strehlow and Baker (1976); 118; 119 Troyan and Levine (1968); 120; 121; 122; 123; 124 Laney (1964); Vervalin (1973e);
125; 126 Chementator (1962 May 28, 68); 127; 128; 129; 130; 131; 132; 133; 134; 135 Walls (1964b); 136; 137; 138; 139 Chementator (1964 Feb. 3, 36); 140 Bulkley and
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(1965 Mar. 29, 26; Aug. 2, 41); FPC (1966); 155; 156; 157; 158 Anon. (1966g, h); Strehlow (1973b); Vervalin (1973e); Kletz (1974e, 1975d, 1977d); Anon. (1987 LPB 77,
p. 1); Selway (1988 SRD R492); 159; 160 Chementator (1966 Jan. 31, 18); 161 Chementator (1966 Oct. 24, 55); Anon. (1967b); Fire J. Staff (1967, 1973d); 162; 163
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(1973e); Strehlow and Baker (1976); 172; 173; 174; 175; 176 NTSB (1968 RAR); 177; 178; 179 Medard (1970); 180; 181 Fontein (1968); Min. of Social Affairs and Public
Health (1968); Strehlow (1973b); Woodworth (1973); Strehlow and Baker (1976); 182 Slater (1978b); 183; 184; 185; 186 J. E. Browning (1969a); NTSB (1971 RAR-7102); 187 Anon. (1970a); 188; 189; 190; 191 NTSB (1970 RAR-70-02); Dowell (1971); Kogler (1971); Strehlow and Baker (1976); 192 NTSB (1971 PAR-71-01); 193 NTSB
(1969 RAR); 194; 195; 196; 197 R. H. Freeman and McReady (1971); Jarvis (1971); Keister, Pesetsky and Clark (1971); Griffith and Keister (1973); 198 Anon. (1970e);
199 Anon. (1969b); 200 Anon. (1971d); 201; 202; 203; 204 MacArthur (1972); 205 NTSB (1970 HAR-71-06); 206; 207 Watrous (1970); NTSB (1972 RAR-72-02); Strehlow
(1973b); Vervalin (1973e); Strehlow and Baker (1976); D. J. Lewis (1991 LPB 101); 208; 209; 210 NTSB (1971 PAR-71-02); 211; 212; 213; 214 Chementator (1970 Jun. 1,
63); 215 NTSB (1972 PAR-72-01); Burgess and Zabetakis (1973 BM RI 7752); Strehlow (1973b); Strehlow and Baker (1976); 216; 217; 218; 219; 220 Chementator (1971
Jul. 26, 55); 221 NTSB (1972 HAR-72-03); Cremer and Warner (1978); 222 Chementator (1971 Nov. 1, 23); NTSB (1972 RAR-72-06); Slater (1978b); 223; 224 Sarsten
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(1971 HAR-72-05); 233; 234; 235 NTSB (1973 RAR-73-01); Strehlow (1973b); Strehlow and Baker (1976); 236 NTSB (1973 PAR-73-02); 237 NTSB (1973 HAR-73-03);
Strehlow and Baker (1976); 238; 239 NTSB (1973 HAR-73-04); 240 Selway (1988 SRD R492); 241; 242; 243 Chementator (1973 Jan. 8, 51); D. J. Lewis (1989c); 244; 245
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(1974 PAR-74-06); Luddeke (1975); 255; 256 Lonsdale (1975); 257; 258 Anon. (1973j); 259; 260; 261 Chementator (1973 Mar. 5, 28; 1974 Apr. 1, 17); US Congress
(1973); D. J. Lewis (1989); 262 Chementator (1973 Jul. 23, 58; Nov. 12, 94); 263; 264; 265; 266 NTSB (1975 PAR-75-02); 267 Chementator (1974 Dec. 23, 21); 268; 269

CASE HISTORIES

(1) Simmons, Erdmann and Naft (1974); (2) Eisenberg, Lynch and Breeding (1975); (3) V. C. Marshall (1977b); (4) Harvey (1979b); (5) HSE (1978b); (6) Slater
È ller (1983); (11) V. C. Marshall (1987); (12) Haastrup and Brockhoff (1990);
(1978a); (7) Gugan (1979); (8) D. J. Lewis (1980d); (9) Harvey (1984); (10) Kier and Mu
(13) M&M (Garrison (1988b); Mahoney (1990); and M&M (1992)); (14) Lenoir and Davenport (1993); (15) D. J. Lewis (1993)

APPENDIX 1/24

Costs

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APPENDIX 1/25

Appendix 1

Notes:
a
Evidently including `excess deaths', characteristic of a severe pollution incident.
b
Gugan (1979) gives two incidents in 1966 in the FRG (his Nos 49 and 50). His No. 49 is named as Raunheim, while No. 50 has no more specific location. For both
the date is given as January and the reference as Bradford and Culbertson (1967). Incident No. 50 is not quoted by Lenoir and Davenport (1993).
c
Slater (1978a) cites an incident in Roumania in 1974 involving ethylene as a VCE with 1d, 50i; this was given in the first edition of this book. The present entry relies
on Anon. (1974k).
d
The figure for deaths refers to prompt deaths; it does not include abortions.

CASE HISTORIES

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Hoyle (1982); 270; 271; 272 NTSB (1975 RAR-75-04); Strehlow and Baker (1976); V. C. Marshall (1980d); 273; 274 R. J. Parker (1975); Strehlow and Baker (1976); 275
Adderton (1974); Strehlow and Baker (1976); 276; 277 NTSB (1975 RAR-75-07); Slater (1978b); 278 Sharry (1975); 279 NTSB (1975 PAR-75-01); 280; 281 NTSB (1974
RAR-74-04); 282 Anon. (1974n); 283; 284; 285 Anon. (1974k); Anon. (1974p); 286; 287 NTSB (1976 RAR-76-01); 288; 289; 290; 291; 292 Chementator (1975 Nov. 24, 17);
Min. of Social Affairs (1976); van Eijnatten (1977); Slater (1978b); 293; 294; 295 NTSB (1976 RAR-76-08); 296 NTSB (1976 PAR-76-05); 297 NTSB (1976 HAR-76-04);
298; 299 HSE (1976b); 300 NTSB (1976 PAR-76-03); 301 Slater (1978b); 302; 303; 304; 305 Chementator (1975 Oct. 27, 53); Anon. (1975n); 306 NTSB (1976 PAR-7607); 307; 308 HSE (1976a); 309 NTSB (1976 HAR-76-07); 310; 311; 312; 313 Anon. (1976n); Rees (1982); 314 NTSB (1977 RAR-77-07); 315 Chementator (1976 Aug. 30,
49); 316; 317; 318; 319: 320 Anon. (1976o); McMullen (1976); NTSB (1977 HAR-77-01); Fryer and Kaiser (1979 SRD R152); 321 HSE (1977b); 322; 323; 324; 325 Slater
(1978b); 326 NTSB (1978 MAR-78-06); D. J. Lewis (1984c); 327; 328; 329; 330 NTSB (1977 PAR-77-03); 331; 332 Temple (1977b); 333; 334; 335; 336; 337; 338; 339; 340
NTSB (1978 HAR-78-04); 341 HSE (1979b); 342 Anon. (1977b); 343; 344; 345 NTSB (1978 PAR-78-02); 346; 347; 348; 349; 350; 351; 352; 353; 354 NTSB (1978 RAR-7804); Stueben and Ball (1980); 355; 356 D. J. Lewis (1991 LPB 100); 357; 358 NTSB (1978 PAR-78-01); 359; 360 Anon. (1977c); Whelan (1977); Kletz (1988 LPB 81); 361
Anon. (1977p, q); Lathrop (1978); Nolan (1979); 362; 363; 364 Chementator (1978 Feb. 27, 64); 365; 366; 367 NTSB (1979 PAR-79-01); 368; 369 NTSB (1978 RAR-7808); 370; 371; 372; 373; 374 Anon. (1978m); 375; 376 Selway (1988 SRD R492); 377; 378 Anon. (1978b); NTSB (1979 RAR-79-01); D. J. Lewis (1992 LPB 105); 379; 380
Anon. (1978k); NTSB (1978 RAR-78-07); 381 Costello (1979); Anon. (1980a, v); 382; 383; 384; 385 NTSB (1980 PAR-80-02); van Meerbeke (1982); 386 NTSB
(1979 RAR-79-11); 387 NTSB (1980 MAR-80-18); 388; 389; 390 NTSB (1980 MAR-80-07); 391; 392; 393; 394 Mississauga News (1979); Amyot (1980); Grange (1980);
Fordham (1981 LPB 44); Lane and Thomson (1981); 395 NTSB Ann Rep. (1979); 396; 397; 398; 399 NTSB (1980 MAR-80-12); 400; 401; 402; 403; 404; 405; 406 HSE
(1980a); Anon. (1980r); 407 NTSB (1980 PAR-80-6); 408; 409; 410; 411; 412; 413; 414; 415 HSE (1981b); 416 NTSB (1980 HAR-80-05); 417; 418 NTSB (1981 RAR-8101); 419; 420; 421 NTSB (1980 PAR-80-01); 422; 423; 424; 425; 426 HSE (1981c); 427; 428; 429 Nilson (1983b); 430; 431 Anon. (1981 LPB 44); Anon. (1983 LPB 52);
432; 433; 434 HSE (1982a); Kletz (1983b); 435 NTSB (1983 HAR-83-01); 436 Garrison (1984 LPB 57); M. F. Henry (1986); 437; 438; 439; 440; 441 NTSB (1983 PAR-8302); 442; 443 NTSB (1983 RAR-83-05); Anon. (1984t); 444; 445; 446; 447 NTSB (1983 PAR-83-03); 448 NTSB (1983 PAR-83-01); 449 HSE (1983b); 450; 451 NTSB (1985
RAR-85-08); 452 NTSB (1983 PAR-83-04); 453; 454 NTSB (1985 RAR-85-10); 455; 456 Dyfed County Fire Brigade (1983); Mumford (1984 LPB 57); Golec (1985);
Steinbrecher (1986); 457; 458; 459; 460 NTSB (1984 PAR-84-01); 461; 462 Burgoyne (1985a); HSE (1985a); 463; 464 Anon. (1984oo); 465; 466 Anon. (1992 LPB 106);
467; 468 Pietersen (1985); Selway (1988 SRD R492); 469 NTSB (1985 PAR-85-01); 470; 471; 472 NTSB (1987 PAR-87-01); 473; 474; 475; 476 NTSB (1986 PAR-86-01);
477 NTSB (1985 RAR-85-12); 478; 479; 480; 481 NTSB (1986 RAR-86-04); 482; 483 NTSB (1985 PAR-85-02); 484; 485; 486 NTSB (1987 PAR-87-01); 487; 488 Anon.
(1986v, w, y); Beck (1986); D. Williams (1986); Anon. (1987 LPB 75); Stallworthy (1987); 489 B. Browning and Searson (1984); 490 Mellin (1991 LPB 100); 491; 492
Anon. (1987l); Anon. (1988c, d); Anon. (1989b); HSE (1989a); Kletz (1989b); K. C. Wilson (1990a, b); 493; 494; 495; 496 Mansot (1989); 497; 498; 499 NTSB (1989
RAR-89-04); 500; 501; 502 Prokop (1988); Wilkinson (1991 SRD R530); Mellin (1992 LPB 106); 503; 504; 505; 506; 507 Anon. (1991 LPB 100); 508; 509 NTSB (1991
RAR-91-04); 510 NTSB (1989 RAR-89-05); 511 Andersson (1991a, b); Kletz (1991a); Anon. (1992 LPB 107, p. 1); Anderson and Lindley (1992 LPB 107); Kukkonen et
al. (1992); Wilday (1992 LPB 108, 109); Kukkonen et al. (1993); 512; 513; 514; 515 OSHA (1990a); Kletz (1991j); 516 HSE (1990b); Anon. (1991 LPB 98, p. 24); 517;
518 NTSB (1990 PAR-90-02); 519 NTSB (1990 RAR-90-02); 520; 521 Hofheinz and Kohan (1989); 522; 523 Anon. (1991 LPB 101, p. 19); 524 NTSB (1991 MAR-91-04);
525; 526 Anon. (1990d); 527; 528; 529 Indian Petrochemicals Corp. (1990); 530 NTSB (1991 PAR-91-01); 531; 532 Anon. (1990g); 533; 534 Kletz (1990 LPB 100);
Mooney (1991); Redman and Kletz (1991); Cates (1992); van Reijendam et al. (1992); 535; 536; 537; 538; 539 Anon. (1991b); I. Thomas (1991); Anon. (1992c);
Croudace (1993 LPB 112); 540; 541; 542; 543 Anon. (1991d); 544; 545 Viera, Simpson and Ream (1993); 546; 547; 548 High Pressure Gas Safety Institute of Japan
Ènfeld (1993); Vennen (1993); 550 Reuter (1994); 551 Anon. (1995)
(1993 LPB 116); 549 Ondrey (1993a, b); Scho

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**A4 Silvertown, London, 1917**

On 19 January 1917 an explosion occurred at the Brunner Mond munitions factory at Crescent Wharf, Silvertown, London. A fire broke out at the melt pot room and took hold. It burned for some minutes when there was a massive explosion. Sixty nine people were killed and 98 seriously injured; there were 328 slight injuries recorded and about 600 were believed to have been treated in the street or by private doctors.

The report of the inquiry stated:

At the time of the explosion the total quantity of TNT on the premises amounted to 83 tons, of which 28 were crude, 27 in process and 28 finished, and there were, in addition, 9 tons of TNT oil in iron drums of which 5 tons were subsequently recovered... The outlines of the craters seem to indicate that altogether about 30 tons of TNT and the remaining 4 tons of TNT oil did not explode, but probably burned away. This would leave 53 tons of TNT to take part in the explosion.

TNT oil is alcohol containing the soluble impurities of TNT.

The explosion formed two separate craters. The smaller was circular in shape with a radius of about 25 ft and some 13 tons of TNT had been present in this area. The larger crater, in the area containing the remaining 40 tons of TNT, was kidney-shaped, with approximate dimensions 150 ft × 50 ft.

Anon. (n.d.b); Ministry of Home Security (n.d.a); Sainsbury (1977)

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**A5 Oppau, Germany, 1921**

At 7.29 a.m. and again at 7.32 a.m. on 21 September 1921 two terrific explosions occurred at the Oppau works of Badische Anilin und Soda Fabrik (BASF).

Figures for the death toll vary. Commentz *et al.* (1921) give the number of dead as 430, including 50 people in the village. According to V.C. Marshall (1987), following BASF (1958), the explosion killed 561, including 4 in Mannheim 7 km away, injured 1500 and destroyed 1000 houses, including 75% of those in Oppau itself. It created a crater 115 m long × 75 m wide × 10 m deep.

The works after the explosion is shown in Figure A1.3. Other effects of the explosion were as follows (Commentz *et al.*, 1921):

Houses in the adjacent city of Ludwigshafen and in Mannheim, which lies opposite to Ludwigshafen on the right bank of the Rhine, were damaged, walls were shaken down and practically all windows were broken. At these places and at Heidelberg, which is about 14 miles from Oppau, the effect of the explosion was first felt by two very heavy earthquake-like shocks. In Mannheim some seconds later and in Heidelberg 82 seconds after the shocks there came an enormous rush of air which broke windows and doors and caused damage to gas holders, oil tanks, and many river barges. The sound of the explosion reached as far as Bayreuth, at a distance of 145 miles, and the air pressure wave caused considerable damage in Frankfurt, which is about 53 miles from the scene of the explosion.
The explosion involved some 4500 tons of a 50:50 mixture of ammonium sulphate and ammonium nitrate. Detonation was set off by blasting powder, which was being used to break up storage piles of material which had become caked, a procedure which had been carried out without mishap some 16,000 times previously.

The danger of using explosives to break up caked ammonium nitrate had been demonstrated earlier in the year in Germany, when on 10 July at Kriewald this procedure led to the explosion of two rail wagons containing 15 te of that substance (D.J. Lewis, 1953).

BASF (1921, 1958); Commentz et al. (1921); J.R. Nash (1976); NBFU (1948); HSE (1978b); V.C. Marshall (1987); D.J. Lewis (1953)

A6 Hamburg, Germany, 1928
On 28 May 1928 a tank containing phosgene exploded at the Solzentalbunkers Germany, on the Hote-Kanal near the harbour area of Hamburg. The wind was at first northerly and then changed to the south-east. At one location 5 miles away the gas was strongly felt. People were also affected by the gas at locations 6 and 11 miles distant.

The prime source (Anon., 1928) states ‘Some 300 or more cubic feet of the gas were released’. V.C. Marshall (1987) suggests that this figure probably refers to the volume of the liquid, which would correspond to about 12 te, close to the figure of 11 te given by N.C. Harris (1981).

11 people were killed and 171 required hospital treatment.
Anon (1928); Hegler (1928); N.C. Harris (1981b); V.C. Marshall (1987)

A7 Neunkirchen, Germany, 1933
On 10 February 1933 an explosion occurred on a waterless gas holder in Neunkirchen in Germany. Work was being done on a bypass pipe between the inlet and outlet mains. Due to a series of actions which is not entirely clear, but which involved measures to bring misaligned flanges into alignment, a small explosion occurred at this bypass and ruptured the outlet main. A flame was seen to go up the side of the gasholder. It had burned for some 5 minutes when the main explosion occurred. The inquiry found that this explosion involved an air mixture which had formed above the piston.

The explosion caused 65 deaths and several hundred injuries.
Anon (1933a, b); Kier and Müller (1983)

A8 Wichita Falls, Texas, 1939
On 12 December 1939 an explosion occurred in a 10 inch diameter crude oil pipeline at Wichita Falls, Texas. A 38 mile section of the line had been emptied to locate and repair minor leaks. The method used was to pass a series of scrapers through the line propelled by air, which was odorized to assist in detecting the leaks, and then to displace the column of air by one of oil. During this latter procedure a scraper propelled by the oil struck one which had stuck in the pipe, evidently causing a spark. The result was an oil film explosion, in which the detonation travelled down the pipeline for over 26.8 miles, rupturing the line at intervals of about 80 ft.

The pattern of ruptures in the pipeline is shown in Figure A1.4.
P. Reed (1939); Armistead (1959); D.J. Lewis (1993)

A9 Tessenderlo, Belgium, 1942
On 21 July 1942 a massive ammonium nitrate explosion occurred at a chemical works at Tessenderlo in Belgium. The death toll is given as of the order of 200.
J.R. Nash (1976)

A10 Ludwigshafen, Germany, 1943
On 29 July 1943 a release occurred from a rail tank car in the BASF works at Ludwigshafen. The tank car contained 16.5 te of a mixture of 80% butadiene and 20% butylene. A vapour cloud formed and ignited. The resultant vapour cloud explosion demolished a block 350 x 100 m within the factory. Fifty-seven people were killed and 439 injured.

According to Giesbrecht et al. (1981), there was a delay of some 10–25 seconds between the rupture and the explosion. These authors indicate that the cause was hydraulic rupture of the tank due to overheating in the sun. If so, the incident is remarkably similar to one which occurred in the same works five years later, as described in Case History A17. Stahl, Strassman and Richard (1949); J.R. Nash (1976); Giesbrecht et al. (1981); D.J. Lewis (1983); V.C. Marshall (1986 LPF 67, 1987)

A11 Bombay, India, 1944
Just after 4.00 p.m. on 14 April 1944 in the Victoria Dock, Bombay, India, a massive explosion occurred on the munitions ship Fort Stikine.

The ship carried some 1400 tons of mixed munitions (bombs, shells, torpedoes, mines, etc.). On its way it had picked up a cargo of cotton. In No. 2 Hold 187 tons of ammunition was stored with cotton bales above, then 500 tons of oil, 1050 drums of lube oil, and finally more explosives. This was contrary to regulations, which stated that cotton is liable to spontaneous combustion if contaminated with oil. Further notes stated that cotton and explosives should be stored at opposite ends of the ship and that oil drums stowed above cotton should be limited to 250 barrels.

By midday on 14 April unloading of the ship was well under way. Soon after, crew on a nearby ship saw wisps of smoke coming from No. 2 Hold of the Fort Stikine, but did not inform the latter. Almost two hours passed before the fire was discovered. Water was applied to the hold using the ship’s three hoses.

The authorities recognized the seriousness of the situation and considered options such as moving or scuttling the ship, but both appeared impractical, since the ship’s engines were down for repair, there were no tugs available and the water was too shallow for scuttling. Moving the ship would also involve disconnecting the fire hoses laid from the dock into No. 2 Hold, which now numbered more than 30.

By 3.30 p.m. although an estimated 900 tons of water had been poured into the hold, the port deck was too hot to walk on and a large patch on the side was glowing red. At 3.50 p.m. a huge column of flame shot up from the hold and at 4.06 p.m. the first massive explosion occurred. Some 34 minutes later there was a second major explosion.

The first explosion killed 60 firemen and set up fires in a 900 m radius. As a result of the two explosions together 10 ships in the docks were destroyed or declared a total loss. Figures for the death toll differ.

A12 Cleveland, Ohio, 1944
At approximately 2.40 p.m. on 20 October 1944 a cylindrical LNG storage tank at the Liquefaction, Storage and Regasification Plant of the East Ohio Gas Company at Cleveland, Ohio, ruptured and discharged its entire contents over the plant and the nearby urban area. The LNG vapour ignited almost immediately and an intense fire burned at the plant, causing great loss of life and extensive damage.

More LNG flowed from the plant as liquid down storm sewers, where it mixed with air and exploded.

The final death toll was 128 and the numbers injured were estimated as 200-400. The greatest loss of life occurred within the plant area.

The plant was the first commercial LNG plant of its kind in the work. Its function was to liquefy and store natural gas during off-peak periods and to regasify it during periods of peak demand. The LNG was stored at 5 psi and −250°F. The plant was built on a site which had been in the company’s possession for 50 years. The site was close to residential and industrial areas.

The cause of the rupture is uncertain. The Bureau of Mines investigation (Elliott et al., 1946 BM RI 3867) concluded that the low carbon steel used in the construction of the vessel may have been unsuitable and that the failure may have occurred due to vibration or seismic shock.

It was pointed out in the report that most industries handling liquid oxygen or air used not carbon steel but stainless steel or suitable non-ferrous metals. Following this accident, the use of the latter materials became more widely favoured in applications of this kind.

The report recommended that the distance between a plant of this kind and the nearest inhabited building should be greater than half a mile.

Following the rupture large quantities of liquid topped by burning vapour had flowed considerable distances from the tank. The report discussed the argument that a dike is not useful for a relatively volatile material such as LPG or LNG, concluded that a dike would have reduced the hazard and recommended that storages for liquefied gases should have a dike.

The report also made a number of other recommendations. These included the open siting of storage tanks to permit good ventilation; the use of precautions to eliminate sources of ignition to the standard considered necessary in explosives plants; the provision of remote closure for the bottom of take valve; the installation of

Figure A1.4 Wichita Falls, 1939: pipeline after the explosion: (a) aerial view showing blackening where repeated ruptures of the pipeline occurred; and (b) elevation view, showing broken ends of the pipeline projecting through the ground (Bureau of Mines)
reliable level indicators and alarms; and the conduct of emergency drills.

Moulton (1944); Coroner (1945); Elliott et al. (1946 BM RI 3867); Burgoyne (1965b); Strelof (1973b); J.R. Nash (1976) (under East Ohio Gas Co.); D.J. Lewis (1980); V.C. Marshall (1983 LPB 52, 1987)

A13 Fauld, UK, 1944
On 27 November 1944 a huge explosion occurred in a munitions store at Fauld, Staffordshire. The store was underground in a former gypsum mine, mined on the ‘crown and pillar’ method. The explosion involved mass detonation of 3500 tons of bombs. Although the store was in the countryside, the explosion killed 68 people and injured 22. It created a massive crater covering 12 acres and 80 ft deep.

The store handled large quantities of bombs for the bombing offensive. This included the repair and re-issue of bombs recovered after jettisoning. The personnel were working under considerable pressure. The inquiry found that the most likely cause was ignorance and disregard of the regulations by personnel working on jettisoned bombs. An armourer testified that he had seen a colleague using a brass chisel to remove a broken exploder from one of the bombs, a practice expressly forbidden. Other witnesses confirmed that such irregularities were by no means uncommon.

J. Reed (1977); Anon. (1992 LPB 103); V.C. Marshall (1992 LPB 105)

A14 Port Chicago, California, 1944
On the evening of 17 July 1944 two vessels, the Quinault Victory and the E.A. Bryan, were berthed at Port Chicago, California, taking on large quantities of cordite and TNT when they were rent by a massive explosion. At dawn next day the vessels, and the 321 men on them, had disappeared. The cause of the explosion was never established, although some authorities implicate deteriorated munitions.

J.R. Nash (1976)

A15 Brest, France, 1947
On 28 July 1947 the vessel Ocean Liberty with a cargo of ammonium nitrate, exploded in the port of Brest, France, killing some 21 people.

J.R. Nash (1976)

A16 Texas City, Texas, 1947
At about 8.10 a.m. on 16 April 1947 fire was observed in bagged ammonium nitrate fertilizer on board the ship Grandcamp in the harbour at Texas City. There were 880 tons of ammonium nitrate in the hold affected and a further 1400 tons in another hold. Frantic efforts were made to extinguish the fire, but the quantity of water used initially was too small and by the time hose lines had been connected to supply larger quantities, the fire was so well established that the crew was ordered to abandon the ship. At 9.15 a.m. the Grandcamp disintegrated with a tremendous thunderclap, killing all persons in the dock, including firemen and a crowd of spectators.

Another ship, the High Flyer, which also had ammonium nitrate on board, was 700ft away and was blown free of its hawsers. On account of the danger of another explosion, volunteers could not be found to move the High Flyer out of the burning area. At 6.00 p.m. ignition of its sulphur cargo occurred. At 1.10 a.m. the next day the High Flyer was ripped apart by the expected explosion.

The report of the National Board of Fire Underwriters (1948) states:

When the Grandcamp blew up, the cargo of peanuts, tobacco leaves, balls of sisal twine, and oil-well drilling equipment were blown in all directions. Shrapnel-like fragments of the ship were hurled in high trajectory, 2000–3000 feet into the air; some travelled more than 10,000 feet from the point of origin. Some of the oil-well drill rods (30 feet in length and 7 inches in diameter, weighing close to 1½ tons) were hurled almost 2 miles and buried 8ft into the ground, like twisted hairpins...

It was virtually impossible to separate the effects of the two successive explosions, but, the report continues:

Daybreak revealed a sickening scene of devastation—demolished concrete structures, masses of twisted wreckage, crippled refineries with battered storage tanks, some crumpled like tin-foil, and sidings of distant warehouses blown apart as if ripped by a tornado. Pitch black columns of smoke from the burning oil tanks spiralled skyward for 3000 feet or more, and were visible for 30 miles. They burned continuously for almost a week. Insurance inspection showed blast damage to over 3,300 dwellings and 130
business buildings, to more than 600 automobiles and some 360 box cars. Approximately 50% of some 250 storage tanks, ranging from 25,000 to 80,000 barrels capacity, were substantially damaged either by concussion, missile or intense fire.

There were 552 deaths and over 3000 injuries in a community of some 15000 people.

Kintz, Jones and Carpenter (1948 BM RI 4245); Nat. Board of Fire Underwriters (1948); Wheaton (1948); Blocker (1949); Blocker and Blocker (1949); J.R. Nash (1976); V.C. Marshall (1983 LPB 52, 1987)

A17 Ludwigshafen, FRG, 1948

On 23 July 1948 a rail tank car containing dimethyl ether ruptured in the BASF works at Ludwigshafen. A vapour cloud formed and after some 6 seconds was ignited by hot work in a workshop. A block 230 m × 170 m was demolished and severe damage was done within an area 570 m × 520 m. The death toll was 207 and the number of injured 3818. The casualties appear to have been confined to the works, the dead all being between 15 and 65 and there being very few women's names listed.

The official report by Stahl, Strassman and Richard (1949) considered four hypotheses for the cause of the rupture: (1) the presence of organic peroxides, (2) the presence of non-condensables, (3) overheating leading to hydraulic rupture and (4) mechanical defects. They were able to rule out the first two and settled on the third: that the tank contents had been heated by the hot summer sun and that the tank, lacking a relief valve, had suffered hydraulic overpressure and rupture. This is the account generally given in the literature.

This explanation has been questioned by V.C. Marshall (1987). He points out that in order to obtain the pressure necessary to achieve hydraulic rupture the investigation was constrained to assume both that the tank was at least 4% smaller in volume than the norm, that this had not been remarked in 19 years of use and that the temperature reached was exceptionally high. He refers to the metallurgical analysis done at the time and described in the report, to the effect that the tank had weak spots. In addition, the tank had been involved the year before in an accident in which the valves had been knocked off. Further, the tank belonged to an ammonia plant and the plate giving the tare weight referred to the permissible filling limit for ammonia. Ammonia is known to cause embrittlement in some steels. The significance of the solar heating could well be that it increased the vapour pressure sufficiently to trigger the rupture.


Figure A1.5 Port Newark, 1951: tank section part buried in ground (The Bettman Archive)
A18 Avonmouth, UK, 1951
On 7 September 1951 a storage tank exploded at the Royal Edward Dock, Avonmouth, Bristol. The tank was being filled with gas oil from a ship. The gas oil was contaminated with petrol, which had leaked through a partition between the gas oil tank and the petrol tank, and this was known to those concerned. The tank was being splash filled and the explosion occurred as two men on the tank roof were gauging the level using a steel tape. The two men were killed.
Evidently a flammable atmosphere had formed in the vapour space of the tank and had been ignited by a discharge of static electricity. The official report (H.E. Watts, 1951) stated: ‘It was therefore quite possible for the steel dip tape to take up a charge of static electricity from the oil in the tank and to discharge it by means of a spark against the edge of the 10 inch manhole in the

Figure A1.6 Bakersfield, 1952: recycling plant after the earthquake (The Bettman Archive)
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top of the tank through which the tape had been inserted.’
H.E. Watts (1951); Anon. (1952); Kletz (1983 LPB 52)

A19 Port Newark, New Jersey, 1951
On 7 July 1951 a fire and BLEVEs devastated a large LPG storage at Port Newark, New Jersey. The storage comprised one section with 70 horizontal bullet tanks, each with a capacity of about 100 m³, and a further 30 tanks nearby. The tanks were not provided with thermal insulation or fixed water sprays. The initial event was experienced as a slight explosion followed by a fire. Within the next two and half minutes there were four small explosions near the seat of this fire, followed half a minute later by a large flash, a muffled explosion and a large fireball. Some 10–15 minutes into the event a BLEVE occurred. The next 100 minutes were punctuated by tank explosions and BLEVEs every 3–5 minutes. In all 73 bullet tanks were destroyed.

The tanks were equipped with emergency isolation valves. Some 30 seconds into the event the button to close these valves was pressed. It was pressed again after two and a half minutes, there being some doubt whether the first time it had been pushed for long enough. In fact, it is estimated that on the side of the valves away from the tanks there was some 100 m³ of LPG, mainly in a 12 in. delivery line from the docks and in 8 in. ring mains; thus there was potentially quite enough fuel to feed the fire even if the tanks themselves were isolated.

In many cases the BLEVEs were accompanied by fireballs rising 750 m into the air. Many of the events registered on the barometer at Newark Airport, showing TNT equivalent of around 25 kg, consistent with the pressure energy in the vapour space of a tank. The damage done by missiles is described as spectacular. One large tank section 17 m long travelled over half a mile, demolishing a filling station and starting a fire. Another fragment ruptured the 12 in. underground water main to the site. Figure A1.5 shows one of the tank section missiles part buried in the ground.

It has been suggested that a possible cause of the initial event was inadequate allowance for thermal expansion in the 8 in. ring mains. These handled propane at two different temperatures, the regular flows and a flow from a vapour recovery unit.

NBFU and FIRONJ (1952); D.J. Lewis (1980, 1993)

A20 Bakersfield, California, 1952
On 21 July 1952 the Paloma condensate recycling plant in Kern County, near Bakersfield, California, was struck by an earthquake. The earthquake had its epicentre about 12 miles away, measured 7.7 on the Richter Scale and had a maximum intensity in the range X–XI. Ground movement was of the order of 0.5 ft vertically and 1 ft horizontally. It was such as to cause a 60 ft high absorption column to swing at the top in an arc of 3 ft and to stretch its foundation bolts some 14 in. Figure A1.6 gives a aerial view of the facility following the earthquake.

The plant had five large butane storage spheres which were not designed to earthquake standards. Two spheres collapsed with rupture of the feed lines. Butane escaped and formed a vapour cloud, which ignited some 90 seconds later at a transformer block. The resultant explosion and fire did extensive damage but there were no deaths or serious injuries.

Jenkins and Oakshott (1955); D.J. Lewis (1980, 1993); Alderson (1982 SRD R246)

A21 Bound Brook, New Jersey, 1952
On 22 December 1952 a plant handling phenolic resin moulding powder at Bound Brook, New Jersey, was wrecked by a dust explosion. The explosion occurred in a dust collector and then travelled through ducting, emerging at several points into floor areas, where it raised clouds of dusts which in turn underwent violent secondary explosions. The probable sequence of events was that a bearing in a hammer mill overheated, the powder in the mill began to smoulder and the smouldering powder passed into a flammable dust mixture in the dust collector. Five people were killed and 21 injured.

NFPA (1957); D.J. Lewis (1993)

A22 Whiting, Indiana, 1955
On 27 August 1955 at the refinery at Whiting, Indiana, a reactor suffered an internal detonation and disintegrated. The reactor vessel was 127 ft tall x 22.5 ft diameter, having a wall 2½ in. thick and weighing 500 te. A separator with a 6 in. thick wall also fractured. The detonation has been estimated as having a TNT equivalent of 5.6 te. Fragments were thrown 1500 ft, one of 60 te landing on the tank farm and another killing a boy at home. The event started a fire which eventually covered 40 acres and lasted for 8 days. There was the one death just mentioned.

The event occurred in the course of start up of a hydroformer unit. The start up procedure involved the circulation through the reactor and separator of inert gas heated in a furnace. Due to a valving error the gas being circulated was in fact a flammable mixture. In due course, the gas temperature at the exit of the furnace rose to 500–600°F, reaching the autoignition temperature. A detonation occurred in the reactor and another in the separator vessel.

Woodworth (1955); R.B. Jacobs et al. (1957); Randall et al. (1957); R.B. Jacobs and Bulkeley (1967); R.B. Jacobs et al. (1973); D.J. Lewis (1980, 1993)

A23 Cali, Columbia, 1956
On 7 August 1956 eight trucks carrying dynamite exploded at Cali, Columbia, killing about 1100 people as they slept, and injured another 2000; some 500 of the dead were soldiers in barracks.

Walker (1973); J.R. Nash (1976)

A24 Uskmouth, UK, 1956
On 18 January 1956 an explosion occurred on the No. 5 60 MW turbogenerator set at the Uskmouth power station of the Central Electricity Authority. The low pressure turbine and generator were totally destroyed and the high pressure turbine and plant severely damaged. Fragments were ejected with considerable force, causing damage to the turbine house. Two persons were killed and nine injured. The cause of the incident was established as machine overspeed.

Lindley and Brown (1958)
A25 Montreal, Canada, 1957
On 8 January 1957 a series of BLEVEs occurred at a set of storage spheres at Montreal, Quebec. There were three spheres in a common bud: one 800 m$^3$, one 1900 m$^3$ and one 2400 m$^3$. The 800 m$^3$ sphere, which held butane, was overfilled due to a faulty level gauge. A vapour cloud formed and found an ignition source, probably at a service station 180 m away, and the flame flashed back to the sphere, where a pool fire started. After some 30 minutes the 1900 m$^3$ sphere, which was less than 20% full, underwent a BLEVE. Some 15 minutes later BLEVEs occurred on the other two spheres also.

Selway (1988 SRD R492)

A26 Signal Hill, California, 1958
On 22 May 1958 an 80 000 bbl tank serving as the feed tank to a viscosity breaking unit at the refinery at Signal Hill, California, erupted. Steam issued, part of the roof was torn off and oil froth flowed out. There was no initial ignition. The oil froth flowed through the plant in a wave about a metre high. A further eruption occurred and the froth ignited. Eventually it covered an area of 27 acres. The fire burned for 40 hours. Two people were killed and 18 injured.

The oil in the tank was at a temperature of 157°C. The source of the water which caused the eruption does not appear to be known; it may have been in the tank already or may have been pumped in by mistake.

Woodworth (1958); Anon. (1959a); D.J. Lewis (1993)

A27 Deer Lake, Pennsylvania, 1959
On 2 June 1959 in the township of Deer Lake, Pennsylvania, a road tank containing LPG slowed to a halt as a school bus in front stopped and was itself struck from behind by a truck. LPG escaped and was rapidly ignited. After some 15 minutes the fire brigade arrived and were told by the driver of the tanker that it would be protected from explosion by its safety valves. They directed water and foam at a nearby wooden building. A crowd of spectators gathered and police had difficulty in moving them on. After the fire had burned for a time variously estimated as 20 to 45 minutes the tanker suffered a BLEVE. Shrubbery at a distance of 150 m was scorched. The tank itself travelled up the street, bouncing off a stone wall. The tank, accompanied by stones and other debris, struck the main group of onlookers, killing most of them. There were 11 fatalities.

Hymes (1985 LPB 65)

A28 Meldrin, Georgia, 1959
On 28 June 1959 a derailment occurred of a rail tank cars containing LPG at Meldrin, Georgia, with tank rupture and release of LPG. A vapour cloud formed and reached a nearby leisure park. Ignition occurred and the resultant vapour cloud fire caused 23 deaths.


A29 La Barre, Louisiana, 1961
At about 8.15 a.m. on 31 January 1961 some 6000 USGal of liquid chlorine were spilled from a derailed tank car in the community of La Barre, Louisiana. A cloud of chlorine gas spread of over an area of approximately 6 square miles. For the most part it hung close to the ground, but in places ‘boiled upwards’ to a height of 80–90 ft. Some 1000 people were evacuated. A series of determinations of the chlorine concentration were made by a team using mobile equipment. The first samples were taken at about 11.15 a.m., when a concentration of 10 ppm was measured at the end of a contaminated area some 200 yd long on a highway parallel to the railway. At about 3.00 p.m. a concentration of 400 ppm was measured 75 yd from the wreck. One person died and about 100 were treated for exposure to chlorine. The fatality was an 11-month old infant in a family which lived in a house approximately 50 yd from the tank car. The chlorine in the house made the infant choke and gasp and the frantic father carried it outside, where the gas concentration was higher still. Although most of the exposure occurred inside the house, this exposure outside was probably critical. The child died in hospital. A 2-month old infant who remained in the house survived.

Joyner and Durel (1962)

A30 Berlin, New York, 1962
On 25 July 1962 a tractor tank semitrailer unit came off the road at Berlin, New York. The vehicle had failed to negotiate a bend, tipped over and jack-knifed. The tank hit a tree and its contents of some 6876 USGal of LPG were released. A vapour cloud formed which covered an area of some 2000 m$^2$ and was 25 m high. There followed a massive vapour cloud fire which caused the deaths of 10 people and injured 17.

Walls (1963–64, 1964a); Kier and Müller (1983)

A31 Doe Run, Kentucky, 1962
On 17 April 1962 at Doe Run, Kentucky, a plant for the manufacture of an ethanolamine from ammonia and ethylene oxide suffered a major explosion. The reactor was supplied with liquid ethylene oxide from a 25 m$^3$ storage vessel. The reactant transfer pumps were provided with an interlock system but problems had been experienced with this system and the control had reverted to manual. A backflow of ammonia occurred into the ethylene oxide tank. A reaction took place which might have been a reaction runaway or a decomposition. The vessel ruptured, releasing a large quantity of ethylene oxide. The vapour cloud ignited immediately, giving an explosion estimated to have had a TNT equivalent of 16 te.

It has been suggested that the mechanism of ignition was may have been free radicals from the initial, internal reaction.

Troyan and Levine (1968); D.J. Lewis (1980, 1993); Mahoney (1990)

A32 Marietta, Ohio, 1962
On 27 April 1962 at Marietta, Ohio, a benzene recycle pump on a phenol production unit became plugged with residue, and whilst attempts were being made to clear it, pressure built up in a stripper column. A 6 in. relief valve operated, discharging benzene vapour, which ignited. Missiles from the resulting explosion severed pipework, releasing large quantities of flammable liquids, which also ignited. One person was killed and three injured.

Mahoney (1990)

A33 Attleboro, Massachusetts, 1964
On 12 January 1964 an explosion occurred in a vinyl chloride polymerization plant at Attleboro, Massachusetts.
An illuminator port had been replaced on one of the reactors but not pressure tested. When the reactor was charged, a small leak developed. As the fitter was tightening the clamping ring, the glass chipped and he was injured; the leak developed. An estimated 4.5 t of vinyl chloride escaped into the building, ignited and exploded with an estimated TNT equivalent of 17.7 t. The explosion broke pipework on all the 20 reactors and released some 68 t of vinyl chloride, which ignited. There was a large fireball. Seven people were killed and 40 injured.

Walls (1964b); D.J. Lewis (1980, 1993); Mahoney (1990)

A34 Niigata, Japan, 1964
On 16 June 1964 the refinery at Niigata, Japan, suffered an earthquake of strength 7.7 on the Richter scale which caused two major fires. The first fire was the result of oil spillage from a floating roof storage tank. The oil was ignited by sparks as the roof smashed against the sides of the tank. Later, a seismic tidal wave engulfed the area and unignited oil spread over the water. For four hours this oil did not ignite. Six hours into the event an explosion occurred in another part of the refinery 1200 ft from the tank which was set of the original fire. This second fire spread to within 350 ft of the first fire but the two did not merge. Two people were killed and 97 storage tanks were destroyed.

Mahoney (1990)

A35 Bow, London, 1965
On 7 August 1965 a flour mill in Bow, London, suffered a dust explosion. The site of the explosion was a 15 t capacity metal flour bin on the third floor. Welding had been in progress shortly before and may have caused overheating of the metal and hence of the flour inside. Two major fires and many smaller ones broke out. Five people were killed and over 40 injured.

Anon (1967c); D.J. Lewis (1993)

A36 Louisville, Kentucky, 1965
On 25 August 1965 at Louisville, Kentucky, an explosion occurred on a plant manufacturing neoprene by polymerization of chlorobutadiene in a compressor circulating monovinyl acetylene (MVA). The investigation concluded that a mechanical failure had caused local overheating in the compressor and that this had led to decomposition of the MVA. There followed a series of explosions, a total of 10 occurring within 13 minutes and of 18 within 90 minutes. The escalation occurred due to transmission through pipework, flame impingement and missiles. Twelve people were killed and eight injured; all the deaths occurred within a radius of less than 100 ft from the original explosion.

Armstead (1966, 1973); Mahoney (1990); D.J. Lewis (1993)

Figure A1.7 Feyzin, 1966: fire at the storage vessels (United Press International)
A37 Natchitoches, Louisiana, 1965
On 4 March 1965 an explosion occurred on a 24 in. high pressure natural gas pipeline at Natchitoches, Louisiana. The explosion was apparently caused by the high pressure gas, there being no evidence of combustion in the pipeline. The splitting action of the pipe propagated the rupture for 27 ft along the pipe. The resultant blowout produced a crater 27 ft long, 20 ft wide and 10 ft deep. Three pieces of metal with a total weight of half a ton were hurled distances of 129–351 ft from the point of rupture. Within 60 seconds there followed an explosion which ‘incinerated’ an area of 13.8 acres. Seventeen people were killed.
FPC (1966); D.J. Lewis (1980)

A38 Feyzin, France, 1966
On 4 January 1966 at Feyzin refinery in France a leak on a propane storage sphere ignited, caused a fire which burned fiercely around the vessel and led to a BLEVE.
The operator had opened two valves in series on the bottom of the sphere in order to drain off an aqueous layer. When this operation was nearly complete, he closed the upper valve and then cracked it open again. There was no flow and he opened the valve further. The blockage, which was presumably hydrate or ice, cleared, and propane gushed out, but the operator was unable to close the upper valve. He did not think at once to close the lower valve and by the time he attempted this, this valve also was frozen open.
The alarm was raised and steps were taken to stop traffic on the nearby motorway. A vapour cloud about 1 m deep spread towards the road. It is believed that a car about 160 m distant on the motorway may have been the source of ignition. It was afterwards found that its engine was not running but its ignition was on and it may have been stalled by taking in a propane-rich mixture at the air intake. Flames appeared to flash back from the car to the sphere in a series of jumps.
The sphere was enveloped in a fierce fire. Its pressure relief valve lifted and the escaping vapour ignited.
The LPG storage installation of which the sphere was a part consisted of four 1200 m³ propane and four 2000 m³ butane spheres. The fire brigade was not experienced in refinery fires and apparently did not cool the burning sphere, presumably on the assumption that the relief valve would protect it. They concentrated instead on cooling the other spheres. About one and a half hours after the initial leakage the sphere ruptured, killing the men nearby. A wave of liquid propane was flung over the compound wall and flying fragments cut off the legs of the next sphere, which toppled so that its relief valve began to emit liquid.
The fire at the storage spheres is shown in Figure A1.7. Plate 32 shows a sphere, toppled and engulfed in flames. Figure A1.8 shows an outline in the ground of one of the victims.
The accident killed 18 people and injured another 81 and caused the destruction of five of the spheres as well as other damage.
Anon. (1966e, g, h); Kletz (1974e, 1975d, 1977d); Anon. (1987 LPB 77, p. 1); Selway (1988 SRD R492); Mahoney (1990); D.J. Lewis (1993)

A39 LaSalle, Canada, 1966
On 13 October 1966 at a plant at LaSalle, Canada, there was a runaway reaction in a styrene polymerization reactor. The bursting disc and dump line both operated, discharging material into the outside yard, creating a vapour cloud. A vapour fog also formed inside the building due to failure of a sight glass on the bursting disc vent. Ignition occurred and the vapour inside and outside the building exploded. It has been estimated that the release of styrene was 0.64 t and that the TNT
equivalent of the explosion was 6.6 t.e. Eleven persons died.


A40 Lake Charles, Louisiana, 1967
Just before dawn at 4.45 a.m. on 8 August 1976 a catastrophic explosion of a cloud of isobutane vapour occurred at the Cities Service refinery at Lake Charles, Louisiana. Seven people were killed and 13 injured and extensive damage was done.

The escape occurred at a valve on a 10 in. isobutane pipeline which ran between an alkylation unit and two storage spheres. The pipeline ran underground, but the valve was located in an open pit, which had filled with water from recent rain. The bolts on the valve bonnet had suffered severe corrosion by vapours from a leaking sulphuric acid pipeline nearby.

That morning operators observed bubbles in the water and realized that there was a leak on the valve. An operator cleared the isobutane by flushing it with 110 psi water from the alkylation unit to sphere No. 1. He then closed the inlet valve on that sphere and began to open that on sphere No. 2. At this point the weakened valve in the pit failed and a geyser of water rose in the air. The operator, thinking that he had made an error, reversed his procedure, closing the valve on sphere No. 2 and opening that on sphere No. 1. As a result, isobutane from sphere No. 1 passed down the pipe and issued from the failed valve.

The amount of isobutane which escaped was estimated as approximately 500 bbl. It formed a vapour cloud which covered about 5 acres. The explosion had the characteristics of a detonation. Calculations indicated that it was equivalent to 10–12 tons of TNT.

The explosion caused a major fire which burned for two weeks until the flammable material had been used up.

Goforth (1970); NFPA (1973); Vervalin (1973e); D.J. Lewis (1980, 1993)

A41 Pernis, The Netherlands, 1968
At 4.15 a.m. on 20 January 1968 an overflow was observed on slops tank 402 at the Shell refinery at Pernis. A hydrocarbon vapour cloud formed slowly over the adjacent area. At 4.23 a.m., after one or two smaller explosions, a violent explosion occurred which caused extensive blast damage and a large fire. The explosion was estimated to have been equivalent to 20 tons of TNT. The fire covered an area of about 250 x 300 m. Two people were killed and 85 were injured, mainly by flying glass.

Slops tank 402 was a 1633 m³ cone roof tank. Owing to cold weather during the previous two weeks, it had been necessary to heat the oil in the tank. It is believed that a layer of water-in-oil emulsion had built up, covering the coils and reducing the heat transfer from them to the oil layer above, so that a substantial temperature difference had developed between the two layers, and that vapour formation at the interface between the two layers initiated mixing, causing further vapour evolution so that the tank overflowed, the hydrostatic pressure at the bottom of the tank was reduced and violent boil-up occurred, giving the condition known as ‘slopopover’.

Fontein (1968); Min. of Social Affairs and Public Health (1968); Wordsworth (1973); D.J. Lewis (1980, 1993)

A42 Dudgeons Wharf, London, 1969
In 1969 an explosion occurred at Dudgeon’s Wharf, London, while an oil storage tank was being demolished. Six people were killed.

Anon. (1970a)

A43 Glendora, Mississippi, 1969
At about 2.45 p.m. on 11 September 1969 a train entered Black Bayou junction near Glendora, Mississippi, pulling 157 rail cars, including eight containing vinyl chloride monomer (VCM). A pedestrian was struck and injured, and application of the emergency brake caused a derailment of 15 cars.

At 3.30 p.m. the VCM manufacturer was informed that his chemical was involved and at 5.00 p.m. that the eight cars were derailed and that one was leaking. A technical expert was requested and the manufacturer sent the VCM plant superintendent, who had 25 years’ experience with the chemical.

At about 8.00 p.m. one of the VCM tanks was ruptured and leaking, and by 10.00 p.m. the leak had ignited. A heavy fog was noticed over the area and it was considered that it might be VCM. The railway management consulted the Handbook of Hazardous Materials, which stated that phosgene could be formed in VCM fires. They rang the company office, who advised that a hazard from phosgene was highly improbable and that the main problem was likely to be from HCl and smoke. Nevertheless, the railway management, the police, the National Guard and the Civil Defense Authorities continued to be worried by the phosgene hazard. The Civil Defense director consulted university chemists, who advised that burning VCM would release phosgene, which could be a hazard to life at a radius of 35 miles. Accordingly, the police and National Guard evacuated all the towns nearby. The evacuation was reported as involving some 30,000 people.

At 6.45 a.m. the next day an explosion occurred which demolished one of the eight VCM tank cars. The explosion caused a second tank car to rupture and ignite. After the fires were extinguished only five full tank cars were recovered.

A report in The Commercial Appeal of Memphis, Tennessee (13 September, 1969) read:

Dawn opened on this tiny Mississippi town Friday with an eerie display of a dirty yellow mushroom cloud rising with a clinging ground fog.

The silence was as thick as the fog, and just as unnatural. It was like something from an Alfred Hitchcock movie, one plantation manager was to remark later.

Throughout Thursday night, thousands of people in 11 Delta towns and outlying rural areas in a 25 mile radius were evacuated following the derailment of an Illinois Central train in Glendora.

For many it was a night of fear resulting from lethal gas being blown away from derailed railroad tank cars ... .

NTSB (1970 RAR-70-02); Dowell (1971); Kogler (1971)

A44 Laurel, Mississippi, 1969
At 4.15 a.m. on 2 January 1969 a freight train with 15 tank cars of LPG derailed in the centre of Laurel,
Mississippi. There was a explosion followed by a further explosion and fireball. The next 40 minutes were punctuated by more explosions as one car after another burst or rocketed. The initial fireball set fire to buildings 200–400 ft away. Other fires were initiated by burning fragments up to 10 blocks distant. The blast caused structural damage within about 400 ft. Very little glass survived within about half a mile and windows broke as far out as 3 miles. Two people died and 976 were injured.

Much of the damage was caused by the impact of rocketing tank cars and the fires which they set going. One 57 ft section travelled through the air and bounced first at 1000 ft distance, then bounced again at 300 ft, and again at 200 ft, and finally went another 100 ft, before coming to rest at a total distance of 1600 ft, where it set fire to houses.

At the first explosion people came out to see what was happening. The streets were full when the second explosion and fireball occurred. People became trapped between fences which ran parallel to the track and the towering fireball 200–400 ft away. There were many burn injuries, and many also from panic.

It is of interest that a National Guard ordnance team, in a controversial procedure, successfully used shaped explosive charges to blow holes in two unruptured tank cars to prevent them exploding.

NTSB (1969 RAR); Eisenberg, Lynch and Breeding (1975)

A45 Texas City, Texas, 1969
On 23 October 1969 at Texas City, Texas, an explosion occurred inside a distillation column of a butadiene unit. The explosion was experienced as a two-part one, first the disintegration of the column and then ignition of the escaping gas. Numerous fragments fell within a radius of 500 ft, some large shell fragments travelled 1500 ft and one 800 lb section fetched up 3000 ft away. All five columns in the butadiene section were toppled or severely damaged. Thirteen people were injured.

The column had been under total reflux. A leak occurred in an overhead line valve so that butadiene was lost and a build-up occurred of vinyl acetylene which on some trays reached a molar concentration of 50–60%.

The internal explosion occurred due to thermal decomposition of vinyl acetylene and ethyl acetylenes.

Freeman and McReady (1971); Jarvis (1971); Keister, Pesetsky and Clark (1971); Griffith and Keister (1973); Mahoney (1990); D.J. Lewis (1993)

A46 Beaumont, Texas, 1970
On 17 September 1970 at Beaumont, Texas, a 60 ft × 40 ft oil slops tank was struck by lightning. The tank failed at the shell-floor seam, releasing 11 000 USgal of oil, which burned. The oil spread to involve in the fire another 16 unbunded tanks nearby.

Mahoney (1990)

A47 Blair, Nebraska, 1970
On 16 November 1970 an overflow occurred on a 40 000 ton refrigerated anhydrous ammonia storage tank at the Gulf Oil Company’s installation at Blair, Nebraska. 160 ton of ammonia was released, but there were no deaths or serious injuries.

The overfilling was the result of an operator error. A factor which may have contributed to the error was the

Figure A1.9 Blair, 1970: ammonia cloud from storage tank: (a) plan view (Slater, 1978a); (b) aerial view showing ammonia cloud covering whole of foreground; and (c) ground level view showing “pancake” shape of cloud (both Enterprise Publishing Company, Blair, Nebraska)
fact that the table of tank levels, or ‘strapping table’, did not indicate clearly the position of the overflow pipe. In addition, the high-level alarm and shutdown system failed to operate and apparently the overflow discharge valve also failed to operate at the set pressure, so that the liquid level in the tank rose until it reached the roof, at which point the overflow valve did open. There was an isolation valve on the overflow line directly below the relief valve. It was not possible to reach this valve and close it on account of the ammonia cloud. If isolation of the overflow line had been possible, much of the overflow could have been prevented. Once the overflow valve had opened, there was a discharge of ammonia to atmosphere. The discharge continued for 2 h.

There was almost no wind and an atmospheric inversion existed, so that initially the weather conditions were at their most unfavourable for dispersion. A low visible cloud of ammonia formed some 8–30 ft thick, covering approximately 900 acres and extending over 9000 ft from the tank. The ammonia cloud shortly after the spill is shown in Figure A1.9. The ‘pancake’ shape of the cloud is clearly shown in Figure A1.9(c). Later, a light breeze arose and helped to keep the cloud from populated areas.

MacArthur (1972)

A48 Brooklyn, New York, 1970

On 30 May 1970 a road tanker carrying liquid oxygen was manoeuvring in the yard of a hospital in Brooklyn, New York, when the tank ruptured violently. The tank was 9.15 m$^3$ capacity but the tanker had just offloaded its first part load. The initial explosion killed the driver and one other person, and windows were broken some 600 ft away. The release of the liquid oxygen resulted in a number of fires. In addition to the two deaths mentioned, 30 people were injured.

The tank was new and had been in service only one month. The investigation found that the ⅞ in. thick aluminium tank shell had suffered appreciable loss of metal, the deficit being 73.5 kg for the shell and internal components. It further found that a chemical reaction had occurred between the oxygen and deposits left in a crevice between a bracket and the tank wall, and that this had generated enough heat to initiate an oxidizing
reaction between the shell and the oxygen vapour. This reaction also had the effect of heating the contents and increasing the vapour pressure. The estimated vapour pressure attained was over 100 bar compared with a design pressure of 15 bar.

NTSB (1971 HAR-71-06); D.J. Lewis (1993)

**A49 Corpus Christi, Texas, 1970**

On 3 August 1970 a refinery at Corpus Christi was hit by Hurricane Celia with winds of 140–160 miles/h and a rainfall of 6–8 in. The main structure of the catalytic cracker was toppled and some 30 tanks were destroyed.

Mahoney (1990)

**A50 Crescent City, Illinois, 1970**

At 6.30 a.m. on 21 June 1970 a derailment occurred on a railway passing through the streets of Crescent City, Illinois. Nine rail tank cars loaded with LPG were among the derailed vehicles. The force of the derailment propelled the 27th car in the train over the derailed cars on front and its coupler struck the tank of the 26th car and punctured it. Propane was released and ignited.

The safety valves of the other tank cars operated and released propane, which fed the fire. At about 7.33 a.m. the 27th car exploded. Four fragments of the tank car were hurled in different directions for distances of 300, 600 and 750 ft. At about 9.40 a.m. the 28th tank car exploded, hurling one fragment which eventually stopped rolling at a distance of 1800 ft. At about 9.45 a.m. the 30th tank car exploded and about 10.55 a.m. the 32nd and 33rd tank cars ruptured almost simultaneously. Fragments from these damaged the 34th and 35th tank cars and caused them to release propane.

The main mechanism of damage in this incident was the rocketing of burning tank cars which hurled massive fragments and fresh fireballs up to 850 ft from the site of the derailment.

The fireball produced by the contents of one of these tank cars, which contained 33,000 USgal (120 m³) of LPG, is shown in Figure A1.10. The fireball was several hundred feet high.

Another photograph of a fireball in this incident is given in Plate 33.

There were no fatalities, but 66 people were injured. There was extensive property damage.

Watrous (1970); NTSB (1972 RAR-72-02); Strehlow (1973b); Eisenberg, Lynch and Breeding (1975); D.J. Lewis (1980, 1991 LPB 101, 1993)

**A51 Linden, New Jersey, 1970**

On 5 December 1970 in a refinery at Linden, New Jersey, local overheating in a hydrocracker unit caused an explosive failure of the 7 in. thick vessel. Severe damage was done to plant over a 300 yard radius, including a catalytic cracker and crude pipe still, where the control room roof collapsed. Shutdown of the other units was effected from a blast resistant control room, which suffered minor damage. Forty persons were injured.

Mahoney (1990)

**A52 Port Hudson, Missouri, 1970**

At 10.07 p.m. on 9 December 1970 an abnormality occurred at a pumping station at Villa Ridge, 15 miles downstream from Port Hudson, Franklin County, Missouri. At 10.20 p.m. there was a sudden increase in throughout at the next upstream pumping station at Rosebud, indicating a major line break. The pipeline failure had occurred near Highway C on high ground and the gas cloud flowed down a sparsely inhabited valley.

At approximately 10.25 p.m. several witnesses became aware of the noise of the escaping jet of propane. A plume of white spray, which was presumably drops of propane and of atmospheric moisture, was seen rising 50–80 ft above the ground. By 10.44 p.m. several families had evacuated their houses and had driven to Highway C, from which they observed the cloud.

At approximately 10.44 p.m. the valley appeared to light up. Witnesses reported no observable period of flame propagation but rather a sudden flash as of lightning. There was an almost immediate overpressure which knocked over one person who was walking about half a mile from the centre of the cloud.

In the Bureau of Mines report on the incident, Burgess and Zabetakis (1973 BM RI 7752) state: ‘We think the witnesses has the unusual experience of observing a gas detonation’. In the succeeding seconds a fire storm was seen to roll up the sloping terrain towards Highway C.

At the time and place of the failure the pipeline pressure was believed to be about 942 psig. The amount of liquid propane which is estimated to have escaped in the first 24 min is 750 bbl.

Burgess and Zabetakis estimate that since the propane issued from the pipe at approximately 1°C, the fraction flashing off would be about a quarter, but that a further appreciable fraction formed drops in the 50–80 ft plume seen by witnesses and that these drops derived their heat of vaporization from the air.

For the estimation of the concentration of propane in the vapour cloud Burgess and Zabetakis use the Pasquill–Gifford model, their work antedating the development of models for heavy gas dispersion and for complex terrain. Thus

\[
\chi = \chi_{cl} \exp \left\{-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{z}{\sigma_z} \right)^2\right\}
\]

[A1.1.0.1]

with

\[
\chi_{cl} = \frac{Q}{\pi \sigma_y \sigma_z H}
\]

[A1.1.0.2]

where \(y\), \(y\), \(z\) are the downwind, crosswind and vertical distances (ft); \(Q\) is the flow rate of propane (ft³/s); \(u\) the average wind velocity (ft/s); \(\sigma_y\), \(\sigma_z\) are the standard deviations in the \(y\), \(z\) directions (ft); \(\chi\) is the concentration of propane (volume fraction); and \(\chi_{cl}\) is the concentration of propane on the centre line (volume fraction).

The calculation given by Burgess and Zabetakis may be summarized as follows. The flow rate \(Q\) of propane is 900 ft³/s at STP, the wind velocity is 8 ft/s and the stability category may be taken as category F in the nomenclature of D.B. Turner (1970). The plume dispersion coefficients \(\sigma_y\) and \(\sigma_z\) are obtained from the graphs given by this author. The lower and upper detonability limits of propane in air given by Benedick, Kennedy and Morosin (1970) are 2.8 and 7.0%, respectively.

The dimensions of the detonable plume thus calculated are shown in Table A1.3 and in Figure A1.11. The total
Table A1.3  Calculated dimensions of detonable plume of propane formed at Port Hudson, Missouri, on 9 December 1970 (after Burgess and Zabetakis, 1973 BM RI 7752) (Reproduced by permission of the Bureau of Mines)

<table>
<thead>
<tr>
<th>Downwind distance (ft)</th>
<th>Plume dispersion coefficients</th>
<th>Centre line concentration (% CL)</th>
<th>Distance from plume axis to rich (r) and lean (l) concentration limits (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>13</td>
<td>7.9</td>
<td>35, 23, 29, 14.2, 17.9</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>10.5</td>
<td>17, 26, 38, 13.9, 20.0</td>
</tr>
<tr>
<td>700</td>
<td>26</td>
<td>14</td>
<td>10, 21, 42, 12.0, 22.4</td>
</tr>
<tr>
<td>870</td>
<td>—</td>
<td>—</td>
<td>7.0, 0, 0, 0, 0</td>
</tr>
<tr>
<td>1000</td>
<td>36</td>
<td>18</td>
<td>5.6, 43, —, —, 21.4</td>
</tr>
<tr>
<td>1400</td>
<td>50</td>
<td>24</td>
<td>3.0, 17, —, 8.2</td>
</tr>
<tr>
<td>1470</td>
<td>—</td>
<td>—</td>
<td>2.8, 0, —, 0</td>
</tr>
</tbody>
</table>

Figure A1.11  Port Hudson, 1970: calculated dimensions of detonable plume of propane (after Burgess and Zabetakis, 1973 BM RI 7752) (Courtesy of the Bureau of Mines)

The mass of gas in 1100000 ft³ of 4.9% propane–air mixture at a temperature somewhat less than ambient is about 100000 lb. The enthalpy release on detonation is 260 kcal/lb. This compares with approximately 500 kcal/lb for TNT. The TNT equivalent of detonable gas is therefore approximately 50000 lb.

Burgess and Zabetakis also present a second calculation which attempts to take better account of the heavier-than-air density of propane–air mixtures and uses the following relations given by Singer and Smith (1953) for gustiness category D:

\[
\sigma_y = 0.44\sigma_z^{0.71}
\]  
\[
\sigma_z = 0.2\sigma_y
\]

This calculation gives the volume of the detonable zone as 1500000 ft³.

Burgess and Zabetakis give an analysis of the blast damage data in both the near and far fields of the explosion. Estimates of the TNT equivalent of the explosion range, with one exception, from 97000 to 150000 lb in the near field, while an estimate in the far field is 98000 lb. This compares with estimates in the range 50000–75000 lb of TNT equivalent inferred from the volume of the detonable cloud.

The efficiency of explosion is calculated by Burgess and Zabetakis as follows. If the 750 bbl of propane which are estimated to have escaped had detonated as a homogenous stoichiometric mixture with air, the enthalpy release would have been \(666 \times 10^9\) kcal.
enthality of detonation of TNT is 10\(^8\) kcal/ton. The explosion was equivalent to some 50 ton of TNT. Thus the explosion gave 50/666  or 7.5% of the maximum theoretical yield, based on combustion of the whole cloud.

The source of ignition of the cloud is uncertain, but Burgess and Zabetakis conclude that it was probably located in one of a group of outbuildings enveloped in the cloud.

The explosion caused no deaths.

NTSB (1972 PAR-72-01); Burgess and Zabetakis (1973 BM RI 7752); Streilow (1973b); Eisenberg, Lynch and Breeding (1975); D.J. Lewis (1980, 1985)

A53 Houston, Texas, 1971

At 1:44 p.m. on 19 October 1971 20 freight cars were derailed at Mykawas Station, which is 10 miles south of the centre of Houston, Texas. Six of the tank cars contained vinyl chloride monomer (VCM) and two others butadiene and acetone. Two of the VCM tank cars punctured. An explosion and fire occurred while the crashed tank cars were still moving. The two punctured tank cars stopped in the burning area. At 2:30 p.m. there was a violent explosion when one of the tanks containing some 100 000 lb of VCM burst, hurling fragments and giving a large fireball. Further tank cars burst, feeding the fire and generating additional missiles.

One fireman was killed and some 50 people, many of them firemen, were injured. The area was sparsely built and populated and damage was slight.

NTSB (1972 RAR-72-06); Eisenberg, Lynch and Breeding (1975); D.J. Lewis (1980)

A54 La Spezia, Italy, 1971

On 21 August 1971 a rollover occurred in an LNG tank at the SNAM LNG terminal at La Spezia, Italy. There was a sudden increase in pressure resulting in discharges from the tank safety valves and vent. The safety valves discharged for about 75 minutes and the vent discharged at a high rate for 3 hours and 15 minutes.

The incident occurred 18 hours after the tank had been loaded from the Esso Brega. The loading had been done through a nozzle at the side of the bottom of the tank, with the heavier, hotter cargo staying on the bottom and displacing the lighter, colder 'heel' of LNG, which had remained in the tank. These conditions were temporarily stable, but over the subsequent period the density of the upper layer increased and that of the lower layer decreased, eventually inducing the rollover. One factor was that the temperature difference between the two layers caused the upper layer to heat up and to become more dense due to boil-off of the lighter fractions. Another factor was a failure of the control valve some 4 hours before the rollover, which caused a reduction in the pressure in the tank which in turn increased the boil-off.

Sarsten (1972)

A55 Longview, Texas, 1971

On 25 February 1971 a 4 in. high pressure ethylene gas pipe broke in a plant near Longview, Texas, and released 1000 lb of ethylene. The vapour cloud found a source of ignition and exploded. The explosion broke numerous other pipes and caused the release of tonnage quantities of ethylene. The resultant larger vapour cloud in turn was ignited and gave a violent explosion.

Four people were killed and 60 were treated in hospital.

Detailed information on the blast damage is given by Eisenberg, Lynch and Breeding (1975).

Eisenberg, Lynch and Breeding (1975); Lauderback (1975); D.J. Lewis (1980)

A56 Pensacola, Florida, 1971

On 11 September 1971 a pipe ruptured on a caprolactam plant at Pensacola, Florida, and released about 74 000 lb of cyclohexane at high pressure and temperature. A dense white cloud of cyclohexane vapour and mist formed which was estimated at over 100 ft high and about 2000 ft across at its maximum. The wind was very calm, but picked up slightly after the rupture.

The cloud was rich enough to stall two trucks enveloped in it from lack of oxygen. Vapour from the cloud was drawn into a power house furnace so that the stack emitted black smoke. However, the cloud did not ignite and eventually dissipated harmlessly.

Eisenberg, Lynch and Breeding (1975); W.B. Howard (1975b); D.J. Lewis (1980); Stueben and Ball (1979)

A57 East St Louis, Illinois, 1972

At about 6.20 a.m. on 22 January 1972 a rail tank car loaded with propylene collided with a stationary hopper car in the Alton and Southern Railway Company's Gateway yard at East St Louis, Illinois.

The tank car had come from the hump classification yard at overspeed. The overriding coupler of the hopper car punctured the tank, the propylene escaped and formed a large vapour cloud which then ignited and exploded.

More than 230 people were injured and extensive damage was done.

The NTSB investigation (1973 RAR-73-01) concluded that the accident was probably caused by the failure of the retarder system in the hump classification yard to decelerate effectively heavy tank cars with oil or grease on their wheel rims, by the absence of a backup system to halt cars passing through the retarders at overspeed and by the routine acceptance of such overspeeds.

NTSB (1973 RAR-73-01); Streilow (1973a); Eisenberg, Lynch and Breeding (1975); D.J. Lewis (1980)

A58 Hearne, Texas, 1972

At 12.30 a.m. on 14 May 1972 a rupture occurred on an 8 in. crude oil pipeline near Hearne, Texas. Crude oil sprayed into the air from a 6 in. split in the top of the pipe, showering the surrounding countryside with oil. The oil flowed along a stream beneath a railway and a highway, and collected in a stock pond 1800 ft from the break.

At 5.00 a.m. the crude oil was ignited by an unknown source. The resultant explosion and fire killed a man and seriously burned two other people. An intense fire several hundred feet high and 1800 ft long burned on the surface of the oil and along the stream, at the railway, the road and the stock pond, and scorched the whole area.

The quantity of oil which escaped and burned was 7913 bbl (332 346 USgal). Some 10% of the oil was fractions lighter than hexane. The mode of break was such as to encourage the separation of these light
hydrocarbon fractions and the formation of a flammable gas cloud. 
NTSB (1973 PAR-73-02); Eisenberg, Lynch and Breeding (1975)

A59 Lynchburg, Virginia, 1972
On 9 March 1972 at Lynchburg, Virginia, a tractor 
semi-trailer tank truck carrying LPG overturned and punctured. A 32 in. hole appeared and some 4000 of 
the load of 9208 USgal escaped before the liquid level 
fell below the hole. A vapour cloud formed and gave rise to 
a fireball. The radius of the fireball was estimated as at 
least 400 ft. Three eye-witnesses standing beside their 
cars at 450 ft distance were severely burned by thermal 
radiation but were not touched by the flames. Two 
persons died and at least five were injured. 
NTSB (1973 HAR-73-03); Eisenberg, Lynch and Breeding (1975)

A60 New Jersey Turnpike, 1972
On 21 September 1972 on the New Jersey Turnpike a tractor 
semi-trailer tank truck carrying 7209 USgal of 
propylene sideswiped a bus. The tractor’s fuel tank and 
the fittings on the propylene tank were damaged and fuel 
and propylene leaks occurred. A friction spark from the 
collision ignited the fuel leak and the fire spread to the 
propylene leak. After some 20–25 minutes the tank 
exploded with a huge fireball. Fragments of the tank 
rocketed: the front section, comprising three-quarters of 
the tank, was found 1307 ft to the north-east; the rear 
head was found 540 ft to the south-west and the rear one 
quart cylindrical section 229 ft to the south-west; tank 
components were mainly strung out in a line stretching 
850 ft to the south-east. Two persons were killed and 28 
injured. 
NTSB (1973 HAR-73-04); Eisenberg, Lynch and Breeding (1975)

A61 Rio de Janeiro, Brazil, 1972
On 30 March 1972 a BLEVE occurred on an LPG 
sphere, one of five, at the Duque de Caxais refinery, Rio 
de Janeiro, Brazil. An operator was engaged in draining 
water from the bottom of a 1600 m³ sphere. He went 
away, leaving open a 2 in. drain valve. When he 
returned, he found that he could not reach the valve to 
turn the flow off, because the jet of liquid, now LPG, had 
created a crater in the crushed stone under the sphere. 
A vapour cloud formed, ignited and flashed back to the 
sphere. Some 15–20 minutes later the relief valve opened and 
the material released ignited. The sphere then 
suffered a BLEVE. Thirty-seven people were killed and 
53 injured. The other four storage spheres survived. 
Mahoney (1990); Selway (1988 SRD R492)

A62 Austin, Texas, 1973
At 10.53 p.m. on 22 February 1973 at Austin, Texas a 
10 in. pipeline failed and released 278,880 USgal of NGL. 
The release blew a 10 ft diameter hole in the ground and a 
vapour cloud spread over the area. Soon after 
11.00 p.m. two cars entered the cloud and stalled; their 
drivers got out. Then a van drove into the cloud and also 
stalled; the passengers got out, whilst the driver tried to 
restart. A large spark emerged from beneath the van and 
flames leaped hundreds of feet in the air. The fire 
burned through the cloud and the eight people in it were 
engulfed in flames. Four died immediately, two later and 
two sustained severe burns. 
NTSB (1973 PAR-73-04); Eisenberg, Lynch and Breeding (1975)

A63 Kingman, Arizona, 1973
On 5 July 1973 a BLEVE and fireball occurred on a rail 
tank car containing propane at Kingman, Arizona. The 
upper surface of the tank had been heated by jet flames 
from a relief valve and coupling leak. 
The event is captured in the NFPA film ‘BLEVE’ and 
has been analysed by Crawley (1982). The tank was a 
‘jumbo’ one and he estimates that the tank capacity was 
150 m³ but assumes that it was perhaps half full. He 
assesses the diameter of the fireball as 400 ft and its 
duration as 10–15 seconds. The estimates given by V.C. 
Marshall (1987) are that some 45 te of propane took part 
and that the fireball radius was 150 m. 
Despite police advice a large crowd of spectators had 
gathered and more than 90 were injured. 
Crawley (1982); Hynes (1985 LFB 65); V.C. Marshall 
(1987)

A64 McPherson, Kansas, 1973
At 4.30 a.m. on 6 December 1973 a major leak occurred 
on the Mid-America Pipeline System at the Conway 
pump station near McPherson, Kansas. Prior to the leak 
an ice storm had been raging for two days and the pump 
station had lost power for 18 hours, although it was 
partially restored by 3.00 a.m. The pipeline had been 
shut down and upon start-up at 4.12 a.m. a block valve 
failed to open, the line was overpressured and burst at a 
point where it had already sustained construction 
damage. 
An estimated 230 tons of anhydrous ammonia escaped 
over a period of half an hour. A low, visible plume of 
ammonia formed and drifted over Highway 56, which is 
some 1000 ft to the south. The weather conditions were 
very stable with a wind speed of some 3–10 mile/h and 
the plume remained narrow. Irritation symptoms were 
experienced and odour was detectable for about 3½ and 8 
miles from the escape, respectively. 
The incident caused no serious casualties. Many 
residents had moved into a nearby town on account of 
power failures caused by the severe weather. Two truck 
drivers drove into the gas cloud on the highway. They 
escaped and were kept in hospital several days. People in 
dwellings ½ mile south of the leak and directly in the 
cloud path were safely evacuated by the Sheriff’s office 
and company personnel. 
By 4.30 p.m. the line had been stopped. 
The same pipeline failed again on 13 August 1979 at a 
point about 22 miles from the first failure. There was a 
release of some 360 tons of anhydrous ammonia. Again 
there were no casualties, but there was a large fish kill. 
NTSB (1974 PAR-74-06); Luddke (1975)

A65 Potchefstroom, South Africa, 1973
At 4.15 p.m. on 13 July 1973 a sudden failure occurred in 
an anhydrous ammonia storage vessel at the 
Potchefstroom works of TRIOMF, a company part-
owned by African Explosives and Chemical Industries 
Ltd. The tank was one of four 50 ton horizontal pressure 
storage bulletins. An estimated 30 tons of ammonia 
escaped from the tank itself and another 8 tons from a 
tank car.
The failure gave rise immediately to a gas cloud some 150 m diameter and 20 m deep. At the time of the accident the air was apparently still, but within a few minutes a slight breeze arose which caused the cloud to move towards a township some 200 m to the north-east. The visible cloud then extended some 450 m downwind and 300 m across.

Deaths occurred both inside and outside the factory fence. At the time there were some 350 persons working in the plant, of whom some 30 were within 70 m of the failed tank. One employee was killed by the blast and eight died while trying to escape from points within a 100 m radius of the tank. Three others died of gassing within a few days.

Outside the factory fence four people were killed immediately and two died a few days later. Thus altogether 18 people were killed.

The occupants of the granulation plant control room 80 m south-east of the failure survived. They put wet cloths over their faces and were taken to safety after some 30 minutes.

The failures occurred in tank No. 3 while it and tank No. 4 were being filled simultaneously from a tank car. Actuation of an excess flow valve on the line between the two tanks prevented the release of the contents of tank No. 4 also. The tank car did not have an excess flow valve and did suffer escape of material.

The cause of the failure was brittle fracture of the dished end of the tank. Evidence suggested that there had been no overpressure or overtemperature of the tank contents and no other triggering event was determined.

The tanks were designed and fabricated in accordance with BS 1515: 1965 and were fabricated and commissioned in 1967. The fabrication is described by Lonsdale (1975):

The dished ends were fabricated from two plates, cold-formed in the major radius, and hot flanged (at 850°C) at the knuckle. The plates had been passed as being in accordance with the requirements of BS 1501-151-28A. The butt welds in the end plates were checked by 100% X-ray after forming and flanging. (Expert metallurgists re-examining the X-rays of the failed dished end considered that two sections of the weld did not conform to the requirements of the BS code.) The Inspection Authority representative considered that conditions in the flanging furnace rendered subsequent heat treatment unnecessary.

The completed tank was not stress-relieved because it is not required by BS 1515. The tanks were given an hydraulic test at 1 1/2 times the design pressure of 250 lb/sq in gauge.

Late in 1971 tank No. 3 was inspected. Two weld faults and a crack were found and were ground out. The tank was hydraulically tested to 347 psig for 30 minutes. Following repairs to a leaking tank level glass isolation valve, the tank was hydraulically tested to 325 psig for 3-4 hours.

Metallurgical testing revealed that the metal of the dished end was below its transition temperature under normal conditions. The minimum Charpy impact testing transition temperatures obtained were 20°C for the fragment and 115°C for the remaining part of the dished end.

Ultrasonic examination of the dished end in No. 4 tank revealed numerous subsurface fissures. Such fissures may have provided the notch from which the brittle fracture in No. 3 tank propagated. After this examination tank No. 4 was withdrawn from service.

Following the inquiry into this accident, the South African authorities laid down that ‘All vessels containing dangerous substances shall be given appropriate heat treatment irrespective of the (construction) code requirements.’

Commenting on this Lonsdale states

Stress-relieving does not overcome fully the damage done by progressive cold-forming of a dished end. This is particularly so where seam welds have had to be made in the dished end. There is a strong case for avoiding the use of progressively cold-formed ends for pressure vessels because of the difficulty of controlling the final state of the metal.

Lonsdale (1975); D.J. Lewis (1993)

A66 St Amand-les-Eaux, France, 1973

On 1 February 1973 a road tanker containing 19 tons of liquefied propane skidded and overturned on a wet road surface in the village of St Amand-les-Eaux. A rupture occurred on the tanker and propane began to escape. The driver of the tanker immediately took steps to stop traffic entering the street and to warn the population. The vapour cloud grew and finally exploded, causing five deaths and 40 injuries. The death toll might well have been higher but for the prompt action of the driver in carrying out his emergency procedures.

Anon. (1975); D.J. Lewis (1980)

A67 Staten Island, New York, 1973

On 10 February 1973 at Staten Island, New York, an explosion occurred inside a large LNG storage tank in which work was being done. The tank was being repaired for a leak in the inner membrane lining and new liner sections were being installed. The tank had been well ventilated before work began. The source of fuel for the explosion was identified as LNG trapped in the insulation behind the liner and vaporized by the heat-sealing operations on the new liner sections. The explosion lifted up the concrete roof of the tank which then fell back into it, crushing the men there. Forty men were killed and three injured.

US Congress (1973); D.J. Lewis (1989, 1993)

A68 Aberdeen, UK, 1974

An incident which occurred at Aberdeen on 17 January 1974, is described by Willcock (1986) in the following terms:

(1) Butane tanker skids on black ice. Shaken and lightly injured driver regains control and stops safely near side kerb; (2) Half an hour later articulated lorry skids on black ice, collides with tanker and shears off emergency discharge valve. Gas starts escaping. Second driver slightly injured; (3) Five minutes later yet another articulated lorry skids and crashes into the other two. One more hurt driver; (4) Police and fire brigade arrive a few minutes later, but before they can get organized a car, trying to stop at the accident, skids into the rear of the tanker. Impact ignites butane.

Willcock (1986)
**A69 Chicago, Illinois, 1974**

Soon after 12:30 p.m. on Friday 26 April 1974 employees at the Bulk Terminals complex in the Calumet Harbor area on the south side of Chicago, Illinois, heard a dull thud and saw fumes rising from the dike of Tank 1502, which contained 3300 m$^3$ of silicon tetrachloride. Bulk Terminals was a storage tank farm with 78 tanks ranging up to 4900 m$^3$ in size, containing products such as vegetable oils and chemicals. It was situated in a built-up area.

This was the start of an incident which involved a massive cloud of irritant gas in a built-up area and was to prove very prolonged. At times the cloud was 8 to 16 km long. It took until May 3 to stop the leak and transfer the material and until May 15 before emissions were finally reduced to tolerable levels.

Investigation found that a pressure release valve on a 6 in. line leading to the tank had been inadvertently closed. A flexible coupling in the line burst under pressure. The whole piping system shifted, cracking a 3 in. line on the tank wall. Liquid silicon tetrachloride escaped, creating a cloud with formation of hydrogen chloride gas.

The initial emergency response was confused. The terminal management awaited action by the owners of the chemical. The fire service first decided not to get involved, because there was no fire. Lime trucks diverted to the scene by the EPA with a view to neutralizing the liquid in the dike were refused entry to the site.

By 3.00 p.m. the cloud was 400 m wide, 300–450 m high and 1600 m long.

Two agents were considered to blanket the liquid in the dike: non-protein high expansion foam and No. 6 fuel oil. At 4.10 a.m. on Saturday 27 April foam was applied but was not effective. At about 10.00 a.m. fuel oil was added and eight truck loads of lime were tipped in. Within an hour the vaporization was dramatically reduced. By noon matters appeared to be under control with a 16-member US Army chemical warfare team involved in transferring the material from the damaged tank.

About 8.00 a.m. on Sunday 28 April, however, heavy rain began to fall on the hydrogen chloride cloud. Power lines were rapidly corroded and sparked like a firework display. By 9.30 a.m. four pumps had become inoperative due to corrosion. Then power failure put a stop to pumping.

The threat existed that the pipe system would suffer further failure and release the remaining 2300 m$^3$ of material into the dike, which had been reduced in capacity by the material added to it. A large pit was dug to take any overflow from the dike and an operation was undertaken to seal the leak using quick drying cement.

On the morning Monday 29 April inspection of the pipe system, undertaken in the cloud with a visibility of some 18 in., indicated that the leak had not been sealed, either because the application had been ineffective or because it had been made at the wrong point. A second concrete pour was undertaken and completed by 11.30 p.m.

By the morning of Tuesday 30 April the emission had been greatly reduced. It took, however, another three days to transfer the liquid out of the tank.

In this incident one person died, 160 were hospitalized and 16000 were evacuated.

Hoyle (1982)

**A70 Climax, Texas, 1974**

On 29 June 1974 at Climax, Texas, a derailment occurred which resulted in the puncture of a rail tank car containing liquid vinyl chloride monomer. The hole in the end of the tank was 4 ft x 4 ft. The vinyl chloride escaped and formed a vapour cloud which travelled 1600 ft to the derailed locomotive, where it ignited. There followed a violent vapour cloud explosion. It was found that the cylinder head had been blown off the diesel engine, which fact led to the hypothesis that vinyl chloride had been ingested into the engine and that the engine explosion had been the trigger for the vapour cloud explosion. The contents of the ruptured tank car continued to burn after the explosion and a flame played on another vinyl chloride tank car which suffered a BLEVE. The explosions occurred in a rail cutting and there were no injuries.

Eisenberg, Lynch and Breeding (1975)

**A71 Decatur, Illinois, 1974**

On 19 July 1974 a vapour cloud exploded in the rail shunting yard at Decatur, Illinois. During shunting operations, a rail tank car was punctured by the coupler of a box car into which it had run, the hole being some 0.3 m$^3$. The tank car contained 69 te of isobutane, which escaped and formed a vapour cloud. There was a delay of 8–10 minutes before the cloud ignited. There then occurred a massive vapour cloud explosion which caused extensive damage. Seven people were killed and 349 injured.

This vapour cloud explosion has been of some interest, because on the basis of the assessment of certain injury and damage effects, the yield of the explosion has been estimated as unusually, even anomalously, high. The matter has been considered by V.C. Marshall (1980d, 1987), who gives a detailed comparison between the explosions at Flixborough and at Decatur, and concludes that the latter was certainly no more severe than the former, that its yield has been overestimated and that it was in fact comparable to that in other vapour cloud explosions. He comments, however, that in a shunting yard the wagons serve to promote turbulence and provide on their undersides vertical confinement.

NTSB (1975 RAR/75-04); Eisenberg, Lynch and Breeding (1975); V.C. Marshall (1980d, 1987)

**A72 Los Angeles, California, 1974**

On Saturday 17 August 1974 an explosion occurred on a load of organic peroxides on a semi-trailer in a storage shed at Los Angeles, California. The load was a mixed one of several different peroxides, totalling 5.3 te. It had been made up on the Friday, but the customer had declined delivery before the weekend, and the semi-trailer was therefore parked in the storage shed until the Monday. On the Saturday smoke and flames were seen coming from the shed and shortly afterwards there was a tremendous explosion. The source of the fire is not known. There were no injuries.

Sharry (1975); D.J. Lewis (1993)
A73 Petal City, Mississippi, 1974
On 25 August 1974 a new salt dome storage was being filled with butane when a release occurred. The capacity of the storage had been miscalculated with the result that the head of the brine being displaced fell below that equivalent to the gas pressure and butane issued at high velocity. A quantity of butane estimated as 40–90 t escaped and formed a vapour cloud extending 2 km. The cloud ignited with a small explosion, there followed a second, stronger explosion and the cloud then burned for 5 hours. It has been suggested that the initial combustion and associated thermals promoted air entrainment into the mainly over-rich cloud so as to create a large elevated flammable volume which then exploded. Twenty-four people were injured.
Anon. (1974n); D.J. Lewis (1993)

A74 Antwerp, Belgium, 1975
On 10 February 1975 an explosion and fire caused extensive damage at a low density polyethylene plant at Antwerp, Belgium. The cause was a leak of ethylene at high pressure due to fatigue failure of a vent connection on the suction of a compressor. Six persons were killed and 13 injured.
Mahoney (1990)

A75 Beek, The Netherlands, 1975
On the early morning of 7 November 1975 the start up of Naphtha Cracker II on the 100,000 tons per annum ethylene plant at the Dutch State Mines (DSM) works at Beek was under way. At about 6.00 a.m. the compressed gas was sent to the low temperature system. At 9.48 a.m. an escape of vapour was observed near the depropanizer. Shortly after, the cloud formed found a source of ignition and there was a massive vapour cloud explosion.
The explosion caused extensive damage and started numerous fires. Fire broke out in the pipeline systems and Tank Farm 2. Six tanks ranging in capacity from 1500 m³ to 6000 m³ within a common dike were burned.
out. An aerial view of the plant after the explosion is shown in Figure A1.12.

The explosion killed 14 and injured 104 people inside the factory, and injured three persons outside it.

The accident was investigated by a team from the Ministry of Social Affairs. Their findings are given in the Report on the Explosion at DSM, Beek on November 1975 (the Beek Report) (Ministry of Social Affairs, 1976). The investigation involved TNO and the Department of Steam Engineering (Stoomwesen). A separate investigation was carried out by the company (van Eijnatten, 1977).

The investigation was hampered by the destruction of the instrument records in the control room. Figure A1.13 shows the state of part of the control panel. A detailed breakdown of the degree of damage done to the instrumentation is given in the report. It was also difficult to obtain useful information from the instruments which were retrieved, due to lack of synchronization, use of wrong recorder charts, lack of ink, inconsistent colour codes and out-of-date instrument diagrams.

The evidence suggested that the escape occurred due to low temperature embrittlement at the depropanizer feed drum, on and around which five fractures were found. Three of these were identified as secondary ruptures, but there were two which could have been primary failures. Two hypotheses were put forward. The principal one considered by the government team was that the initial rupture occurred on a 40 mm pipe connecting the feed drum to its safety valve.

The function of the feed drum was to take the C3 fraction from the bottom of the de-ethanizer and a stream from the condensate stripper and pass this mixed liquid and vapour feed to the depropanizer. If the depropanizer were fouled, the feed drum could give a rough cut between the C3 fraction and the heavier liquids. The normal operating temperature of the drum was 65°C.

At the time of the start up, the reboiler of the de-ethanizer column was not operating properly. Possibly the circulation of hydrocarbons through the reboiler was reduced by thickening of the liquid. In consequence, the bottom product from the de-ethanizer was a liquid at about 0°C or lower with a high C2 content. Discharge of this de-ethanizer stream into the feed drum would give flashing and could result in a temperature as low as -10°C.

Figure A1.13 Beek, 1975: damage to instrumentation in the control room (Ministry of Social Affairs, 1976)
Coincidentally there was a half-hour interruption in the flow from the condensate stripper due to a failure in the propylene compressor system. As a result, a layer of liquid containing a large proportion of C₆s was deposited on top of a layer of warm C₃ liquid in the feed drum. From the evidence the two layers had not mixed to any appreciable extent and the top layer was at about −10°C.

The feed drum material was a carbon steel which can normally be used at temperatures as low as −10 to −20°C. The fracture occurred at an autogenous weld. With such welds ageing can occur which could raise the transition temperature possibly up to 0°C.

An alternative hypothesis which the government team considered was that the rupture had been caused by explosion of organic peroxides which might have been formed from material trapped in a section of flush pipe which was isolated and which was found to have ruptured.

The amount of flammable material which escaped prior to the explosion was estimated at about 5.5 tons of hydrocarbons, mainly propylene. There is some uncertainty, however, about this figure.

The best estimate of the cloud shape from the explosion damage is that shown in Figure A1.14. The location of the damage indicated that the depth of the cloud did not exceed 4 m.

The estimated time which elapsed between the rupture and the explosion is approximately two minutes.

From eye-witness accounts the source of ignition was identified as the flash drums in Section 1.

The quantity of flammable material which exploded was estimated as about 800 kg of propylene with an energy release equivalent to 2.2 tons of TNT.

From the damage to the control room it was calculated that an overpressure of 0.2–0.3 bar must have acted on the walls. But the estimated overpressure required to cause the damage to the cold blowdown drum was approximately 1 bar.

The damage outside the factory was entirely breakage of glass. The bulk of the damage was within a radius of

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**Figure A1.14** Beek, 1975: simplified site plan of the works showing the estimated dimensions of the vapour cloud (Ministry of Social Affairs, 1976. Reproduced by permission.)
4.5 km. It was believed that the pressure at this distance might have been about 0.005 bar, which is sufficient to break thin glass. It was suggested that damage beyond this distance may have been due to the deflection of shock waves by reflecting layers in the upper atmosphere. Flying glass caused one of the three injuries outside the factory.

The incident illustrates the stress created by a developing emergency of this kind and the confusion liable to ensue. At about 9.35 a.m. the operators were engaged in dealing with start-up problems. One entered the control room and called out ‘Something has gone on C11 and there’s an enormous escape of gas’. He was distressed and was rubbing his eyes. He staggered against the telephone switchboard. A second operator ran to the entrance and tried to get out, but his view was obscured by a thick mist. He smelled the characteristic odour of C4–C4 hydrocarbons and realized there must be a major leak. He gave orders for the fire alarm to be sounded and ran out through another entrance to look at the gas cloud. He was seen from another office by a third man, apparently terrified and pointing to a gas cloud near the cooling plant.

Some witnesses stated that the fire alarm system in the control room failed. The investigation concluded, however, that the fire alarm system was in good working order before the explosion, but that none of the button switches for the fire alarm was operated.

Another aspect of the emergency was that the telephone lines to DSM were partially blocked by overloading. This did not affect rescue work, however, because the rescue services had their own channels of communication.

Min. of Social Affairs (1976); van Eijnatten (1977); D.J. Lewis (1980, 1993)

A76 Eagle Pass, Texas, 1975
At 4.20 p.m. on 29 April a Surtgas tractor tank semitrailer carrying LPG on US Route 277 near Eagle Pass, Texas, swerved to avoid a car in front which slowed suddenly to make a turn. The tank semitrailer separated from the tractor, struck a concrete wall and ruptured, releasing LPG. Witnesses described a noise like that of a violent storm, followed immediately by an explosion. Simultaneously, fire covered the area and there was then a second explosion.

The large front section of the tank rocketed up, struck an elevated sign, travelled 1029 ft and struck the ground; bounced up and travelled 278 ft; struck and demolished a mobile home; bounced up again and travelled 347 ft over another mobile home, causing it to burst into flames and be destroyed; and finally fetched up 1654 ft from its starting point.

Sixteen people, including the driver, were killed and 512 suffered burns.
NTSB (1976 HAR-76-04)

A77 Ilford, Essex, 1975
At 11.10 a.m. on 5 April 1975 an explosion occurred at the factory of Laporte Industries Ltd at Ilford, Essex. The explosion was in a Lurgi electrolysis plant. The plant suffered extensive damage and one man who was injured subsequently died.

The electrolysis plant produced hydrogen for process use and oxygen as a waste product by electrolysis of potassium hydroxide solution. The investigation concluded that the explosion probably occurred on the oxygen separating drum into which hydrogen had leaked. After the accident the company carried out a mass balance on the hydrogen flows just prior to the explosion and found that no less than 50% was unaccounted for.

The ingress of hydrogen into the oxygen drum was apparently due to corrosion/erosion in the electrolysis cells. The internal breakdown of the cells had probably been initiated some time before the accident. On 2 April a cracking noise was heard in the cell block, which may have indicated minor explosions.

There was a system of monitoring the purity of the hydrogen and oxygen streams by hourly gas analyses performed by the process operator. The evidence suggested that these analyses were not always carried out and that assumed values were entered in the process log. One operator stated that he only did the analyses two or three times in every 12 hours.

The report on the accident by the HSE (1976b) estimated that on the basis of the explosion damage the 1690 l oxygen drum contained a 13.5% hydrogen, 86.5% oxygen mixture and the explosion produced a shock wave equivalent to 22 kg of TNT. It was calculated that this explosion would have caused an overpressure of 1.03 kPa at 220 m and of 0.21 kPa at 660 m on an open site.

The most powerful explosion would have been produced by a stoichiometric mixture of 66% hydrogen, 33% oxygen. Assuming a pressure equal to the set pressure of the relief valve on the drum, 515 psig, this composition would have produced a shock wave equivalent to 90 kg of TNT and this was calculated to cause an overpressure of 1 kPa at 350 m and 0.21 kPa at 1050 m.

The factory was in an urban area with houses 180 m and a school 210 m from the electrolysis plant. Although on an open site some damage might be expected from an explosion of the size described at these distances, none actually occurred. Probably this was due to the fact that the electrolysis plant was housed in a building designed and constructed to direct any blast upwards.

HSE (1976b)

A78 Scunthorpe, Lincolnshire, 1975
At about 1.25 a.m. on 4 November 1975 the Queen Victoria blast furnace at the Appleby Frodingham works of the British Steel Corporation (BSC) was tapped. By about 2.00 a.m. some 175 tons of iron had been run into the first torpedo ladle and the stream was diverted into the second ladle. Some 10–15 minutes later intense flames and sparks began to issue from the blow pipe on No. 3 tuyère. The furnace crew tried to keep the pipe cool by spraying it with water and took steps to bring the furnace off blast to allow a new pipe to be fitted. While this was going on, a substantial water leak was observed coming from the furnace, but its source could not be located because of the flames. The water ran down the casthouse floor and entered the full torpedo ladle.

Just before 2.47 a.m. the shift manager’s instruction to remove the full ladle was passed on to the loco driver and shunter by traffic control. The traffic personnel were informed that water was running into the ladle. At 2.47 a.m. an explosion occurred as the ladle was moved.
Some 90 tons of metal were ejected. Four people were killed and 15 injured, and a further seven died later.

The energy of explosion was estimated from the structural damage as 2.5 MJ or the equivalent of 1 lb of high explosive. The energy required to eject the hot metal was estimated to have a maximum value of 12 MJ. The thermal energy in the hot metal was some 10000 times greater than this.

Investigation revealed that the water leak was probably due to the failure by corrosion of a steel blanking plug on a cooling water pipe. Such plugs had been in use for at least 20 years. It transpired that there was among the employees considerable collective experience of previous failures of blanking plugs, although in most cases the knowledge of individuals was limited.

HSE (1976a)

A79 Baton Rouge, Louisiana, 1976

On 10 December 1976 a massive chlorine release occurred from a storage vessel at Baton Rouge, Louisiana. The vessel was a horizontal bullet tank 125 ft long and 11 ft diameter resting on a load cell weighing system. An internal explosion caused the vessel to fall off its supports so that it was pierced by a metal upstand on the ground. Over a period of 5.6 hours 90.7 te of chlorine was released. A gas cloud formed described as a 42 mile long wedge, lying over the Mississippi river and sparsely populated areas. Ten thousand people were evacuated. Three persons were treated for minor irritation.

The cause of the tank displacement was an internal explosion of a natural gas–chlorine mixture at one end of the vapour space in the half full tank which produced a liquid surge along the length of the tank so that the momentum of the liquid caused the tank to jump off its supports. The tank was normally padded with nitrogen. The same nitrogen system was connected to the gland seals of hydrogen compressors in order to exclude air from the hydrogen. There was in addition a natural gas system which could be used on the gland seal as a more economic alternative. Due to the cold weather trouble had been experienced with natural gas condensate and the nitrogen system was in use. At some stage the lines to the nitrogen and natural gas systems were open at the same time and natural gas at higher pressure got into the nitrogen system. When the plant was restarted, an explosion occurred in the chlorine liquefaction system. It then spread via a balance line to the vapour space of the chlorine tank.

Anon. (1976n); Rees (1982); D.J. Lewis (1984b, 1993)

A80 Geismar, Louisiana, 1976

On 24 May 1976 an explosion occurred on a large polyglycol ether reactor. The cause is believed to have been loss of agitation possibly combined with failure of a temperature transmitter and/or addition of insufficient catalyst. The explosion hurled the reactor head some 1400 ft and fragments ruptured a large polyglycol ether tank and severed the sprinkler system riser. Unreacted ethylene oxide and propylene oxide and other reactor contents escaped and there was a major fire involving the reactor and tank farm areas.

Mahoney (1990)

A81 Kings Lynn, Norfolk, 1976

At approximately 5:10 p.m. on Sunday 27 June 1976 an explosion occurred on the Clopidol plant of the Dow Chemical Company at King's Lynn, Norfolk. One man was killed and extensive damage was done to the plant and buildings. The explosion involved the detonation of Zoalene, a poultry feed additive.

Some months before it had been discovered that stocks of Zoalene had fallen below their normal level of purity and it was decided to remove water, one of the main impurities, by drying the material in a drier on the Clopidol plant.

The drier was provided with dust explosion protection, including nitrogen inerting, explosion suppression devices and explosion relief.

On 25 June at 3:00 p.m. a batch of Zoalene was charged to the drier. At 2:00 p.m. on 26 June the steam to the drier was shut off. The material was left in the drier, however, at a temperature of approximately 120–130°C. At 5:07 p.m. the following day sound was heard coming from the drier and the shift foreman activated the emergency procedures. At 5:10 p.m. the explosion occurred.

Zoalene was known to be a reactive chemical, but, as the incident showed, the hazard of a change to the process which involved holding the material at a moderately high temperature for a prolonged period was not fully appreciated and there were no instructions for the discharge of the material on completion of drying.

The accident also revealed deficiencies in the methods available for screening materials to detect exothermic reactions. Zoalene had been screened by the company using differential thermal analysis, but this had revealed no exotherm at the processing temperature. After the accident samples of Zoalene were tested by RARDE using differential scanning calorimetry. Exotherms were found in the temperature range 248–274°C.

Zoalene samples were also tested by the company using the new technique of accelerating rate calorimetry developed by Dow itself. It was found that samples would self-heat to decomposition if held under adiabatic conditions at 120–125°C. At the time of the accident the company was working through a programme of screening its reactive chemicals, but had not yet checked Zoalene.

The investigation described in the report of the HSE (1977b) concluded that the explosion had been a detonation with an energy release of 200–300 lb of TNT, that a temperature of over 800°C had been reached before detonation occurred and that there had been an extremely rapid pressure rise, probably to over 10000 psi.

The report gives a detailed map of the locations of the fragments from the explosion.

HSE (1977b)

A82 Los Angeles, California, 1976

On 17 December 1976 a violent explosion occurred aboard the tanker Sansinena at Los Angeles, California. The ship had offloaded a cargo of light crude oil and was loading Bunker C oil. It was equipped with neither a vapour recovery nor a cargo tank inerting system. The explosion is believed to have been initiated by a spark from a pump. The force of the explosion threw the
centre section and the bridge onto the dockside, leaving the bow and stern sections afloat.

NTSB (1978 MAR-78-06); D.J. Lewis (1984c); Mahoney (1990)

A83 Plaquemine, Louisiana, 1976
On 30 August 1976 at Plaquemine, Louisiana, the top was blown off a transfer oil surge tank on an ethylene oxide plant, causing a serious fire and damage to six reactors and other equipment. A leak between the shell and tube sides of a reactor heat exchanger had allowed air at 200 psig to enter the heat transfer system.

Mahoney (1990)

A84 Southwest Freeway, Houston, Texas, 1976
At about 10.45 a.m. on 11 May 1976 in Houston, Texas, a tractor tank semi-trailer carrying ammonia went through a bridge rail on the interstate highway 1610 and fell some 15 ft onto the Southwest Freeway, US 59. The interchange was the busiest in the state and at the time traffic was quite heavy. The tank, which held 19 te of liquid anhydrous ammonia, burst.

The crash was caused by the excessive speed of the vehicle and by sloshing of the liquid in the partially loaded tank. However, the speed did not exceed 54 mile/h.

The ammonia was released and formed a visible fog. It was a bright sunny morning with a wind speed of 7 mile/h. The initial height of the cloud determined from photographs was about 30 m. The cloud was observed to reach a width of about 300 m and a length of 600 m. One photograph showed a tail to the left-hand side, indicating the typical sloping behaviour of heavy gas. It is estimated that the ammonia evaporated and the cloud dispersed within about 5 minutes. The driver of the truck and five other people were killed, 78 taken to hospital and about another 100 injured. Apart from the driver all the casualties were due to gassing.

A view of the junction after the accident, showing the area of vegetation damage due to the ammonia, is given in Plate 35.

Anon (1976b); McMullen (1976); NTSB (1977 HAR-77-01); Fryer and Kaiser (1979 SRD R152)

A85 Breachad, Renfrew, Scotland, 1977
On 4 January 1977 the Breachad Container Clearance Depot, a chemicals warehouse, was destroyed by a serious fire and explosions. The fire had been started inadvertently by boys who had built a 'den' beside the warehouse and had lit a fire to warm themselves. The explosions caused widespread roof and window damage within a radius of a mile. The warehouse had contained some 67 te of sodium chlorate stored in 1774 steel drums. Investigations showed that under intense heat this substance is capable of giving explosions of the severity which occurred.

This incident drew attention to the hazard of sodium chlorate. It emerged that since 1899 sodium or potassium chlorate had been implicated in six explosions, the then most recent being in Hamilton, Lanarkshire in 1969 and in a ship in Barcelona in 1974. Subsequently there occurred in the UK two other warehouse explosions involving sodium chlorate, one on 21 January 1980 at Barking, Essex (HSE, 1980a) and one on 25 September 1982 at Salford (HSE, 1983b).

Anon. (1979a); HSE (1979); Matthews (1981).

A86 Brindisi, Italy, 1977
On 8 December 1977 a large gas release occurred on an ethylene plant at Brindisi, Italy, resulting in a vapour cloud explosion and fire, with extensive damage. The sewers were unable to handle the fire water and burning hydrocarbon liquids floated on it to a depth of some 18 in. Three persons died and 22 were injured.

Anon. (1977b); Mahoney (1990)

A87 Puebla, Mexico, 1977
On 19 June 1977 a leak occurred on one of a group of vinyl chloride monomer storage bullets. A fitter had made an error in removing an actuator from a liquid discharge valve on the tank, taking out the wrong bolts so that the valve plug suddenly popped out, allowing an escape through the 3 in. valve body. The release continued for 80 minutes in calm conditions, the vapour cloud formed being 1100 ft long, 800 ft wide and 5 ft deep. Five minutes later the cloud caught fire and flashed back to the tanks. A further five minutes later one tank suffered a BLEVE. Three more tank explosions followed. One person was killed and three injured.

D.J. Lewis (1991 LPB 100, 1993)

A88 Umm Said, Qatar, Persian Gulf, 1977
On 3 April 1977 a catastrophic failure occurred on a storage tank at Umm Said, Qatar, in the Persian Gulf. The tank was a single-wall carbon steel refrigerated atmospheric tank holding 37 000 m3 of liquid propane at -42°C. A wave of propane liquid swept over the bund, boiling on the sand. It entered the adjacent separation plant and was ignited. There was a massive fire which did extensive damage, burned out of control for two days and was extinguished only after 8 days. Seven persons were killed and 13 injured.

Information on this incident is still hard to come by. The failure is said to have occurred at a weld on the tank. It is reported that the same weld had been responsible for a leak a year before in which a vapour cloud formed and travelled 500 ft but did not ignite.

Anon. (1977a); Whelan (1977); D.J. Lewis (1980, 1993); Ketz (1988 LPB 81)

A89 Westwego, Louisiana, 1977
On 23 December 1977 a series of explosions took place in the silos of a large grain elevator at Westwego near New Orleans, Louisiana. There were some 73 reinforced concrete silos 35 m high and ranging in diameter from 8 to 10 m. Contents included corn, wheat and soya beans.

The first explosion, which occurred in the morning, caused the top 20 m of a 75 m high head house to fall onto an office building. Explosions continued through the morning. More than half the silos were completely destroyed and others severely damaged. The wreckage of some of the silos is shown in Figure A1.15.

More than 50 people were working on the complex when the explosions occurred. Thirty-six persons were killed and 10 injured. Most of the dead were in the crushed office building.

The source of ignition for the first explosion has not been determined. At the time the relative humidity was
Figure A1.15  Westwego, 1977: grain silos after the explosion (United Press International)

low, which would be conducive both to the presence of
fine dust suspensions and to static electricity.
This disaster is comparable in scale for dust explosions
with that at Flixborough for vapour cloud explosions.
Less than a week later, on 29 December 1977, there
was a further series of explosions in another grain
elevator at Galveston, Texas, in which 15 people died.
Anon. (1977p, q); Lathrop (1978); Nolan (1979): D.J.
Lewis (1993)

A90  Abqaiq, Saudi Arabia, 1978
On April 15 1978 internal corrosion of a 22 in. 500 psig
gas transmission pipeline on a gas processing plant at
Abqaiq, Saudi Arabia, resulted in a leak which then
expanded so that the line parted. A vapour cloud
estimated as 405 ft × 435 ft spread through the plant.
Some seven minutes later ignition occurred at a flare
1500 ft downwind. The escaping gas is described as
having a jet/whipping action which threw a 22 ft pipe
section 400 ft so that it struck a spheroidal storage tank.
A second vapour cloud formed and was ignited by the
initial fire, resulting in a vapour cloud explosion.
Mahoney (1990)

A91  Donnellson, Iowa, 1978
At 12.02 a.m. on August 4 1978 a leak of liquid propane
ignited on an 8 in. LPG pipeline of the Mid-America
Pipeline System (MAPCO) in the rural area of
Donnellson, Iowa. The pipeline pressure was over
800 psig and the leak came from a 33 in. split in the
pipe. The intense fire killed two people and severely
burned three others as they fled their homes; one of the
injured later died. Some 157 500 US gal of liquid escaped
and 75 acres were burned.
The investigation by the NTSB (1979 PAR-79-01) found
that the failure occurred due to a dent and gouge in the
pipe sustained in 1962 before the line was complete
combined with stresses created when the line was
lowered 3 months prior to the incident.
V.C. Marshall quotes this incident as involving 435 te
of propane and giving a fireball of 305 m radius. The
NTSB report refers to eye-witness reports of a 'bonfire'
and states that when firefighters arrived about 12.20 a.m.
they found a towering flame 400 ft high.
NTSB (1979 PAR-79-01); V.C. Marshall (1987)

A92  Texas City, Texas, 1978
On 30 March 1978 a series of fires and explosions
occurred at LPG storage spheres at Texas City, Texas.
There were three spheres, each 800 m³. One of the spheres suffered overpressure while it was being filled, due to failure of a pressure gauge and also of a relief valve. It cracked and leaked LPG. The leak ignited giving a massive fireball.

Accounts differ in their description of the events which followed. According to Selway (1988 SRD R492), after 20 minutes a second sphere, which was only partially full, suffered a BLEVE. The third sphere, which was virtually empty, failed due to a heat-induced rupture at the top, but remained upright. Thus all three spheres were damaged, but there was only one BLEVE event. Mahoney (1990) states that during the 20 minutes following the fireball, five horizontal bullets and four vertical ones were damaged by missiles and that the other two spheres were also damaged in this way. The missiles started fires and hit the fire water storage tank and electrical fire pumps, although two diesel fire pumps remained operable.


A93 Waverly, Tennessee, 1978
On 24 February 1978 an explosion occurred of an LPG rail tank car at Waverly, Tennessee. Two days before, on 22 February, a freight train conveying two LPG tank cars derailed. There was no immediate release. A check the following day showed that both tank cars were damaged but no leak could be detected. Both tank cars were underneath box wagons and these were lifted off. On 24 February as preparations were in hand to transfer the contents of the tank cars, one of them, which had suffered a long gauge-like scrape along one side, suddenly ruptured into four pieces and released its contents of 59.4 te of LPG. Seconds later the gas ignited, probably by burning equipment nearby, giving a fireball. There followed a fire which did extensive damage. Sixteen people were killed and 43 injured.

Anon. (1978b); NTSB (1979 RAR-79-01); D.J. Lewis (1992 LPB 105, 1993)

A94 Youngstown, Florida, 1978
At about 1.55 a.m. on the night of 26 February 1978 a freight train of the Atlanta and Saint Andrews Bay Railway derailed near Youngstown, Florida. In the derailment a rail tank car containing liquid chlorine was punctured when it struck another tank car. The approximate position of the tank cars following the derailment is shown in Figure A1.16.

A chlorine gas cloud formed and moved towards State Highway 231, which ran parallel to the railroad at a distance of 300 ft. The weather conditions were a temperature of 50–55°F and a light westerly wind of 2–3 knots. There were already some patches fog around and drivers, used to foggy conditions and unable to see the colour of the cloud as it was night, drove into it. Three vehicles drove right off the road and into the ditch. One motorist said the gas was so thick ‘You couldn’t see your hand in front of your face’. Seven motorists abandoned their cars and died while trying to escape, whilst an eighth drove through the cloud but died a short distance down the road.

The train’s engineer at the head of the train alerted the conductor at the rear by radio and then tried to escape through the cloud; he became lost and mired in a swamp, being rescued 6 hours afterwards. The head

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**Figure A1.16** Youngstown, 1978: approximate positions of rail tank cars after the derailment (after NTSB, 1978 RAR-78-07)
brakeman, who had been with the engineer, circled round to the highway and started to alert traffic. The conductor and rear brakeman tried to inform the railroad facility at Panama City, but it was not manned after midnight. They began to rouse local residents and notified the police; almost 30 minutes had elapsed before the first emergency call was completed. They then went to the highway to assist in alerting traffic. The report by the NTSB (1978 RAR-7807) states

The head and rear brakeman both imperilled their lives by their repeated exposure to the chlorine gas cloud to stop and warn motorists of the dangerous situation. Their heroic actions saved many people from death or serious injury.
The emergency service evacuated people, first in a 5 mile and then in a 10 mile radius.
At 9:00 a.m. aerial observation revealed a gas cloud 3 miles wide and 4 miles long with a maximum height of 1000 ft. If the wind had been in a less favourable direction, the town of Youngstown would have been engulfed in the cloud.
The chlorine gas killed eight people, as mentioned, and injured another 50. Some 2500 people were evacuated.
Anon. (1978k); NTSB (1978 RAR-78-07)

A95 Bantry Bay, Eire, 1979
At about 1.06 a.m. on 8 January 1979 the Total oil tanker 
Bteleguise blew up at the Gulf Oil terminal at Bantry Bay, Eire. The ship had completed the unloading of its cargo of heavy crude oil. No transfer operations were in progress. The first sign of trouble occurred at about 12.31 a.m. when a sound like distant thunder was heard and a small fire was seen on deck. Ten minutes later this was spread aft along the length of the ship, being observed from both sides. The fire was accompanied by a large plume of dense smoke. About 1.06-1.08 a.m. a massive explosion occurred. The vessel was completely wrecked and extensive damage was done to the jetty and its installations. There were 50 deaths.
The inquiry (Costello, 1979) found that the initiating event was the buckling of the hull, that this was immediately followed by explosion in the permanent ballast tanks and the breaking of the ship's back and that the next explosion was the massive one involving simultaneous explosions in No. 5 centre tank and all three No. 6 tanks. It further found that the buckling of the hull occurred because it had been severely weakened by inadequate maintenance and because there was excessive stress due to incorrect ballasting.
The ship was an 11-year old 61,776 GRT tanker. The weakened hull was the result of conscious and deliberate decisions not to renew certain of the longitudinals and other parts of the ballast tanks which were known to be seriously weakened, taken because the ship was expected to be sold, and for reasons of economy. The vessel was not equipped with a loadicator computer system, virtually standard equipment, to indicate the loading stress. It did not have an inert gas system, which should have prevented or at least mitigated the explosions.

At the jetty there had been a number of modifications which had degraded the fire fighting system as originally designed. One was the decision not to keep the fire mains pressurized. Another was an alteration to the fixed foam system which meant that it was no longer automatic. Another was decommissioning of a remote control button for the foam to certain monitors.
Another issue was the absence of the dispatcher from the control room at the terminal. It was to be expected that had he been there, he would have seen the early fire and have taken action.
In a passage entitled ‘Steps taken to suppress the truth’ the tribunal states that active steps were taken by some personnel at the terminal to suppress the fact that the dispatcher was not in the control room when the disaster began, that false entries were made in logs, that false accounts were given to the tribunal and that serious charges were made against a member of the Gardai (police) which were without foundation.
The inquiry report gives a long list measures which might have prevented or mitigated the disaster:

- Had the vessel been properly maintained...
- Had Total supplied the ship with a loadicator...
- Had the dispatcher in the Control Room observed the initiation of the disaster...
- Had the alert been raised at the beginning of the disaster...
- Had the tug been moored in sight of the jetty...
- Had the decision to discontinue the automatically pressurized fire-main not been taken...

and so on.
Anon. (1979l); Costello (1979); Anon. (1980a); Mahoney (1990)

A96 Good Hope, Louisiana, 1979
On 30 August 1979 a freighter collided with the butane barge 
Panama City at a jetty on the Mississippi at Good Hope, Louisiana, striking it amidships, severely puncturing at least one of its tanks and causing a fireball. Twelve persons died and 25 were injured.

A97 Mississauga, Toronto, Ontario, 1979
At 23.52 on Saturday 10 November 1979 at Mississauga, Toronto, a freight train derailed led to fires, explosions and a chlorine gas release, in an emergency lasting 11 days. The train had 25 rail cars of which 19 held hazardous materials, in a mixed load of flammables and toxics, including propane, toluene, styrene, caustic soda and chlorine.
The derailed occurred due to lack of lubrication of a plain journal axle bearing on the 33rd car, a propane tanker. The red-hot axle, complete with wheels, parted from the tank car. Some 2 km further on at a location where there was a road crossing and points, this vehicle became detached from the front portion of the train. Many of cars in the rear section derailed. Several tanks were ruptured and a fire broke out. The brakes in the front section of the train were applied automatically and looking back the locomotive crew saw a fire and a tank car rocking off.
There followed a series of explosions, one within a minute and another just after midnight at 00.10. At 00.15 a propane tank suffered a BLEVE in which one half travelled 2300 ft and buried itself 20 ft into the ground. At 00.24 another BLEVE of a propane tank car occurred.
There was a single chlorine tank car containing 90 te of liquid chlorine. This tank lost part of its insulation and a flame impinged on the bare metal. There was an iron-chlorine reaction which burned a 3 ft diameter hole in
the tank. Chlorine began to escape through the hole. The effect was less serious than it might have been, since the effect of the fire was to cause the gas to rise in the thermal currents.

The emergency developed over an extended period. Initially the emergency services did not know what was in the train; the manifest was found, but it was in code. There was, however, a strong smell of chlorine. At 1.30 a readable version of the manifest was obtained, identifying the chlorine tank car. At 3.00 the decision was made to evacuate the surrounding population, an exercise which eventually resulted in the evacuation of 215,000 people. The holed chlorine tank car was identified by a helicopter survey.

At 9.00 on Tuesday 13 November an initial attempt was made to plug the hole in the chlorine tank car, but without success; a second attempt succeeded. When subsequently the tank was emptied, only 18 te of chlorine was recovered.

During Tuesday afternoon 143,000 people were allowed back home. The rest did not return until after an absence of six days.

Detailed timetables of the incident itself and of the evacuation are given by Fordham (1981 LPB 44).

The only injuries were those caused to eight firemen by inhalation of the noxious gases.

Mississauga News (1979); Amyot (1980); Grange (1980); Anon. (1981); Fordham (1981 LPB 44); Lane and Thomson (1981); D.J. Lewis (1993)

A98 Borger, Texas, 1980

On 20 January 1980 a refinery at Borger, Texas, suffered extensive damage. Details are lacking, but it appears that a vessel was subjected to a pressure much in excess of its working pressure, the relief valve operated but was ineffective due to ice blockage and the vessel ruptured, releasing 34 m³ of hydrocarbon liquids. A vapour cloud formed and ignited, giving a vapour cloud explosion with a TNT equivalent of some 15 te. The blast destroyed the alkylation unit and boiler plant and shut down the whole refinery. Forty-one people were injured.

The ice plug is reported as due to freezing by propane of water which had accumulated in the flare system.

Mahoney (1990); D.J. Lewis (1993)

A99 Wealdstone, Middlesex, 1980

About 19.15 on 20 November 1980 an escape of propane began from a storage vessel in the factory yard of Whitefriars Glass Ltd at Wealdstone, Middlesex. The vessel was a 10 te vessel which contained 5 te of propane. The watchman smelled the odorized gas, but searched first inside the building, until he heard a hissing sound and saw a white cloud about 1.2 m deep around the base of the tank. Meanwhile a passer-by had called the fire brigade. The escape lasted several hours. Some 2100 people were evacuated from the area. One person had to attend hospital.

The release was caused by the removal by the works engineer and a fitter of three of the four bolts on an adapter piece on the drain valve of the tank. The valve had two sections. The upper, body section was bolted to the underside of the tank. The lower, adapter section had a spigot which extended into the upper section and held the ring seals in place against the ball. In other words, the adapter was an essential part of the valve.

This was not known, however, to the persons who removed the bolts.

The work on the valve had occurred during the afternoon. The delay between the removal of the bolts and the escape was attributed by the investigators to the accumulation in the vessel of non-volatile, viscous residues due to the removal of propane as gas from the top of the tank over a period of at least 10 years.

HSE (1981c)

A100 Montana, Mexico, 1981

At 17.52 on 1 August 1981 a train derailment resulted in a massive release of chlorine near Montana, Mexico. The train consisted of 38 wagons, including 32 rail tank cars containing liquid chlorine. It was moving down a steep and winding valley at a 3% gradient when its brakes failed. The driver radioed to other trains on the single track to warn them, and two trains drew into loops. The train derailed at over 80 km/h on a bend 350 m beyond Montana station.

All the chlorine tank cars were 55 short tons, say 50 te, capacity. The pile-up included 28 of the 32 chlorine cars. Most were badly damaged. One tank car lost its dished end and the shell was propelled 2000 m. A second was split along its side. A third had a 0.5 m diameter hole, probably the result of an iron–chlorine fire, which could well have resulted from ignition of the cork insulation by red hot brakes. Four other tank cars suffered damage to their valves, which were ripped off or dislodged so that they leaked. It is estimated that 100 te of chlorine escaped in the first five minutes and 300–350 te in all.

The population of Montana was some 400 people. There was also a passenger train with some 300 people at the station. The weather conditions to be expected at the time of day would be a warm wind blowing up the valley, towards the village. The vegetation up the valley was burned by the gas cloud passing up it; there was also discoloration some 50 m down the slope and up the sides for a vertical distance of about 50 m. The highest concentrations appear to have occurred in a strip 1000 m long × 40 m wide. Seventeen persons died, four in the caboose of the train and 13 from gassing. About 1000 people were received in hospital and 256 were detained.


A101 Stalybridge, UK, 1981

At about 23.30 on 6 September 1981 a violent explosion occurred at the works of Chemstar Ltd at Stalybridge. Failure of cooling water to the condenser of a still had allowed hexane vapour to issue through the vent, and the escaping vapour found a source of ignition. One person was killed and one injured.

The investigators found that the normal water supply was not available, a temporary supply had been used which proved to be erratic and there was inadequate flow indication; that the vent had not been routed to a point outside the building; and that the training and supervision of the operator were inadequate.

HSE (1982a); Kletz (1983b)

A102 Caracas, Venezuela, 1982

At about 6.17 a.m. on 19 December 1982 an explosion blew the top off a large oil storage tank at the electricity company at Caracas in Venezuela. The oil in the tank
caught fire and burned. Firemen arrived and attempted to control the fire and people stood watching it. After some hours there was a violent boilover of the tank contents and burning liquid ran down the hill on which the tank stood towards firemen and spectators.

The power station was owned by C.A. La Electricidad de Caracas and was built in 1978. The tank involved was No.8 storage tank, which was one of two cone roof tanks each 55 m × 17 m, the other tank being No.9. Each tank had its individual bund and had two forms of fire protection. One was a 100 mm water drench pipe which ran to the centre of the roof and was designed to cascade water over the roof and shell to prevent overheating and the other was a semi-fixed foam system with five risers.

No.8 tank contained No.6 fuel oil and at the start of the incident the depth of oil was 7.5 m. It had been feeding the boilers for six days prior to the fire.

At 6.15 a.m. while it was still dark, two men went up on the roof of No.8 tank to gauge it, and a third waited in a vehicle. About two minutes later the roof blew off and at the same time the lines within the bund were ruptured. One of the foam risers on the tank was damaged. The source of ignition is not known, but neither man had a flashlight and it is possible a match was lit to read the gauge line.

It is not known if either the water or foam fire protection systems on No.8 tank operated. The power company had no fire brigade and the nearest public fire service was a half hour journey away over winding roads.

Some 8 hours after the fire began a violent boilover of No.8 tank occurred. Burning oil surrounded No.9 tank and flowed down the hill into the sea, but was kept from the power station by a concrete wall. The inrush of air lifted roof panels at the power station 300 m away.

The boilover killed 40 firemen and many civil defence workers and spectators. 153 people are known to have died and 7 were missing.

Boilover is defined by the NFPA as follows:

Boilover shall mean an event in the burning of certain oils in an open top tank when, after a long period of quiescent burning, there is a sudden increase in fire intensity associated with the expulsion of burning oil from the tank. Boilover occurs when the residues from surface burning become denser than the unburned oil and sink below the surface to form a hot layer which progresses downward much faster than the regression of the liquid surface. When this hot layer, called a 'heat wave', reaches water or a water-in-oil emulsion in the bottom of the tank, the water first is superheated and subsequently boils almost explosively, overflowing the tank. Oils subject to boilover must have components having a wide range of boiling points, including both light ends and viscous residues. These characteristics are present in most crude oils and can be produced in synthetic mixtures.

The heat wave travels at a rate which in most crude oils is some 300–460 mm/h but can be as great as 900–1200 mm/h. Its temperature can be as high as 315°C. When water comes into contact with the heat wave, it vaporizes to steam with a volume expansion of 1700:1 or more.

Normally No.6 fuel oil is regarded as not being subject to boilover. However, it is common practice in the US to blend it. It is reported that the power company’s specifications allowed 5–20% light fractions, that the oil had a flashpoint of 71°C, that it was intended to be heated in storage to 65°C, but that the oil return temperature shown by the control room records was 80°C and the storage temperature was 82°C. The tank high-temperature alarms had sounded at midnight, some 6 hours prior to the incident.


A103 Livingston, Louisiana, 1982
On 28 September 1982 a freight train conveying hazardous materials derailed at Livingston, Louisiana. The train had 27 tank cars some of them with jumbo tanks of 30,000 USgal. Seven tanks cars held petroleum

Figure A1.17 Livingston, 1982: rail tank cars burning after the crash (National Transportation Safety Board, 1983)
products and the others a variety of substances, including vinyl chloride monomer, styrene monomer, perchlorethylene, hydrogen fluoride and metallic sodium.

The incident developed over a period of days. The first explosion did not occur until three days after the crash. The second came on the fourth day. The third was set off deliberately by the fire services on the eighth day. The scene is shown in Figure A1.17.

Meanwhile the 3000 inhabitants of Livingston were evacuated. Some were not to return home until 15 days had passed.

One factor contributing to the derailment was the misapplication of brakes by an unauthorized rider in the engine cab, a clerk who was 'substituting' for the engineer. Over the previous six hours the latter had drunk a large quantity of alcohol.

The incident demonstrated the value of tank car protection. Many of the cars were equipped with shelf-couplers and head shields, and there was no wholesale puncturing and rocketing. Tanks also had thermal insulation which resisted the minor fires occurring for the two or more hours which it took the fire services to evacuate the whole town.

NTSB (1983 RAR-83-05); Anon. (1984)

A104 Bloomfield, New Mexico, 1983
At 12.04 p.m. on 26 May 1983 at the El Paso Natural Gas Company’s Blanco Field Plant near Bloomfield, New Mexico, a gasket on a compressor failed and natural gas at 815 psig began to escape into the building. Two operators heard the noise. One tried to shut off the gas supply to the compressors, the other to shut down the compressor engine. Before they could effect these operations, the gas ignited and exploded, and both were severely burned. One compressor was destroyed and a second severely damaged.

The investigation by the NTSB (1983 PAR-83-04) found that the probable cause was improper tightening of the compressor head bolts and lack of procedures for, and training in, bolt tightening. The report gives a detailed discussion of the bolting problem together with guidance on bolt tightening.

It also criticized the emergency response, in that there was a failure to effect prompt relief of the high pressure gas by activating the blowdown system.

NTSB (1983 PAR-83-04)

A105 Bontang, India, 1983
On 14 April 1983 on an LNG plant at Bontang, India, the main cryogenic heat exchanger, 141 ft long × 14 ft diameter, ruptured during a startup. The shell side operating pressure was 25.5 psi but it was exposed to gas at a pressure in excess of 500 psi. The explosion gave rise to missiles and a fire. The flow from a pressure controller on the shell and the flows from relief valves on the shell and tube sides of the exchanger vented to a common line. The investigation found that a valve on this line was closed, disabling both the pressure control and the pressure relief. The valve in question had apparently been omitted from the valve checklist for plant startup.

Mahoney (1990)

A106 Milford Haven, UK, 1983
On 30 August 1983 a fire broke out on the roof of a large crude oil floating roof storage tank at the refinery at Milford Haven, Dyfed, Wales. The tank was 78 m diameter × 20 m high with a capacity of 94 100 m³ and was 50% full. It stood in a very large bund with dimensions 90 m × 180 m. The fire took hold and a massive tank fire ensued with an estimated burn-off rate of 300 te/h of oil. After 12.5 hours boilover occurred, thousands of tonnes of burning oil flowed into the bund and a fire column rose 3000 ft high. Two hours later there was a further boilover.

The floating roof had developed a split which allowed vapours and some oil to escape onto the roof. Ignition was attributed to hot carbon particles from the flame. An upset had resulted in a large flow of hydrocarbons to the fire which could have dislodged particles from the stack top.

There was a major fire fighting operation. Oil was pumped out from the bottom of the burning tank at a rate of 700 te/h. The foam supplies available on site were sufficient for a floating roof tank seal fire, but not for the fully developed tank fire, and supplies were sought outside. There were two other storage tanks at a wall-to-wall distance of 61 m from the burning tank, and an early priority was to cool the outside of these to inject foam inside. Eventually, after the boilovers, enough foam was obtained, some 305 m³, to mount a full foam attack, first on the fire in the bund and then on that in the tank itself. This process lasted 15 hours with the fire fighting being done under conditions of extreme heat. In the boilover events, firemen were affected by flash burns and by dry hot air.

A detailed timetable of the incident is given by Mumford (1984 LPB 57).

Dyfed County Fire Brigade (1983); Mumford (1984 LPB 57); Golec (1985); Steinbrecher (1986); Mahoney (1990); D.J.Lewis (1993)

A107 Abbeyestead, UK, 1984
On 23 May 1984 a group of people were assembled in the valve house of the Lune/Wyre Water Transfer Scheme at Abbeyestead for a presentation when there was a violent explosion. The explosion occurred soon after the pumping system had been started up. The pumps had not been run for 17 days and the tunnel which conveyed the water was not full of water, its usual condition, but had been emptied through a drain valve which had been opened to remove silt. Subsequent tests showed that during this period groundwater would have leaked into the tunnel at a rate of 1000 te/d. This water contained dissolved methane, which mixed with the air in the tunnel. The only venting of the tunnel was through the grilled floor of the valve house. Thus when the pumps were started and water moved up the tunnel, the methane-air mixture was displaced and came up through the grill into the valve house, where it found a source of ignition. The explosion killed 16 and injured 28; all the 44 persons in the valve house itself were killed or injured.

Anon. (1984pp); Anon. (1985a); Burgoyne (1985a); HSE (1985a); Liou (1985 LPB 66); V.C.Marshall (1987)

A108 Cubatao, Brazil, 1984
On 24 February 1984 just before midnight a leak of petrol occurred on the Petrobas pipeline passing through the shanty town of Vila Soca at Cubatao in São Paulo state, Brazil. The petrol caught alight and a fire devastated the houses. The death toll was 508.
Vila Soca was a shanty town of some 2500 dwellings. The number of people living there is uncertain, but is estimated as 8000, perhaps even 12000. The pipeline was 30 years old. For 20 years the company had protested that Vila Soca had been built illegally on its land, but had nevertheless provided water and electricity.

A leakage from the pipeline was noticed the day before the fire and a resident telephoned the company. In the leak which led to the disaster some 700 te of petrol escaped from the pipeline. The spread of the flammable liquid through the shanty town and under the houses was aided by water on the ground and by a small stream. A two-minute warning was given but this was not enough for the inhabitants to evacuate. The petrol caught fire and straight away created an inferno. Houses burned and exploded as the petrol beneath them ignited. It was 45 minutes before the fire brigade arrived by which time most of the shanty town had been destroyed.

Anon. (1984oo); Kletz (1985p)

A109 Fort McMurray, Alberta, 1984
On 15 August 1984 at Fort McMurray, Alberta, hydrocarbon liquids close to their autoignition temperature were released from a 10 in. slurry recycle oil line on a fluidized-bed coking unit. A vapour cloud formed and ignited almost at once. The fire, which did extensive damage, was fed by further releases of hydrocarbon liquids, the flows being largely under gravity but in part from pumps which could not be shut down. Fire fighting was hampered by rupture of a 500 psig steam line supplying the compressor turbine drives. The failure of the recycle line was due to erosion. Subsequent metallurgical examination showed that an 18 in. long section of carbon steel had been inserted in error into the alloy steel pipe.

Mahoney (1990)

A110 Las Piedras, Venezuela, 1984
On 13 December 1984 in a refinery at Las Piedras, Venezuela, an 8 in. oil line fractured and sprayed hot oil at 700 psi and 650°F across a roadway onto hydrogen units. Ignition occurred, and the ensuing intense fire led to rupture of a 16 in. gas line, which resulted in a massive jet flame, leading to further line ruptures, some of which occurred with explosive force. The initial failure was a circumferential fracture in the heat affected zone in the parent metal about 1.5 in. from the weld.

Mahoney (1990)

A111 Romeoville, Illinois, 1984
On 23 July 1984 a column at the Lemont refinery of Union Oil at Romeoville, Illinois, suffered a spontaneous failure. The vessel was an absorption column 8.5 ft diameter × 55 ft high in which a propane/butane feedstock was contacted with methylethanolamine (MEA). Just prior to the burst, an operator noticed a horizontal crack about 6 in. long at the 10 ft level. He went up a ladder to try to shut of the inlet valve and then saw that the crack had grown to some 2 ft. He had initiated evacuation of the area when the column failed.

The column tore apart at the 10 ft level weld and the 45 ft top section, weighing some 20 te, rocketed up, landing about 975 m away on a tower carrying a 138 kV power feed line to the area. The tower contents, estimated as 79.5 m³ of propane/butane and 8.75 m³ of MEA, escaped and formed a vapour cloud, which ignited within seconds, giving a vapour cloud explosion. Some 30 minutes later a second explosion occurred when a vessel in the alkylation section suffered a BLEVE with associated fireball and missiles. The explosions and fire caused extensive damage. Seventeen people were killed and 31 injured.

The vapour cloud explosion disrupted the electrical power supply, putting out of service a 2500 USgal/min electrical fire pump. One of the explosions sheared off a fire hydrant, reducing the pressure available from the two 2500 USgal/min diesel-driven fire pumps. A fragment from the BLEVE landed on a unifying unit, initiating a major fire there.

The blast resistant control centre, some 400 ft from the absorber, suffered little structural damage.

The absorber vessel had a history of hydrogen attack problems. Over the years since 1972 repairs and modifications had been done, and the vessel continued in service.

Mahoney (1990); D.J.Lewis (1993); Vervalin (1987)

A112 Priola, Italy, 1985
On 19 May a major fire occurred on an ethylene plant at Priola in Italy. A faulty temperature probe initiated isolation of the hydrogenation unit in the cold section, and while the operators were trying to re-establish control, the relief system operated. At the same time fire was observed at the base of the de-ethanizer column. The hydrocarbon released ignited and an intense fire engulfed the adjoining ethylene and propylene distillation columns and spread to the storage area. The water deluge system protecting the storage tanks proved inadequate due to the intensity of the fire. In due course a tall, vertical propane tank exploded, its top section rocketing up some 500 m, and just missing a gas holder. Two propylene tanks fell over, one on a pipe rack and the other against an ethylene tank. In all, five of the eight ethylene and propylene tanks either exploded or collapsed.

Mahoney (1990)

A113 Schweizerhalle, Basel, Switzerland, 1986
On 1 November 1986 a fire broke out in Warehouse 956 at the Schweizerhalle (Mutenz) works of Sandoz in Basel, Switzerland. The warehouse held large quantities of agrochemicals. Attempts to extinguish the fire using foam were ineffective and water had to be used, in large quantities. It was not possible to contain this water within the site and, as a result, 10,000 m³ entered the Rhine carrying with it some 30 te of chemicals, including an estimated 150 kg of highly toxic mercury compounds dissolved in aqueous concentrates. The incident did severe ecological damage.

A not dissimilar incident, though one on a much smaller scale, occurred at Morley, Yorkshire, in 1982, when the river Calder was contaminated by chemicals in water used in fighting a fire which had broken out in a warehouse storing herbicides (V.C.Marshall, 1987).

Anon. (1986v, w, y); Beck (1986); D.Williams (1986); Anon. (1987 LPB 75, p. 11); Stallworthy (1987)

A114 Thessalonika, Greece, 1986
On 24 February 1986 an oil terminal at Thessalonika, Greece, experienced a small fire when a oil spillage in a bund was ignited by hot work. The privately-owned terminal had 12 fixed and floating roof storage tanks
holding crude oil, fuel oil and gasoline. Over the course of seven days, ground fires escalated until they covered 75% of the terminal area and involved 10 of the tanks. The escalation of the initial small fire was due in large part to accumulation of oil from previous spillages; to leaks from flanges exposed to the fire, which then fed it; and to the failure of fire fighting efforts in the early stages. By the first day seven tanks were affected.

In the course of the succeeding days, several events occurred which led to major escalations. On Tank 3 overpressure caused the shell-floor seam to burst so that the whole contents flowed out, feeding the fire and involving two more tanks. Tank 8 suffered a boilover with a fireball 300 m high and ejection of burning oil over a wide area, some travelling up to 150 m. The fire fighting was hampered, and firemen endangered, by burn-back of flame in areas where the oil fire had already been extinguished by foam.

B. Browning and Scaron (1989)

A115 Antwerp, Belgium, 1987

On 3 July 1987 an explosion occurred inside an ethylene oxide purification column at the BP Chemicals works at Antwerp, Belgium. The explosion was due to decomposition of the ethylene oxide and was accompanied by a fireball, which started a number of secondary fires. These, together with blast and missiles, caused extensive damage. Fourteen people were injured.

The investigators considered two main hypotheses for the cause. One was that there was a leak of ethylene oxide into the insulation, leading to self-heating and then ignition of the leak, resulting in the heating of the ethylene oxide in the column itself. The other was the development of a hot spot inside the column due to exothermic polymerization of ethylene oxide catalysed by rust. The first explanation was preferred.

Mellin (1991 LPB 100)

A116 Grangemouth, Scotland, 1987

In 1987 there occurred at BP plants in the Grangemouth, Scotland, area three incidents, which were the subject of investigations by the HSE (1989a).

Incident on 13 March 1987

On March 13 1987 a fire occurred when a maintenance team broke a flange in the flare line, hydrocarbons escaped and were ignited. There was a quite serious fire which lasted some hours. Two men were killed and two injured.

The release occurred when two fitters started to break a flange in order to maintain a valve (V17). As they did so, vapour and a little liquid came out. They queried the situation with the process shift supervisor, who inspected the site and assured them that there could only be a small quantity present and it was safe to continue. They did so, and as the last bolt was undone, the crane holding the spacer increased its lift, the spacer sprung upwards, and liquid under pressure poured out. A vapour cloud formed and ignited. The source of ignition was almost certainly the engine of a nearby diesel air compressor.

It was considered that that if the fire was extinguished, fuel might continue to issue with the potential for a vapour cloud explosion and that if the flame receded into the pipe, there might be an internal explosion. For a while, therefore, fuel gas was fed into the line to keep the flame alight.

The liquid which escaped had been held in a section of the flare line near a knockout drum. It should have drained via a small bore pipe into the knockout drum, but the entry of the pipe was blocked. The valve on this pipe had been checked as open, but the possibility of blockage had not been taken into account. The liquid was there in the first place because valve V17, thought to be fully closed, was in fact part open. The valves suffered from build-up of pyrophoric scale. They had no indicators showing positively the valve position. It is estimated that there was about 50 m³ of hydrocarbons in the line at the time and that 20 m³ may have escaped.

Among the findings of the investigation were that there was a need for position indicators on the valves; that there had been inadequate planning of the work to be done; that the check that the flare line had been drained was ineffective; that the response to the first, small leak was inadequate; that the procedure for flame breaking was incorrect; that when opening lines with pyrophoric scale, air should be excluded positively by a nitrogen purge, rather than reliance placed on its exclusion by flammable gases present; and that the exhaust gas spark arrester was missing. There should have been a requirement that in breaking a flange sufficient bolts remain in place whilst a gradual opening is made using a flange spreader.

Incident on 22 March 1987

On 22 March 1987 an explosion occurred during the start up of a hydrocracker unit at the Grangemouth refinery. It involved the disintegration of a low pressure separator. One fragment from the vessel, weighing 3 t, landed on the foreshore 1 km away.

Accompanied by a fireball, the explosion initiated a severe fire. The refinery sustained extensive damage. One person was killed.

The LP separator (V306) was 3.05 m diameter x 9.1 m long with a design pressure of 9 bar and a calculated burst pressure of 50 bar. It was fitted with a 3 in. relief valve designed for fire relief. Its disintegration was caused by breakthrough of gas from the HP separator (V305) due to loss of level control in the base of the latter. The HP separator pressure was 155 bar. The plant was in start-up mode and the process lines on V306 were closed.

The gas breakthrough occurred due to loss of control of the level at the base of the V305. The pipework taking off the liquid split into two lines, one passing through the valve on the level control loop LIC 3-22 and the other through that on H 3-22. The breakthrough occurred through the LIC 3-22 valve. This valve had been fitted with a low level trip, but this had been removed in 1985. The liquid at the base of V305 tended to give vortices and the trip system suffered from spurious trips which caused production difficulties. There was an extra-low level alarm, but this had been on for months, until the bulb failed, and was regarded as spurious. The two float switches were fire damaged, but there was evidence that one had been incorrectly assembled and that on the other the small bore piping was blocked. The operators tended to place more reliance on the measurement provided by a nucleonic level gauge. However, this gauge had a zero error, showing a 10% reading when
the true reading was zero. An audit had shown that there was a problem in control of the level on the vessel. In the shift in which the incident occurred valve LIC 3-22 was opened manually at least three times. Just before the explosion, it was opened again, and the level was lost.

The HSE report states:

The refinery had procedures for routine monitoring of interlocks, alarms and trips, but on the checklist for the hydrocracker some were omitted. The detection, trip and alarm systems for extra-low level in V305, had been inoperative for a long time and maintenance staff and operators presumed that these were no longer required. Training of new operators carried out by experienced operators helped to perpetuate this misconception.

Although the refinery chief instrument engineer noted in 1985 that the LIC 3-22 trip solenoid had been disconnected, this was not followed up. (paragraph 89)

The report states that there should have been both a high integrity trip system for level control and a pressure relief system capable of handling the maximum anticipated gas flow and that fuller consideration should have been given to proposals to make modifications to the plant.

It emerged that there had been a previous incident on V305 which was probably a gas breakthrough, but on that occasion the process valves on V306 were open.

The force of the blast was mainly downwards, while the fragments travelled upwards. The TNT equivalent of the explosion was estimated as 90 kg.

Major problems were experienced in the fire fighting. Within 12 hours all foam and water streams were discharging at a rate of 12 000 USgal/min. The drains were unable to cope with this flow. Hydrocarbons bubbled up in other parts of the site and floated on the water. The situation was exacerbated by large quantities of heavy, waxy material which caused blockages.

**Incident on 11 June 1987**

On 11 June 1987 at Dalmeny, near Grangemouth, a fire broke out during sludge cleaning work by a contractor in a storage tank, and one man died. The men had airline breathing apparatus (BA) to protect against toxic fumes, but there was no mechanical ventilation and no regular monitoring of the atmosphere. The sludge had a flashpoint of less than 0°C. It transpired that the fire broke out when one man, who had taken off his BA, dropped a cigarette end.

The investigation revealed that there were a number of deficiencies in the arrangement of the contract with the contractor and in the conduct of its personnel. The contractor was a specialist one, well-known, considered competent and already working on site. There was no written procedure for the work. There was inadequate enforcement of the 'no smoking' rule, and some contractor's personnel had not received the BP refinery rules booklet. Also inadequate was enforcement of the use of the BA. There was no lighting inside the tank and men discovered they could see better if they took the BA off. The team worked largely unsupervised. They wore the BA when entering and leaving the tank, and evidently also when the supervisor was about to visit, but some did not wear it all the time. The supervisor himself had on occasion removed his BA inside the tank to give verbal instructions.

Anon. (1988c, d); Anon. (1987); Anon. (1989b); Anon. (1989 LPB 89, p. 13); HSE (1989a); Kletz (1989b); Mahoney (1990); K.C. Wilson (1990a, b); D.J. Lewis (1993)

**A117 Pampa, Texas, 1987**

On 17 November 1987 at Pampa, Texas, a vapour cloud explosion occurred on a plant for the liquid phase oxidation of butane to acetic acid and acetic anhydride using air at about 700 psig. There were three reactors with a capacity of 38 m³. During the start up of one reactor a rupture or explosion occurred in the line taking the air to the reactor or in the reactor manifold, and butane and acetic acid flowed out. The vapour cloud which formed was ignited by gas-fired boilers some 60 m away, the delay before ignition being about 10 seconds. The resultant explosion did extensive damage. One aspect of this was that the blast severed piping in many of the sprinkler systems and also ruptured the underground fire water main, rendering the water pressure inadequate for its purpose. Three people were killed and 37 injured.

Mahoney (1990); D.J. Lewis (1993)

**A118 Port Herriot, Lyon, France, 1987**

On 2 June 1987 the Shell depot at Port Edouard Herriot, near Lyon, France, with some 76 tanks, experienced a severe fire. Two persons were killed and 8 injured.

At the time of the account quoted the cause of the incident was not established. It states that at the relevant time of 13.15 work was being carried out on an electric cable for welding equipment and that the power was off but due to be switched on again at 13.30. The initial event was the formation of a spray in the area of the pumps. There was then a flash.

There followed a series of explosions and fires. Twelve minutes into the event a tank holding 250 m³ rocketed up 200 m and fell outside the compound. There was a rapid escalation with five further tanks rocketing and falling inside the depot. Tank 6 exploded in what was probably a boilover. The associated fireball was 450 m high and 200 m 'wide'. During the night the fire progressed further.

The extent of the escalation was attributed in large part to the fact that the tanks were old, and did not have a rupture seam in the roof, so that they tended to burst at the base, releasing the whole contents.

Control of the fire was not achieved until 11.00 on 3 June after two heavy duty foam monitors, each of 6 m³/min capacity, obtained from outside, had been brought into play at 6.30. Among the conclusions drawn in respect of fighting such a fire were that the temperature of the wall of the vapour space of a tank engulfed in fire can rise within two minutes to 500°C, above the auto-ignition temperature for many flammable mixtures; that water cooling used while the foam attack is being prepared may be ineffective and may cause severe degradation of structures; that 4-hour fire insulation may not be sufficient; that concrete bunds may not last out and that earth mounds are preferable; and that an effective foam attack requires heavy duty equipment capable of 4-6 m³/min.
Another conclusion was the need to review the fire permit system: the number, the nature and relationships between the permits.

Mansot (1989)

A119 Ras Tanura, Saudi Arabia, 1987
On 15 August 1987 a leak occurred on a gas plant at Ras Tanura, Saudi Arabia. There were two parallel gas fractionation trains with propane feed. Prior to the incident there had been a number of power interruptions which caused shutdown of one or other of the plants. It is believed that a leak of propane developed in one train, the probable source being a flange on a 4 in. relief line and that the release continued for about half an hour. A large vapour cloud formed and ignited. The ignition was probably from a security vehicle which had stalled and was being restarted. Severe damage was caused.

Mahoney (1990)

A120 Floreffe, Pennsylvania, 1988
On 2 January 1988 an oil storage tank of the Ashland Oil Company at Floreffe, Pennsylvania, suffered catastrophic failure during its initial filling. The tank was a 120 ft diameter \( \times 48 \) ft high coned roof tank. It was 40 years old and had been dismantled at a former site and re-erected. The failure was a sudden rupture. The force of the fluid spurted out one side caused the tank to move 100 ft backwards off its foundations. Some 92,400 bbl of diesel fuel were spilled. The oil overflowed the bund and much of it went into the river.

The investigation found that the rupture occurred due to low temperature embrittlement initiated at a flaw in the tank shell base metal, about 20 cm up from the bottom. The flaw had been created by an oxyacetylene cutting torch and had been there since the initial fabrication. The actual fracture was in the shell base metal; it did not follow the welds but crossed them. In its previous service, the tank had stored heated product, while in its new service the product was not heated. It was the first time that in its new service the tank had been filled to maximum capacity in cold weather.

Prokop (1988); Mahoney (1990); Wilkinson (1991 SRD R530); Mellin (1992 LBP 106)

A121 Norco, Louisiana, 1988
On 5 May 1988 an explosion occurred on a catalytic cracker at the refinery at Norco, Louisiana. There was a rupture, due to internal corrosion, on an 8 in. elbow in the depropanizer overhead piping, which released 9 te of hydrocarbons. A vapour cloud formed and after about 30 seconds found a source of ignition, probably the FCC charge heater. The resultant vapour cloud explosion did extensive damage and caused immediate failure of all utilities. It put out of action fire water and the four diesel fire pumps, and for several hours the fire fighting effort was limited. Some 20 major vessel or line failures occurred. Analysis of bolt stretch on columns indicated an overpressure up to 10 psi. Seven people were killed and 28 injured.

Mahoney (1990); D.J.Lewis (1993)

A122 Antwerp, Belgium, 1989
On 7 March 1989 the BASF ethylene oxide plant at Antwerp experienced two explosions, each with a fireball. The first occurred in column K303, separating ethylene oxide and acetaldehyde, which disintegrated. The pipework on another column, K302, fractured, so that the column depressurized and flame flashed back into it, causing a second internal explosion, separated from the first by 26 seconds. The blast, missiles and secondary fires caused extensive damage. Five people were injured.

The investigation found that low cycle fatigue had caused a hairline crack in a welded seam on piping to a level indicator system, resulting in a small leak of ethylene oxide. This led to an accumulation of auto-oxidizable polyethylene glycols in the insulation. Removal of the metal covering of the insulation allowed self-heating to proceed. The insulation reached a temperature which was sufficient to cause decomposition of ethylene oxide stagnant in the piping of the level control system, though it would not have been enough to overcome the cooling effect of flowing vapour.

Mahoney (1990); Kletz (1990e); Anon. (1991 LBP 100, p. 1)

A123 Baton Rouge, Louisiana, 1989
On 24 December 1988 an explosion occurred in a refinery at Baton Rouge, Louisiana. An 8 in. diameter pipeline ruptured, releasing a mixture of ethane and propane. A record low temperature (10°F) may have contributed to the failure. The escaping vapour found a source of ignition and there was a vapour cloud explosion. The explosion ruptured a pipe band containing some 70 lines. These included lines for power, steam and fire water, and there was a partial loss of all these utilities. The extensive fire involved two large storage tanks, 12 small tanks and two separator units.

Mahoney (1990)

A124 Jonova, Lithuania, 1989
On 20 March 1989 a refrigerated atmospheric ammonia tank failed at Jonova, Lithuania, leading to both a toxic release and a fire of ammonia as well as fire in a fertilizer store. Seven people were killed and 57 injured.

The tank was 29 m diameter \( \times 20 \) m high of single wall construction with perlite insulation held in place by an outer steel shell and with a surrounding 14 m high reinforced concrete wall. It had a capacity of 10,000 m\(^3\) and at the time held 7000 te of liquid ammonia at -33°C. The capacity of each of the two pressure relief valves was 4200 m\(^3\)/h. The site also had two fertilizer stores, one for 15,000 te and one for 20,000 te as well as one for 20,000 te of ammonium nitrate.

The rupture was sudden and the force of the release caused the tank to move sideways from its base, smash through the concrete wall and fetch up 40 m away, leaving its bottom still on the foundations. The devastation around the tank was severe. The escaping liquid ammonia formed a pool which in places was 0.7 m deep. The vapour above the pool suddenly caught fire and the whole area was engulfed in flames. The fire set alight material on a conveyor belt to the 15,000 te store of NPK fertilizer, a ‘cigar burning’ material. The burning conveyor fell into the store and initiated a self-sustaining decomposition.

After 12 hours the pool of ammonia had evaporated. The fertilizer continued to burn for 3 days.
The plant was 12 km from Jonova, a town of about 40,000 inhabitants. A large cloud of ammonia and nitrous fumes spread 35 km, covering an area of 400 km². The cloud height is described as being 100, 400 and 800 m at distances of 5, 10 and 20 km, respectively. Some 32,000 people were evacuated.

The events leading up to the rupture were as follows. Due to an error, 14 te of warm ammonia at 10°C were transferred to the tank, where they formed a layer on the bottom. In due course this layer rose suddenly to the surface. The event was akin to a ‘rollover’, although this term is normally associated not with a pure liquid but with one of varying composition, such as LNG. The higher vapour pressure of the warmer liquid caused a sudden rise in pressure in the tank, which the pressure relief valves were unable to handle, and the tank burst. At the time the refrigeration compressors were not working, but this probably played little part in the incident.

Kletz (1991a); Andersson (1991a, b); Anon. (1992 LPB, p.11); Andersson and Lindley (1992 LPB 107); Kukkonen et al. (1992); Wilday (1992 LPB 108, 109); Kukkonen et al. (1993)

A125 Peterborough, UK, 1989
On 22 March 1989 an explosion occurred in the yard of Vibroplant Ltd at Peterborough on a ICI truck carrying commercial explosives. The driver had missed his way and shortly after 9.30 a.m., approximately, entered the yard to turn round, when, as the vehicle passed over a speed ramp, there was a minor explosion inside the load compartment which blew the rear roller shutter door open. The driver stopped the vehicle, and he and the attendant got out to investigate. Smoke and flames were coming through gaps at the side of the door but no fire could be seen inside. They alerted the Vibroplant personnel in the yard and one of the latter telephoned the emergency services. At first only a small amount of black smoke was to be seen coming from the vehicle, but as the fire progressed there were minor detonations, or ‘pops’, and thick yellow smoke began to emerge. At 9.43–9.44 a.m. two fire tenders arrived. At 9.45 a.m. the load exploded. The scene following the explosion is shown in Figure A1.18. One person was killed and 107 were injured, of whom 84 were treated in hospital.

The load was a mixed one, consisting 150 kg of Powergel 800; 500 kg of Powergel E800; 56 kg of Magna Primers; 76 kg of Ammon-Gelit; detonators and fuseheads. The latter included uncut Cerium combs, 2400 in three boxes. The total mass of explosive had a TNT equivalent of some 800 kg.

The cause of the explosion was determined as a box of Cerium fusehead combs which were in unsafe packaging.

Figure A1.18 Peterborough, 1989: Vibroplant works yard after the explosion (Courtesy of the Peterborough Evening Telegraph)
The report of the HSE (1990b) gives details of the damage and injury done by the event. With respect to damage, the analysis includes the following:

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Overpressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean area</td>
<td>14 78</td>
</tr>
<tr>
<td>Fireball</td>
<td>18 44</td>
</tr>
<tr>
<td>Total destruction of cavity brick/block walls of steel framed building</td>
<td>30 14</td>
</tr>
<tr>
<td>Serious damage to concrete frames of building</td>
<td>110 1.7</td>
</tr>
<tr>
<td>Window breakage:</td>
<td>90% 225 0.69</td>
</tr>
<tr>
<td></td>
<td>50% 360 0.37</td>
</tr>
<tr>
<td></td>
<td>Up to 580 0.19</td>
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</tbody>
</table>

Further details are given in the HSE report. HSE (1990b); Anon. (1991 LPB 98, p. 24)

A126 Richmond, California, 1989
On 10 April 1989 in a refinery at Richmond, California, a 2 in. line carrying hydrogen at about 2800 psi suffered a failure, apparently at a weld, giving rise to a jet flame, which impinged on the support of a reactor, 100 ft high and at least 10 ft diameter and with a wall thickness of 7 in., in a hydrocracker unit. The resultant failure of the reactor led to extensive damage.
Mahoney (1990)

A127 Ufa, Soviet Union, 1989
On 4 June 1989 a massive vapour cloud explosion occurred in an LPG pipeline at Ufa in the Soviet Union. A leak had occurred in the line the previous day or, possibly, several days before. In any event, the engineers responsible had responded not by investigating the cause but by increasing the pressure. The leak was located some 890 miles from the pumping station, at a point where the pipeline and the Trans-Siberian railway ran in parallel through a defile in the woods, with the pipeline some half a mile from, and at a slightly higher elevation than, the railway. On the day in question the leak had created a massive vapour cloud which is said to have extended in one direction five miles and to have collected in two large depressions.
Some hours later two trains, travelling in opposite directions, entered the area. The turbulence caused by their passage would promote entrainment of air into the cloud. Ignition is attributed to the overhead electrical power supply for one or other of the trains. There followed in quick succession two explosions and a wall of fire passed through the cloud. Large sections of each train were derailed and the derailed part of one may have crashed into the other. The death toll is uncertain, but reports at the time gave the number of dead as 462 and of those treated in hospital as 706, many with 70–80% burns.
Plate 37 gives a view of the site, showing the vegetation damage caused by the explosion.
Hofheinz and Kohan (1989); D.J.Lewis (1989 LPB 90, 1993)

A128 Bangkok, Thailand, 1990
At 22.30 on 24 September 1990 a road tanker carrying LPG was involved in a traffic accident at a busy road junction in the centre of Bangkok. Some 5 t of LPG was released but did not ignite immediately. When the cloud did ignite, there was evidently a flash fire, but accounts spoke also of an explosion, probably from gas which had entered a nearby building. In the worst-affected area, almost all the shop houses on both sides of the street were destroyed. Reports gave some 68 persons dead and over 100 injured.
The vehicle was a flat bed lorry carrying two LPG tanks. The two tanks were interconnected by two lines and it appears that these were severed in the accident. The tanker had no license to carry LPG.

A129 Chalmette, Louisiana, 1990
On 3 November 1990 in a refinery at Chalmette, Louisiana, failure involving a heat exchanger shell led to a release of hydrocarbons. A vapour cloud formed,
Figure A1.19  Peterborough, 1989: site plan showing location of certain injuries (Health and Safety Executive, 1990c): (a) persons blown to the ground by the explosion; and (b) persons suffering perforated eardrums (Courtesy of HM Stationery Office)
was ignited by a heater and gave a vapour cloud explosion which did extensive damage.

Marsh and McLennan (1992)

**A130 Nagothane, India, 1990**

On 6 November 1990 at Nagothane, India, a leak occurred on a pipeline transporting ethane and propane to a gas cracker complex. A vapour cloud formed and ignited at an offsite gas treatment and compression facility. The cracker was not damaged by the resultant vapour cloud explosion, but serious damage was done to the offsite units. There were 31 deaths.

Marsh and McLennan (1992)

**A131 Stanlow, Cheshire, 1990**

On 20 March 1990 a reactor at the Shell plant at Stanlow, Cheshire, exploded. The explosion was due to a reaction runaway.

The vessel was a 15 m³ batch reactor containing some 13.5 t of reaction mixture. The reaction was the Halex production of 2,4-difluorinitrobenzene (DFNB), using N,N-dimethylacetamide (DMAC) as solvent. The DFNB was then reacted to obtain the final product 2,4-difluoroaniline (DFA).

The batch had been heated from ambient to 165°C over three hours, in the normal way. It then rose above 170°C, instead of starting to dip slightly, and, unusually, began to vent gas. In the following ten minutes the heating was switched over to cooling, but the temperature and pressure in the reactor continued to rise, at an increasing rate. The control room operators were unaware of the runaway; they were looking at a different display on the VDU. They were alerted to it by an outside operator.

The pressure in the vessel reached a value later assessed as about 60–80 bar, which compares with the relief valve set pressure of 5 bar. The event generated blast, a fireball and missiles. The vessel body unwrapped into a flat plate and the cover was hurled 200 m; other missiles went up to 500 m. The reactor structure collapsed, the fluoroaromatics plant was devastated and structural damage was done to nearby buildings. One man subsequently died, and five others were injured.

There was evidence, from an eyewitness and from a severely burned lamp fitting which became a missile (Missile 47), that prior to the explosion there had been a jet flame above the reactor for some 30–120 seconds before the explosion, the leak coming from a flange or crack. The blast damage in the works had some unusual characteristics, decreasing only slowly with distance. The reactor had a vapour space of 3 m³, but the blast damage was much greater than could be accounted for by a physical explosion involving such a volume, and a combustive event was indicated. Analysis pointed to an event giving a long impulse with a duration time of perhaps 400 ms, compared with, say, no more than 50 ms for a vapour cloud explosion on the one hand and 10 seconds for an unconfined fireball on the other. The relatively long duration of the explosion would be due to the rate limitation imposed by air entrainment. The investigators called the event which occurred a `highly congested fireball'. The fetch of the missiles pointed to a pressure at the source in the range 60–80 bar. It was estimated that some 10 t of material had been ejected from the reactor at about 70 bar in a congested area and had been ignited by the jet flame above the vessel acting as a strong ignition source. These 10 t had an energy of combustion of 230,000 MJ; the event was consistent with an energy release of about one fifth of this.

Much of the damage done was due to the rarefaction wave. Many components were more sensitive to a negative that to a positive pressure deviation.

The investigation found that the runaway was due to the presence of acetic acid. This was detected by smell in the contents of a vent knockout vessel, and, much later, it was identified in a sample of the DMAC from the batch. Investigation revealed a rather complex chemistry. It showed that, when added to a Halex reaction mixture, acetic acid causes exothermic reaction and gas evolution. The DFMB process involved a later stage of batch distillation in which the successive fractions were toluene, DMAC and DFNB. The investigators discovered that during one such batch water had entered the still via a leaking valve. The water had been removed by prolonged azetotropic distillation, using toluene. Under these conditions, DMAC undergoes slow hydrolysis, giving dimethylaniline and acetic acid. However, for there to be any significant yield of acetic acid, the presence of DFNB is necessary, since this reacts with the dimethylaniline, and thus shifts the equilibrium. On this occasion, the DMAC had then been further distilled to purify it. It turned out, however, that DMAC and acetic acid form a maximum boiling azeotrope with a boiling point close to that of pure DMAC. The presence of the acetic acid in the DMAC was not detected by the measurement of boiling point nor by the particular gas chromatographic method in use. Thus the water ingress incident evidently led to a batch of recycled DMAC which was contaminated with acetic acid, with the consequences described.

Anon. (1991b); Kletz (1991 LPB 100); Mooney and Kletz (1991); Redman (1992); van Reijendam et al. (1992)

**A132 Coode Island, Melbourne, Australia, 1991**

On 21 August 1991 an explosion occurred at A Terminal of Terminal Pty at Coode Island, Melbourne, Australia. The site involved had 45 storage tanks, none pressurized, with a vapour recovery system. A 230 t acrylonitrile tank was lifted off its base and projected over four other tanks into the forecourt. There followed a series of bund and tank fires and tank explosions, at the end of which only 13 tanks were left undamaged. There were no deaths or serious injuries.

The cause of the initial explosion has not yet been established. Some of the explanations considered are rehearsed by L.Thomas (1991), including his own of exothermic polymerization in the vapour recovery system. A critique of this explanation is given by Croudcake (1993 LPB 112).

Anon. (1991b); L.Thomas (1991); Anon. (1992c); Alexander (1992a); Marsh and McLennan (1992); Croudcake (1993 LPB 112)

**A133 Seadrift, Texas, 1991**

At 1.18 a.m. on 12 March 1991 an ethylene oxide redistillation column at the Union Carbide plant at Seadrift, Texas, exploded. A large fragment from the explosion hit pipe racks and released methane and other
flammable materials. All utilities at the plant were lost. There was a substantial loss of fire water from water spray systems damaged or actuated by loss of plant air. The explosion and ensuing fire did extensive damage and one person was killed.

The plant had been down for routine maintenance. Startup began in the late afternoon of 11 March, but the plant was shut down several times by trip action before the cause was identified and rectified. Operation was finally established around midnight. The plant had been operating normally for about an hour when the explosion occurred.

The explosion was attributed to the development of a hot spot in the top tubes of the vertical, thermosiphon reboiler such that the temperature reached over 500°C instead of the normal 60°C, combined with a previously unknown catalytic reaction, involving iron oxide in a thin polymer film on the tube, which resulted in decomposition of the ethylene oxide.

A low recirculation ratio in the reboiler could give in some of the tubes low flow, loss of liquid film and stagnant vapour. The account by Viera, Simpson and Ream (1993) gives a detailed discussion of measures to ensure that all the heated surfaces of the reboiler are kept wetted.

Marsh and McLennan (1992); Viera, Simpson and Ream (1993)

**A134 Bradford, UK, 1992**

On 21 July 1992 a series of explosions leading to an intense fire occurred in a warehouse at Allied Colloids Ltd, Bradford. None of the workers at the factory was injured but three residents and 30 fire and police officers were taken to hospital, mostly suffering from smoke inhalation. The fire gave rise to a toxic plume and the run-off of water used to fight the fire caused significant river pollution.

The HSE investigation (HSE, 1993b) concluded that some 50 minutes before the fire two or three containers of azidosobutyronitrile (AZDN) kept at a high level in Oxystore 2 had ruptured, probably due to accidental heating by an adjacent stream condensate pipe. AZDN is a flammable solid incompatible with oxidizing materials. The spilled material probably came in contact with sodium persulphate and possibly other oxidizing agents, causing delayed ignition followed by explosions and then the major fire.

The warehouse contained two storerooms. Oxystore No. 1 was designed for oxidizing substances and Oxystore No. 2 for frost-sensitive flammable products; this second store was provided with a steam heating system. In 1991 an increase in demand for oxidizers led to a change of use, with both stores now being allocated to oxidizing products. A misclassification of AZDN as an oxidizing agent in the segregation table used led to this flammable material being stored with the oxidizers.

In September 1991 the warehouse manager, after discussions with the safety department, submitted a works order for modifications to the oxstores, including Zone 2 flameproof lighting, temperature monitoring equipment, smoke detectors and disconnection of the heater in Oxystore 2. An electrician made a single visit in which he did not disconnect the heater but simply turned the thermostat to zero. Although safety-related, the work was given low priority and 10 months later none of it had been started.

The explosion started at 2.20 p.m. and the first fire appliance arrived at 2.28 p.m. The fire services experienced considerable difficulties in obtaining a water supply adequate to fight the fire. At 3.40 p.m. power was lost on the whole site when the electricity board cut off the supply because the fire was threatening the main substation. The loss of power led to the shut down of the works effluent pumps and escape of contaminated fire water from the site.

The fire services made early contact with the company’s incident controller and strongly advised the sounding of the emergency siren, but this was not done until 2.55 p.m., when the incident had escalated. The fire gave rise to a black cloud of smoke which drifted eastward over housing. The company stated on the day that the smoke was non-toxic. The HSE report, which gives a map of the smoke plume, states that ‘it was in fact smoke from a burning cocktail of over 400 chemicals and only some of them would have been completely destroyed by the heat of the fire’.

The HSE report cites evidence that the warehouse had not been accorded the same safety priority as the production functions. It came under the logistics department, none of whose 125 personnel had qualifications as a chemist or in safety.

HSE (1993b); Anon. (1994 LPB 119, p. 15); V.C. Marshall (1994 LPB 117)

**A135 Castleford, UK, 1992**

At about 1.20 p.m. on Monday, 21 September, 1992 a jet flame erupted from a manway on the side of a batch still on the Meissner plant at Hickson and Welch Ltd at Castleford. The flame cut through the plant control/office building, killing two men instantly. Three other employees in these offices suffered severe burns from which two later died. The flame also impinged on a much larger four-storey office block, shattering windows and setting rooms on fire. The 63 people in this block managed to escape, except for one who was overcome by smoke in a toilet; she was rescued but later died from the effects of smoke inhalation.

The flame came from a process vessel, the ‘60 still base’, used for the batch distillation of organics, which was being raked out to remove semi-solid residues, or sludge. Prior to this, heat had been applied to the residue for three hours through an internal steam coil. The HSE investigation (HSE, 1993b) concluded that this had started self-heating of the residue and that the resultant runaway reaction led ignition of evolved vapours and to the jet flame.

The 60 still base was a 45.5 m³ horizontal, cylindrical, mild steel tank 7.9 m long and 2.7 m diameter. The still was used to separate a mixture of the isomers of mononitroethylene (MNT, or NT), two of which (oNT and mNT) are liquids at room temperature and third (pNT) a solid; other byproducts were also present, principally dinitrotoluene (DNT) and nitrocresols. It is well known in the industry that these nitro compounds can be explosive in the presence of strong alkali or strong acid, but in addition explosions can be triggered if they are heated to high temperatures or held at moderate temperatures for a long period.
The still base had not been opened for cleaning since it was installed in 1961. Following a process change in 1988 a build-up of sludge was noticed, the general consensus being that it was about 1820 litres, equivalent to a depth of about 10 cm, though readings had been reported of 29 cm and, the day before the incident, of 34 cm. One explanation of this high level was that on 10 September the still base had been used as a ‘vacuum cleaner’ to suck out sludge left in the ‘whizzer oil’ storage tanks 162 and 163, resulting in the transfer of some 3640 litres of a jelly-like material. The intent had been to pump this material to the 193 storage but the transfer was slow and was not completed because the material was thick. The batch still was used for further distillation operations, which were completed on September 19. The still base was then allowed to cool and on September 20 the remaining liquid was pumped to the 193 storage.

On September 17 the shift and area managers discussed cleaning out the still base. The former had been told by workers that the still had never been cleaned out and he realized that the sludge covered the bottom steam heater battery. It was agreed to undertake a clean-out. The area manager gave instructions that preparations should be made over the weekend, but when he arrived on the Monday morning nothing had been done. He was concerned about the downtime, but was assured that this could be minimized and gave instructions to proceed.

At 9.45 a.m. the area manager gave instructions to apply steam to the bottom battery to soften the sludge. Advice was given that the temperature in the still base should not be allowed to exceed 90°C. This was based solely on the fact that 90°C is the flash point of MNT isomers. However, the temperature probe in the still was not immersed in the liquid but in fact recorded the temperature just inside the manway. Further, the steam regulator which let down the steam pressure from 400 psig (27.6 bar) in the steam main to 100 psig (6.9 bar) in the batteries was defective. Operators compensated for this by using the main isolation valve to control the steam. This valve was opened until steam was seen whispering from the pressure relief valve on the battery steam supply line. This relief valve was set at 100 psig but was actually operating at 135 psig (9 bar), at which pressure the temperature of the steam in the battery tubes would be about 180°C.

The clean-out operation, which had not been done in the previous 30 years, was not subjected to a hazard assessment to devise a safe system of work, and there were defects in the planning of and permit-to-work system of the operation. The task was largely handled locally with minimal reference to senior management and with lack of formal procedures, although such procedures existed for cleaning other still bases on the site. The permits were issued by a team leader who had not worked on the Meissner plant for 10 years prior to his appointment on September 7. At 10.15 a.m. he made out a permit for a fitter to remove the manlid. The fitter signed on about 11.10 a.m. and shortly after went to lunch. Operators who were standing by offered to remove the manlid and the same team leader made out a permit for them to do so. When the fitter returned from lunch it was realized that the still base inlet had not been isolated and a further permit was issued for this to be done.

Meanwhile, the manlid had been removed. The area manager asked for a sample to be taken. This was done using an improvised scoop. He was told the material was gritty with the consistency of butter. He did not check himself and mistakenly assumed the material was thermally stable tar. No instructions were given for analysis of the residue or the vapour above it. Raking out began, using a metal rake which had been found on the ground nearby. The near part of the still base was raked. The rake did not reach to the back of the still and there was a delay while an extension was procured. The employees left to get on with other work and it was at this point that the jet flame erupted.

The HSE report states that analysis of damage at the Meissner control building at 13.4 m from the manway source indicated that at this building the jet flame was 4.7 m diameter. The jet lasted some 25 seconds and had a surface emissive power of about 1000 kW/m2. The temperature at 6 m from the manway would have been about 2300°C.

The company employed some highly qualified staff with considerable expertise in the manufacture of organic nitro compounds. The HSE report describes some of the investigations of thermal stability, safety margins, etc., in which these staff were involved. It also comments in relation to the incident in question, ‘Regrettably this level of understanding was not reflected in the decision which was made on 21 September when it was decided that the 60 still base would be raked out.’

As soon as the personnel at the gate office saw the flame one of them made a 999 emergency call. The employee requested the fireman to be below the flare to assist. But spoke only to the former before the call was terminated at the exchange. Thereafter incoming calls prevented further outgoing calls for assistance.

Just over a year before the incident the management structure had been reorganized. This involved replacing a hierarchical structure with a matrix management system, eliminating the role of plant manager and instituting a system in which production was coordinated through senior operatives acting as team leaders. The area managers had a significant work load. In addition to their production duties they had taken over responsibility for the maintenance function, which had previously been under the works engineering department. Managers were not meeting targets for planned inspections under the safety programme, and this was said to be due to lack of time.

C. Butcher (1994); HSE (1994b); Keltz (1994 LPB 119)

A136 Sodegaura, Japan, 1992
At 15.52 on 16 October 1992 at the Fuji Oil Sodegaura refinery at Sodegaura City, Japan, a large release of hydrogen occurred from a rupture on a feed/reactor effluent heat exchanger on the heavy oil indirect desulfurization unit as the plant was being started up after a shutdown. There was a delay of a few minutes, during which personnel took measures to try to stop the release, before the leak found a source of ignition and exploded. Ten were killed and seven injured.

The investigation found that the leak occurred at a gasket retainer on the heat exchanger as illustrated in
Figure A1.20 Sodegaura, 1992: simplified diagram of heat exchanger gasket retainer. The gasket retainer suffered wear at the point marked X and repair was made by grinding, with loss of metal broadly as shown by the dotted portion (after the High Pressure Gas Safety Institute of Japan, 1993 LPB 116)

Figure A1.20. The gasket retainer had shrunk due to repeated thermal cycling and it suffered wear at the point shown as X on the diagram. The defect was detected and during a shutdown the surface was repaired by grinding. However, the effect of this was to cause the retainer to ride beyond the groove so that when the retainer was heated during startup, a gap opened up and the escape occurred.

High Pressure Gas Safety Institute of Japan (1993 LPB 116)

A137 Hoechst Incidents, Germany, 1993
On 22 February 1993 an accident occurred at the Griesheim works of Hoechst which was unprecedented in the company's 130-year history. By April 2 there had been at five sites a series of no less than 14 incidents, comprising 11 releases, two fires and one explosion, of which three were considered serious by the company.

Incident on 22 February 1993
The first of these, at 4.14 a.m. on 22 February, was a reaction runaway which occurred when a reactor for the production of o-nitroanisol was charged with reaction mixture with the agitator off and the latter was then switched on. Some 10 te of material was discharged through two safety valves. The ambient temperature was −2°C and most of the material solidified, but the residual gas cloud spread across the Main and affected an area of some 30 hectares in Frankfurt.

The information available to the works manager, a materials safety data sheet conforming to the DIN standard, was that o-nitroanisol is ‘slightly toxic’, and he gave this description to the press. As it happened, the previous Friday this data sheet had been the subject of a revision, to the effect that the substance had been found to be carcinogenic to rats when administered in large doses over a long period. The revision had been known to the company's specialists since November 1992 but not to the works manager. The toxicity of the substance was the subject of press comment.

Incident on 15 March 1993
The second serious incident, was on 15 March, on one of four parallel trains for the production of polyvinylalkohol. At the location in question in normal operation the material was in gel form on a conveyor belt inside an enclosure, but at the time the belt was stopped and empty. That morning the enclosure, which was normally kept inerted with nitrogen, was inspected. A precutter was still operating. An explosion occurred which killed the shift supervisor and injured the section manager. There followed a fire, which gave rise to a large column of smoke visible for some distance but which was rapidly brought under control.

An investigation by the authorities concluded that the enclosure had contained flammable vapours, that air had entered the enclosure during the inspection and that tramp metal had entered, giving rise to a spark at the precutter.

Incident on 2 April 1993
The third incident, on 2 April, involved a release of oleum. The release occurred when air pressure was applied to a vessel containing oleum and, due to a blockage in an outlet pipe, caused by crystallization, the oleum passed instead into an absorber where it reacted violently with the absorbent. A glass pipe ruptured and some 500 kg of oleum was released.

Owing to difficulties experienced with the alarm system some 13 people at the research centre came in contact with the cloud and received treatment at the medical centre.

Ondrey (1993a, b); Schönfeld (1993); Vennen (1993)

A138 Dronka, Egypt, 1994
On 2 November 1994 blazing liquid fuel flowed into the village of Dronka, Egypt. The fuel came from a depot of eight tanks each holding 5000 te of aviation or diesel fuel. The release occurred during a rainstorm and was said to have been caused by lightning. Reports put the death toll at more than 410.

Reuter (1994)

A139 Ukhta, Russia, 1995
Early in the morning on 27 April 1995 an ageing gas pipeline exploded in a forest in northern Russia. Reports described fireballs rising thousands of feet in the air and the inhabitants of the city of Ukhta, some eight miles distant, as rushing out in panic. At Vodnya, six miles away, the sky was so bright that people thought the village was on fire. The pilot of a Japanese aircraft passing over at some 31000 ft perceived the flames as rising most of the way towards his plane.

Anon. (1995)

A1.11 Case Histories: B Series
One of the principal sources of case histories is the MCA collection referred to in Section A1.1. There are a number of themes which recur repeatedly in these case histories. They include:

Failure of communications
Failure to provide adequate procedures and instructions
Failure to follow specified procedures and instructions  
Failure to follow permit-to-work systems  
Failure to wear adequate protective clothing  
Failure to identify correctly plant on which work is to be done  
Failure to isolate plant, to isolate machinery and secure equipment  
Failure to release pressure from plant on which work is to be done  
Failure to remove flammable or toxic materials from plant on which work is to be done  
Failure of instrumentation  
Failure of rotameters and sight glasses  
Failure of hoses  
Failure of, and problems with, valves  
Incidents involving exothermic mixing and reaction processes  
Incidents involving static electricity  
Incidents involving inert gas

The most frequently mentioned operations are

<table>
<thead>
<tr>
<th>Operation</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading</td>
<td>38</td>
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<tr>
<td>Maintenance</td>
<td>82</td>
</tr>
<tr>
<td>Pipe fitting</td>
<td>27</td>
</tr>
<tr>
<td>Process reaction</td>
<td>66</td>
</tr>
<tr>
<td>Sampling</td>
<td>24</td>
</tr>
<tr>
<td>Steamline</td>
<td>32</td>
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<tr>
<td>Tank entry</td>
<td>39</td>
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<tr>
<td>Transfer</td>
<td>46</td>
</tr>
<tr>
<td>Unloading</td>
<td>64</td>
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<td>Welding</td>
<td>36</td>
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The most frequently mentioned equipments are

<table>
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<th>Equipment</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>Centrifuge</td>
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</tr>
<tr>
<td>Pump</td>
<td>27</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>60</td>
</tr>
<tr>
<td>Drum</td>
<td>27</td>
</tr>
<tr>
<td>Rotameter, sight glass</td>
<td>57</td>
</tr>
<tr>
<td>Industrial truck</td>
<td>59</td>
</tr>
<tr>
<td>Tank car</td>
<td>35</td>
</tr>
<tr>
<td>Laboratory</td>
<td>86</td>
</tr>
<tr>
<td>Tank truck</td>
<td>86</td>
</tr>
<tr>
<td>Valve</td>
<td>86</td>
</tr>
</tbody>
</table>

In the 2108 case histories described the most frequently mentioned chemicals and the corresponding number of entries are

<table>
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<th>Chemical</th>
<th>Frequency</th>
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</thead>
<tbody>
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<td>Ammonia</td>
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<tr>
<td>Chlorine</td>
<td>37</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>88</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>46</td>
</tr>
</tbody>
</table>

It is emphasized, however, that in many instances it is not appropriate to assign a single cause.

Accounts of some typical case histories, many of which are taken from the MCA collections, are given below.

The descriptions are generally briefer than those given in the original sources, which should be consulted for further details.

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**Figure A1.21** Batch reactor after explosion (Anon., 1977n)
B1 A pilot plant batch reactor was started at 5.40 a.m. as soon as catalyst was added the temperature and pressure began to increase. In accordance with normal operation venting was carried out. But this was slow and difficult due to carryover of liquid and solids from the reactor to the vent lines. At about 6.45 a.m. the agitator stopped as a result of overload. The vent lines blocked, the pressure increased rapidly and the building had to be evacuated. It was re-entered about 7.20 a.m., when the pressure was found to be 750 psi. Thereafter the reaction subsided as the reactants were used up. The pressure relief valve was set at 750 psi, but was found to be blocked as a result of the incident. The cause of the reaction runaway was overcharging of reactants at the start of the batch. (MCA 1966/15, Case History 867.)

B2 A batch chlorinator exploded suddenly killing employees and doing extensive damage. The reaction temperature was controlled automatically by manipulating the chlorine flow. During the batch the measured temperature fell sharply and it was realized that the thermocouple had failed. The agitator was stopped and the brine cooling was shut off while the instrument was repaired, but delay in stopping chlorine flow resulted in a high temperature giving decomposition reactions. The explosion blew the reactor cover through the roof and the reactor itself was driven down into the floor. Flammable gases were released which burned and caused the casualties mentioned. The explosion also ruptured chlorine and ammonia lines. The works emergency plan was activated, involving both local area services and mutual aid from other chemical firms. (MCA 1962/14, Case History 371.)

B3 In a process involving chlorination of paraffin in a reactor, chlorine gas was piped into the system in a carbon steel pipe. The pipe ruptured and released paraffin and chlorine, which caused a fire and did extensive damage. Subsequent investigation revealed that the contents of the reactor had leaked into the pipe and had reacted with the chlorine vapour. Severe oxidation of the steel pipe by chlorine and/or hydrogen chloride led to the pipe rupture. (NFPA 1973.)

B4 An explosion occurred in a batch reactor which blew the top right off the vessel. The vessel was supported by steelwork two-thirds of the way up its side. The force of the explosion pushed the reactor 2½ ft into the floor, which was 3 ft below, as shown in Figure A1.21. Fragments of the lid of the vessel, which contained a bursting disc, were scattered over the countryside. (Anon. 1977n.)

B5 The loaded basket of a 48 in. suspended-type centrifuge suddenly became unbalanced and in consequence the shaft flew out and broke the outlet pipe of an adjacent centrifuge. The investigation indicated that the imbalance had been caused by a sudden escape of cake from one side of the basket due to a hole in the cloth. (MCA 1966/15, Case History 645.)

B6 A 2000 ft³ diborane surge tank disintegrated causing severe loss. The failure fragmented the tank and reduced to rubble a 24 in. thick reinforced concrete wall barricading it on three sides. Fragments travelled 2200 ft and one cut four process lines in a unit 1800 ft distant. The tank was 8 ft inside diameter × 30 ft long. It was designed for a working pressure of 206 psi with a safety factor of 4. Prior to the installation it had been completely radiographed and stress-relieved. At the time of the explosion the tank pressure and temperature were 192 psig and 12°C. The cause of the explosion was not certain, but the most probable explanation appeared to be a defect in the tank aggravated by high stresses at the attachment weld of the platform support. (MCA 1966/15, Case History 730.)

B7 A safety shut-off valve on the gas supply to the burner in the combustion chamber of a drier remained open after the unit was shut down. There was no indication to show whether the valve was open or closed. On relighting the burner the operator made several errors, including that of opening the main valve on the gas supply to the burner before lighting the pilot burner. When the lighted taper was inserted into the combustion chamber, there was an explosion. (MCA 1966/15, Case History 1068.)

B8 A reactor with a water jacket collapsed inwards due to overpressure in the jacket, the water from the jacket mixed with the reaction mass, and hot steam and chemicals erupted violently through a sight glass and a rupture disc on the reactor. The overpressure of the jacket took place during the initial heating of the reactor charge and occurred because the inlet and outlet valves on the jacket were closed and there was no pressure relief device on the jacket, although there was a bursting disc on the reactor itself. (MCA 1966/14, Case History 333.)

B9 A cabinet containing sparking electrical equipment was pressurized with nitrogen to exclude flammable gases. Nitrogen from the same main was used to ‘egg’ acetone out of a process vessel. The nitrogen pressure fell as a result of heavy demand, acetone passed back into the nitrogen and got into the cabinet. Subsequently the nitrogen flow to the cabinet was shut off, air leaked in and mixed with the acetone, and there was an explosion. (Kletz, 1976b.)

B10 Butadiene from a reactor passed back up a line used for adding emulsifier through an obstructed non-return valve. The emulsifier tank had an open vent, so that the butadiene got out into the building and exploded. The explosion caused flames 75 ft high and was heard 10 miles away. Damage was minimized, however, by the light construction of the building which ruptured at the roof and at two of the walls. (Mallek, 1969.)

B11 In a pilot plant acetaldehyde oxidation column the arrangements involved purging the column with nitrogen and then supplying acetaldehyde to the column by nitrogen pressure. The oxidation was carried out by admitting a controlled flow of oxygen to the column. The pipework allowed the nitrogen to be used to purge the column and part of the oxygen pipe. There was nothing to stop oxygen at higher pressure passing into the nitrogen in case of a leaking valve or of incorrect operation. During operation the operator observed a
leak on the acetaldehyde supply drum and was told to shut the plant down. A few minutes later an explosion occurred which killed 4 people. From the investigation it appeared that oxygen had leaked via the nitrogen purge line into the acetaldehyde drum, in which reaction occurred with large rises in temperature and pressure and eventually a detonation. (MCA 1962/14, Case History 117).

B12 A malfunction of the control equipment allowed raw gas to accumulate in a direct-fired textile fibre drier. When circulating fans were turned on, the drier exploded. (Doyle, 1969.)

B13 In an air liquefaction plant an electrical failure caused the control valve on an oxygen line to open and pass oxygen into a nitrogen line. The nitrogen was compressed and then used as wash liquid for the offgas from an ethylene plant. The nitrogen wash cold box exploded. (Doyle, 1969.)

B14 In a chlorine liquefaction system ‘gunk’ was warmed prior to removal from a cold trap. A leaky steam valve allowed overheating of the gunk. This contained sufficient nitrogen trichloride to explode. (Doyle, 1969.)

B15 A vacuum system failed on a small still distilling a chloronitro compound. This allowed the temperature to rise and give a self-accelerating decomposition. A large still adjacent to the small one was seriously damaged. (Doyle, 1969.)

B16 A reboiler distilling epichlorhydrin from a mixture with tar was heated by steam. The thermocouple on the steam control loop tarred up and gave an incorrect reading. The only control of conditions in the column became the operator’s response to the temperature at the top of the column. This proved inadequate, the reboiler overheated and an explosion occurred. (Doyle, 1972a.)

B17 In a furnace cracking ethylene dichloride to vinyl chloride under computer control the flow of ethylene dichloride to the furnace was controlled to maintain an optimum temperature in the cracked gas exit line. A furnace tube split and reduced the cracking gas flow and the cracked gas temperature. The control action increased the flow of ethylene dichloride. The furnace tubes burned up. (Doyle, 1972a.)

B18 A common type of ‘Dowtherm’ vaporizer is a single coil in which the liquid is superheated, followed by a flash chamber. There is an interlock between a flowmeter on the liquid line to the coil and the fuel flow controller, so that the coil is not heated unless liquid is flowing through it. A vaporizer of this type was started up after a shut-down and the coil immediately exploded. The impulse lines to the differential pressure transmitter had frozen just before the shut-down, showing a normal flow, and during the shut-down the exit line from the coil also froze up. On start-up the interlock did not work owing to the incorrect signal from the flowmeter and the heating of the coil caused pressure to build up and rupture it. (Doyle, 1972a.)

B19 Excess water was removed from a hydrogen peroxide–water mixture by vacuum distillation. As a precaution against attempting to vaporize a dangerous concentration of peroxide, the liquid level and vapour temperature were measured: a low level or a high temperature signal operated a valve to dump de-ionized water into the reboiler. The hydrogen peroxide solution produced large quantities of heavy foam. The float-type level instrument measured the foam rather than the liquid level. After some erratic readings it gave a seriously inaccurate one while the level was low, and the reboiler exploded. (Doyle, 1972a.)

B20 The agitator on a batch nitration reactor was stopped, but the process operator was unaware of this. Instrumentation which should have cut off the acid feed to the reactor and given an alarm signal of agitator stoppage apparently failed to work. When the agitator started up again, the reactor exploded. (Fritz, 1969.)

B21 In an ethylene cracking furnace the flow of fuel to the furnace was manipulated to control the temperature of the gas leaving the furnace. The temperature measuring instrument failed and gave a low reading. The control action increased the heat to the furnace. The furnace was designed to supply mainly latent heat of vaporization to the process stream with a small amount of superheat. Thus the vapour temperature was sensitive to the additional heat input and rose rapidly. The piping overheated and ruptured, releasing ethylene gas which was ignited by the burners of an adjacent furnace. The resultant fire did severe damage. (H.D. Taylor and Redpath, 1971.)

B22 Ammonia synthesis gas at 2000 psig was passed through a scrubber which was fed with weak aqueous ammonia. The liquid from the bottom of the column passed to a vertical holdup tank with a 2 in atmospheric vent. The level of liquid in the base of the column was controlled automatically. The control valve in this loop stuck in the open position. Liquid and gas from the column surged into the holdup tank and ruptured it. The escaping gas was approximately 75% hydrogen and it ignited, causing a fire. (MCA 1966/15, Case History 598.)

B23 A flow ratio control loop failed and allowed excess hydrogen to enter a catalytic tower. Hot spots developed, causing thermal decomposition of the hydrocarbon-hydrogen stream and rupture of the tower. (MCA 1966/15, Case History 609.)

B24 A flame failure occurred on the burner of a Dowtherm vaporizer and the procedure for relighting the burner was initiated. The fire box was checked and the automatic control system which purges and lights the flame was activated. A short developed across the fuel selector switch of the system, causing fuel gas to enter the combustion chamber during the purge cycle and thus creating a flammable fuel-air mixture. When the purge cycle was complete and the pilot light was ignited, an explosion occurred. (MCA 1966/15, Case History 821.)
B25 An inert gas generator was found to have produced a flammable oxygen mixture. The ‘fail safe’ flame failure device had failed. The trip system on the oxygen content of the gas generated had caused shutdown when the oxygen content in some of the equipment reached 5%, but did not prevent creation of a flammable mixture in the holding tank. (MCA 1966/15, Case History 679.)

B26 An air supply enriched with 2–3% oxygen was provided for flushing and cooling air-supplied suits after use. A failure of the control valve on the oxygen–air mixing system caused this air supply to contain 68–76% oxygen. An employee used the supply to flush his air-supplied suit, disconnected the lines, removed his helmet and lit a cigarette. His oxygen-saturated underclothing caught fire and he received severe burns. (MCA 1966/15, Case History 884.)

B27 A chlorine cell room was experiencing operational difficulties. A failure of the control system caused a back pressure to develop. When the operating personnel tried to shut the system down using manual controls, a failure of this equipment caused a serious chlorine release. One of two compressors taking hydrogen from a low pressure gasholder continued to operate and failure of a low level trip created a negative pressure, allowing air to leak in. An explosion occurred in the cooling coils of the compressor. Hydrogen from another part of the process was introduced into the holder in an effort to maintain production. The hydrogen-air mixture in the holder diffused into the catalyst purification unit, where a high temperature developed, causing a second explosion. The failure of the gasholder trip to operate was due to the fact that the timer had been bypassed by a ‘jumper’. (MCA 1966/15, Case History 694.)

B28 An explosion occurred on a vinyl chloride polymerization plant at Minamata, killing 4 and injuring 8 other people inside the factory and slightly injuring 2 people outside it by flying glass. The polymerization reaction in No. 3 reactor was complete and the operators intended to discharge the contents, but No. 4 reactor was discharged in error. The reaction in this reactor was incomplete and the vinyl chloride monomer escaped and exploded. (MCA 1966/15, Case History 816.)

B29 A rigger was removing manhole covers from a vinyl chloride reactor when he apparently became confused and removed the cover from a reactor which was operating under pressure. A large quantity of vinyl chloride vapour was released. It ignited to give a flash fire, which killed the rigger and 2 labourers. (MCA 1970/16, Case History 1132.)

B30 In an ethylene oxide plant inert gas was circulated through a process containing a catalyst chamber and a heat removal system. Oxygen and ethylene were continuously injected into the inert gas and ethylene oxide was formed over the catalyst, liquefied in the heat removal section and passed to the purification system. On shut-down of the circulating compressor an interlock stopped the flow of oxygen and the closure of the valve was indicated by a lamp on the panel. During one shut-down the lamp showed the oxygen valve closed. The process operator had instructions to close a hand valve on the oxygen line, but he expected the maintenance team to restore the compressor within 5–10 minutes and did not close the valve. The process loop exploded. The oxygen control valve had not in fact closed. A solenoid valve on the control valve bonnet had indeed opened to release the air and it was the opening of this solenoid which was signalled by the lamp on the panel. But the air line from the valve bonnet was blocked by a wasps’ nest. (Doyle, 1972a.)

B31 A catalyst bed was regenerated by circulating nitrogen through an electric heater, the bed and a cooler. The flow meter on the nitrogen line choked with dust early on and the process operators learned to make do without it, controlling the plant by the nitrogen temperature at the bed inlet. One day the cooler blocked with dust and the temperature at the bed inlet stuck at its normal value. The heater over-heated and at 740°C its high temperature trip operated and cut off the power. The operator, seeing that the other instrument readings were normal, assumed the trip to be faulty and switched the power back on. The trip operated and was over-ridden three times in one hour. There was a shift change during this hour. Finally the heater shell burst. (Kletz, 1974b.)

B32 A tank had to be filled with enough raw material to last a day. The operator watched the tank level and switched off the pump when the required level was reached. One day after several years operation and some 1000 fillings, the man let the tank overflow. So a trip system was installed as an additional safeguard. The operator, however, got in the habit of using the trip system as a replacement and got on with something else. The plant manager knew about this, but was happy to see the improvement in productivity. However, since the trip system can be expected to fail about once in 18 months, the overall system had actually become less reliable. (Kletz, 1974d.)

B33 An explosion occurred in the open air in the vicinity of a hydrogen vent stack and caused severe damage. It was normal practice to vent hydrogen for periods of approximately 45 minutes. On this particular occasion there was no wind, the hydrogen failed to disperse and the explosion followed. (MCA 1966/15, Case History 1097.)

B34 An operator was adding charcoal impregnated with catalyst from a plastic bag into a reactor containing caustic soda blanketed with nitrogen. The charcoal dust ignited and there was a flash fire. It is believed that the ignition was caused by static electricity. (MCA 1966/15, Case History 1094.)

B35 An employee was repairing a blower on the vent stack of a dissolver. When he had finished the work, he switched the machine on, but observed that it was not operating. He reached into the stack to give the fan blades a turn and there was an explosion. The vent stack had contained a flammable mixture, which was probably ignited by static electricity from the man’s body. (MCA 166/15, Case History 703.)
B36 A man was filling his cigarette lighter from a gallon can of naphtha when he dropped the lighter. It apparently struck on the wheel and gave a spark. Flammable vapour from a nearby drum filling plant ignited and caused a violent explosion. (MCA 1970/16, Case History 1175.)

B37 A substantial section of lagging along the pipework of a process heating fluid system became contaminated with the fluid, which was a low volatility mineral oil, due to a pump gland leak. A lagging fire occurred, the symptoms of which were that first smoke was seen rising from the lagging, then the heating fluid rose 50°C above its set temperature of 270°C and finally the pump and a considerable length of pipe became enveloped in flames. The latter were quickly dealt with, but the temperature of the heating fluid continued to rise. Soon afterwards a small explosion occurred in a covered oil header tank housed inside a building. There was a large release of oil and fumes from the tank and these then exploded violently, causing severe damage to the building. The probable explanation was that some of the oil had been heated above its spontaneous ignition temperature and had been forced by expansion back up into the header tank, where its vapour met air and ignited. (Gugan, 1974a.)

B38 A large spray drying plant with direct heating from a combustion chamber was being run in. The combustion system had been operating at a very low firing rate under manual control for some 24 hours. The fuel oil to the burner was pumped by a positive displacement pump through thermostatically controlled heaters, excess oil being bypassed around the pump. After firing had continued unsupervised some hours, there was a sudden eruption of flame through a hinged explosion panel near the combustion chamber and a man walking past was enveloped. Investigation showed that the eruption of flame could be explained by a gross increase in fuel flow to the burner, even though a manual valve on the fuel line was still at its original setting. It was also discovered that a fire had developed in the lagging of the fuel oil system, the lagging having become saturated with oil due to leaks from pipe joints occurring during the initial pressure testing. The reason for the increase in fuel oil flow was probably a rise in the oil temperature to a value much in excess of that set on the thermostat, so that there was a decrease in oil viscosity and an increase in the quantity flowing through the valve. (Gugan, 1974a.)

B39 Dried material from a double-drum steam drier was passed from a bag packer via a spout with a cotton apron to a leverpak. A small dust explosion occurred at the apron and led to a fire in the bagging plant and leverpak. It was considered from investigation that the dust had been ignited by a spark discharge of static electricity. The cotton apron was non-conducting and the bag packer was not earthed. (MCA 1966/15, Case History 653.)

B40 An operator was in the process of unloading titanium carbide dust from 2 ft conical ball mill. He had removed 95% of the material. The mill was being rotated in order to clean it when a dust cloud ignited. He received severe burns from which he later died. The product had been milled to a finer size than desired and thus rendered highly reactive. (MCA 1966/15, Case History 618.)

B41 A set of air compressors comprising four three-stage 740 h.p. machines with a discharge pressure and temperature of 350 psi and 350°F had been in operation for about 8 hours following a plant shut-down. The third-stage cylinder in one of the compressors was faulty and the 125 psi relief valve between the second and third stages began to relieve air intermittently. The third-stage discharge temperature went off the instrument scale at 400°F before the compressor could be shut down. Some 15 minutes later the overhead discharge line was observed to be glowing red hot. Before the other compressors could be shut down, the line ruptured and a flash fire occurred. Investigation indicated that lubricating oil had ignited in the compressor cylinder and discharge line. (MCA 1962/14, Case History 35.)

B42 An explosion occurred in a vinyl chloride pump and seriously injured an operator. The pump was on the ‘recovered’ vinyl chloride monomer (RVCM) system. The line sections before and after the pump had been removed and the explosion occurred in the idle vented pump about an hour later. The investigation showed that the entire RVCM system was contaminated with vinyl chloride polyperoxide, which is an unstable material. There had been three abnormal occurrences on the plant prior to this accident. The RVCM gas compressors had not shut down at low pressure due to the failure of a pressure switch. There had been an accumulation of RVCM liquid in the stage tanks for days. And the acidity level in the vinyl chloride feed to the polymerizers had been high. (MCA 1970/16, Case History 1551.)

B43 A four-stage reciprocating compressor used to compress nitrogen from 15 to 3000 psig exploded with a ‘brilliant flash’ and projected fragments up to 160 ft from the building. Previous to the explosion the machine had been shut down to change the third-stage suction and discharge valves and again to correct an error in the installation of the former. Investigation showed that the discharge valve had been installed in the reversed position and that compression of the gas under these conditions could give a pressure of 16800 psig and a temperature of 1310°F. This temperature exceeded the autoignition temperature of the lubricating oil. There may have been oxygen present due to the maintenance operations. These conditions resulted in the explosion. (MCA 1966/15, Case History 1056.)

B44 A 40000 gal horizontal tank was used to produce aqueous ammonia by introducing water at the top and anhydrous ammonia at the bottom. The tank was emptied and the water flow was started to make the next batch. The tank imploded due to the vacuum created by the absorption of the ammonia vapours by the water. (MCA 1966/15, Case History 916.)

B45 A holding tank containing 'heaves' from cracking furnaces suddenly erupted blowing oil, water and steam over the adjacent area. It is believed that condensate had come in contact with the hot oil, which was at a
temperature of 600–700°F, thus generating large quantities of steam. (MCA 1962/14, Case History 453.)

B46 A storage tank was not in use and was boxed up with some water inside. Rusting took place, the oxygen of the air in the tank was depleted and the tank collapsed inwards. (Anon., 1977n.)

B47 A storage tank was cleaned out and filled with a high purity liquid. A polyethylene bag was put over the vent to prevent contamination. It was a hot day and the temperature of the liquid in the tank rose. There was a sudden shower, vapour in the tank condensed and the tank collapsed inwards. (Anon., 1977n.)

B48 Cold liquid was pumped into a storage tank containing hot liquid. The liquid in the tank was cooled, the vapour pressure fell and the tank collapsed inwards. (Anon., 1977n.)

B49 Modifications were required to a high pressure chlorine main. The main was isolated and men began work. The supervisor then realized that there might be some chlorine present in a section of pipework at the tank car rack. The pipework was connected to the main, but there was an isolation valve between the main and the pipework. He assumed that this valve was shut and initiated measures to remove any chlorine present in the pipework section. There was liquid chlorine in this pipework and it passed via the isolation valve into the main and gassed the fitters working there. The isolation valve was subsequently found to be frozen in the part open position. (MCA 1966/15, Case History 707.)

B50 An employee went into a water cistern to install some control equipment and immediately collapsed into water 2 ft below. A second employee who had accompanied him ran to fetch assistance. Minutes later he came back with several others, two of whom entered the cistern and also collapsed. Meanwhile the alarm had been raised. The fire services arrived and a crowd gathered. While the fire officer was putting on his self-contained breathing apparatus, one of the bystanders, saying that he could swim, descended into the cistern. The fire officer then went in, but took off his mask, presumably to call for some equipment, and collapsed. All five people died due to hydrogen sulphide poisoning. (MCA 1970/16, Case History 1213.)

B51 ‘A double fatality occurred in a steel works whilst two fitters were changing a gearbox valve for a blast furnace system. One or both men opened a valve allowing gas to escape at a rate of 50,000 cu. ft. per hour. Of another two men who went to investigate the volume of gas passing through the valve, one was overcome by gas (but later recovered) and the other escaped to summon assistance. Safety precautions should have included either the isolation of the system upstream from the valve or the use of suitable breathing apparatus by the workmen. Although both maintenance men had been issued with compressed airline breathing apparatus it was found after the accident that only one of these was connected with the air supply and neither was being worn. The fatalities highlighted the dangers of complacency which can occur when a system has operated without incident for years and also the need to ensure that workers employed in such situations are adequately trained in the use of breathing apparatus.’ (Annual Report of HM Chief Inspector of Factories, 1974.)

B52 During plant commissioning a temporary filter was put in a compressor suction line, as shown in Figure A1.22. The filter was located between the compressor and the low suction pressure trip. The filter blocked, the suction pressure fell below atmospheric, air was sucked in and a decomposition reaction occurred further on in the process where there was a higher pressure. Two pipe joints sprung and gas escaped and ignited. The resulting fire caused £100,000 damage and delayed the commissioning many months. (Henderson and Kletz, 1976.)

B53 An olefins plant was severely damaged during commissioning by a fire in the refrigeration section of the gas separation plant. Although no one was seriously injured, the fire burned for 15 hours and caused delay to the commissioning and considerable damage and consequential loss. The cause of the fire was that the low pressure refrigeration section, which was designed for 50 psig pressure, was subjected to a pressure of 400 psig. The overpressure occurred because of closure of a 12 in. valve on the exit of this section, installed during construction to allow high pressure gas to be used to assist in drying the plant prior to commissioning. The installation of the valve had been well debated in the plant operating team and with the process design contractor. But the installers did not follow the well-established requirement of providing pressure relief protection on the low pressure system. (Heron, 1976.)

B54 A works had a special network of air lines installed some 30 years ago for use with breathing apparatus only. The supply to this network was taken off the top of the general purpose compressed air main as it entered the works, as shown in Figure A1.23. One day a man wearing a face mask inside a vessel got a faceful of water. He was able to signal to the anti-gas man and was rescued. Investigations revealed that the compressed air main had been renewed and that the branch to the breathing apparatus network had been connected to the bottom of the compressed air main. As a result a slug of water in the main would all go into the catchpot and fill it more quickly than it could empty. (Henderson and Kletz, 1976.)

B55 Pressure relief on a low pressure refrigerated ethylene tank was provided by a relief valve set at about 1.5 psig and discharging to a vent stack. When the

![Figure A1.22 Compressor system after modification (Henderson and Kletz, 1976) (Courtesy of the Institution of Chemical Engineers)](image-url)
Figure A1.23  Air offtake for breathing apparatus as originally installed (Henderson and Kletz, 1976) (Courtesy of the Institution of Chemical Engineers)

Figure A1.24  Mobile crane overturned on to plant (Anon., 1977n)

design had been completed, it was realized that if the wind speed was low, cold gas coming out of the stack would drift down and might then ignite. The stack was not strong enough to be extended and was too low to use as a flare stack. It was suggested that steam be put up the stack to disperse the cold vapour and this
suggestion was adopted. The result was that condensate running down the stack met cold vapour flowing up, froze and completely blocked the 8 in. pipe. The tank was overpressured and it burst. Fortunately the rupture was a small one, the ethylene leak did not ignite and was dispersed with steam while the tank was emptied. (Henderson and Kletz, 1976.)

**B56** A metal chute used to transfer a powder from a metal hopper into a metal vessel was replaced by a plastic hose. The flow of powder down the chute caused a charge of static electricity to build up in the hose and, although the hose was a conductor, the polypropylene end pieces used to connect it to the hopper and the vessel were not, and the charge was unable to dissipate. A spark occurred and the dust was ignited. (Heron, 1976.)

**B57** A relief valve weighing 258 lb was being removed from a plant. A 25 ton telescopic jib crane with a jib length of 124 ft and a maximum safe radius of 80 ft was used to lift the valve. The driver failed to observe this maximum radius and went out to 102 ft radius. The crane was fitted with a safe load indicator of the type which weighs the load through the pulley on the hoist rope, but this does not take into account the weight of the jib, so that the driver had no warning of an unsafe condition. The crane overturned on to the plant, as shown in Figure A1.24. (Anon., 1977n.)

**B58** Halfway through the unloading of a tank truck of anhydrous ammonia a stream of liquid was observed leaking from the bonnet of the stop valve on the unloading line. The truck was taken off line and the storage tank was vented to a neutralizing pit to relieve its pressure. Considerable difficulty was experienced in reducing the pressure in the tank sufficiently to stop the flow of liquid ammonia. There was no shut-off between the leaking valve and the tank. Eventually the pressure was reduced by using a compressor and exhausting it to atmosphere. Investigation indicated that the failure of the valve was caused by a combination of a flaw in the body and strain induced by excessive pressure on one of the stud bolts. (MCA 1970/16, Case History 1114.)

**B59** A storage tank 108 ft diameter × 49 ft high containing refrigerated propane at a pressure less than 1 psig was overpressured and ruptured at Ras Tanura refinery, Saudi Arabia. The propane caught fire and gas from pilot-operated relief valves on two similar tanks, one containing propane and one butane, was also set alight. The ruptured tank burned out in some 36 hours, while the butane and propane tank vent fires burned for 3 and 6 days, respectively. One person was killed and 115 were injured, and serious damage was done.

Just prior to the incident the refrigeration plant had been shut down. The intention was to go over to autorefrigeration in which the propane tank would be cooled by boiling off liquid and venting it into the blowdown system. But this autorefrigeration could not be established, because the blowdown line was blocked with liquid butane. The reason for the presence of the butane was that a remotely operated isolation valve had not fully closed, because the valve spring was prevented from operating properly by paint and corrosion products.

There was a steady rise in the pressure in the propane tank up to and then beyond the relief valve set pressure of 1 psi. The operators, both at the end of one shift and at the beginning of the next, tried to find out the cause of the rise in pressure, but they did not alert the supervisors. (Laney, 1964.)

**B60** An operator checked the level in a storage tank and then began pumping in a volatile monomer from a tank wagon. The vent pipe of the storage tank was blocked, however, and a large quantity of monomer flowed out of the dip leg. (MCA 1970/16, Case History 1192.)

**B61** A tank truck was being loaded with ethyl acetate. The loader heard what he described as a 'sizzling' sound and looked in, but could see nothing. Soon after an explosion occurred. The investigation showed that the earthing arrangements on the tank were in good order. The evidence suggested that the explosion was caused by static charge on the surface of the liquid. (MCA 1966/15, Case History 986.)

**B62** A tank trailer containing 6876 gal of propane under pressure ruptured on the highway 560 ft from the centre of the town. The propane escaped and exploded, causing 10 deaths, 17 injuries and extensive damage. The investigation revealed various undesirable features of the tank, including weld defects which would create areas of enhanced stress concentration, differences of alignment between the cylinder and the end parts, and possible embrittlement of the plates due to the use of a heating process to effect chamfering. (MCA 1966/15, Case History 879.)

**B63** Acetic acid was being pumped out of one compartment of a two-compartment trailer. The manhole cover was propped open. The operator climbed on the tanker to obtain a sample. In order to do this he had to lift the manhole cover back. When he had taken the sample, he closed the manhole cover completely. A few seconds later the tank imploded as a result of the vacuum generated by the continued pumping. The tank was equipped with a spring-loaded vacuum breaker, but either this failed to open or it was undersized. (MCA 1966/15, Case History 1011.)

**B64** A tractor semitrailer transporting 7000 gal of propane was modified by inserting a tee-piece between the excess flow valve and the manual shut-off valve on the 3 in. discharge line. The joint was connected to the tractor fuel tank by a ½ in. hose to allow the vehicle to be filled en route. There was another manual shut off valve on the ½ in. line. The hose broke in transit. The leakage flow rate was too small to activate the excess flow valve. The driver stopped the vehicle, shut off the engine and told the trainee driver to shut off the smaller hand valve. When the latter touched the valve, the propane vapours ignited and he was engulfed in flames. The gas continued burning for another 1½ hours. The trainee driver died in the fire, which also caused other injuries and damage. (MCA 1966/15, Case History 995.)
B65  An explosion occurred in a terraced house in East Street, Thurrock, in 1969 which blew a hole in the floor at the foot of the staircase. The wife of the householder fell in while carrying her child and both were injured. The Times (9 April, 1969) reported

Investigators found that the explosion had been caused by the ignition of a mixture of petrol vapours and air and that the vapour was the result of a spillage of petrol two years before.

The spillage involved 367 tons of petrol on rail sidings in July, 1966, and the investigation suggested that there was probably an eight-foot thick band of petrol vapour lying well beneath the surface of the ground in the East Street area. The vapour had been raised to the surface because of exceptionally heavy rainfall.

The distance from the point of spillage to the house was several hundred yards. (Kletz, 1972b.)

B66  On 30 November, 1962 at Cornwall, Ontario, a chlorine rail car was in a siding when a failure of the anchor section occurred and 30 ton of chlorine escaped. The siding was on the downwind side of town. Police and firemen organized prompt evacuation of the several hundred people in the rural area downwind of the spillage. Some 89 people were gassed. (Simmons, Erdmann and Naft, 1974.)

B67  On 9 August, 1963 in Philadelphia, Pennsylvania, a chlorine rail tank car was rammed and a 1 in. loading line was broken. For a short period there was an escape of chlorine, amounting probably to no more than 1 ton. The release was in the middle of a built-up area, however. The number of people gassed was at least 430. (Simmons, Erdmann and Naft, 1974.)

A1.12 Some Other Incidents and Problems

Some other incidents and problems related to safety and loss prevention are listed in Table A1.4 under the following heads: (1) power loss, weather and earthquake; (2) safety and safety legislation; (3) transport and transport legislation; (4) pipelines and pipelines legislation; (5) toxic chemicals in the workplace; (6) pollution; (7) pollution legislation; (8) abandonment of actual or planned production; and (9) litigation.

The references in Table A1.4, which are quoted by date only, are to accounts given by ‘Chementor’ in Chemical Engineering. The information given refers primarily to the USA.

The table shows very clearly the increasing public concern with health and safety and with pollution in the process industries which began to build up from the early 1970s.

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<th>Table A1.4 Some incidents and problems in the process industries 1965–77</th>
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1974 Feb. 4, 20  1977 Apr. 11, 74
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1970 May 18, 75  1977 Jan. 31, 56
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APPENDIX 1/80  CASE HISTORIES

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Oil spills

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Noise

8 Abandonment of actual or planned production

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<td>Nov. 10, 118</td>
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<td>Feb. 8, 17</td>
<td>Nov. 24, 20</td>
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<td>Jul. 26, 56</td>
<td>1976 Jan. 19, 49</td>
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<td>Sep. 6, 27</td>
<td>1977 Jan. 31, 55</td>
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<tr>
<td>1972 Mar. 20, 53</td>
<td>Oct. 10, 69</td>
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This list includes cases where abandonment of actual or planned production was a serious possibility, even if it did not in fact occur.

9 Litigation

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<td>1970 Mar. 23, 59</td>
<td>1975 Nov. 24, 17</td>
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A1.13 Notation

- $Q$: flow rate of propane (ft$^3$/s)
- $u$: average wind velocity (ft/s)
- $x, y, z$: downwind, cross-wind and vertical distances (ft)
- $\sigma_y, \sigma_z$: standard deviations in crosswind, vertical directions (ft)
- $\chi$: concentration of propane (volume fraction)
- $\chi_d$: concentration of propane on centreline (volume fraction)
Appendix

Flixborough

2

Contents

A2.1 The Company and the Management A2/2
A2.2 The Site and the Works A2/3
A2.3 The Process and the Plant A2/3
A2.4 Events Prior to the Explosion A2/3
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A2.7 The Explosion – 2 A2/11
A2.8 Some Lessons of Flixborough A2/14
A2.9 Critiques A2/18
At about 4.53 p.m. on Saturday 1st June 1974 the Flixborough Works of Nypro (UK) Ltd (Nypro) were virtually demolished by an explosion of warlike dimensions. Of those working on the site at the time, 28 were killed and 36 others suffered injuries. If the explosion had occurred on an ordinary working day, many more people would have been on the site, and the number of casualties would have been much greater. Outside the Works injuries and damage were widespread but no-one was killed. Fifty-three people were recorded as casualties by the casualty bureau which was set up by the police; hundreds more suffered relatively minor injuries which were not recorded. Property damage extended over a wide area, and a preliminary survey showed that 1821 houses and 167 shops and factories had suffered to a greater or lesser degree.

(R.J. Parker, 1975 – the Flixborough Report, para. 1)

The Flixborough explosion was by far the most serious accident which had occurred in the chemical industry in the UK for many years.

The explosion was in the reactor section, Section 25A, of the caprolactam plant.

Within a month of the disaster a Court of Inquiry under the chairmanship of Mr R.J. Parker was set up under Section 84 of the Factories Act 1961 to establish the causes and circumstances of the disaster and to point out any lessons which might be learned.

The Court’s report The Flixborough Disaster, Report of the Court of Inquiry (R.J. Parker, 1975) (the Flixborough Report) is the most comprehensive inquiry conducted in the UK into a disaster in the chemical industry in the UK.

The Flixborough disaster was of crucial importance in the development of safety and loss prevention in the UK. It made both the industry and the public much more aware of the potential hazard of large chemical plants and led to an intensification both of the efforts within industry to ensure the safety of major hazard plants and of the demands for public controls on such plants.

The setting up of the Advisory Committee on Major Hazards (ACMH) at the end of 1974 was a direct result of the Flixborough disaster.

The impact of Flixborough was reinforced by that of the Seveso disaster two years later.

The description of the Flixborough disaster given below is necessarily a brief one, and is mainly based on the Flixborough Report and on the work of Sadée, Samuels and O’Brien (1976–77). Other accounts at the time include those of J.I. Cox (1976b) and Gugan (1976). Further critical accounts are described in Section A2.9.

Selected references on Flixborough are given in Table A2.1.

Table A2.1 Selected references on Flixborough

| Report of the Court of Inquiry | R.J. Parker (1975) |
| Reports presented to the Court | Artingstall (1975); Ball (1975a); V.J. Clancy (1975a); Cottrell and Swann (1975a); J.I. Cox (1975b); A.G. Evans (1975); Gill (1975); Gugan (1975a); T.B. Jones (1975); V.C. Marshall (1975d); F. Morton (1975); Munday (1975a); Newland (1975); Nypro (UK) Ltd (1975); A.F. Roberts (1975b); Sadée (1975); Samuels and O’Brien (1975) |

Further accounts

Anon. (1974b); Ball and Steward (1974); T.B. Jones and Spracklen (1974); V.C. Marshall (1974, 1976a,b, 1982; LPB 48, 1984, 1987, 1994 LPB 117); Steward (1974); Tinker (1974); Anon. (1975d); Ball (1975b, 1976); Cottrell and Swann (1975b, 1976); J.I. Cox (1975a, 1976a); Dimeo (1975); FPA (1975/27); Gugan (1975b, 1976, 1979); R. King (1975a–c, 1976a,b, 1977, 1990, 1991); Kinnersly (1975); Kletz (1975c,e, 1976e, 1984e,f); McLain (1975a); Munday (1975b, 1976a); Rakestraw and Hildrew (1975); W. Smith (1975); Tucker (1975); F. Warner (1975a,b); BRE (1976/7); HSE (1976 HSE 1, HSE 2); O’Reilly (1976); Sadée, Samuels and O’Brien (1976–77); R.L. Allen (1977a,b); C.L. Bell (1977, 1979); V.J. Clancy (1977a,c); Mecklenburg (1977a,b); H.D. Taylor (1977); Slater (1978a); Anon. (1979b); Harvey (1979b); W.G. Johnson (1980); D.J. Lewis (1980d, 1989a); D.C. Wilson (1980); Anon. (1981a); Offord (1983); Cullen (1984); Davidson (1984); Crooks (1990 LPB 96); Turner (1994 LPB 117)

A2.1 The Company and the Management

A2.1.1 The company

The Flixborough Report (paras 12–14) states

The site was originally occupied in 1938 by a company called Nitrogen Fertilisers Limited, a subsidiary of Fisons Limited and used for the manufacture of ammonium sulphate. In 1964 Nypro was formed, owned jointly by Dutch State Mines (DSM) and Fisons Limited. It acquired the site from Nitrogen Fertilisers Limited. Between 1964 and 1967 plant was built for the production of caprolactam, which is a basic raw material for the production of Nylon 6, by a process, the first step of which was the production of cyclohexanone via the hydrogenation of phenol. The works were commissioned and production commenced in 1967. They were then and remained until the disaster the only works in the UK producing caprolactam.

In 1967 Nypro was reconstituted with DSM owning 45%, the National Coal Board 45% and Fisons Limited 10%. Almost at once design began for additional plant to increase the capacity of the works from 20 000 tons of caprolactam per annum to 70 000 tons per annum. This additional plant, referred to as Phase 2, was completed at a cost of some £15 m. in 1972. Its distinguishing feature for present purposes is that in it the cyclohexanone necessary for the production of caprolactam was produced by the oxidation of cyclohexane instead of via the hydrogenation of phenol. In 1972 DSM acquired the holding of Fisons Limited and from then until after the disaster Nypro was owned as to 55% by DSM and as to the remaining 45% by the NCB.

From the safety point of view, the oxidation process introduced new dimensions. Cyclohexane, which is in many of its properties comparable with petrol, had to be stored. More importantly, large quantities of cyclohexane...
had to be circulated through the reactors under a working pressure of about 8.8 kg/cm² and a temperature of 155°C. Any escape from the plant was therefore potentially dangerous.

Nypro (UK) Limited was therefore a relatively small, single-site company operating a major hazard process.

A2.1.2 The management
The management of the company is described in the Flixborough Report (paras 19–27). The description includes the following information of particular relevance to the caprolactam plant:

Managing Director Mr R.E. Selman, qualified chemical engineer (HTS, Delft)
General Works Manager Mr J.H. Beckers, qualified chemical engineer (MTS, Heerlen)
Plant Manager Area 1 and Utilities Mr C.L. Bell, chartered chemical engineer
Plant Manager Area 2 Mr P.H. Cliff (to 1 May, 1974), chartered engineer (fuel); Mr R. Everett (from 1 May, 1974), HND in chemistry
Works Engineer Vacant (formerly Mr Riggall)
Areas 1 and 2 Engineer Mr A.B. Blackman
Services Engineer Mr B.F. Boynton, ONC in electrical engineering, NCB (Class 1) engineering certificate
Safety and Training Manager Mr E. Brenner

Area 2 covered Section 25A of the cyclohexane plant.
The previous Works Engineer, Mr Riggall, had left and steps were being taken to replace him, but at the time of the accident there was no Works Engineer. In the absence of a Works Engineer a co-ordinating function was exercised by the Services Engineer. In addition, the engineering staff were told that if they had problems, they could call on the assistance of Mr J.F. Hughes of the NCB.

The Flixborough Report (para. 27) states that following the departure of Mr Riggall ‘There was no mechanical engineer on site of sufficient qualification, status or authority to deal with complex or novel engineering problems and insist on necessary measures being taken’. The report is critical of the fact that the Area 2 and Services Engineers had been asked to assume responsibilities which they should not have had to shoulder.

A2.2 The Site and the Works
The Flixborough works is on flat, low-lying land on the east bank of the River Trent some six miles to the south of the point where that river joins the Humber. The nearest villages are Flixborough itself and Ancotts, both of which are about half a mile away. The town of Scunthorpe lies at a distance of approximately three miles.
The works is surrounded by fields and the population density in the neighbourhood beyond is very low.

A site plan is shown in Figure A2.1. The diagram also shows the vapour cloud, as described below. An aerial view of the works before the explosion is given in Figure A2.2.

Other plants on the site included an acid plant and a hydrogen plant. There was also a large ammonia storage sphere.

A2.3 The Process and the Plant
The cyclohexane plant, shown in Figure A2.3, consisted of a train of six reactors in series in which cyclohexane was oxidized to cyclohexanone and cyclohexanol by air injection in the presence of a catalyst. The feed to the reactors was a mixture of fresh cyclohexane and recycled material. The product from the reactors still contained approximately 94% of cyclohexane. The liquid reactants flowed from one reactor to the next by gravity. In subsequent stages, the reaction product was distilled to separate the unreacted cyclohexane, which was recycled to the reactors, and the cyclohexanone and cyclohexanol, which were converted to caprolactam. The design operating conditions in the reactor were a pressure of 8.8 kg/cm² and a temperature of 155°C. The reaction is exothermic.

The heat required for initial warmup and for supplementation of the heat of reaction during normal operation was provided by a steam-heated heat exchanger on the reactor feed. The steam flow to the exchanger was controlled by an automatic control valve. There was a bypass around this valve, which was needed to pass the larger quantities of steam required during startup.

Removal of the heat of reaction from the reactors during normal operation was effected by vaporizing part of the cyclohexane liquid. The cyclohexane vaporized passed out in the off-gas from the reactors. The rest of this off-gas was mainly nitrogen with some unreacted oxygen.

The off-gas passed through the feed heat exchanger (C2544) and then through a cooling scrubber (C2521) and an absorber (C2522), in which the cyclohexane was condensed out, and thence via an automatic control valve to a flare stack.

The atmosphere in the reactor was controlled using nitrogen from high pressure nitrogen storage tanks. The nitrogen was brought into the works by tankers.
The reactor pressure was controlled by manipulating the control valve on the off-gas line. Safety valves venting into the relief header to the flare stack were set to open at 11 kg/cm².

A trip system was provided which shut off air to, and injected nitrogen into, the reactors in the event of either a high oxygen content in the off-gas or a low liquid level in the nitrogen supply tank. This trip could be disarmed, however, by setting to zero the timer fixing the duration of the purge.

The layout of the reactors in Section 25A is shown in Figure A2.4.

A2.4 Events Prior to the Explosion
On the evening of 27 March 1974 it was discovered that Reactor No. 5 was leaking cyclohexane. The reactor was constructed of ½ in. mild steel plate with ¼ in. stainless steel bonded to it on the inside. A vertical crack was found in the mild steel outer layer of the reactor. The leakage of cyclohexane from the crack indicated that the inner stainless steel layer was also defective. It was decided to shut the plant down for a full investigation.
The following morning inspection revealed that the crack had extended some 6 ft. This was a serious state of affairs and a meeting was called to decide action. The decision was taken to remove Reactor No. 5 and to
Figure A2.1 Simplified site plan of the works of Nypro (UK) Ltd at Flixborough (Sadée, Samuels and O’Brien, 1976–77) (Courtesy of HM Stationery Office). The diagram also shows the estimated dimensions of the vapour cloud.
install a bypass assembly to connect Reactors No. 4 and 6 so that the plant could continue in production.

The openings to be connected on these reactors were 28 in. diameter, with bellows on the nozzle stubs, but the largest pipe which was available on site and which might be suitable for the bypass was 20 in. diameter. The two flanges were at different heights so that the connection had to take the form of a dog-leg of three lengths of 20 in. pipe welded together with flanges at each end bolted to the existing flanges on the stub pipes on the reactors. The bypass assembly is shown in Figure A2.5.

Calculations were done to check (1) that the pipe was large enough for the required flow and (2) that it was capable of withstanding the pressure as a straight pipe. No calculations were made which took into account the forces arising from the dog-leg shape of the pipe.

No drawing of the bypass pipe was made other than in chalk on the workshop floor.

The existing stub pipes were connected to the reactors by bellows, as shown in Figure A2.5. No calculations were done to check whether the bellows would withstand the forces caused by the dog-leg pipe.

The bypass assembly was supported by a scaffolding structure, as shown in Figure A2.5. This scaffolding was intended to support the pipe and to avoid straining of the bellows during construction of the bypass. It was not suitable as a permanent support for the bypass assembly during normal operation.

No pressure testing was carried out either on the pipe or on the complete assembly before it was fitted. A pressure test was performed on the plant, however, after installation of the bypass. The equipment was tested to a pressure of 9 kg/cm², but not up to the safety valve pressure of 11 kg/cm². The test was pneumatic not hydraulic.

Following these modifications the plant was started up again. The bypass assembly gave no trouble. There did appear, however, to be an unusually large usage of nitrogen on the plant and this was being investigated at the time of the accident.

On 29 May the bottom isolating valve on a sight glass on one of the vessels was found to be leaking. It was decided to shut the plant down to repair the leak.
On the morning of 1 June start up began. The precise sequence of events is complex and uncertain. The crucial feature, however, is that the reactors were subjected to a pressure somewhat greater than the normal operating pressure of 8.8 kg/cm².

A sudden rise in pressure up to 8.5 kg/cm² occurred early in the morning when the temperature in Reactor No. 1 was still only 110°C and that in the other reactors was less, while later in the morning, when the

Figure A2.3  Simplified flow diagram (not to scale) of the cyclohexane oxidation plant at Flixborough (R.J. Parker, 1975) (Courtesy of HM Stationery Office)
temperature in the reactors was closer to the normal operating value, the pressure reached 9.1-9.2 kg/cm².

The control of pressure in the reactors could normally be effected by venting the off-gas, but this procedure involved the loss of considerable quantities of nitrogen. Shortly after warm-up began, it was found that there was insufficient nitrogen to begin oxidation and that further supplies would not arrive until after midnight. Under these circumstances the need to conserve nitrogen would tend to inhibit reduction of pressure by venting.

A2.5 The Explosion – 1

During the late afternoon an event occurred which resulted in the escape of a large quantity of cyclohexane. As already explained, this event was the rupture of the 20 in. bypass system, without or with contribution from fire on a nearby 8 in. pipe. The cyclohexane formed a vapour cloud and the flammable mixture found a source of ignition.

At about 4.53 p.m. there was a massive vapour cloud explosion.

The explosion caused extensive damage and started numerous fires. Aerial views of the plant after the explosion are shown in Figures A2.6 and A2.7.

Reactors No. 4 and 6 and the debris of the bypass assembly are shown in Figure A2.8. Another view of the reactor train is given in Plate 36. The blast and the fires destroyed not only the cyclohexane plant but several other plants also. Many of the fires were in the tank farm.

The blast of the explosion shattered the windows of the control room and caused the control room roof to collapse. Of the 28 people who died in the explosion, 18 were in the control room. Some of the bodies had suffered severe injuries from flying glass. Others were crushed by the roof. No-one escaped from the control room.

The main office block was also demolished by the blast of the explosion. Since the accident occurred on a Saturday afternoon, the offices were not occupied. If they had been, the death toll would have been much higher.

The locations of the control room and main office block are shown in Figures A2.1 and A2.2 and the states of these buildings after the explosion in Figures A2.6 and A2.7.

The fires on the site burned for many days. Even after 10 days the fires were hindering rescue work on the site. The large ammonia sphere was lifted up a few
inches. It leaked slightly at a flange, but the leak was not serious.

A2.6 The Investigation

An immediate investigation of the disaster was made by the Factory Inspectorate, which issued an interim report. On its appointment, the Court of Inquiry took control of the main investigations. The work of recovering, identifying and examining wreckage and of conducting relevant tests, was undertaken by the Safety in Mines Research Establishment (SMRE). The Court appointed the consulting engineers Cremer and Warner as its technical advisers. Other government bodies, consultants and universities were involved in the numerous studies undertaken.

Some of the possible causes of failure of the bypass assembly were outlined early in the inquiry by the DSM counsel. They included (1) failure of the 20 in. pipe due to a small pressure rise; (2) prior failure of the 8 in. pipe; (3) prior failure of some other part of the system; and (4) an explosion in the air-line to the reactors. He suggested several possible causes for a pressure rise in the 20 in. pipe: (1) entry of high pressure nitrogen into the system due to instrument malfunction; (2) entry of water into the system; (3) temperature rise in the system due to excessive heating by steam in reboiler of C2544; (4) leakage of steam from a tube in C2544; (5) explosion of peroxides formed in the process; and (6) explosion due to air in the system.

The inquiry established (Flixborough Report, para. 6) that the cause of the disaster was 'The ignition and rapid acceleration of deflagration, possibly to the point of detonation, of a massive vapour cloud formed by the escape of cyclohexane under a pressure of at least 8.8 kg/cm² and a temperature of 155°C and that the escape was from Section 25A of the cyclohexane plant'.

There was no dispute that the main part of the cyclohexane came from the 20 in. bypass assembly, but there was come uncertainty whether the mechanical failure of the assembly was the primary failure or whether it was a secondary failure caused by another
event elsewhere. Three hypotheses were advanced: (1) the 20 in. pipe hypothesis, (2) the 8 in. pipe hypothesis, and (3) the superheated water hypothesis.

A large proportion of the report is concerned with a discussion of the first and second hypotheses, but the Court decided emphatically in favour of the first.

The 20 in pipe hypothesis is that the 20 in. bypass pipe ruptured in one stage as a result of the internal pressure and temperature conditions which probably occurred in the final shift.

The site investigation revealed that the 20 in. pipe had yielded at the lower mitre, or 'jack-knife', and that the bellows had undergone gross permanent deformation, or 'squirm'.

The arrangement of the pipe was such as to subject the bellows to shear forces due to the internal pressure in the pipe as shown in Figure A2.9. The two thrusts PA are parallel and separated by a distance 2e and thus give a turning moment $2PAe$ which is balanced by shear forces $F = PAE/L$. The shear forces give rise to bending moments and the maximum bending moment is at the mitre joints and is $PAE/L$. This system of forces can lead to failure in two ways. The shear force may cause squirm of the bellows. The bending moments may cause failure of the pipe by buckling one of the mitres. As already mentioned, these effects had been neglected in the calculations done on the bypass assembly.

These mechanisms were studied in comprehensive, full-scale investigations by SMRE, by Nottingham University and the Mining Research and Development Establishment, Bretby. The results of the tests are complex, but, in brief, they showed that squirm of the bellows could occur at pressures at or near the operating pressure. They did not show jack-knifing and rupture following squirm. A mechanism for the latter was given by Newland (1975), who developed a theory based on the energies involved, which showed that at pressures above normal operating pressures but below the safety valve pressure there could occur squirm of both the bellows, followed by jack-knifing of the pipe, resulting in complete rupture. The pressures for jack-knifing and rupture to be a consequence of squirming were estimated to be as follows:

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<td>9.3 kg/cm²</td>
<td>9.9 kg/cm²</td>
<td>10.6 kg/cm²</td>
</tr>
<tr>
<td>160°C</td>
<td>9.1 kg/cm²</td>
<td>9.7 kg/cm²</td>
<td>10.4 kg/cm²</td>
</tr>
</tbody>
</table>

Other mechanisms of squirm alone and jack-knifing alone were investigated, but appeared less probable.

The Court concluded that the rupture of the 20 in. pipe assembly was a probability, albeit a low one, under the pressure and temperature conditions which occurred in the last shift.

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**Figure A2.6** Works of Nypro (UK) Ltd at Flixborough after the explosion—1 (R.J. Parker, 1975) (Courtesy of HM Stationery Office)
The 8 in. pipe hypothesis is somewhat more complex. The 8 in. pipe ran between separators S 2538 and S 2539. The location and details of the pipe are shown in Figures A2.4 and A2.10, respectively. There was a block valve, a non-return valve and a lagging box on the pipe. The pipe was made of stainless steel.

Essentially the hypothesis was that a directed flame had occurred from the lagging box and had caused rupture of the pipe from which cyclohexane then escaped to form a vapour cloud. This hypothesis was advanced by Cox and Gugan.

The hypothesis had its origin in eye-witness accounts of the events immediately prior to the explosion and in the condition of the equipment found in the site investigation. The latter revealed that there was a 50 in. split on the elbow of the 8 in. pipe and subsequent studies showed that the crack was caused by creep cavitation. The 50 in. split also exhibited a petal crack which was due to zinc embrittlement and a separate 3 in. crack due to the same cause was found on the straight vertical section of the pipe. In addition, two loose bolts were found on the non-return valve. There was some doubt as to whether these had been loose before the explosion, but the Court concluded that this was probably the case.

The 8 in. pipe hypothesis may be summarized as follows. There were two loose bolts on the non-return valve. Then either there was a slow leakage of material over an extended period and a lagging fire which caused further expansion of the bolts and growth of the leak, or there was a sudden gasket burst and ignition of the leak by static electricity. In either case there was a directed flame from the lagging box. A sprinkler sensor head near the non-return valve failed to detect the fire. The flame burned off the lagging on the pipe elbow and caused a vapour blanket in the pipe and a vapour lock at the intrados so that the pipe overheated. The pipe suffered creep cavitation at the intrados and the 50 in. rupture occurred. Zinc from galvanized wire dripped onto the pipe and caused zinc embrittlement, but this was not responsible for the main failure. The cyclohexane issued from the 50 in. crack and put out the flame. A fire then occurred in the region of the fin fan coolers which melted the zinc on the finned tubes and raised them to a temperature at which zinc embrittlement occurs. There followed an explosion in the region of one of the fan
motors which caused the 20 in. bypass to jack-knife and rupture.

The foregoing account is a necessarily highly simplified summary of a very complex argument. The Court's report gives a detailed account of this hypothesis but rejects it. It draws an analogy between the sequence of events required by the hypothesis with the balancing of billiard balls one on top of another and states 'This balancing of ten balls is analogous to what is postulated for the 8-inch pipe hypothesis'.

The third hypothesis is that the failure of the 20 in. bypass assembly was due to sudden evolution of vapour from a layer of superheated water at the bottom of Reactor No. 4. The water might have been present in the reactor initially or might have come from a leak in the steam-heated heat exchanger on the feed. Such a water layer was able to build up in the vessel more easily because the reactor agitator was not in use. This theory, advanced by R. King, was mentioned, but did not figure prominently at the inquiry. It has been described in a number of articles by King (1975a–c, 1976a, b, 1977).

### A2.7 The Explosion – 2

Another aspect of the Flixborough investigation is the studies conducted on the explosion itself. Accounts of the explosion have been given in the Flixborough Report, by Gugan (1976) and by Sadée, Samuels and O'Brien (1976–77).

According to Sadée, Samuels and O'Brien the quantity of cyclohexane available in the five reactors and one after-reactor was 120 te. The normal operating pressure and temperature were 8.8 kg/cm² and 155°C, respectively. After the explosion it was found that the vessels still contained 80 te, so that the maximum quantity involved in the explosion was 40 te. These authors estimate that about 30 te escaped before the explosion.

*Figure A2.8* Reactors No. 4 and 6 and the bypass assembly at Flixborough after the explosion (R.J. Parker, 1975) (Courtesy of HM Stationery Office)
and they take this quantity as the basis of their calculations.

The flow from each of the two pipe stubs, which were opposite each other, but at slightly different heights, would form a turbulent momentum jet with the two opposing jets impinging on each other, thus giving very effective mixing.

It is estimated by Sadée, Samuels and O'Brien that 50%, or 15 te, of the cyclohexane would flash off as vapour and that the other 50% would form a mist. Whether or not the mist would then evaporate depends on the amount of air entrained by the jet. The authors state that evaporation is possible provided that the concentration of cyclohexane does not exceed 10%.

Sadée, Samuels and O'Brien have calculated the dimensions of a stationary, free jet of cyclohexane at 1 MPa and 150°C emitted from a 700 mm diameter opening and forming a cloud containing equal masses of vapour and liquid in air. This jet is shown in Figure A2.11. The jet is 215 m long and has a maximum diameter of 25 m. The jet volume with a concentration exceeding the low flammability limit (1.2%) is 64400 m³ and that with a concentration within the flammable range (1.2-8%) is practically the same. The average concentration in the flammable part of the jet is 1.85%, which is close to the stoichiometric proportion. The quantity of cyclohexane within the flammable part of the jet is 4 te. If two such jets are assumed, the quantity is 8 te.

The jets actually formed were not free jets, but were affected by the ground and the reactors. Taking these factors into account, the authors estimate the quantity of cyclohexane within the flammable part of the two jets as 22.4 te.

Sadée, Samuels and O'Brien present calculations on the assumption that the quantity of cyclohexane involved in the explosion was 30 te. This amount of cyclohexane mixed with air to yield a flammable concentration of 2% gives a cloud volume of 400000 m³.

The precise shape of the cloud is uncertain, as is the source of ignition. From the carbon deposition and explosion damage the estimate of the cloud ground zero and shape is that shown in Figure A2.1. The source of ignition may have been the hydrogen plant. An alternative estimate of the cloud shape has been given by J.L. Cox (1976b).

Various estimates have been made of the time which elapsed between the times of rupture and of the explosion, mostly ranging between 30 and 90 seconds. An estimate of 45 seconds has been widely quoted.

There is evidence from carbon deposition and from eye-witness accounts that there was a flash fire as well as an explosion in the vapour cloud.

From eye-witness accounts it appears that there may have been a short period during which the cloud had found a source of ignition and combustion was occurring at the edge of the cloud, but the cloud was expanding...
Figure A2.10 Elevation view of 8 in. line at Flixborough, showing typical lagging box around valve (R.J. Parker, 1975) (Courtesy of HM Stationery Office)

faster than the flame speed. Assuming a constant flow of vapour into the cloud, the velocity of outward expansion would fall as the cloud diameter increased and a point would be reached at which the velocity would fall below the flame speed. The flame would then travel rapidly towards the centre of the cloud.

One effect of such a flash fire would be to cause a sudden and lethal depletion of the oxygen concentration.

There was evidence of two explosive events. An ionosphere recorder trace obtained at Leicester University (T.B. Jones and Spracklen, 1974; T.B. Jones, 1975) showed two disturbances, a smaller precursor followed by the main event. The time interval between them was some 45 seconds.

Estimates of the energy of explosion were made in several ways, including estimation from ionospheric readings (T.B. Jones, 1975), from the barograph of a glider in the vicinity (Gugan, 1975a) and from a blast damage survey (A.F. Roberts, 1975; Samuels and O'Brien, 1975).

The most detailed estimates of explosion energy are those derived from the blast damage survey. The results of this survey have been discussed by Gugan (1976), Munday (1975b) and Sadée, Samuels and O'Brien (1976–77). The latter give a detailed listing and photographs of structural damage.

The blast damage effects caused by the explosion have been assessed by Sadée, Samuels and O'Brien and are shown in Figure A2.12, in which the individual data bars give the ranges of peak overpressure determined from structural damage versus distance from the assumed epicentre of the explosion.

The estimates of the energy of the explosion made by different workers depend on the explosion model used.
Most estimates are based on the simplest model, in which the only parameter is the mass of TNT. These estimates are generally in the range 15–45 t of TNT.

An alternative two-parameter model describes the explosion in terms of both the mass of TNT and the height of the explosion. Using this model, Sadée, Samuels and O’Brien estimate that the explosion was equivalent to 16±2 t of TNT at a height of 45±24 m above ground. 16 t of TNT have a calorific value of approximately 1.6 t of cyclohexane; the calorific value of TNT is 1600 kcal/kg and that of cyclohexane is 11 127 kcal/kg.

The curve given by Sadée, Samuels and O’Brien in Figure A2.12 is based on this two-parameter TNT model. If the cloud contained 30 t of cyclohexane and gave an explosion equivalent to the combustion of about 1.6 t, the explosion efficiency was about 5%. This efficiency is based on the total quantity of cyclohexane in the cloud.

The maximum overpressure at the centre of the cloud is uncertain. The maximum overpressure obtained from the structural damage, as described by Sadée, Samuels and O’Brien, was 0.7 bar. These authors state, however, that the theoretical curve in Figure A2.12 indicates an overpressure of 1 bar at the cloud boundary.

Some estimates of the pressure developed within the cloud are considerably higher. These estimates are typically based on calculation of the forces required to give damage effects such as the bending of steel posts or crushing of steel vessels. Thus, for example, V.J. Clancy (1977a) states that where local effects occurred as a result of features such as confinement, pressures of up to perhaps 5–7 bar have been estimated. The pressures calculated in this way would normally be reflected pressures.

### A2.8 Some Lessons of Flixborough

There are numerous lessons to be learned from the Flixborough disaster. A list of some of these is given in Table A2.2. Many of these lessons were highlighted in the Court’s report.

The lessons include both public controls on major hazard installations and the management of such installations by industry. In the latter area there are lessons on both management systems and technological matters and on both design and operational aspects.

The fact that alternative hypotheses were advanced concerning the cause of the explosion does not detract from these lessons, but rather means that a greater number of lessons can be drawn.

Some of these lessons are now considered.

#### Public controls on major hazard installations

The effect of the Flixborough disaster was to raise the general level of awareness of the hazard from chemical plants and to make the existing arrangements for the control of major hazard installations appear inadequate.

The government therefore set up the Advisory Committee on Major Hazards (ACMH) to advise on means of control for such installations. The committee issued three reports (Harvey, 1976, 1979b, 1984). Its recommendations are described in Chapter 4.

This work was a major input to the development of the EC Major Accident Hazards Directive, which was implemented in the UK as the CIMAH Regulations 1984. These require the operator of a major hazard installation to produce a safety case.

Major hazard installations receive a greater degree of supervision by the local Factory Inspectorate. The CIMAH safety case plays an important part in this.

#### Siting of major hazard installations

As the Flixborough Report (para. 11) points out, the casualties from the explosion might have been much greater if the site had not been in open country.

The siting of major hazard installations is a matter of utmost importance. On the one hand distance is the only sure guarantee of safety, but on the other provision of increased spacing may be very wasteful of land.

The question of the siting of major hazard installations, or more generally land use planning in relation to such installations, became a principal concern of the ACMH, and is treated in its three reports. Controls on major hazards through land use planning are discussed in Chapter 4 and Appendix 25. Siting is also considered in Chapter 10.
Figure A2.12  Peak overpressure versus distance at Flixborough estimated from blast damage (Sadée, Samuels and O’Brien, 1976–77) (Courtesy of HM Stationery Office)

Licensing of storage of hazardous materials
The Flixborough Report (para. 194) states

As at 1st June 1974 Nypro were storing on site 330,000 gallons of cyclohexane, 66,000 gallons of naphtha, 11,000 gallons of toluene, 26,400 gallons of benzene and 450,000 gallons of gasoline. The storage of these potentially dangerous substances is nominally controlled by the local authority issuing licences under the Petroleum (Consolidation) Act 1928. In fact the only licences that had been issued related to 7000 gallons of naphtha and for a total of 1500 gallons of gasoline. The unlicensed storage of large quantities of fluids had no effect upon this disaster but it is clearly useless to have a licensing system which is so ineffective that it can lead to such results.

The situation at Flixborough revealed the need for better methods of notification of major hazard installations to the local planning authorities and for greater guidance to these authorities by the HSE.

The notification of major hazard installations is a requirement of the NIHHS Regulations 1982 and of the CIMAH Regulations 1984. These notification requirements and the advice now given by the HSE to local planning authorities are discussed in Chapter 4.

Regulations for pressure vessels and systems
The escape of cyclohexane at Flixborough was caused by a failure of the integrity of a pressure system.

Current legislation on pressure systems in the UK consisted of regulations for steam boilers and receivers.
Table A2.2 Some lessons of Flixborough

Public control of major hazard installations  
Siting of major hazard installations  
Licensing of storage of hazardous materials  
Regulations for pressure vessels and systems  
The management system for major hazard installations  
  The structure  
  The people  
  The systems and procedures  
The safety officer  
Relative priority of safety and production  
Use of standards and codes of practice  
Limitation of inventory in the plant  
Engineering of plants for high reliability  
Dependability of utilities  
Limitation of exposure of personnel  
Design and location of control rooms and other buildings  
Control and instrumentation of plant  
Decision-making under operational stress  
Restart of plant after discovery of a defect  
Control of plant and process modifications  
Security of and control of access to plant  
Planning for emergencies  
The metallurgical phenomena  
  Nitrate stress corrosion cracking  
  Creep cavitation of stainless steel  
  Zinc embrittlement of stainless steel  
  Use of clad mild steel  
Unconfined vapour cloud explosions  
Investigation of disasters and feedback of information on  
  technical incidents  

and air receivers. It failed to cover the Flixborough situation in two crucial respects. It applied only to steam and air and not to hazardous materials such as cyclohexane. And it dealt only with pressure vessels and not with pressure systems. This latter point is relevant, because at Flixborough the failure occurred in a pipe not a vessel.

The Flixborough Report (para. 209) recommends that existing regulations relating to the modification of steam boilers should be extended to apply to pressure systems containing hazardous materials.

Following Flixborough the HSE set about developing comprehensive regulations for pressure systems, which finally emerged as the Pressure Systems Regulations 1989. These regulations are described in Chapters 3 and 12.

Moreover, individuals tended to be overworked and thus more liable to error.

The management system, however, is more than the individuals. It includes the whole structure which supports them. Thus the system should provide, for example, for the coverage of absence due to resignation, illness and so on.

The use of a comprehensive set of procedures is another important aspect of the management system. A crucial procedure which was deficient at Flixborough was that for the control of plant modifications.

The role of the safety officer at Flixborough was not well defined.

The importance for major hazard installations of the management and the management system was the single most prominent theme in the work of the ACMH. Emphasis by the HSE on management aspects has steadily grown. The Cullen Report on the Piper Alpha disaster recommended that offshore the safety case should cover the safety management system and this is implemented in the offshore regulations. This aspect is discussed in Chapters 4 and 6.

Relative priority of safety and production

The Flixborough Report (paras 57, 206) drew attention to the conflict of priorities between safety and production. It states

We entirely absolve all persons from any suggestion that their desire to resume production caused them knowingly to embark on a hazardous course in disregard of the safety of those operating the Works. We have no doubt, however, that it was this desire which led them to overlook the fact that it was potentially hazardous to resume production without examining the remaining reactors and ascertaining the cause of the failure of the fifth reactor. We have equally no doubt that the failure to appreciate that the connection of Reactor No. 4 to Reactor No. 6 involved engineering problems was largely due to the same desire.

Use of standards and codes of practice

As the Flixborough Report (paras 61–73) describes, the 20 in. bypass assembly was not constructed and installed in accordance with the relevant standards and codes of practice.

The principal standard relevant to the modification was BS 3351: 1971. The report quotes extracts from this standard:

4.6.2. For axial bellows, the piping shall be guided to maintain axially of the bellows and anchored at adjacent changes in direction to prevent the bellows being subjected to axial load due to fluid pressure.

5.4.2.1. When expansion joints are used, the advice of the manufacturer should be sought with regard to the guiding, anchoring and support of the adjacent pipework.

The bellows manufacturer, which was Teddington Bellows Ltd, produced a Designers Guide which made it clear that two bellows should not be used out of line in the same pipe without adequate support for the pipe.

The use of standards and codes of practice is described in Chapters 3, 6 and 12.
Limitation of inventory in the plant
The Flixborough Report (para. 14) makes it clear that the large inventory of flammable material in the plant contributed to the scale of the disaster.

The Second Report of the ACMH proposes that limitation of inventory should be taken as a specific design objective in major hazard installations.

The limitation of inventory is a particular aspect of the more general principle of inherently safer design, which is now widely recognized. This is discussed in Chapter 11.

Engineering of plants for high reliability
The explosion at Flixborough occurred during a plant start up. The Flixborough Report (para. 206) suggests that special attention should be given to factors which necessitate the shut down of chemical plant so as to minimize the number of shutdown/start up sequences and to reduce the frequency of critical management decisions.

The reliability of plant is considered in Chapters 7 and 12.

Dependability of utilities
The high pressure nitrogen required for the blanketing of the reactors at Flixborough was brought into the works by tankers. There was insufficient nitrogen available during the start up when the explosion occurred. The Flixborough Report (para. 211) emphasizes the importance of assuring dependable supplies of nitrogen where these are necessary for safety.

The dependability of utilities is discussed in Chapter 11.

Limitation of exposure of personnel
The Flixborough Report (para. 1) states that the number of casualties would have been much greater if the explosion had occurred on a weekday instead of on a Saturday.

The First Report of the ACMH (para. 68) suggests that limitation of exposure of personnel be made a specific design objective.

Aspects of limitation of exposure are controls on access to hazardous areas and design and location of buildings in or near such areas.

The limitation of exposure of personnel is described in Chapters 10 and 20.

Design and location of control rooms and other buildings
Of the 28 deaths at Flixborough 18 occurred in the control room. The Flixborough Report (para. 218) refers to various suggestions made to the inquiry concerning the siting of control rooms, laboratories, offices, etc., and the construction of control rooms on blockhouse principles.

The construction of buildings for chemical plant is considered in the First Report of the ACMH (para. 69).

The design and location of control rooms and other buildings is discussed in Chapters 10 and 20.

Control and instrumentation of plant
The control and instrumentation system was not a prominent feature in the Flixborough inquiry. The Flixborough Report (para. 204) considered that the controls in the control room followed normal practice. But it also states 'Nevertheless we conclude from the evidence that greater attention to the ergonomics of plant design could provide rewarding results'.

Control system design and human factors in process control are described in Chapters 13 and 14.

Decision-making under operational stress
The Flixborough Report (para. 205) draws attention to the problem of decision-making under operational stress and emphasizes the desirability of reducing the number of critical management decisions which have to be made under these conditions.

Such critical decisions are not necessarily confined to management, however. Process operators may also be required to take important decisions in emergency conditions.

The process operator in emergency situations is discussed in Chapter 14.

Restart of plant after discovery of a defect
Following the discovery of the serious defect in Reactor No. 5 at Flixborough, the reactor was removed, a bypass assembly was installed and the plant was started up again. The Flixborough Report (para. 57) is critical of the fact that the remaining reactors were not examined and the cause of the failure in the fifth reactor was not ascertained before plant start up.

The procedures for restart of the plant after discovery of a defect are discussed in Chapter 20.

Control of plant and process modifications
The Flixborough Report (para. 209), states

The disaster was caused by the introduction into a well designed and constructed plant of a modification which destroyed its integrity. The immediate lesson to be learned is that measures must be taken to ensure that the technical integrity of plant is not violated.

As it happens, there was also a process modification at Flixborough, although this is not emphasized in the report. The agitator in Reactor No. 4 was not in use at the time of the disaster. The absence of agitation in the reactor could have allowed a water layer to accumulate more easily in the bottom of the vessel. The sudden evoluation of vapour from superheated water was advanced by King as a possible cause of the rupture of the bypass pipe assembly.

The control of plant and process modifications is discussed in Chapters 6 and 21.

Security of and control of access to plant
The Flixborough Report (para. 194) draws attention to the fact that there were two unguarded gates through which it was possible for anyone at any time to gain access, although this fact did not contribute to the disaster.

The security of plants is considered in Chapter 20.

Planning for emergencies
The Flixborough Report (para. 222) calls for a disaster plan for major hazard installations.

Emergency planning is described in Chapter 24.
The metallurgical phenomena
The Flixborough disaster drew attention to several important metallurgical phenomena. Thus the Flixborough Report describes the nitrate stress corrosion cracking of mild steel (paras 53, 212); the creep cavitation of stainless steel (para. 214); the zinc embrittlement of stainless steel (para. 213); and the use of clad mild steel vessels (para. 224).

The HSE subsequently issued Technical Data Notes (1976 TDN 53/1, 53/2; 1977 TDN 53/3) on the first three of these problems.

It was apparent from the discussion in the engineering profession following publication of the report that although metallurgical specialists were aware of failure due to zinc embrittlement, the phenomenon was not well known among engineers generally.

The metallurgical features of pressure systems are discussed in Chapter 12.

Vapour cloud explosions
The explosion at Flixborough was a large vapour cloud explosion. Although such explosions had become more common in the preceding years, none compared with Flixborough in scale and impact. The Flixborough Report (para. 215) draws attention to the marked lack of information on the conditions under which a vapour cloud can give an explosion.

Since Flixborough, a large amount of work has been done on vapour cloud explosions. An account is given in Chapter 17.

Investigation of disasters and feedback of information on technical incidents
The Flixborough disaster was investigated by a Court of Inquiry. There was some feeling in the engineering profession that a legal inquiry of this kind is not a satisfactory means of establishing the facts concerning technical incidents. This aspect is considered in the following section.

The Flixborough Report (para. 216) states that the inquiry would have been greatly assisted if the essential instrument records in the control room had not been destroyed in the explosion and recommends that consideration be given to systems for recording and preserving vital plant information such as the ‘black box’ recorder used in aircraft.

The investigation of disasters and the feedback of information from technical incidents is considered in Chapter 27.

The points just outlined by no means exhaust the lessons to be learned from the Flixborough disaster. In particular, there are many instructive aspects of the 8 in. pipe hypothesis relating to such features as lagging fires, directed flames and sprinkler sensor performance.

A2.9 Critiques
The Flixborough inquiry has been the subject of a number of critiques which have centred mainly on (1) the form of the inquiry; (2) the examination of the hypotheses; (3) the design of the plant; (4) the management of the plant; and (5) technical issues. These include those of R.L. Allen (1977b), Mecklenburgh (1977a), D.J. Lewis (1989a), R. King (1990) and L. Thomas and Gugan (1993), and the mainly technical discussions of Gugan (1979) and V.C. Marshall (1987).

King gives a detailed description of the plant and it operation and diagrams showing the original plant and the modified plant.

Mecklenburgh, King and Thomas and Gugan argue that the legal format is not conducive to elucidating the facts about technical issues. The question is discussed in detail in Chapter 27.

With regard to the examination of hypotheses, Thomas and Gugan argue that the possible role of explosive reactions, described by Alexander (1990b, c), was insufficiently explored. With regard to the 8 in. pipe hypothesis, while accepting that the inquiry devoted considerable effort to exploring it, they are critical of the arguments used in dismissing it.

Thomas and Gugan rehearse various aspects of the 20 in. and 8 in. pipe hypotheses. Aspects of the 8 in. pipe hypothesis are also discussed by Marshall.

King gives an account of his own hypothesis that there was a pressure rise in Reactor No. 4 due to the evolution of water vapour from water present in that reactor. He also gives the background to the removal of the agitator from Reactor No. 4.

King is critical of the conclusion that the crack in Reactor No. 5 was due to nitrates in the cooling water, the finding of a DSM report. He quotes an HSE source to the effect that the reactor vessel drawing specified a maximum thrust on the 28 in. stubs of 9 te, whereas at normal operating conditions the thrust was 38 te. He suggests that the nitrates found were from cooling water sprayed on the already-formed crack.

The design of the plant is also criticized by Marshall, who argues that it would have been better to use not gravity flow involving the 28 in. pipe connections but pumped flow which would have allowed the use of much smaller diameter pipes.

With regard to the operation of the plant, King is critical of the decision to remove the agitator from Reactor No. 4, which, among other things, increased the hazard from water accumulation in the vessel.

Thomas and Gugan point to the facts that the plant was shut down to deal with leaks and was then restarted because ‘the leaks had cured themselves’; that the oxygen trip was disarmed; the production was continued even though there was a shortage of nitrogen; and that the plant was started up again after the failure of Reactor No. 5 without inspection of the other reactors.

One technical issue discussed by King is the thrust exerted by unrestrained bellows on the systems to which they are connected, which tends to be underestimated.

Lewis gives some alternative estimates of the size of the release. He states that the inventory of the cyclohexane oxidation unit exceeded 120 te. Re-examination of the reactor section at a pressure of 8.6 bar shows that it had an inventory of 230 te with another 150 te in the attached distillation section at 14.7 bar.

He also discusses the problem of determining the efficiency of the explosion compared with TNT. Estimates were made from long range effects and from medium range damage surveys, and both point to a TNT equivalent of 15–20 te. There were major difficulties, however, in fitting TNT curves to the damage observed.
The TNT efficiency is difficult to assess, depending as it does on the estimate of the mass within the flammable region and on the blast curves used.

Gugan gives a detailed discussion of certain particular damage effects. They include crushing of a vessel, from which he estimates an overpressure of 0.76 MPa (110 psi); damage to drain covers, for which his over-pressure estimate is 1 MPa; and bending of a reactor agitator shaft and deformation of lamp standards. He suggests that in general the analysis of the damage relied too much on the effects of overpressure to the neglect of the influence of impulse and dynamic pressure.

Marshall regards the vapour cloud explosion at Flixborough as of particular interest in that it is the best documented and most studied case, and is thus an exemplar. He gives a detailed analysis of the estimates of over-pressure made from the damage effects, treating separately those in the near and far fields. The results show wide scatter, and he concludes that it is peculiarly difficult to estimate the energy release of such an explosion from damage.
Appendix 3

Seveso

Contents

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A3.12 Some Lessons of Seveso A3/13
At 12.37 on Saturday 9 July 1976 a bursting disc ruptured on a chemical reactor at the works of the Icmesa Chemical Company at Meda near Seveso, a town of about 17,000 inhabitants some 15 miles from Milan. A white cloud drifted from the works and material from it settled out downwind. Among the substances deposited was a very small amount of TCDD, one of the most toxic chemicals known. There followed a period of great confusion due to lack of communication between the company and the authorities and the latter's inexperience in dealing with this kind of situation. Over the next few days in the contaminated area animals died and people fell ill. A partial and belated evacuation was carried out. In the immediate aftermath there were no deaths directly attributable to TCDD, but a number of pregnant women who had been exposed had abortions.

A Parliamentary Commission of Inquiry, drawn equally from the Chamber of Deputies and the Senate and chaired by Deputy B. Orsini, was set up. The Commission’s report (the Seveso Report) (Orsini, 1977, 1980) is a far-ranging inquiry not only into the disaster but also into controls over the chemical industry in Italy. The impact of the Seveso disaster in Continental Europe has in some ways exceeded that of Flixborough and has led to much greater awareness of process industry hazards on the part of the public and demands for more effective controls.

The EC Directive on Major Accident Hazards of 1982 was a direct result of the Seveso disaster, and indeed this Directive was initially often referred to as the ‘Seveso Directive’.


Selected references on Seveso are given in Table A3.1.

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**Table A3.1 Selected references on Seveso**

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<tr>
<th>Further accounts</th>
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**TCDD**

Herxheimer (1899); Kumig and Schulz (1957); Schulz (1957); Bauer, Schulz and Spiegelberg (1961); Higginotham et al. (1968); Verrett (1970); Vos et al. (1973); Schetz et al. (1973); WHO (1977); Cattabeni, Cavallaro and Galli (1978); A. Hay (1982); Rice (1982); Anon. (1984p); Tschirley (1986); EPA (1994a,b)

**Previous TCP and TCDD accidents**

Hoffmann (1957); Schulz (1957); Bleiberg et al. (1964); US Senate (1970); Milnes (1971); May (1973); Daldnerup (1974)

**A3.1 The Company and the Management**

The site at Seveso was operated by the company Industrie Chimiche Meda Societa Azionara (ICMESA), using a process developed by its parent company Givaudan, which was itself owned by Hoffmann La Roche.

Icmesa started in Naples in 1926 and began operations in Meda in 1946. Givaudan acquired a majority shareholding in Icmesa in 1965. In the same year Givaudan was itself taken over by Hoffmann La Roche. Icmesa was an Italian company and the other two companies were Swiss.

The management of the three companies and the officials of the local authorities involved are described in The Superpoison. The following information is relevant:

Icmesa
General Manager H. von Zwehl
Technical Manager C. Barni
Production Manager P. Paolletti
Factory Doctor E. Bergamaschini

Givaudan
Managing Director G. Waldvogel
Technical Director J. Sambeth
Director of Dubendorf Laboratories B. Vaterlaus

Hoffman La Roche
Technical General Manager R. Seheff
Clinical Research Director G. Reggiani

Local Authorities
Mayor of Seveso F. Rocca
Mayor of Meda F. Malgrati
Medical Health Officer G. Ghetti
Acting Health Officer F. Uberti

Regional Minister of Health V. Rivolta
Chief Medical Officer, Milan Province V. Eboli
Chief Medical Officer, Lombardy V. Carreri
Director of Provincial Health Laboratory, Milan A. Cavallaro

Magistrate S. Adamo
A3.2 The Site and the Works

When Icmesa built its works at Meda the site was surrounded by fields and woods. Over the years, however, the area near the site was developed.

The reactor, Reactor A101, in which the runaway occurred was in Department B of the works.

A3.3 The Process and the Plant

The process which gave rise to the accident was the production of 2, 4, 5-trichlorophenol (TCP) in a batch reactor.

TCP is used for herbicides and antiseptics. Givaudan required it for making the bacteriostatic agent hexachlorophene. It manufactured its own because the herbicide grades contained impurities unacceptable in this application. Between 1970 and 1976 some 370 t of the chemical were produced.

The reaction was carried out in two stages. Stage 1 involved the alkaline hydrolysis of 1, 2, 4, 5-tetrachlorobenzene (TCB) using sodium hydroxide in the presence of a solvent ethylene glycol at a temperature of 170-180°C to form sodium 2, 4, 5-trichlorophenate. The reaction mixture also contained xylene, which was used to remove the water by azeotropic distillation. In Stage 2 the sodium trichlorophenate was acidified with hydrochloric acid to TCP and purified by distillation. The reaction scheme is shown in Figure A3.1.

Completion of the Stage 1 reaction some 50% of the ethylene glycol would be distilled off and the temperature of the reaction mixture lowered to 50-60°C by the addition of water.

The process was a modification by Givaudan of a process widely used in the industry. The conventional process used methanol rather than ethylene glycol and operated at some 20 bar pressure.

In this reaction the formation of small quantities of TCDD as a by-product is unavoidable. At a reaction temperature below 180°C the amount formed would be unlikely to exceed 1 ppm of TCP, but with prolonged heating in the temperature range 230-260°C it could increase a thousand-fold.

During manufacture nearly all (99.7%) of the TCDD formed concentrated in the distillation residues from which it was collected and incinerated. Only 0.3% found its way into the TCP, giving a maximum concentration of 10 ppb.

The reactor was a 138751 vessel with an agitator and with a steam jacket supplied with steam at 12 bar. The saturation temperature of steam at this pressure is 188°C. The controls on the reactor were relatively primitive. There was no automatic control of the heating. The reactor system is shown in Figure A3.2.

The reactor was provided with a bursting disc set at 3.5 bar and venting direct to atmosphere. The prime purpose of this disc was to prevent overpressure when compressed air was being used on the reactor.

The works had an incinerator for the destruction of hazardous plant residues at temperatures of 800-1000°C.

A3.4 TCDD and its Properties

The properties of TCDD are given in the Seveso Report and in Dioxin, Toxicological and Chemical Aspects by Cattabeni, Cavallaro and Galli (1978) and by Rice (1982).

2, 3, 7, 8-tetrachlorodibenzo-p-dioxin, which is also known as TCDD or dioxin, has the formula

![TCDD structure]

It is generated by the elimination of two molecules of HCl from 2, 4, 5-trichlorophenol

![TCP structure]

TCDD is one of the most toxic substances known. In 1954 an accident at the Boehringer TCP plant in Hamburg led to a painstaking investigation by Schulz (1957) of the causes of chloracne in people who had been exposed. He found that the cause was not the TCP itself but an impurity which he identified as TCDD, or

![Reaction scheme for production of 2, 4, 5-trichlorophenol (TCP)]
dioxin. Actually there is a family of dioxins, TCDD being the most toxic.

The toxicity of TCDD is reviewed in the Seveso Report. The LD$_{50}$ data quoted in the report are shown in Table A3.2, Section A. The lowest LD$_{50}$ quoted is for guinea pigs and is 0.6 μg/kg, i.e. a dose of $0.6 \times 10^{-3}$ per unit of body weight. The report also gives a table showing the toxicity of TCDD relative to that of other well-known poisons. An extract from this is shown in Table A3.2, Section B. TCDD is therefore an ultratoxic substance.

TCDD can be taken into the body by ingestion, inhalation or skin contact. A leading symptom of TCDD poisoning is chloracne, which is an acne-like skin effect caused by chemicals. A mild case of chloracne usually
clears within a year, but a severe case can last many years. Other effects of TCDD include skin burns and rashes and damage to liver, kidney and urinary systems and to the nervous system. It appears to have an unusual ability to interfere with the metabolic processes. There are varying degrees of evidence for carcinogenic, mutagenic and teratogenic properties. These are reviewed in the report.

TCDD is a stable solid which is almost insoluble in water and resistant to destruction by incineration except at very high temperatures.

**A3.5 Previous Incidents Involving TCP and TCDD**

The manufacture of TCP had resulted in a number of accidents prior to Seveso and its hazards and problems were recognized, to the extent that some companies had withdrawn from the business.

A list of incidents, based on that given in the Seveso Report, is shown in Table A3.3.

The original method of making TCP was to heat trichlorobenzene (TCB) and sodium hydroxide with methanol at about 200°C and 20 bar.

In 1949 there was a large release from a pressurized TCP reactor at the Monsanto plant at Nitro, West Virginia, when a valve ruptured. A total of 228 people were affected to some degree. In 1953 a TCP reactor explosion at BASF, affecting 42 people. Another TCP reactor explosion occurred at the Boehringer plant at Hamburg in 1954, 40 workers being affected. It was this incident which led to the discovery by Schulz of the ultratoxic properties of TCDD. At the Rhone-Poulenc TCP plant at Pont de Clais near Grenoble there were 100 cases of dioxin poisoning in the period 1953–1970 and explosions in 1956 and 1966, affecting 17 and 20 people, respectively. In 1963 at the Philips-Duphar plant on the North Sea Canal near Amsterdam a reaction runaway on a pressurized TCP reactor blew the top off the reactor, even though the relief valve had blown, and affected some 30 people. In 1964 the operating procedure at the Dow plant at Midland, Michigan, was changed and an accident occurred which affected 60 people. In some of these incidents a small number of those exposed subsequently died, apparently from the exposure.

The incidents did not cause any direct exposure of the public, but they did reveal the difficulties of preventing the workers’ families being affected and of decontaminating the plant. In the Ludwigshafen accident one man got chloracne just by using his father’s towel.

Various attempts were made at Ludwigshafen to remove the dioxin from the plant building, including the use of detergents, the burning off of the surfaces, the removal of insulating material and so on, but these were not effective. Eventually the whole building was demolished under controlled conditions and the debris buried. At Duphar some 50 people were involved in cleaning up the plant, of whom four died within two years, though the connection between the incident and the deaths was unresolved. The plant was sealed for ten years and then dismantled from the inside brick by brick, the rubble was embedded in concrete and the concrete blocks were sunk in the Atlantic.

In 1968 an accident occurred at the Coalite TCP plant at Bolsover. Coalite utilized a modification of the Givaudan process, using ethylene glycol and operating at atmospheric pressure, but with ortho-dichlorobenzene (ODCB) as the second solvent to remove the water formed. The use of this second solvent reduced the amount of expensive ethylene glycol which had to be used and not all of which was recovered after the batch. Research indicated that further reduction might be made in the amount of ethylene glycol used and a trial was carried out on the plant using half the normal quantity. A reaction runaway occurred, blew the top off the reactor and released flammable vapours which exploded and killed the shift chemist.

The workers who had been in the building were affected but appeared to recover after ten days and the

**Table A3.3 Some incidents involving TCDD**

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Injured</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1949</td>
<td>Nitro, WV (Monsanto)</td>
<td>117</td>
<td>Overheating leading to explosion</td>
</tr>
<tr>
<td>1953</td>
<td>Ludwigshafen (BASF)</td>
<td>55</td>
<td>Overheating leading to explosion</td>
</tr>
<tr>
<td>1954</td>
<td>Hamburg (Boehringer)</td>
<td>37</td>
<td>Exposure during plant operation</td>
</tr>
<tr>
<td>1956</td>
<td>Pont de Clais (Rhone-Poulenc)</td>
<td>17</td>
<td>Explosion</td>
</tr>
<tr>
<td>1956</td>
<td>USA (Hooker)</td>
<td>?</td>
<td>Overheating</td>
</tr>
<tr>
<td>1960</td>
<td>USA (Diamond Shamrock)</td>
<td>?</td>
<td>Overheating</td>
</tr>
<tr>
<td>1963</td>
<td>N. Sea Canal (Philips-Duphar)</td>
<td>30</td>
<td>Overheating leading to explosion</td>
</tr>
<tr>
<td>1964</td>
<td>Midland, MI (Dow)</td>
<td>30</td>
<td>Explosion</td>
</tr>
<tr>
<td>1964</td>
<td>Neuratovice (Spolana)</td>
<td>72</td>
<td>Exposure during plant operation</td>
</tr>
<tr>
<td>1966</td>
<td>Pont de Clais (Rhone-Poulenc)</td>
<td>21</td>
<td>Explosion</td>
</tr>
<tr>
<td>1968</td>
<td>Bolsover (Coalite)</td>
<td>79</td>
<td>Overheating leading to explosion</td>
</tr>
<tr>
<td>1970?</td>
<td>(Bayer)</td>
<td>5</td>
<td>Exposure during plant operation</td>
</tr>
<tr>
<td>1972</td>
<td>(Linz Chemie-Werke)</td>
<td>50</td>
<td>Exposure during plant operation</td>
</tr>
<tr>
<td>?</td>
<td>(Thompson Hayward)</td>
<td>?</td>
<td>Overheating leading to explosion</td>
</tr>
<tr>
<td>1976</td>
<td>Seveso (Icmesa)</td>
<td></td>
<td>Overheating</td>
</tr>
</tbody>
</table>
undamaged part of the plant was thoroughly cleaned and brought back into use, the damaged part being sealed off. Some weeks later chloracne symptoms appeared not only among those who had been in the plant at the time of the accident but among others who had worked in the building occasionally after it had been cleaned. Within seven months there were some 79 cases of chloracne. Stringent hygiene measures were instituted and the cases gradually cleared. The most seriously contaminated part of the plant was dismantled and buried in a deep hole.

The causes of the accident were investigated by Milnes (1971). He found that an exothermic reaction occurs between ethylene glycol and sodium hydroxide starting about 230°C and rising rapidly to about 400°C. He also showed that TCDD is formed by reaction of sodium trichlorophenate and sodium hydroxide as described above. Further, he demonstrated that whereas at the normal reaction temperature of 180°C the amount of TCDD formed is only a few ppm, at 250°C large amounts are formed. Subsequent work has shown that formation of TCDD is zero below 153°C, less than 1 ppm at 180°C but 1600 ppm in 2 hours at 230–260°C (Orsini, 1980).

A3.6 Events Prior to the Release

The start of the batch began at 16.00 on Friday 9 July. The reactor was charged with 2000 kg TCB, 1050 kg sodium hydroxide, 3300 kg ethylene glycol and 600 kg xylene.
Table A3.4  Timetable of events at Seveso

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul. 9 Friday</td>
<td>16.00 Final reactor batch started</td>
</tr>
<tr>
<td>10 Saturday</td>
<td>5.00 Final reactor batch interrupted</td>
</tr>
<tr>
<td></td>
<td>12.37 Bursting disc on reactor ruptures</td>
</tr>
<tr>
<td></td>
<td>Barni visits houses near plant to warn against eating garden produce. He asks carabinieri to repeat warning but they refuse</td>
</tr>
<tr>
<td>11 Sunday</td>
<td>Barni and Paoletti inform von Zwehl. They are unable to contact Gherri or his deputy. They inform Rocca and Malgrati. Von Zwehl informs Sambeth</td>
</tr>
<tr>
<td>12 Monday</td>
<td>Rocca and Uberti visit ICMESA. Letter of von Zwehl to Health Officer</td>
</tr>
<tr>
<td>13 Tuesday</td>
<td>Report of Uberti to Rocca and Malgrati</td>
</tr>
<tr>
<td>14 Wednesday</td>
<td>Sambeth and Vaterlaus inspect Dept B and contaminated area. Uberti writes to Provincial Health Officer in Milan</td>
</tr>
<tr>
<td>15 Thursday</td>
<td>Dubendorf Laboratories give first analyses showing high TCDD content. Sambeth telegraphs Waldvogel in Turkey and asks von Zwehl to inform local authorities. Sambeth informs Hoffmann La Roche and seeks clinical advice and permission to close plant. Rumours grow in Seveso. Citizens invade Uberti’s office. Rocca and Uberti meet von Zwehl. They decide to declare polluted zone and to post warning notices</td>
</tr>
<tr>
<td>16 Friday</td>
<td>Workforce go on strike. Efforts are made to contact Gherri in remote holiday farmhouse. Warning notices are erected. Rocca, Uberti and others meet von Zwehl again. Uberti insists on evacuation. Rocca requests and obtains permission for evacuation from Deputy Prefect of Milan. Rocca contacts journalist friend</td>
</tr>
<tr>
<td>18 Sunday</td>
<td>Cavallaro’s team of health inspectors investigate contaminated area. Rocca, Gherri, Cavallaro and Adamo meet von Zwehl. Cavallaro presses to know identity of poison released. Adamo threatens to arrest ICMESA management</td>
</tr>
<tr>
<td>19 Monday</td>
<td>Waldvogel arrives in Seveso and offers local authority financial compensation, which is refused</td>
</tr>
<tr>
<td>20 Tuesday</td>
<td>Cavallaro and Gherri meet Vaterlaus in Zurich. Vaterlaus reveals that poison released was TCDD. Uberti’s letter to Provincial Health Officer in Milan arranges. 16.00 Gherri telephones Rocca to say substance was TCDD. Prefect in Milan is informed</td>
</tr>
<tr>
<td>21 Wednesday</td>
<td>9.30 Meeting at prefecture. Rivolta and Carreri take over responsibility. Carabinieri arrest von Zwehl and Paoletti</td>
</tr>
<tr>
<td>23 Friday</td>
<td>9.00 Meeting at prefecture. Rivolta decides against evacuation. Reggiani visits Rocca and urges evacuation. Reggiani asks to leave Deputy Prefect’s meeting unheard</td>
</tr>
<tr>
<td>24 Saturday</td>
<td>9.30 Meeting of regional health council, Vaterlaus presents map of locations affected. Council decides to recommend evacuation and defines evacuation zone (part of Zone A)</td>
</tr>
<tr>
<td>26 Monday</td>
<td>179 people evacuated</td>
</tr>
<tr>
<td>29 Thursday</td>
<td>Zone A extended and further 550 evacuated</td>
</tr>
</tbody>
</table>

After the reaction had taken place, part of the ethylene glycol was distilled off, but the fraction removed was only 15% instead of the usual 50% so that most of the solvent was left in the vessel. Distillation was interrupted at 5.00 on 10 July and heating was discontinued but water was not added to cool the reaction mass. The reactor was not brought down to the 50-60° temperature range specified. The temperature recorder was switched off, the last temperature recorded being 158°C.

The shift ended at 6.00. This time coincided with the closure of the plant for the weekend. The reactor was left with the agitation turned off but without any action to reduce the temperature of the charge.

During the weekend, with the steam turbine on reduced load, the steam supply to the reactor jacket became superheated, its temperature being about 300°C.

**A3.7 The Release – 1**

At 12.37 on 9 July the bursting disc on the reactor ruptured. The maintenance staff heard a whistling sound and a cloud of vapour was seen to issue from a vent on the roof giving rise to ‘the formation of a dense cloud of considerable altitude’. The release lasted some 20 minutes.

A maintenance foreman, G. Bruno, who was passing, heard the disc rupture and realized something was wrong. He ran with two colleagues, R. Vito and C.
Galante, to the boiler room to start up the large fire water pump, then to the stores to get protective clothing. They approached Department B, where they felt the heat from the reactor. Bruno called in the technical manager, C. Barni, who arrived at 13.10 as the escape was subsiding. About an hour after the release began Vito and Galante were able to begin gingerly admitting cooling water to the reactor system.

The release contaminated the vicinity of the plant with TCDD. Figure A3.3 is a map of the area, showing the zones later established and Table A3.5 gives the concentrations later measured in these zones.

The area of Zone A was 108 hectare (1.08 km²) with concentrations of TCDD averaging 240 µg/m² and rising to over 5000 µg/m². The area of Zone B was 269 hectare (2.69 km²) with concentrations averaging 3 µg/m² but rising to 43 µg/m². In the Zone of Respect, Zone R, which had an area of 1430 hectares (14.3 km²), the concentrations varied from indeterminable to 5 µg/m².

A3.8 The Emergency and the Immediate Aftermath

The release set in train a series of events which were to have profound repercussions. They are described in detail in The Superpoison. It is possible here to give only a brief outline.

When the situation had been brought under control in the works, Barni visited houses near the plant and warned people not to eat the garden produce. He asked the carabinieri to repeat the warning, but they refused, unless there was authorization from the municipal health officer.

There were few obvious signs of an accident, although surfaces were covered with a thin, oily film.

The municipal health officer, G. Ghetti, was on holiday in a remote farm house not on the telephone.

On Sunday 11 July Barni visited P. Paoletti, the production director, and they together contacted the general manager, von Zwehl, who was on holiday in the Alps. They then visited the mayor of Seveso, F. Rocca, and recommended that people living near the plant be warned not to eat garden produce. Rocca agreed to inform the carabinieri. He also brought in the mayor of Meda, F. Malgrati, since the Icmesa plant lay within the Meda boundaries.

The same day von Zwehl informed J. Sambeth, technical director of Givaudan. Sambeth realized that there was a dioxin hazard and asked what temperature the reactor had reached. He told von Zwehl to close off Department B and have samples from the reactor sent to the Dubendorf laboratories of Givaudan at Zurich. Normally he would have discussed the problem with the managing director of Givaudan, G. Waldvogel, but the latter was on holiday in Turkey.

On Monday 12 July Rocca together with the acting health officer for Meda and Seveso, F. Uberti, visited Icmesa and saw von Zwehl, who convinced them that there was no serious health hazard. Von Zwehl wrote a letter to the health officer. On the material released the latter said:

Since we are not in a position to evaluate the substances present in the vapour or to predict their exact effects, but knowing the final product is used in manufacturing herbicides, we have advised householders in the vicinity not to eat garden produce.

On Tuesday 13 July Uberti sent a report to Rocca and Malgrati, enclosing a copy of von Zwehl's letter. He believed the release was one of the minor accidents which occur periodically.

On Wednesday 14 July Sambeth and Vaterlaus, director of the Dubendorf laboratories, came to Seveso, inspected Department B and tried to work out how high a temperature the reactor had reached. They also inspected the contaminated land.

Uberti wrote the same day to the provincial health officer in Milan. The letter did not arrive until 20 July.

On Thursday 14 July the first analyses from the Dubendorf laboratory came through to Sambeth. They showed high dioxin contents. Sambeth telegraphed Waldvogel in Turkey. He warned von Zwehl to advise the local authorities that the release may have contained toxic by-products.

He also contacted Hoffmann La Roche to seek clinical advice and permission to order closure of the plant. The clinical research director of Hagemann, G. Reggiani, was not familiar with TCDD, but agreed to take over the health aspect and began to inform himself about the substance.

Meanwhile rumours were growing in Seveso and a group of citizens invaded Uberti's office.

Rocca and Uberti met von Zwehl again. He agreed to pay compensation for any damage, produced a map of the polluted area, and suggested that people be advised not to eat garden produce and that warning notices be posted. He was not, however, prepared to say what the poison was. The visitors decided to declare a polluted zone and post notices.

On Friday 16 July the erection of warning notices began. At this point the workforce at Icmesa went on strike. Rocca and Uberti had a further meeting with von Zwehl where they again pressed to be told the identity of the poison.

Uberti now urged Rocca to carry out an evacuation. Ghetti was contacted in his remote farmhouse, agreed to return but left the decision to Rocca. Rocca requested and obtained permission to evacuate from the Deputy Prefect of Milan. He also contacted a journalist friend.

On Saturday 17 July Il Giorno carried front page headlines about the 'Poison gas' at Seveso. The accident became a national issue and the press descended on the town.

The same day Uberti contacted A. Cavallaro, director of the provincial health laboratories in Milan.

On Sunday 18 July Cavallaro's team of health inspector arrived to investigate the contaminated area.

Rocca, Ghetti, Cavallaro and a local magistrate, S. Adamo, met again with von Zwehl. Cavallaro pressed to know the poison involved. Adamo threatened to arrest the Icmesa management.

On Monday 19 July Waldvogel arrived in Seveso. He offered the local authorities compensation, which they refused.

On Tuesday 20 July Cavallaro and Ghetti met Vaterlaus in Zurich. He revealed that the poison was TCDD. Ghetti telephoned Rocca with this information. The Prefect in Milan was informed.
On Wednesday 21 July a meeting was held at the prefecture. The regional minister of health, V. Rivolta, now took charge of the medical aspects together with V. Carreri, director of health services for Lombardy.

On the same day the carabinieri arrested von Zwehl and Paoletti.

On Friday 23 July there was another meeting at the prefecture. Rivolta was against evacuation. Meanwhile Reggiani had decided that evacuation was essential and arrived in Seveso to urge this view. He saw Rocca, who told him the decision was out of his hands. He came into the meeting at the prefecture but was asked to leave unheard.

Later that day Rivolta addressed a meeting in Seveso town hall and gave reassurances about the hazards. Reggiani stated his disagreement with Rivolta and called for evacuation. He was unable to make his view prevail. At his hotel in Milan he was warned that the carabinieri were about to arrest him and drove north in haste to Switzerland.

There followed a meeting in Lugano between Waldvoegel, Sambeth and Vaterlaus, who had a map of the contaminated areas based on the analyses carried out by his laboratories. Reggiani told the Givaudan men of his experiences. It was agreed that an attempt must be made to persuade the Italian authorities to evacuate and that Vaterlaus, who was deemed less likely to be arrested, should do this.

On Saturday 24 July a meeting of the regional health council was held in Milan. Vaterlaus presented his map of the areas affected. An evacuation zone was defined and the decision was taken to recommend evacuation.

On Monday 26 July 179 people were evacuated from an area which was later defined as part of Zone A. On Thursday 29 July a further 550 people were evacuated from another area which was also part of what became Zone A.

Eventually three zones, Zone A, Zone B and the Zone of Respect were defined, as described above. 733 people were evacuated from Zone A and 5000 in Zone B were put under medical surveillance, but allowed to remain in their homes.

The release posed a serious problem for the Italian authorities, who were obliged to seek assistance from international experts in medical diagnosis and treatment and in analytical and decontamination procedures.

A3.9 The Investigation

The work of the Commission took place against a background of intense national concern.

The terms of reference of the Commission were wide-ranging. They have been described by V.C. Marshall (1980c) as follows: 'These terms of reference appear to have combined the functions in UK terms of the Flixborough inquiry, the Major Hazards Advisory Committee and the Royal Commission on the Environment'.

The report produced by the Commission, the Seveso Report (Orsini, 1980), covers a large number of topics, including the history of TCP production, the history of Icmesa, the toxicity of TCDD, the causes of the accident, the consequences of the accident in terms of contamination and health effects, the health measures taken, the reclamation of the contaminated land, the actions and responsibilities of the management and of the local and regulatory authorities and the recommendations.

The report adduces four causes of the accident:

(1) Interruption of the production cycle.  
(2) Method of distillation.  
(3) Set pressure of bursting disc.  
(4) Failure to install collection/destruction system for material vented.

The production cycle was interrupted at 5.00 on 10 July and the reactor was left without agitation or cooling.

In the process described in the original Givaudan patent the charge was acidified before distillation. In the process used at Icmesa the order of these two steps was reversed. This allowed prolonged contact time between the ethylene glycol and sodium hydroxide.

Another modification to the original process was a change in the molar proportions of the reactants from

1 TCB: 2 NaOH: 11.5 ethylene glycol

to

1 TCB: 3 NaOH: 5.5 ethylene glycol

which increased the molar concentration of sodium hydroxide.

The setting of the bursting disc was 3.5 bar. The function of this device was to guard against overpressure from the compressed air which was used to transfer materials to the reactor. The inquiry found that if the set pressure had been lower, venting would have occurred at a lower, and less hazardous, temperature.

No device was installed to collect or destroy any toxic materials vented. The bursting disc manufacturer's catalogue stated 'Bursting discs may be preferred in the case of fluids of great value and high toxicity where the loss of such fluids should be avoided. In this case a second receiver tank is required to recover the discharged fluid'. There was no such tank on the plant.

Besides listing these four points the report makes a number of other comments. On the reactor itself it states

Proof has been provided both of the inadequacy of the measuring equipment for a number of fundamental parameters and also the absence of any automatic control system. Measurement of acidity was carried out manually by immersion of a rod with an indicator chart (sic) through a secondary inspection window.

The reactor vessel was not given a hydraulic test as the reactor was considered to operate at atmospheric pressure. The fitting of the bursting disc was not reported to the state pressure vessel inspectors.

The report recommends improved regulatory arrangements for the control of hazardous plants and, in this connection, places some reliance on the introduction of the EC Directive which came to be known as the 'Seveso Directive'.

The viewpoint of the companies has been given in several publications. The accident itself has been described by Sambeth (1983). The view of Hoffmann La Roche has been stated by Homberger et al. (1979).

A3.10 The Release – 2

The contents of the reactor at the time of the accident have been given as 2030 kg sodium trichlorophenate,
Figure A3.4  Reactor temperature profiles measured for accident at Seveso (Sambeth, 1983) (Courtesy of Chemical Engineering)

Figure A3.5  Reactor temperature profiles calculated for period preceding accident at Seveso (after Theofanous, 1981) (Courtesy of Nature)

540 kg sodium chloride, c.1000 kg ethylene glycol and 1600 kg sodium ethylene glycolate, diethylene glycol and polyethylene glycol.

It is known that above 230°C such a mixture will undergo an exothermic decomposition reaction. Accidents had been known to occur involving a reaction runaway above this temperature.

The actual temperature profile in the reactor has been given by Sambeth (1983) and is shown in Figure A3.4. Due to the interruption of the batch the usual sharp reduction in the temperature of the charge at the termination of the reaction did not take place and after 7.5 hours the explosion occurred.

Investigations carried out after the accidents using differential thermal analysis showed that there exist two
slow exotherms (Theofanous, 1981, 1983). One starts at about 185°C, peaking at 235°C and giving a 57°C adiabatic temperature rise. The other starts at about 255°C, peaking at 265°C and giving an estimated 114°C temperature rise. The adiabatic induction times for the two exotherms are 2.1 and 0.5 hours, respectively. The decomposition exotherm starts at about 280–290°C and shows a rapid pressure rise at about 300°C.

A mechanism for the reaction runaway has been proposed by Theofanous. This is that due to layering of the reaction mix the amount of residual heat in the upper section of the reactor wall was sufficient to raise the temperature of the top layer of liquid to c. 200–220°C, a temperature high enough to initiate exotherms leading to decomposition. The calculated temperature profiles for this theory are shown in Figure A3.5.

In the conduct of the final batch there were failures of adherence to operating procedures. W.B. Howard (1985) instances (1) failure to distill off 50% of the glycol; (2) failure to add water; (3) failure to continue agitation; (4) switching off of the reactor temperature recorder; and (5) failure to bring the reactor temperature down from its value of 158°C to the normal value of 50–60°C.

A3.11 The Later Aftermath, Contamination and Decontamination

As described above, there was a prolonged period in which the authorities tried to assess the situation and determine measures for dealing with it. They were advised by a team from Cremer and Warner (C&W), and an account has been given by Rice (1982).

The release was modelled using fluid jet and gas dispersion models and predictions made of the probable ground level concentrations of TCDD. Accounts have been given by Comer (1977) and Rice (1982). In this work the reaction mass was taken as 2800 kg ethylene glycol, 2030 kg trichlorophenol 2030, 542 kg sodium chloride and 562 kg sodium hydroxide.

Estimates of the amount of TCDD generated in the reactor and dispersed over the countryside vary. Cattabeni, Cavallaro and Galli (1978) give an estimated range of 0.45 to 3 kg released. The amount assumed in the C&W modelling work was 2 kg.

Other parameters used in the modelling were bursting disc rupture pressure 376 kPa; vent pipe diameter 127 mm; discharge height above ground 8 m. The bursting disc rupture was assumed to a first approximation to be due to the vapour pressure of ethylene glycol at 250°C. From these data the value obtained for the vapour exit velocity was 274 m/s. Two limiting cases were considered for the discharge: Case A, pure vapour (density 1.61 kg/m³) and Case B, a two-phase vapour-liquid mixture (density 8.99 kg/m³). Eyewitness accounts indicated that the actual event was intermediate between these two extremes. For Case A the total plume rise was estimated as 83 m with the downwind distance to the maximum height as 103 m and the corresponding figures for Case B were 55 m and 95 m, respectively. Figure A3.6 shows the estimated ground concentration contours for a 2 kg release taken from this work.

The modelling work proved useful in defining the problem and planning the decontamination. The results showed that beyond about 1.5 km there was little difference in the concentration estimates for the two cases. There was good agreement between the predicted and the measured concentrations. This gave some confidence that the amount released was indeed about 2 kg. There had been some speculation by scientists that an amount as high as 130 kg had been released.

Initially, various methods of decontamination were put forward by various parties. TCDD is virtually insoluble in water, which reduces the threat to the water supply, but means that the effect of rain is to transfer it from the vegetation to the soil rather than to remove it. One method of removal suggested was burning and proposals were made to burn the contaminated ground with flame throwers. It was feared, however, that unless a temperature of at least 1000°C were attained, the TCDD would not be destroyed but simply swept up and deposited elsewhere. Another method proposed was to apply a mixture of olive oil and cyclohexane to the ground, so that the TCDD would dissolve in the oil and be broken down by the ultraviolet radiation of the sun. This was

![Figure A3.6 Estimated concentrations of TCDD at Seveso (Comer, 1977. Reproduced by permission.)](image-url)
Figure A3.7  Measured concentrations of TCDD at Seveso, showing reduction of concentration with time (Cavallaro, Tebaldi and Gualdi, 1982) (Courtesy of Atmospheric Environment)
Table A3.5  Concentrations of TCDD in Zones A and B at Seveso (after Orsini, 1980)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Concentration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (µg/m²)</td>
<td>Maximum (µg/m²)</td>
</tr>
<tr>
<td>A1</td>
<td>580.4</td>
<td>5477</td>
</tr>
<tr>
<td>A2</td>
<td>521.1</td>
<td>1700</td>
</tr>
<tr>
<td>A3 (north)</td>
<td>433.0</td>
<td>2015</td>
</tr>
<tr>
<td>A3 (south)</td>
<td>93.0</td>
<td>441</td>
</tr>
<tr>
<td>A4</td>
<td>139.9</td>
<td>902</td>
</tr>
<tr>
<td>A5</td>
<td>62.8</td>
<td>427</td>
</tr>
<tr>
<td>A6</td>
<td>29.9</td>
<td>270</td>
</tr>
<tr>
<td>A7</td>
<td>15.5</td>
<td>91.7</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>43.8</td>
</tr>
</tbody>
</table>

n.v.d. = no value determined

abandoned, because instead of sun there was rain, and it was feared that the dissolved TCDD would be washed into the rivers and might penetrate the water table. A third approach involved the use of specially bred microbes capable of digesting toxic substances. Mixtures of more than a dozen strains of microorganisms bred on chemical substrates were already used to degrade chemical wastes, including cyanides and herbicides.

The decontamination measures actually carried out are described by Rice. They include collection of vegetation and cleaning of buildings by high intensity vacuum cleaning followed by washing with high pressure water jets.

It is worth mention that people may also have been affected by materials in the reactor charge other than TCDD. V.C. Marshall (1980) indicates that on the basis of the ground concentrations found in the contaminated area a minimum of 0.25 kg was released. He points out that there were some 5–10 te of charge in the reactor and that several tonnes of material including sodium hydroxide must have been ejected. He suggests that burns around the hands and other parts of the body suffered by 413 persons who did not develop chloracne were probably caused by sodium hydroxide.

Figure A3.7 gives plots of the actual ground concentrations, showing the change with time, obtained by Cavallaro, Tebaldi and Gualdi (1982).

Data from the official report on ground concentrations in zones A and B are given in Table A3.5.

### A3.12 Some Lessons of Seveso

Some of the numerous lessons to be learnt from the Seveso disaster, many of which were brought out in the Commission’s report, are listed in Table A3.6. Some of them are similar to those from Flixborough, while others are different, reflecting both the different substances and processes and the different company and national situations involved.

Some of these lessons are now considered:

**Public control of major hazard installations**

The Seveso disaster had the effect of raising the general level of awareness of the hazard from chemical plants in Italy and in Europe generally and highlighted the deficiencies in the existing arrangements for the control of major hazards.

The Italian government set up the Commission of Inquiry to investigate the cause of the disaster and to make recommendations. It also gave strong support to the development of the EC Directive.

**Siting of major hazard installations**

The release at Seveso affected the public because in the period since the site was first occupied housing development had encroached on the area around the plant. The accident underlined the need for separation between hazard and public.

**Acquisition of companies operating hazardous processes**

A lesson which has received relatively little attention is the problem faced by a company which becomes owner by acquisition of another company operating a hazardous process. At Seveso the problem was compounded by the fact that Icmesa was owned by Givaund and the latter by Hoffmann La Roche, so that the company ultimately responsible was at two removes. As a result the directors of the latter were not familiar with the hazards.

**Hazard of ultratoxic substances**

Seveso threw into sharp relief the hazard of ultratoxic substances. The toxicity of TCDD is closer to that of a chemical warfare agent than to that of the typical toxic substance which the chemical industry is used to handling.
As it happened, the British Advisory Committee on Major Hazards was presenting its First Report, giving a scheme for the notification of hazardous installations, when Seveso occurred. It contained no notification proposals for ultratoxics. In the Second Report this deficiency was rectified. The EC Directive places great emphasis on toxic and ultratoxic materials.

Hazard of undetected exotherms
The characteristics of the reaction used had been investigated and the company believed it had sufficient information. It was well aware of the hazard from the principal exotherm. Subsequent studies showed, however, that other, weaker exotherms existed which, given time, could also cause a runaway.

The complete identification of the characteristics of the reaction being operated is particularly important. If these are not known, or only partially known, there is always the danger that the design will not be as inherently safe as intended, that operating modifications will have unforeseen results and/or that protective measures will be inadequate.

Hazard of prolonged holding of reaction mass
The interruption of the reaction and the holding of the reaction mass for a prolonged period after the main reaction was complete without reducing the temperature gave time for the weak exotherms to occur and lead to runaway.

Inherently safer design of chemical processes
The reactor was intended to be inherently safe to the extent that the use of steam at 12 bar set a temperature limit of 188°C so that the contents could not be heated above this by the heating medium. Unfortunately this feature was defeated by allowing the reaction charge to stand hot for too long so that there occurred the weak exotherms, which the company did not know about.

The bursting disc was not intended for reactor venting, but, as the Commission pointed out, if the set pressure of the disc had been lower, the reactor would have vented at a lower temperature and hence with less dioxin in the charge.

Control and protection of chemical reactors
The control and protection system on the reactor was primitive. Operation of the reactor was largely manual. There was no automatic control of the cooling and no high temperature trip.

The reactor was not designed to withstand a runaway reaction. It was not rated as a pressure vessel to withstand pressure build-up prior to and during venting, the disc was not designed for reaction relief and there was no tank to take the ultratoxic contents of the reactor.

Adherence to operating procedures
The conduct of the final batch involved a series of failures to adhere to the operating procedures.

Planning for emergencies
As the account given above indicates, the handling of the emergency was a disaster in its own right. Information on the chemical released and its hazards was not immediately available from the company. There was failure of communication between the company and the local and regulatory authorities and within those authorities. Consequently there was lack of action and failure to protect and communicate with the public. These deficiencies might in large part have been overcome by emergency planning.

Difficulties of decontamination
The incident illustrates the difficulties of decontamination of land where the contaminant is both ultratoxic and insoluble in water.
Appendix 4

Mexico City

Contents

A4.1 The Site and the Plant A4/2
A4.2 The Fire and Explosion – 1 A4/3
A4.3 The Emergency A4/5
A4.4 The Fire and Explosion – 2 A4/7
A4.5 Some Lessons of Mexico City A4/7
At about 5:35 a.m. on the morning of 19 November 1984 a major fire and a series of explosions occurred at the PEMEX LPG terminal at San Juan Ixhuatpec (San Juanico), Mexico City. Some 500 people were killed and the terminal was destroyed.

The accident was investigated by a team from TNO which visited the site about two weeks after the disaster and has published its findings (Pietersen 1985). A further account has been given by Skandia International (1985).

Selected references on Mexico City are given in Table A4.1.

Table A4.1 Selected references on Mexico City

| Anon. (1985v, hh); Berenblut et al. (1985); Cullen (1985); Kletz (1985p); Pietersen (1985, 1985 LPB 64, 1986a,b, 1988a); Skandia International (1985); Hagon (1986) |

A4.1 The Site and the Plant

The site of the PEMEX terminal is shown in Figure A4.1 and an aerial photograph of the installation itself in Figure A4.2.

The oldest part of the plant dates from 1961–62 and was thus over 20 years old. In the intervening period residential development had crept up to the site. This process of encroachment is clearly visible from the aerial photographs shown in Figure A4.3. By 1984 the housing was within 200 m of the installation with some houses within 130 m.

The terminal was used for the distribution of LPG which came by pipeline from three different refineries. The main LPG storage capacity of 16,000 m³ consisted of six spheres and 48 horizontal cylinders. The daily throughput was 5,000 m³. The layout of the terminal with storage tank capacities is shown in Figure A4.4. The two larger storage spheres had individual capacities of

![Figure A4.1: Area plan of the PEMEX site at Mexico City (Pietersen 1985) (Courtesy of TNO)
2400 m$^3$ and the four smaller spheres capacities of 1600 m$^3$. The site covered an area of 13000 m$^2$.

The plant was said to have been built to API standards and much of it to have been manufactured in the USA.

A ground level flare was used to burn off excess gas. The flare was submerged in the ground to prevent the flame being extinguished by the strong local winds.

Adjoining the PEMEX plant there were distribution depots owned by other companies. The Unigas site was some 100–200 m to the north and contained 67 tank trucks at the time of the accident. Rather further away was the Gasomatico site with large numbers of domestic gas cylinders.

A4.2 The Fire and Explosion – 1

Early in the morning of 18 November the plant was being filled from a refinery 400 km away. The previous day the plant had become almost empty and refilling started during the afternoon. The two larger spheres and the 48 cylindrical vessels had been filled to 90% full and the four smaller spheres to about 50% full, so that the inventory on site was about 11000 m$^3$, when the incident began.

About 5.30 a.m. a fall in pressure was registered in the control room and also at a pipeline pumping station 40 km distant. An 8 in. pipe between sphere F4 and the Series G cylinders had ruptured.
The control room personnel tried to identify the cause of the pressure fall but without success.

The release of LPG continued for some 5–10 min. There was a slight wind of 0.4 m/s. The wind and the sloping terrain carried the gas towards the south-west. People in the nearby housing heard the noise of the escape and smelled the gas.

When the gas cloud had grown to cover an area which eyewitnesses put at 200×150 m with a height of 2 m, it found the flare and ignited. It was 5.40 a.m. The cloud caught fire over a large area, giving a high flame and causing violent ground shock.

When this general fire had subsided, there remained a ground fire, a flame at the rupture and fires in some 10 houses.

Workers on the plant now tried to deal with the escape. One drove off to another depot to summon help. Five others who may have been on their way to the control room or to man fire pumps were found dead, and badly burned. At a late stage someone evidently pressed the emergency shut down button.

In the neighbouring housing some people rushed out into the street, but most stayed indoors. Many thought it was an earthquake.

At 5.45 a.m. the first BLEVE occurred. About a minute later another explosion occurred, one of the two most violent during the whole incident. One or two of the smaller spheres BLEVEd, giving a fireball 300 m diameter.

A rain of LPG droplets fell on the area. Surfaces covered in the liquid were set alight by the heat from fireballs. People burned like torches. There followed a series of explosions as vessels suffered BLEVE. There were some 15 explosions over a period of an hour and a half. BLEVE occurred of the four smaller spheres and many of the cylindrical vessels.

The explosions during the incident were recorded on a seismograph at the University of Mexico. The timing of the readings is shown in Table A4.2, Section A. As the footnote indicates, it is suggested by Skandia that the initial explosion, or violent deflagration, was probably not recorded.

The damage caused is shown in Figure A4.5, which shows the area of main housing damage and the fall of missiles. An aerial photograph of the plant after the disaster is shown in Figure A4.6. Plate 35 illustrates shows some of the damage.

Numerous missiles were generated by the bursting of the vessels. Many of these were large and travelled far. Twenty-five large fragments from the four smaller spheres weighing 10–40 te were found 100–890 m away. Fifteen of the 48 cylindrical vessels weighing 20 te became missiles and rocketed over 100 m, one travelling 1200 m. This cylinder is shown in Plate 36. Four cylinders were not found at all. The missiles caused damage both by impact and by their temperature, which was high enough to set houses alight.
Table A4.2  Timetable of events at Mexico City

A  Seismograph readings

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 h</td>
<td>44 min</td>
<td>52 s</td>
</tr>
<tr>
<td>2</td>
<td>5 h</td>
<td>46 min</td>
<td>01 s</td>
</tr>
<tr>
<td>3</td>
<td>6 h</td>
<td>15 min</td>
<td>53 s</td>
</tr>
<tr>
<td>4</td>
<td>6 h</td>
<td>31 min</td>
<td>59 s</td>
</tr>
<tr>
<td>5</td>
<td>6 h</td>
<td>47 min</td>
<td>56 s</td>
</tr>
</tbody>
</table>

Disturbances 2 and 7 were the most intense with a Richter scale intensity of 5
Skandia suggest that the first violent combustion may not have been recorded

B  General timetable

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.30</td>
<td>Rupture of 8 in. pipe. Fall of pressure in control room</td>
</tr>
<tr>
<td>5.40</td>
<td>Ignition of gas cloud. Violent combustion and high flame</td>
</tr>
<tr>
<td>5.45</td>
<td>First explosion on seismograph, a BLEVE</td>
</tr>
<tr>
<td></td>
<td>Fire department called</td>
</tr>
<tr>
<td>5.46</td>
<td>Second BLEVE, one of most violent</td>
</tr>
<tr>
<td>6.00</td>
<td>Police alerted and civilian traffic stopped</td>
</tr>
<tr>
<td>6.30</td>
<td>Traffic chaos</td>
</tr>
<tr>
<td>7.01</td>
<td>Last explosion on seismograph, a BLEVE</td>
</tr>
<tr>
<td>7.30</td>
<td>Continuing tank explosions*</td>
</tr>
<tr>
<td>8.00-10.00</td>
<td>Rescue work at its height</td>
</tr>
<tr>
<td>11.00</td>
<td>Last tank explosion</td>
</tr>
<tr>
<td>12.00-18.00</td>
<td>Rescue work continues</td>
</tr>
<tr>
<td>23.00</td>
<td>Flames extinguished on last large sphere</td>
</tr>
</tbody>
</table>

* Explosions of cylindrical vessels

When the fire began, people were already on their way to work. Eyewitnesses spoke of a huge hot, red light, intense heat, smoke and lack of air, blast waves and missiles. The following account by Nicanor Santiago, a mason, is typical:

Around 5.30 a.m. I went to work. It was still dark when I took my bicycle out of the house, when suddenly there was this huge light, red and hot. I could see nothing at all. The huge light blinded me. I could not feel anything except that everything was hot. Then I heard some explosions and a second blast. The walls of my house were rocking, it was an earthquake. I was lying on the pavement and close to me all sorts of matter came falling out of the sky. There was a lot of broken glass, chairs and flower pots were flying all over the place.... I suddenly remembered the PEMEX gas plant and I saw a big tongue of fire and a very big orange mushroom, and then a felt another explosion. Pieces of molten metal were dropping out of the sky and I felt intense heat waves burning my clothes and my hair. I ran into the bedroom, everything was dark inside and there was plenty of smoke. I could not see anything. I could not breathe for the gas. I noticed something huge fell on top of the house and a rush of air threw me out of the house into the street. By then I was really frightened and I started to run as fast as I could. I do not know where my wife and children got to. They may even be unidentified in a mass grave.

A timetable of events during the disaster is given in Table A4.2, Section B.

A4.3 The Emergency

Accounts of the emergency give little information about the response of the on-site management in the emergency and deal mainly with the rescue and fire fighting. The site became the scene of a major rescue operation which reached a climax in the period 8.00–10.00 a.m. Some 4000 people participated in rescue and medical activities, including 985 medics, 1780 paramedics and 1332 volunteers. At one point there were some 3000 people in the area. There were 363 ambulances and five helicopters involved.

The rescuers were at risk from a large BLEVE. The Skandia report states: 'If a BLEVE had occurred during the later morning, a large number of those 3000 people who were engaged in rescue and guarding would have been killed.'

The fire services were called by surrounding plants and by individual members of the public about 5.45 a.m. They went into the plant area only 3 hours after the start of the incident. Initially, they moved towards the Gasomatico site, where a sphere fragment had landed and started a fire which caused the domestic gas cylinders to explode.

The fire brigade also fought the fire on the two larger spheres, which had not exploded. They were at appreciable risk from BLEVE of the spheres. In the event, however, these burnt themselves out. The last flames on the spheres went out about 11.00 p.m. Some 200 firemen attended the site.
Figure A4.5  Area plan of the PEMEX site at Mexico City, showing damage to housing area and fall of missiles (Pietersen 1985) (Courtesy of TNO)
A4.4 The Fire and Explosion – 2

The TNO report gives much technical information on the course of the disaster and on the fire and explosion phenomena which occurred during it.

It discusses the effects of explosions, including vapour cloud explosions, BLEVEs and physical explosions; the effects of fire engulfment and heat radiation; and the effects of missiles, including fragments from bullet tanks and spheres.

The report gives estimates of the overpressure from BLEVE of the principal vessels. It states that the degree of blast damage to housing was not great; that the vapour cloud explosion effects were not responsible for major damage; that the second explosion, a BLEVE, was the most violent and did damage houses; that the worst explosion damage was probably from gases which had accumulated in houses; and that much of the damage was done by fire.

Films were available for many of the BLEVEs, though not for the second, violent explosion. From this evidence, the BLEVEs had diameters of 200–300 m and durations of some 20 seconds. Heavy direct fire damage was done at distances up to about 300 m, which agrees reasonably well with the estimates of fireball size.

A very large fire burned on the site for about an hour and a half, punctuated by BLEVEs.

Details are given of the number, size and range of fragments from spheres and bullet tanks.

Information on BLEVEs and missiles in the TNO report is given in Chapters 16 and 17.

A4.5 Some Lessons of Mexico City

Some of the lessons to be learned from Mexico City are listed in Table A4.3.

Siting of major hazard installations
The high death toll at Mexico City occurred because the housing was too near to the plant. At the time the plant was constructed the area was undeveloped, but over the years the built-up area had gradually crept up to the site.

Layout and protection of large LPG storages
The total destruction of the facility occurred because there was a failure of the overall system of protection,

<table>
<thead>
<tr>
<th>Table A4.3 Some lessons of Mexico City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siting of major hazard installations</td>
</tr>
<tr>
<td>Layout of large LPG storages</td>
</tr>
<tr>
<td>Gas detection and emergency isolation</td>
</tr>
<tr>
<td>Planning for emergencies</td>
</tr>
<tr>
<td>Fire fighting in BLEVE situations</td>
</tr>
<tr>
<td>Boiling liquid expanding vapour explosions</td>
</tr>
</tbody>
</table>
which includes layout, emergency isolation and water spray systems.

Gas detection and emergency isolation
One feature which might have averted the disaster is more effective gas detection and emergency isolation. The plant had no gas detector system and, probably as a consequence, emergency isolation was too late.

Planning for emergencies
One particularly unsatisfactory aspect of the emergency was the traffic chaos which built up as residents sought to flee the area and the emergency services tried to get in.

Another was risk run by the large number of rescuers who came on site from a BLEVE of one of the larger spheres.

Fire fighting in BLEVE hazard situations
The fire services appear to have taken a considerable risk in trying to fight the fire on the two larger spheres. The potential death toll if a BLEVE had occurred was high.

Boiling liquid expanding vapour explosions
After Flixborough the problem of vapour cloud explosions received much attention. Mexico City demonstrates that boiling liquid expanding vapour explosions are an equally important hazard.

Mexico City represents the largest series of major BLEVEs which has occurred and provides much information on these.
Appendix 5

Bhopal

Contents

A5.1 The Company and the Management A5/2
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A5.3 The Process and the Plant A5/2
A5.4 MIC and Its Properties A5/4
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A5.6 The Release A5/6
A5.7 The Emergency and the Immediate Aftermath A5/7
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A5.9 The Late Aftermath A5/8
A5.10 Some Lessons of Bhopal A5/9
Early in the morning of 3 December 1984 a relief valve lifted on a storage tank containing highly toxic methyl isocyanate (MIC) at the Union Carbide India Ltd works at Bhopal, India. A cloud of MIC gas was released onto housing, including shanty towns, adjoining the site.

Close on 2000 people died within a short period and tens of thousands were injured. The casualty figures are discussed further in Section A5.9.

The accident at Bhopal is by far the worst disaster which has ever occurred in the chemical industry. Its impact has been felt world-wide, but particularly in India and the USA.

Following the accident the Government of India (GoI) set up an inquiry which reported at the end of 1985 (Varadarajan, 1985). An investigation was conducted by the US parent company the Union Carbide Corporation (UCC), which issued its own report (the Union Carbide Report) (Union Carbide, 1975). Another investigation was carried out by the ICFTU-ICF (1985). In its initial investigation Union Carbide had limited access to documents and personnel, and it subsequently ceased to be published further findings (Kalelkar, 1988). These investigations are described in Section A5.8.


Table A5.1 Selected references on Bhopal and MIC

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl isocyanate</td>
<td>Kimmerle and Eben (1964); ten Berge (1985)</td>
</tr>
</tbody>
</table>

A5.1 The Company and the Management

Union Carbide began operations in India in 1904 and by 1983 had 14 plants operating in the country. Its Indian interests were held by Union Carbide India Ltd (UCIL). UCIL was owned 50.9% by the American parent company Union Carbide Corporation (UCC) and 49.1% by Indian investors. UCC thus retained a majority share, having persuaded the Indian government to waive its usual requirement for Indian majority shareholding, on the basis of the technological sophistication of the plant and the export potential.

UCIL began operations at Bhopal in 1969. Initially the plant formulated carbamate pesticides from concentrates imported from the USA. In 1975 UCIL was licensed to manufacture its own carbaryl with the trade name Sevin. The process selected was the same as at the UCC plant at W. Virginia, but initially the MIC intermediate was imported from the latter source. Production began in 1979. The plant had a capacity of 5250 t/y, but the market was less than expected. Production peaked at 2704 t in 1981 and fell to 1657 t in 1983. At these levels of sales the plant had problems of profitability.

Prior to the accident the management structure of UCIL changed and the Bhopal pesticides plant was put under the direction of the Union Carbide battery division in India.

A5.2 The Site and the Works

The location of the UCIL works at Bhopal is shown in Figure A5.1. The works was in a heavily populated area. Much of the housing development closest to the works had occurred since the site began operations in 1969, including the growth of the J.P. Nagar shanty town. Although these settlements were originally illegal, in 1984 the government gave the squatters rights of ownership on the land to avoid having to evict them. Other residential areas which were affected by the gas cloud had been inhabited for over 100 years.

A5.3 The Process and the Plant

In the process used at Bhopal methyl isocyanate (MIC) was made using the reaction scheme shown in Figure A5.2. The process itself is shown in Figure A5.3. Monomethylamine (MMA) is reacted with excess phosgene in the vapour phase to produce methylcarbamoyl chloride (MCC) and hydrogen chloride and the reaction products are quenched in chloroform. The unreacted phosgene is separated by distillation from the quench liquid and recycled to the reactor. The liquid from the still is fed to the pyrolysis section where MIC is formed. The stream from the pyrolyser condenser passes as feed to the MIC refining still (MRS). MIC is obtained as the top product from the still. The MIC is then run to storage.

Phosgene was produced on site by reacting chlorine and carbon monoxide. The carbon monoxide was also produced on site.

The MIC storage system (MSS) consisted of three storage tanks, two for normal use (Tanks 610 and 611) and one for emergency use (Tank 619). The tanks were 8 ft diameter × 40 ft long with a nominal capacity of 15000 USGals. They were made of 304 stainless steel with a design pressure of 40 psig at 121°C and with a hydrostatic test pressure of 60 psig. A diagram of the storage tank system is shown in Figure A5.4.

A 30 ton refrigeration system was provided to keep the tank contents at 0°C by circulating the liquid through an external heat exchanger.
Figure A5.1 Simplified plan of the area near the Union Carbide India Ltd works at Bhopal (M.P. Singh and Ghosh, 1987). The diagram also shows the estimated dimensions of the gas cloud. (Courtesy of Elsevier Science Publishers)

There was on each storage tank a pressure controller which controlled the pressure in the tank by manipulating two diaphragm motor valves (DMVs), a make-up valve to admit nitrogen and a blowdown valve to vent vapour. Each tank had a safety relief valve (SRV) protected by a bursting disc. It also had a high
A reaction scheme (Union Carbide, 1985. Reproduced by permission.)

Figure A5.3 Process for production of MIC (Union Carbide, 1985. Reproduced by permission.)

temperature alarm and low and high level alarms.

A vent gas scrubber (VGS) and a flare were provided to handle vented gases. The VGS was a packed column 5 ft 6 in. diameter in which the vent gases were scrubbed with caustic soda. There were two vent headers going into the column: the process vent header (PVH), which collected the MIC system vents, and the relief valve vent header (RVVH), which collected the safety valve discharges. Each vent header was connected both to the VGS and the flare and could be routed to either. The vent stack after the VGS was 100 ft (33 m) high. A diagram of the vent gas scrubber system is shown in Figure A5.5.

The VGS had the function of handling process vents from the PVH and of receiving contaminated MIC, in either vapour or liquid form, and destroying it in a controlled manner.

The function of the flare was to handle vent gases from the carbon monoxide unit and the MMA vaporizer safety valve and also vent gas from the MIC storage tanks, the MRS and the VGS.

In the two years preceding, the number of personnel on site were reduced, 300 temporary workers being laid off and 150 permanent workers pooled and assigned as needed to jobs, some of which they said when interviewed they felt unqualified to do. The production team on the MIC facility was cut from 12 to 6.

A5.4 MIC and Its Properties

MIC is a colourless liquid with a normal boiling point of 39°C. It has a low solubility in water. It is relatively stable when dry, but is highly reactive and in particular can polymerize and will react with water. It is flammable
and has a flashpoint of -18°C and a lower flammability limit of 6% v/v. It is biologically active and highly toxic.

The high toxicity of MIC is indicated by the fact that its TLV at the time was 0.02 ppm. This is very low relative to most typical compounds handled in industry.

MIC is an irritant gas and can cause lung edema, but it also breaks down in the body to form cyanide. The cyanide suppresses the cytochrome oxidase necessary for oxygenation of the cells and causes cellular asphyxiation.

Information on the inhalation toxicity of MIC is given by Kimmerle and Eben (1964) and ten Berge (1985).

MIC can undergo exothermic polymerization to the trimer, the reaction being catalysed by hydrochloric acid and inhibited by phosgene. It also reacts with water, iron being a catalyst for this reaction. This reaction is strongly exothermic.

A5.5 Events Prior to the Release

In 1982 a UCC safety team visited the Bhopal plant. Their report gave a generally favourable summary of the visit, but listed ten safety concerns, including:

3. Potentials for release of toxic materials in the phosgene/MIC unit areas and storage areas, either due to equipment failure, operating problems, or maintenance problems.
4. Lack of fixed water spray protection in several areas of the plant.

7. Deficiencies in safety valve and instrument maintenance program.
8. Deficiencies in Master Tag/Lockout procedure application.
10. Problems created by high personnel turnover at the plant, particularly in operations.

Following this visit valves on the MIC plant were replaced, but degraded again. At the time of the accident the instruments on Tank 610 had been malfunctioning for over a year.

Between 1981 and 1984 there were several serious accidents on the plant. In December 1981 three workers were gassed by phosgene and one died. Two weeks later 24 workers were overcome by another phosgene leak. In February 1982 18 people were affected by an MIC leak. In October 1982 three workers were injured and nearby residents affected by a leak of hydrochloric acid and chloroform.

Following this latter accident workers from the plant posted a notice in Hindi which read: ‘Beware of fatal accidents... Lives of thousands of workers and citizens in danger because of poison gas... Spurt of accidents in the factory, safety measures deficient.’ These posters were also distributed in the community.

About a year before the accident a 'jumper line' was connected between the process vent header and the relief valve vent header. Figure A5.4 shows the MIC storage tank and pipework arrangements. The jumper...
Figure A5.5  Flow diagram of the vent gas scrubber system (Bhushan and Subramanian, 1985) (Courtesy of Business India)

line is between valves 1 and 2. The object of the modification was to allow gas to be routed to the VGS if repairs had to be done on one of the vent headers. In June 1984 the 30 ton refrigeration unit cooling the MIC storage tanks was shut down. The charge of Freon refrigerant was drained from the system.

In October the VGS was turned off, apparently because it was thought unnecessary when MIC was only being stored not manufactured. In the same month the flare tower was taken out of service, a section of corroded pipe leading to it being removed so that it could be replaced.

Another feature was that difficulty was being experienced in pressurizing MIC storage Tank 610. It appeared that since nitrogen was passing through the make-up valve satisfactorily, the blowdown valve was leaking and preventing pressurization.

According to plant workers there were other instrumentation faults. The high temperature alarm had long been faulty. There were also faults on the pressure controller and the level indicator.

The plant had a toxic gas alarm system. This consisted of a loud siren to warn the public and a muted siren to warn the plant. These two sirens were linked and could be activated from a plant toxic alarm box. The loud siren could be stopped from the control room by delinking the two. A procedure had been introduced according to which after delinking the loud siren could be turned on only by the plant superintendent.

Plant workers stated that on the morning of 2 December washing operations were undertaken. Orders were given to flush out the downstream sections of four filter pressure safety valves lines. These lines are shown in Figure A5.4. In order to carry out this operation Valve 16 on the diagram was shut, Valves 18–21 and 22–25 opened and then Valve 17 opened to admit water.

It was suggested water might have entered MIC storage Tank 610 as a result of this operation — the water washing theory. On this hypothesis, water evidently leaked through Valve 16, into the RVVH header and passed through the jumper line into the PVH header and thence into Tank 610. This would require that Valves 3 and 12 were open to connect the tank to the PVH and Valves 1 and 2 open to connect the RVVH to the PVH via the jumper line.

A5.6 The Release

On the evening of 2 December a shift change took place on the plant at 22:45. At 23:00 the control room operator noticed that the pressure in Tank 610 was 10 psig. This was higher than normal but within the 2–25 psig operating pressure of the tank. At the same time the field operator reported a leak of MIC near the VGS. At 00:15 the field operator reported an MIC release in the process area and the control room operator saw that the pressure on Tank 610 was now 30 psig and rising rapidly. He called the supervisor and ran outside to the
tank. He heard rumbling sounds coming from the tank and a screeching noise from the safety valve and felt heat from the tank. He returned to the control room and turned the switch to activate the VGS, but this was not in operational mode, the circulating pump not being on.

At 00:20 the production supervisor informed the plant superintendent of the release. At 00:45 operations in the derivative unit were suspended due to the high concentration of MIC.

At 01:00 an operator in this unit turned on the toxic gas alarm siren. After five minutes the loud siren was switched off leaving the muted siren on.

At about the same time the plant superintendent and control room operator verified that MIC was being emitted from the VGS stack to atmosphere and turned on and directed at the stack fixed fire water monitors to knock down the vapour.

Water was also directed at the MIC tank mound and at the vent header to the VGS. Steam issued from the cracks in the concrete showing that the tank was hot.

One plant supervisor tried to climb the structure to plug the gas leak but was overcome, falling and breaking both legs.

Some time between 01:30 and 02:30 the safety valve on tank 610 reseated and the release of MIC ceased.

About 02:30 the loud siren was switched on again.

The cloud of MIC gas spread from the plant towards the populated areas to the south. There was a light wind and inversion conditions.

People in the housing around the plant felt the irritating effect of the gas. Many ran out of their houses, some towards the plant. Within a short period animals and people began to die.

A colony of some 2 km from the plant, where nearly 10,000 people lived, it was reported that within four minutes 150 died, 200 were paralysed and 600 rendered unconscious and that 5000 were severely affected.

People tried to telephone the plant but were unable to get through. At 01:45 a magistrate contacted the plant superintendent.

The cloud of toxic gas hung around the area for the whole of 3 December. During the day it stopped moving towards the city, but resumed its movement in that direction during the night.

A5.7 The Emergency and the Immediate Aftermath

Large numbers of people were affected by the toxic gas and very large numbers fled their homes.

The two hospitals principally concerned, the Hamidia and the Javaprasaks Hospitals, were overwhelmed with casualties.

The difficulties were compounded by the fact that it was not known what the gas was or what its effects were. Speculation about the gas, including suggestions that it was phosgene, continued in the world press for some days.

The company provided little advice. Initially, it stated that MIC causes eye irritation but is not lethal.

As early as noon on 3 December doctors at the Gandhi Memorial College carried out post-mortems which gave strong evidence of cyanide poisoning. Victims had died of respiratory arrest, but there was no evidence of the cyanosis due to the deoxygenation of the blood which normally accompanies pulmonary asphyxiation and there were cases where there was no evidence of pulmonary oedema.

There developed a conflict of views on the appropriate treatment. The standard treatment for cyanide poisoning is sodium thiosulphate. One group took the view that this should not be given until cyanide poisoning was established by analyses, another argued that it was well known that in cyanide poisoning the cyanide may be metabolized, leaving little trace. There followed a period in which the advice given was not clear. It was not until 3 February that an authoritative and unambiguous recommendation that sodium thiosulphate be used was issued by the Indian Council for Medical Research.

The Indian Central Bureau of Investigation (CBI) took control of the site and began a criminal investigation.

A5.8 The Investigations

A5.8.1 Government of India investigation

An investigation of the incident was undertaken by the Government of India (GoI). It issued in December 1985 the Report on Scientific Studies on the Factors Related to Bhopal Toxic Gas Leakage by a team chaired by Dr. Varadarajan (1985).

The report refers to the fact that it was reported that about 21:30 on 2 December an operator was clear for a possible choke in the RVH lines downstream of the phosgene stripping still filters by water flushing, without inserting a blind. The 6 in. isolation valve on the RVH was presumably closed but if it had not been leak-tight, water could enter the RVH. This water could have found its way into the Tank 610 via the blowdown DMV or through the SRV and bursting disc.

A5.8.2 Union Carbide investigation – 1

A team from UCC arrived in Bhopal on 6 December charged with the tasks of assisting in the safe disposal of the remaining MIC and investigating the accident. The first task was completed on 22 December and the team returned home on 2 January.

The investigation was severely constrained by the CBI control of the site and by the criminal investigation. The team were allowed only limited access to plant records and personnel. They were permitted to talk to certain persons, but not to interview staff directly involved in the incident. They were allowed to take samples from Tank 610, but not to open and inspect the tank and its piping or to take samples from elsewhere on the plant. An account of the situation is given by Kalelkar (1988b).

On their return home the investigators carried out a programme of some 500 experiments to establish what had occurred. The most abundant component in the residues was MIC trimer, others present in significant quantities being the components conveniently referred to as DMI, DMU, TMU, TMB and TRMB. There were also iron, chromium and nickel in approximately their proportions in 304 stainless steel and some 5% chloride.

Trimerization had obviously occurred, but it was unclear what other reactions had taken place. The investigators carried out experiments in which the principal materials believed to have been in the tank, namely MIC, chloroform, water and iron, were heated at 200°C and developed a reaction scheme which accounted
for the production, starting from these materials, of the components found in the residue with the exception of TRMB, which they considered they could account for.

From plant records Tank 610 contained prior to the incident 41 t (90,400 lb; 11,290 USgal) of liquid. The team estimated that Tank 610 had originally contained 1000–2000 lb (120–240 USgal) water and 1500–3000 lb chloroform. The source of the water was uncertain. The chloroform could be accounted for by the fact that the MIC refining still had been operated at a temperature higher than normal and in preparation for shutdown MIC with a high chloroform content has been sent to Tank 610 rather than Tank 619. The iron could have come from corrosion, given high chloroform and water contents and high temperature.

The scenario which the investigators invoked to explain the events is as follows. The contents of Tank 610 were initially at 15–20°C. Some 1000–2000 lb water entered the tank in a manner unknown. The exothermic reaction between MIC and water led to an increase in temperature and also in pressure due to evolution of carbon dioxide. The higher temperature and presence of chloroform caused accelerated corrosion. The iron thus produced catalysed the exothermic trimerisation of MIC.

Calculations showed that reaction of some 40% of the MIC would generate enough heat to vaporize the rest. This would give some 36,000 lb of solids in the tank, but only an estimated 10,000 lb were found. There may have been appreciable loss of solids and liquid through the relief vent.

The period during which the relief valve was open was reported to have been about 2 hours. It was calculated that in order to vent most of the tank contents in this time the discharge rate would have had to be 40,000 lb/h, of which 29,000 lb/h were vapour and 11,000 lb/h solids/liquid mixture and that this would have required a pressure averaging 180 psig. The temperature reached was estimated as in excess of 200°C. These conditions would have been attained during the course of the venting. With the safety valve lifting at 40 psig the initial discharge would have been 10,000 lb/h.

The report puts forward the hypothesis that the water was directly introduced into Tank 610, either inadvertently or deliberately through the process vent line, nitrogen line or other piping. It refers to the washing operation on the filter pressure safety value lines and states that this section of line had not been isolated using a blind, but that passage of water to Tank 610 through several reportedly closed valves is unlikely.

The report draws attention to a number of factors which contributed to the accident. These include the facts that refrigeration had been discontinued, that a blind was not used to isolate the lines being washed out, that the MIC refining still was operated at a higher than normal temperature, that the VSG did not work, and that the flare was out of commission.

At the press conference held to present the report the UCC spokesman suggested that the water may have come from a nearby utility station which supplied water and nitrogen to the area: ‘If someone had connected tubing to the water line instead of the nitrogen line, either deliberately or intending to introduce nitrogen into the tank, this could account for the presence of the water...’ The press interpreted this as a suggestion by UCC that the cause of the accident was sabotage.

Subsequently UCC agreed that there was no direct evidence for this hypothesis.

A5.8.3 Union Carbide investigation – 2
Following the involvement of the Indian Government in litigation in the US courts, UCC was allowed access to personnel who had been involved on the plant and was able to gather evidence in support of its original hypothesis. An account of this extension of the UCC investigation is given by Kalelkar (1988b).

Against the water washing hypothesis he makes the following points. First, the water was introduced through a 5 in. inlet (Valve 17). The difference in head between this point and the inlet to Tank 610 was some 10.4 ft. There were three open bleeder valves close to the inlet point which would limit the backpressure of water to 0.7 ft. Second, there were a number of valves between the inlet point and the tank and for water to pass these would have had to be open or not leak-tight. One of these valves, close to the inlet point, had been shut since 29 November 1984. It was given a one-hour test during which no water leaked through it. Third, for water to reach Tank 610 it would have had to fill the 6 in. diameter connecting pipe, 65 ft of 8 in. RVVH, with numerous branches running off, and then some 340 ft of 4 in. RVVH. The amount of water to do this was estimated as 4500 lb. On 8 February 1985 the CBI ordered a hole to be drilled in the lowest point of the PVH. For the hypothesis to hold this section, which had no bleeders or flanged joints, should have been full of water; it was completely dry.

In support of the hypothesis of direct entry of water into Tank 610 the arguments presented by Kalelkar may be summarized as follows. First, an instrument supervisor, not on duty that night, stated that he had found the local pressure indicator on the tank missing; this was one of the few points to which a water hose could be connected. Second, a water hose was found nearby. Third, there was evidence that the operators had become aware earlier in the evening that water had entered Tank 610 and had taken steps to deal with the situation. Fourth, the plant logs showed evidence of extensive tampering and alteration.

The plant could be supplied with MIC from Tank 610 or Tank 611, the MIC being passed to a one tonne tank, the Sevin charge pot. There were difficulties with the pressure in Tank 610 and the transfers had been made from Tank 611. However, investigation showed that the MIC in the Sevin charge pot contained water. It had evidently come from Tank 610. Water is heavier than MIC and Tank 610 had a bottom outlets. The hypothesis is that the operators, aware that water had got into Tank 610 and wishing to remove it, on this occasion drew the MIC from that tank rather than from Tank 611.

Kalelkar suggests that the addition of water to Tank 610 may have been the act of a disgruntled employee.

A5.9 The Late Aftermath
The precise numbers of the dead and injured at Bhopal are uncertain. The scale of the accident was such that it led to much confusion. People have continued to die of the effects over a period of years. The official Indian Government estimate of the death toll about two years after the event was 1754. By 1989 this had risen to 3150
and by 1994 to 4000. Other figures given are 30,000 permanently or totally disabled; 20,000 temporary cases; and 50,000 with minor injury.

The ICFTU-ICEF report in 1985 states that the number of people treated in the state hospitals had been given by Dr Nagu, the Director of Health Services for Madhya Pradesh, as approximately 170,000. Some 130,000 were treated in Bhopal hospitals, mainly for lung and eye injuries, and some 40,000 in 22 other districts. Some 12,000 of the 170,000 were in a critical condition and 484 died. He estimated the total number of dead as 2000.

The disaster led to various sets of court proceedings. The Government of India instituted criminal proceedings against UCC, which at the time of writing remain extant. The GoI also became a party to proceedings in the US courts. In 1987 UCC made a ‘final settlement’ with the GoI of $470 m. Victims tried to challenge this in the US courts, but the US Supreme Court ruled that they lacked legal standing to do so.

**A5.10 Some Lessons of Bhopal**

**A5.10.1 Some lessons**
The lessons to be learnt from Bhopal are numerous. A list of some of them is given in Table A5.2. They combine many of the lessons of Flixborough and Seveso.

Some of these lessons are now considered:

**Public control of major hazard installations**
The disaster at Bhopal received intense publicity for an extended period and put major hazards on the public agenda world-wide, but particularly in India and the USA, which had not reacted so strongly to Flixborough and Seveso, whose impact had been felt most in Europe.

**Siting of and development control at major hazard installations**
Very large numbers of people were at risk from the plant at Bhopal. This situation was due in large part to the encroachment of the shanty towns, which came up to the site boundary. Although these settlements were illegal, the Indian authorities had acquiesced in them.

**Table A5.2 Some lessons of Bhopal**

| Public control of major hazard installations | Management of major hazard installations |
| Siting of and development control at major hazard installations |
| Highly toxic substances |
| Runaway reactions in storage |
| Water hazard in plants |
| Relative hazards of materials in process and in storage |
| Relative priority of safety and production |
| Limitation of inventory in the plant |
| Set pressure of relief valves |
| Disabling of protective systems |
| Maintenance of plant equipment and instrumentation |
| Isolation procedures for maintenance |
| Control of plant and process modifications |
| Information for authorities and public |
| Planning for emergencies |

In this instance, however, this was not the whole story. The accident showed that site was close enough to areas populated before the plant was built to present a hazard when used for the production of a chemical as toxic as MIC. If the manufacture of such a chemical was envisaged from the start, the problem may be regarded as one of siting. If not, it may be viewed as one of intensification of the hazard on the site.

**Management of major hazard installations**
The plant at Bhopal was by any standards a major hazard and needed to be operated by a suitable competent management. The standards of operation and maintenance do not give confidence that this was so.

There had been recent changes in the responsibility for the plant which suggest that the new management may not have been familiar with the exigencies of major hazards operation. However, many of the problems on the plant appear to have antedated these changes.

**Highly toxic substances**
MIC is a highly toxic substance, much more toxic that substances such as chlorine which are routinely handled in the chemical industry. The hazard from such highly toxic substances has perhaps been insufficiently appreciated.

This hazard will only be realized if there is a mechanism for dispersion. At Bhopal this mechanism was the occurrence of exothermic reactions in the storage tank.

**Runaway reaction in storage**
The hazard of a runaway reaction in a chemical reactor is well understood, but that of such a reaction in a storage tank had received little very attention. At Bhopal this occurred due to ingress of water. Where such a reaction could act as the mechanism of dispersion for a large inventory of a hazardous substance, the possibility of its occurrence should be carefully reviewed.

**Water hazard in plants**
In general terms the hazard of water ingress into plants is well known. In particular, water may contact hot oil and vaporize with explosive force or may cause a frothover, it may corrode the equipment and it may cause a blockage by freezing. Bhopal illustrates the hazard of an exothermic reaction between a process fluid and water.

**Relative hazard of materials in process and in storage**
There has been a tendency to argue that the risks from materials in storage are less than from materials in process, since, although usually the inventories in storage are larger, the probability of a release is much less. The release at Bhopal was from a storage tank, albeit from one associated with a process.

The relative hazard of materials in process and in storage is discussed Chapter 22.

**Relative priority of safety and production**
The features which led to the accident have been described above. As indicated, the *Union Carbide Report* itself refers to a number of these.
The ICFTU-ICEF report states that at the time of the accident the plant was losing money and lists a number measures which had been taken, apparently to cut costs. These include the manning cuts and the cessation of refrigeration.

Limitation of inventory in the plant
The hazard at Bhopal was the large inventory of highly toxic MIC. The process was the same as that used at UCC's West Virginia plant. UCIL had stated that it regarded this inventory as undesirable, but was overruled by the parent company, which wished to operate the same process at both plants.

Processes are available for the manufacture of MIC which require only small inventories of the material. Moreover, carbaryl can be made by a route which does not involve MIC. The alternatives to the use of MIC are discussed by Kletz (1988h).

Set pressure of relief devices
It is desirable from the operational viewpoint for the set pressure of a relief valve to be such that the valve opens when the pressure rise threatens the integrity of the vessel but not when normal minor operating pressure deviations occur. Where the cause of potential pressure rise is a runaway reaction, however, there is a penalty in setting a high set pressure in that this may allow the reaction to reach a higher temperature and to proceed more rapidly before venting starts, so that there is a need to balance these two factors.

Disabling of protective systems
It was evidently not appreciated that the flare system was a critical component for the protection of the plant, since it was allowed to remain out of commission for the three months prior to the accident. It is essential that there be strict procedures for the disabling of any item which is critical for protection and that the time for which the item is out of action be kept to a minimum.

Maintenance of plant equipment and instrumentation
The 1982 UCC safety team drew attention to the problems in the maintenance of the plant. The Union Carbide Report gives several examples of poor maintenance of plant equipment and instrumentation and the ICFTU-ICEF report gives further details. Workers stated that leaking valves and malfunctioning instruments were common throughout the plant.

Maintenance was also very slow. The flare system, which was a critical protective system, had been out of commission for three months before the accident.

Isolation procedures for maintenance
A particular deficiency in the maintenance procedures was the failure to isolate properly the section of plant being flushed out by positive isolation using a slip plate or equivalent means. The fact that the water may not have entered in this way does not detract from this lesson.

Control of plant and process modifications
A principal hypothesis to explain the entry of water into Tank 610 is that the water passed through the jumper line. The installation of this jumper line was a plant modification. Company procedures called for plant modifications to be checked by the main office engineers, but were evidently disregarded.

There was also a process modification which more certainly contributed to the accident. This is the decommissioning of the refrigeration system, so that the temperature in Tank 610 was higher than the 0°C for which the system was designed.

Information for authorities and public
UCIL had not provided full information on the substances on site to the authorities, emergency services, workers or members of the public exposed to the hazards. Many workers interviewed said they had had no information or training about the chemicals.

Planning for emergencies
The response of the company and the authorities to the emergency suggests that there was no effective emergency plan.

Within the works defects revealed by the emergency include the hesitation about the use of the siren system and the lack of escape routes.

The preliminary condition for emergency planning to protect the public outside the works is provision to the authorities of full information about the hazards. This was not done. In consequence the people exposed did not know what the siren meant or what action to take, the hospitals did not know what they might be called on to handle, and so on.

Likewise, the essential action in an actual emergency is to inform the authorities what has happened and what the hazards are. On the morning of the accident the hospitals were in the dark about the nature and effects of the toxic chemical whose victims they were trying to treat.

A5.10.2 An accident model
An accident model for Bhopal given by Kletz (1988h) is shown in Figure A5.6.
<table>
<thead>
<tr>
<th>Event</th>
<th>Recommendations for prevention/mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public concern compelled other companies to improve standards</td>
<td>Provide information that will help public keep risks in perspective.</td>
</tr>
<tr>
<td>Emergency not handled well</td>
<td>Provide and practise emergency plans.</td>
</tr>
<tr>
<td>About 2000 people killed</td>
<td>Control building near major hazards.</td>
</tr>
<tr>
<td>Scrubber not in full working order</td>
<td>Keep protective equipment in working order. Size for foreseeable conditions.</td>
</tr>
<tr>
<td>Flare stack out of use</td>
<td>Keep protective equipment in use even though plant is shut down.</td>
</tr>
<tr>
<td>Both may have been too small</td>
<td></td>
</tr>
<tr>
<td>Discharge from relief valve</td>
<td></td>
</tr>
<tr>
<td>Refrigeration system out of use</td>
<td></td>
</tr>
<tr>
<td>Runaway reaction</td>
<td></td>
</tr>
<tr>
<td>Rise in temperature</td>
<td>Train operators not to ignore unusual readings.</td>
</tr>
<tr>
<td>Water entered MIC tank</td>
<td>Carry out hazops on new designs. Do not allow water near MIC.</td>
</tr>
<tr>
<td>Decision to store over 100 tonnes MIC</td>
<td>Minimize stocks of hazardous materials.</td>
</tr>
<tr>
<td>Decision to use MIC route</td>
<td>Avoid use of hazardous materials.</td>
</tr>
<tr>
<td>Joint venture established</td>
<td>Agree who is responsible for safety.</td>
</tr>
<tr>
<td></td>
<td>To achieve the above: Train chemical engineers in loss prevention</td>
</tr>
</tbody>
</table>

*Figure A5.6* An accident model for Bhopal, showing critical events and recommendations (Kletz, 1988h) (Courtesy of Butterworths)
Appendix

6

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A6.5 Some Lessons of Pasadena  A6/4
Shortly after 1.00 p.m. on 23 October 1989 a release occurred on a polyethylene plant at the Phillips 66 Company’s chemical complex at Pasadena, near Houston, Texas. A vapour cloud formed and ignited, giving rise to a massive vapour cloud explosion. There followed a series of further explosions and a fire. Twenty-two people on the site were killed and one later died from injuries, making a death toll of 23. The number injured are variously given as 130 and 300.

A report on the investigation of the accident has been issued by OSHA (1990a). Other accounts include those of Mahoney (1990), T. Richardson (1991) and J.N. Scott (1992).

Selected references on Pasadena are given in Table A6.1.

Table A6.1 Selected references on Pasadena

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>Reference</th>
</tr>
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<tr>
<td>Anon. (1989 LPB 90, p. 0); Anon. (1990 LPB 94, p.30); Mahoney (1990); OSHA (1990a); Redmond (1990); Vervalin (1990b); Bond (1991 LPB 97); Kletz (1991j); T. Richardson (1991); J.N. Scott (1992)</td>
<td></td>
</tr>
</tbody>
</table>

A6.1 The Site and the Plant

The Phillips works was sited in the Houston Chemical Complex along the Ship Channel, the location of a number of process companies.

The plant on which the release occurred was Plant V, one of two active polyethylene plants in the complex. The plant operated at high pressure (700 psi) and high temperature. The process involved the polymerization of ethylene in isobutane, the catalyst carrier. Particles of polyethylene settled out and were removed from settling legs.

A6.2 Events Prior to the Explosion

On the previous day work began to clear three of the six settling legs on Reactor No. 6, which were plugged. The three legs were prepared by a company operator and were handed over to the specialist maintenance contractors, Fish Engineering. The configuration of a typical leg is shown in Figure A6.1.

At 8.00 a.m. on Monday, 23 October, work began on the second of the three blocked legs, Leg No. 4. The isolation procedure was to close the DEMCO ball valve and disconnect the air lines to it.

The maintenance team partially disassembled the leg and were able to remove part of the plug, but part remained lodged in the pipe 12–18 in. below the ball valve. One of the team was sent to the control room to seek assistance. Shortly after, at 1.00 p.m., the release occurred.

Although both industry practice and Phillips corporate safety procedures require isolation by means of a double block system or a blind flange, at local plant level a procedure had been adopted which did not conform to this.

It was subsequently established that the DEMCO ball valve was open at the time of the release. The air hoses to the valve had been cross-connected so that the supply which should have closed it actually opened it. The hose connectors for the ‘open’ and ‘close’ sides of the valve were identical, thus allowing this cross-connection to be made. Although procedures laid down that the air hoses should not be connected during maintenance, there was no physical barrier to the making of such a connection. The ball valve had a lockout system but it was inadequate to prevent the valve being inadvertently or intentionally opened during maintenance.

A6.3 The Explosion

The mass of gas released was estimated as some 85 200 lb of a mixture of ethylene, isobutane, hexene and hydrogen, which escaped within seconds. The release was observed by five eyewitnesses. A massive vapour cloud formed and moved rapidly downwind.

Within 90–120 seconds the vapour cloud found a source of ignition. Possible ignition sources were a gas-fired catalyst activator with an open flame; welding and cutting operations; an operating forklift truck; electrical gear in the control building and the finishing building; 11 vehicles parked near the polyethylene plant office; and a small diesel crane, although this was not operating.

The TNT equivalent of the explosion was estimated in the OSHA report as 2.4 tons. An alternative estimate from seismograph records is 10 tons.

There followed two other major explosions, one when two 20 000 USgal storage tanks exploded and the other when another polyethylene plant reactor failed catastrophically, the timings being some 10–15 minutes and some 25–45 minutes, respectively, after the initial explosion. One witness reported hearing 10 separate explosions over a 2-hour period.

Debris from the explosion was found 6 miles from the site.

All 22 of those who died at the scene were within 250 ft of the point of release and 15 of them were within 150 ft.

Injuries which occurred outside the site were mainly due to debris from the explosion.

The explosion resulted in the destruction of two HDPE plants. The plant after the explosion is shown in Plate 38.

A6.4 The Emergency and the Aftermath

People in the immediate area of the release began running away as soon as they realized that gas was escaping. The alarm siren was activated, but the level of noise in the finishing building was such that there was a question whether some employees there failed to hear it.

The immediate response to the emergency was provided by the site fire brigade, which undertook rescue and care of the injured and began fighting the fire. Twenty-three persons were unaccounted for, but for an extended period the area of the explosion remained dangerous to enter.

Severe difficulties were experienced in fighting the fires resulting from the explosion. There was no dedicated fire water system, water for fire fighting being drawn from the process water system. The latter suffered severe rupture in the explosion so that water pressure was too low for fire fighting purposes. Fire hydrants were sheared off by the blast. Fire water had to be brought by hose from remote sources such as settling...
ponds, a cooling tower, a water treatment plant and a water main on a neighbouring plant. These difficulties were compounded by failures of the fire pumps. The electrical cables supplying power to the regular fire pumps were damaged by the fire so that these pumps were put out of action. Further, of the three backup diesel fire pumps one was down for maintenance and one quickly ran out of fuel. Despite these problems the fire was brought under control within some 10 hours.

The handling of the emergency was handicapped by the facts that the intended command centre had been damaged and that telephone communications were disrupted. Telephone lines were jammed for some hours following the accident.

The emergency response was co-ordinated by the site chief fire officer and involved the local Channel Industries Mutual Aid (CIMA) organization, a co-operative of some 106 members in the Houston area.
More than 100 people were evacuated from the administration building across the Houston Ship Channel by the US Coast Guard and by Houston fireboats; they would otherwise have had to cross the area of the explosion to reach safety.

The media were quickly aware of the explosion and within an hour there were on site 150 media personnel from 40 different organizations.

The financial loss in this accident is comparable with, and may exceed, that of the Piper Alpha disaster. Redmond (1990) has quoted a figure of $1400 million, divided almost equally between property damage and business interruption losses.

On the basis of a review of company reports and of the defects found during the investigation of the disaster, OSHA issued a citation to the company for wilful violations of the ‘general duty’ clause. The citation covered the lack of hazard analysis; plant layout and separation distances; flammable gas detection; ignition sources; building ventilation intakes; and the fire water system; the permit system; isolation for maintenance.

A6.5 Some Lessons of Pasadena

Some of the lessons to be learned from Pasadena are listed in Table A6.2.

Management of major hazard installations

The OSHA report details numerous defects in the management of the installation. Some of these are described below.

Hazard assessment of major hazard installations

According to the report, the company had made no use of hazard analysis or an equivalent method to identify and assess the hazards of the installation.

Plant layout and separation distances

The report was critical of the separation distances in the plant in several respects. It stated that the separation distances between process equipment plant did not accord with accepted engineering practice and did not allow time for personnel to leave the polyethylene plant safely during the initial vapour release; and that the separation distance between the control room and the reactors was insufficient to allow emergency shut down procedures to be carried out.

Location of control room

As just mentioned, the control room was too close to the plant. It was destroyed in the initial explosion.

Building ventilation intakes

The ventilation intakes of buildings close to or downwind of the hydrocarbon processing plants were not arranged so as to prevent intake of gas in the event of a release.

Minimization of exposure of personnel

Closely related to this, there was a failure to minimize the exposure of personnel. Not only the control room but the finishing building had relatively high occupancy.

Escape and escape routes

As already stated, the separation distances were not such as to allow personnel on the polyethylene plant to escape safely. Further, the only escape route available to people in the administration block (other than across the ship channel) was across the area of the explosion.

Gas detection system

Despite the fact that the plant had a large inventory of flammable materials held at high pressure and temperature, there was no fixed flammable gas detection system.

Control of ignition sources

The control of ignition sources around the plant was another feature criticized in the OSHA report.

Permit-to-work systems

The OSHA report stated that an effective permit system was not enforced for the control of the maintenance activities either of the company’s employees or of contractors.

Isolation procedures for maintenance

In this incident the sole isolation was a ball valve which was meant to be closed but was in fact open. There was no double block system or blind flange.

The practice of not providing positive isolation was a local one and violated corporate procedures. The implication is that it had not been brought to light by any safety audits conducted.

Integrity of fire water system

The practice of relying for fire water on the process water system and the failure to provide a dedicated fire water system meant that the fire water system was vulnerable to an explosion.

Dependability of fire pumps

The electrical cables to the regular fire pumps were not laid underground and were therefore vulnerable to damage by explosion and fire. One of the back-up diesel
pumps had insufficient fuel and one had been taken out for maintenance without informing the chief fire officer.

Audibility of emergency alarm
As described, the level of noise in some areas was such that the employees might not have been able to hear the siren.

Follow-up of audits
The OSHA report criticized the company’s failure to act upon reports issued previously by the company’s own safety personnel and by external consultants which drew attention to unsafe conditions.

Planning for emergencies
The disaster highlighted a number of features of emergency planning. The company had put a good deal of effort into planning and creating personal relationships with the emergency services, by means such as joint exercises, and these paid off. The value of planning, training and personal relations was one of the most positive lessons drawn.

Another area in which a proactive approach proved beneficial was in relations with the media. Senior personnel made themselves available, and the company evidently felt it received fair treatment.

One weakness of the emergency planning identified was that it had not envisaged a disaster of the scale which actually occurred.

The incident brought out the need to be able to respond clearly to calls from those liable to be affected about the toxicity of the fumes and smoke generated in such an event.

The behaviour of rescue helicopters posed a problem. Personnel on the ground had no means of communication with them and the craft tended to come in low, creating the danger of blowing flames or toxic fume onto those below. A need was identified for altitude and distance guidelines for helicopters.
Appendix

Canvey Reports

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A7.3  First Canvey Report: Identified Hazards  A7/6
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A7.6  First Canvey Report: Assessed Risks and Actions  A7/26
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A7.10 Second Canvey Report: Technical Aspects  A7/32
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APPENDIX 7/2  CANEY REPORTS

The most comprehensive hazard assessment of non-nuclear installations in the UK is the Canvey study carried out for the HSE by SRD.

The first phase of the work is described in Canvey: An Investigation of Potential Hazards from Operations in the Canvey Island/Thurrock Area (the First Canvey Report) (HSE, 1978b). The report is in two parts: Part 1 is an introduction by the HSE and Part 2 the SRD study.

The origin of the investigation was a proposal to withdraw planning permission for the construction of an additional refinery in the area. Two oil companies, Occidental Refineries Ltd and United Refineries Ltd, had been granted planning permission for the construction of oil refineries. The construction of the Occidental refinery was begun in 1972, but was halted in 1973 pending a major design study review. United Refineries had valid planning consents, but had not started construction. It was a public inquiry into the possible revocation of the planning permission for the United Refineries development which gave rise to the investigation.

Responses to the First Canvey Report centred mainly on two aspects: the methodology used and the magnitude of the assessed risks. The HSE commissioned further work, leading to the Second Canvey Report (HSE, 1981a), in which the methodology is revised and the assessed risks are rather lower.

An account of the first report is given in Sections A7.1–A7.6, of the response to that report in Section A7.7 and of the second report in Sections A7.8–A7.10.

A map of the Canvey/Thurrock area showing the principal installations and populated areas is given in Figure A7.1.

Selected references on the Canvey Reports are given in Table A7.1.

A7.1 First Canvey Report

The terms of reference of the investigation were

In the light of the proposal by United Refineries Limited to construct an additional refinery on Canvey Island, to investigate and determine the overall risks to health and safety arising from any possible major interactions between existing or proposed installations in the area, where significant quantities of dangerous substances are manufactured, stored, handled, processed and transported or used, including the loading and unloading of such substances to and from vessels moored at jetties; to assess the risk; and to report to the Commission.

The members of the investigating team were appointed as inspectors of the HSE under the provisions of the Health and Safety at Work etc. Act 1974 and were given specified powers to enable them to make the necessary inquiries.

The overall approach taken in the investigation was

(1) To identify any potentially hazardous materials, their location and the quantities stored and in process.
(2) To obtain and review the relevant material properties such as flammability and toxicity.
(3) To identify the possible ways in which failure of plants might present a hazard to the community.
(4) To identify possible routes leading to selected failures. Typically, the factors examined included operator errors, fatigue or aging of plant, corrosion, loss of process control, overfilling, impurities, fire, explosion, missiles, and flooding.

(5) To quantify the probability of the selected failures occurring and their consequences.

The investigation involved the identification of the principal hazards of the installations and activities in the area, the assessment of the associated risks to society and to individuals, and the proposal of modifications intended to reduce these risks.

Some 30 engineers were engaged in the investigation, which cost about £400 000.

A7.2 First Canvey Report: Installations and Activities

The principal hazardous installations and activities identified in the investigation are summarized in Table A7.2. These installations are now briefly described.

British Gas Corporation

The British Gas Corporation operates on Canvey Island a methane terminal which is used for the importation and storage of LNG from Algeria. There are some 50 shipments of LNG a year made by two specially designed ships each with a cargo capacity of about 12000 t. The LNG is pumped ashore from a single jetty into above-ground and in-ground fully refrigerated storage tanks with a combined total capacity of approximately 100 000 t. The natural gas is sent out as vapour by pipeline except for a small amount which goes out by road.

The terminal is also used for the fully refrigerated storage of liquid butane. A pipeline from the butane tanks crosses the area.

In addition, new LNG ships are commissioned at the terminal by using the LNG from the storage tanks to cool down the ships’ cargo tanks.

Texaco Ltd

Texaco Ltd operates on Canvey Island storage for petroleum products, but not LPG, with a total capacity of more than 80 000 t. The petroleum products are brought in by sea via two jetties and are sent out by sea, road and pipeline.

London and Coastal Wharves Ltd

London and Coastal Wharves Ltd also operates on Canvey Island storage for a wide range of substances, including petroleum products and other flammable and toxic materials, with a total capacity of more than

Table A7.1  Selected references on Canvey Reports

Canvey Reports

HSE (1978b, 1981a)

Reviews and critiques

N. Turner (1975); Anon. (1980, p. s); Cremer and Warner (1980); Hansard (1980); V.C. Marshall (1980a); Anon. (1981 r.w); R. Ward (1981); A.F. Grant (1982); IChemE (1982a, b); Rashash (1982a); Anon. (1983c); Petts (1985a)
Figure A7.1 First Canvey Report: map of the Canvey/Thurrock area, showing principal installations and populated areas (Health and Safety Executive, 1978b) (Courtesy of HM Stationery Office)
<table>
<thead>
<tr>
<th>Location</th>
<th>Company</th>
<th>Installation or activity</th>
<th>Storage</th>
<th>Employees</th>
<th>Transport in</th>
<th>Transport out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canvey Island</td>
<td>British Gas Corporation</td>
<td>LNG terminal</td>
<td>Fully refrigerated storage of LNG (atmospheric pressure, &lt; −162°C) 6 × 4000 t above-ground tanks 2 × 1000 t above-ground tanks 4 × 20 000 t in-ground tanks. Fully refrigerated storage of butane (atmospheric pressure, &lt; 10°C) 1 × 10 000 t tank 2 × 5000 t tanks</td>
<td>200</td>
<td>Sea</td>
<td>Mainly pipeline (as vapour) but some road</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Petroleum products storage</td>
<td>Atmospheric storage of petroleum products &gt;80 000 t total capacity</td>
<td>130</td>
<td>Sea</td>
<td>Pipeline, road, sea</td>
</tr>
<tr>
<td></td>
<td>Texaco Ltd</td>
<td>Flammable and toxic liquids storage</td>
<td>Atmospheric storage of liquids &gt;300 000 t total capacity</td>
<td>50</td>
<td>Mainly sea but some road</td>
<td>Pipeline (Texaco oil). Rest mainly road but some sea</td>
</tr>
<tr>
<td></td>
<td>London and Coastal Wharves Ltd</td>
<td>Oil refinery (proposed)</td>
<td>Pressure storage of LPG (atmospheric temperature) 2 × 750 t propane spheres 2 × 400 t butane spheres</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Occidental Refineries Ltd</td>
<td>Oil refinery (proposed)</td>
<td>Pressure storage of LPG (atmospheric temperature) 4 × 200 t propane spheres 3 × 900 t butane spheres. Process and storage containing hydrogen fluoride</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>United Refineries Ltd</td>
<td>Oil refinery (proposed)</td>
<td>Pressure storage of LPG (atmospheric temperature) 1 × 1000 t + 14 other vessels, giving 4000 t total capacity</td>
<td>800</td>
<td>LPG produced on site</td>
<td>Pipeline, road, rail, sea</td>
</tr>
<tr>
<td>Coryton</td>
<td>Mobil Oil Co. Ltd</td>
<td>Oil refinery</td>
<td>Pressure storage of LPG (atmospheric temperature) 4 × 1000 t LPG spheres. Fully refrigerated storage of LPG (atmospheric pressure) 1 × 5000 t tank. Process and storage containing hydrogen fluoride</td>
<td></td>
<td></td>
<td>Pipeline, road, rail, sea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oil refinery (extension)</td>
<td>Pressure storage of LPG (atmospheric temperature)</td>
<td>LPG produced on site</td>
<td>Pipeline, road, rail, sea</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Facility</td>
<td>Storage Details</td>
<td>Capacity</td>
<td>Transport Method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
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<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Calor Gas Ltd</td>
<td>LPG terminal</td>
<td>Pressure storage of LPG (atmospheric temperature): 3 × 60t propane vessels, 2 × 60t butane vessels + cylinders, giving 500t total inventory</td>
<td>100</td>
<td>Pipeline (from oil refineries) Road (cylinders, bulk tankers)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell Haven Shell Oil U.K. Ltd</td>
<td>Oil refinery</td>
<td>Pressure storage of LPG (atmospheric temperature): 1 × 1700t butane sphere, +3 other butane spheres, giving 3200t total butane capacity, 4 × 400t propane spheres, 3 × 135t LPG horizontal vessels. Fully refrigerated storage of liquid anhydrous ammonia (atmospheric pressure, −33°C): 1 × 14 000t tank. Process and storage containing hydrogen fluoride: 2 × 40t vessels.</td>
<td>1900</td>
<td>LPG produced on site Pipeline, road, rail, sea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stanford-le-Hope Fisons Ltd</td>
<td>Ammonium nitrate plant</td>
<td>Storage of 92% aqueous ammonium nitrate solution: 1 × 5000t tank, 1 × 2000t tank. Ammonia storage: Semi-refrigerated pressure storage of liquid anhydrous ammonia (pressure above atmospheric, 6°C): 1 × 2000t sphere.</td>
<td>80</td>
<td>Ammonium nitrate produced on site Road Ammonia used on site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canvey/Thurrock area</td>
<td>General</td>
<td>Transport of hazardous materials by river, road, rail and pipeline.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
300,000 t. Part of the site is leased to Texaco. The materials are brought in mainly by sea via a single jetty but also by road and are sent out mainly by road but also by sea. Oil is sent out by Texaco by pipeline.

**Mobil Oil Co. Ltd**
Mobil Oil Co. Ltd operates at Coryton an oil refinery as well as a bulk distribution depot and a large research and technical services laboratory. Oil is brought in by sea into storage tanks and is drawn off from these as required to the refinery. LPG is produced on site. The total storage capacity is more than 1500000 t. Products are sent out by sea, road, rail and pipeline.

In addition, at the time of the investigation Mobil was undertaking a major extension to the refinery.

**Calor Gas Ltd**
Calor Gas Ltd operates at Coryton an LPG terminal for the filling of gas cylinders. The gas is supplied by pipeline from both the nearby refineries and is held in storage vessels with a total capacity of 350 t. The gas cylinders bring the total inventory on site to 500 t. LPG is sent out in road cylinders and in bulk tankers.

**Shell Oil UK Ltd**
Shell Oil UK Ltd operates at Shell Haven an oil refinery. Oil is brought in by sea into storage tanks and is drawn off from these as required to the refinery. LPG is produced on site. The total storage capacity is more than 3500000 t. Products are sent out by sea, road, rail and pipeline.

There is also on site a large fully refrigerated storage tank for liquid anhydrous ammonia with a capacity of 14000 t. Ammonia is brought in by sea and sent out by sea and road, and occasionally by rail.

**Fisons Ltd**
Fisons Ltd operates at Stanford-le-Hope an ammonium nitrate plant in which strong ammonium nitrate solution is produced by reacting together ammonia and nitric acid, the latter itself being made on site from ammonia. The ammonium nitrate is stored in two large heated tanks with a total capacity of 7000 t and is sent out by road. Liquefied anhydrous ammonia for the process is brought in by rail and is stored in a large semi-refrigerated pressure storage sphere with a capacity of 2000 t.

**Other activities**
Explosives are trans-shipped at Chapmans Anchorage at the eastern end of Canvey Island, while there is a specified anchorage for explosives ships at the other end of the area.

Ships passing up and down the river are obliged to travel fairly close to the sea walls and jetties within the area.

### A7.3 First Canvey Report: Identified Hazards

The investigation identified several principal hazards in the area. These are:

1. oil spillage over bund:

<table>
<thead>
<tr>
<th>Table A7.3</th>
<th>First Canvey Report: selected references used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. of Defence (n.d.); Wardle (n.d.); Brodie (1956); B.R. Morton, Taylor and Turner (1956); Cremer (1959, 1961); Minorsky (1959); Cremer and Callaway (1961); Pasquill (1961, 1965); Patty (1962); R.K. Davis et al. (1963); Blokker (1964); Bryant (UKAEA 1964 AHSB(RP) R42); Glassstone (1965); Yih (1965); van Dolah et al. (1966 BM RI 6773); Resplandy (1967); Brasie and Simpson (1968); Slade (1968); G.A. Briggs (1969); Clough and Garland (1970b); Kiwan (1970b); Bryce-Smith (1971); Finney (1972); MacArthur (1972); Brobst (1972); Feldbauer et al. (1972); Humbert-Basset and Montet (1972); Oppenheim, Kuhl and Kamel (1972); Burgess and Zabetakis (1973 BM RI 7752); Kuhl, Kamel and Oppenheim (1973); May, McQueen and Whipp (1973); Strethlow (1973b); Battelle Columbus Lab. (1974); L.E. Brown, Wesson and Welker (1974b); Dicken (1974, 1975); Geiger (1974); Hosker (1974b); Kneebone and Prew (1974); Munday and Cave (1974); Murata et al. (1974); NTSB (1974 PAR 74-06); Reed (1974); Simmons, Erdmann and Naft (1974); van Ulden (1974); CIA (1975/8); Germeles and Drake (1975); Getling (1975); J. Hall, Barrett and Ralph (1975); Lonsdale (1975); Raj et al. (1975); DoE (1976b); Gifford (1976b); MacMullen (1976); Munday (1976a); Neff, Meroney and Cermak (1976); Carver et al. (1977); R.A. Cox and Roe (1977); Davenport (1977b); Fitzpatrick and Goddard (1977); Havens (1977)</td>
<td></td>
</tr>
</tbody>
</table>

See also Appendix 28 (HSE and SRD; UKAEA, SRD)
### Table A7.4  First Canvey Report: some failure and event data used (after Health and Safety Executive, 1978b)

<table>
<thead>
<tr>
<th>Installation or activity</th>
<th>Frequency of spontaneous failure of pressure vessel</th>
<th>10^-5/y – 10^-4/y</th>
<th>Canvey Report page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure vessels (LPG, ammonia, HF)</td>
<td>Frequency of spontaneous failure of pressure vessel</td>
<td>10^-5/y – 10^-4/y</td>
<td>57, 59, 69</td>
</tr>
<tr>
<td>Pressure circuit (HF)</td>
<td>Frequency of spontaneous failure of pressure circuit</td>
<td>10^-4/y</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>Frequency of release due to operational fault</td>
<td>10^-4/y</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>Frequency of penetration of pressure circuit by missile</td>
<td>10^-4/y</td>
<td>59</td>
</tr>
<tr>
<td>High speed rotating machine</td>
<td>Frequency of disintegration of rotor</td>
<td>10^-4/y – 10^-3/y</td>
<td>58</td>
</tr>
<tr>
<td>Pipework (LPG)</td>
<td>Frequency of failure of pipework (whole refinery installation)</td>
<td>5 x 10^-3/y</td>
<td>56</td>
</tr>
<tr>
<td>Pump (LPG)</td>
<td>Frequency of catastrophic failure of pump</td>
<td>10^-4/y</td>
<td>56</td>
</tr>
<tr>
<td>LPG filling point</td>
<td>Frequency of large vapour release</td>
<td>5 x 10^-3/y</td>
<td>58, 81</td>
</tr>
<tr>
<td>LNG tank (above ground)</td>
<td>Frequency of serious fatigue failure</td>
<td>2 x 10^-4/y</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Frequency of overpressurization by overfilling</td>
<td>10^-5/y – 10^-4/y</td>
<td>63, 95</td>
</tr>
<tr>
<td></td>
<td>Frequency of rollover involving structural damage</td>
<td>10^-5/y – 10^-4/y</td>
<td>63, 95</td>
</tr>
<tr>
<td>Jetty pipework (LNG)</td>
<td>Frequency of catastrophic failure of jetty pipework</td>
<td>10^-4/y – 10^-3/y</td>
<td>63</td>
</tr>
<tr>
<td>Fire</td>
<td>Frequency of major fire in a refinery</td>
<td>0.1/y</td>
<td>55, 130</td>
</tr>
<tr>
<td>Explosion</td>
<td>Probability of refinery explosion, given major refinery fire</td>
<td>0.5</td>
<td>130</td>
</tr>
<tr>
<td>Missiles</td>
<td>Probability of missile generation, given refinery explosion</td>
<td>0.1</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Frequency of missile-generating explosion in refinery</td>
<td>5 x 10^-3 /y</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Average number of missiles generated per explosion</td>
<td>c. 6</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Probability of missile hitting large storage sphere at 300m</td>
<td>10^-3</td>
<td>55</td>
</tr>
<tr>
<td>Unconfined vapour cloud explosion</td>
<td>Frequency of unconfined vapour cloud explosion in a refinery</td>
<td>10^-3 /y</td>
<td>69, 130</td>
</tr>
<tr>
<td>Pipeline (butane)</td>
<td>Frequency of failure of pipeline (15/20 cm diameter)</td>
<td>3 x 10^-4/km y</td>
<td>85</td>
</tr>
<tr>
<td>Rail transport</td>
<td>Frequency of derailment of rail tank car</td>
<td>1 x 10^-6/train km travelled</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>Probability of overturning, given derailment</td>
<td>0.2</td>
<td>79</td>
</tr>
<tr>
<td>Installation or activity(^a)</td>
<td>Canvey Report page(s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of accident of road tanker involving spillage</td>
<td>1.6 \times 10^{-8}/km travelled</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>Sea transport (Port of London)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of ship–ship collision of moderate severity due to harbour movements</td>
<td>0.5 \times 10^{-4}/harbour movement</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>Frequency of berthing contact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of grounding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of spillage due to harbour movements: ammonia carrier</td>
<td>3.1 \times 10^{-5}/harbour movement</td>
<td>149</td>
<td></td>
</tr>
<tr>
<td>Frequency of fire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of ship–ship collision of moderate severity in transit in estuary</td>
<td>2.3 \times 10^{-5}/movement</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>Frequency of spillage due to ship–ship collision in transit: ammonia carrier</td>
<td>5 \times 10^{-6}/movement</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Jetty incidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of shipboard explosion at jetty: ammonia ship, Shell jetty</td>
<td>\times 10^{-4}/harbour movement</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Frequency of fire or explosion at jetty: LPG, Occidental, Mobil jetty</td>
<td>4 \times 10^{-5}/harbour movement</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Aircraft movements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>See Section A7.5.5 of this Appendix</td>
<td></td>
<td>139–140</td>
<td></td>
</tr>
<tr>
<td>Helicopter movements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of helicopter accident – total accidents</td>
<td>3 \times 10^{-7}/km flown</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>– fatal accidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 \times 10^{-8}/km flown</td>
<td>141</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) The data given in this table are in most cases heavily qualified and the original report should be consulted for the description of the background to and the application of these data.
large terminals and storages at Fisons and at Shell. The spillage might occur at sea or on land.

A severe toxic release might also occur if there is a rupture of storage or process plant containing hydrogen fluoride. This hazard is presented by the allylation facilities at Shell, at the Mobil extension and at the proposed Occidental refinery.

The investigators also identified and assessed other hazards, but these are not considered here.

**A7.4 First Canvey Report: Failure and Event Data**

The investigation required the estimation of the probabilities of various occurrences and of their consequences.

Some of the sources of information on such probabilities used in the study were

1. UK industries, including oil, chemical and other process industries and transport;
2. government organizations such as those concerned with fire, and road, rail and sea and air transport;
3. professional institutions, e.g. Institution of Chemical Engineers, Institution of Civil Engineers, American Institute of Chemical Engineers;
4. international safety conference proceedings, e.g. loss prevention in the process industries, ammonia plant safety and hazardous materials spills;
5. industry-based associations, e.g. Chemical Industries Association, Institute of Petroleum, American Petroleum Institute, Liquefied Petroleum Gas Industry Technical Association;
6. international insurance interests, e.g. Lloyds, Det Norske Veritas, and industrial risk insurers, Fire Protection Association;
7. overseas government and international agencies, e.g. US Coast Guard, US Department of Transportation, OECD and EEC;
8. specialized research laboratories;
9. individual subject specialists known or recommended to the investigating team.

Selected references used in the Canvey Report are given in Table A7.3.

The degree of uncertainty associated with the probability estimates is indicated by the following code:

(a) assessed statistically from historical data – this method is analogous to the use of aggregate estimates in economic forecasting;
(b) based on statistics as far as possible but with some missing figures supplied by judgement;
(c) estimated by comparison with previous cases for which fault tree assessments have been made;
(d) ‘dummy’ figures – likely always to be uncertain, a subjective judgement must be made;
(e) not used;
(f) fault tree synthesis, an analytically-based figure which can be independently arrived at by others.

The coding (a) denotes a value based on historical failure or event data. The coding (b) indicates that the value is again based on historical data as far as possible, although with some exercise of judgement, but also that given more effort a firmer value would probably be obtained. The coding (d) indicates that the value is based on judgement and the prospects of ever reducing the uncertainty are poor. Category (d) factors are effectively dummy values. Conclusions should not be drawn from these without testing for sensitivity. The value of a (d) category factor is generally not very small: it is typically 0.3 and exceptionally 0.1. The coding (f) denotes a value synthesized by fault tree methods. This category is in fact very little used in the study. Instead use is made of (c) category factors. The coding (c) indicates that the value is based on a value previously obtained for a similar situation using fault tree methods.

The Canvey Report contains much useful information on failure and event data. Some of these data are given in Section A7.5 and in Table A7.4. It is emphasized that these data are given here for illustrative purposes and that the report itself should be consulted for the description of the background to and the application of these data.

**A7.5 First Canvey Report: Hazard Models and Risk Estimates**

The investigation involved the study of a wide range of hazards and scenarios.

The projects which were initiated as part of the investigation were

1. consideration of known history of identified storage tanks and their possibility of failure;
2. probability of particular storage tanks or process vessels being hit by missiles caused by fires or explosions on site or adjacent sites, by fragmentation of rotating machines or pressure vessels, or transport accidents;
3. effects of vapour cloud explosions on people, houses, engineering structures, etc.;
4. evaporation of LNG from within a containment area on land or from a spill on water;
5. special problems of frozen earth storage tanks for LNG and the effect of flooding;
6. study of possible failures in handling operations;
7. consideration of the possible benefits and practicability of evacuation;
8. civil engineering aspects of the sea-wall – the chance of it being breached by subsidence, explosion or impact of ships, consideration of the timing of improved defences, consideration of the time for floods to rise;
9. statistics of ship collisions and their severity, groundings, etc., applying extensive world experience to the Canvey Island area;
10. reliability and analysis of fluid handling practices, ship to shore, and store to road vehicles and pipelines;
11. toxicology of identified hazardous substances;
12. studies to determine the lethal ranges for various releases of toxic or explosive materials leading to a number of special studies such as (a) the behaviour of ammonia spilt on water or land, and (b) an assessment of the relative importance of explosion or conflagration from a cloud of methane or liquefied petroleum gas.

The subjects which are considered in appendices to the report are
(1) a review of current information on the causes and effects of explosions of unconfined vapour clouds (F. Briscoe);
(2) fires in bunds – calculations of plume rise and position of downwind concentration maximum (R. Griffiths);
(3) a quantitative study of factors tending to reduce the hazards from airborne toxic clouds (J.R. Beattie);
(4) the dispersal of ammonia vapour in the atmosphere with particular reference to the dependence on the conditions of emission (F. Abbey, R.F. Griffiths, S.R. Haddock, G.D. Kaiser, R.J. Williams and B.C. Walker);
(5) statistics on fires and explosions at refineries (J.H. Bowen);
(6) missiles – penetration capability (E.A. White);
(7) discussion of data base for pressure vessel failure rate (T.A. Smith);
(8) risk of aircraft impacts on industrial installations in the vicinity of Canvey Island (L.S. Fryer);
(9) the dispersion of gases that are denser than air, with LNG vapour as a particular example (G.D. Kaiser);
(10) not used;
(11) the risk of a liquefied gas spill to the estuary (D.F. Norworthy);
(12) the toxic and airborne dispersal characteristics of hydrogen fluoride (J.R. Beattie, F. Abbey, S.R. Haddock, G.D. Kaiser);
(13) transient variation of the wall temperature of an LNG above-ground storage tank during exposure to an LNG fire in an adjacent bund (J.R. Fothergill);
(14) the escape of 1000t of anhydrous ammonia from a pressurized storage tank (L.S. Fryer, G.D. Kaiser and B.C. Walker);
(15) graphical calculation of toxic ranges for a release of 1000t of ammonia vapour (J.H. Bowen);
(16) effect of unbundled spill of hydrocarbon liquid from refinery at Canvey Island (A.N. Kinkead);
(17) estimated risk of missile damage causing a vapour cloud release from existing and proposed LPG storage vessels at the Mobil refinery, Coryton (D.F. Norworthy);
(18) risks of accidents involving road tankers carrying hazardous materials (L.S. Fryer);
(19) toxicology of lead additives (S.R. Haddock);
(20) compatibility of materials stored at London and Coastal Wharves Ltd (S.R. Haddock);
(21) blast loading on a spherical storage vessel (J. Wall);
(22) statistical comment on data on distribution of cracks found on inspection of steel vessel (J.C. Moore);
(23) calculation of resistance of ship hull to collision (A.N. Kinkead);
(24) reduction of apparent risk by shared experience (J.H. Bowen).

The treatment of some of the topics which is given in the report is now described. These topics are

(1) failure of pressure vessels;
(2) failure of pressure piping;
(3) failure of pipelines;
(4) generation of and rupture by missiles;
(5) crash of and rupture by aircraft;
(6) ship collision and other accidents;
(7) flow of a large release of oil;
(8) temperature of the wall of an LNG tank exposed to an LNG fire in an adjacent bund;
(9) evaporation of LNG and ammonia on water;
(10) dispersion of an LNG vapour cloud;
(11) unconfined vapour cloud fire and explosion;
(12) ammonium nitrate explosion;
(13) toxicity of chlorine, ammonia, hydrogen fluoride and lead additives;
(14) dispersion of ammonia and hydrogen fluoride vapour clouds;
(15) factors mitigating casualties from a toxic release;
(16) road tanker hazards;
(17) evacuation.

It is emphasized that the following summary of the methods used in the report is necessarily highly compressed and that the report itself should be consulted for a fuller discussion of the methods themselves and of the background to and application of the methods.

A7.5.1 Failure of pressure vessels
Spontaneous failure of pressure vessels is considered as a possible initiating event for releases of LPG, ammonia and hydrogen fluoride. The report discusses spontaneous failure of pressure vessels in Part 2, Section 5.3.2, and in Appendix 7 and the sensitivity of the results for LPG, ammonia and hydrogen fluoride releases in Part 2, Sections 17.14–17.16.

It reviews the surveys of pressure vessel failures available at that date, as described in Chapter 12, and concludes that the UK survey data are broadly applicable to LPG storage vessels.

For vessels covered by the surveys the frequency of a fault requiring repair or withdrawal from service was about $3 \times 10^{-5}$/y. If it can be assumed that the critical defect length is less than the wall thickness, so that detection is easier, and that there is an effective inspection system, a reasonable estimate of the probability of detection is 90%. The frequency of an undetected fault would then be about $3 \times 10^{-5}$/y.

A catastrophic failure rate of pressure vessels of $10^{-5}$/y is used in the study.

In addition, however, the sensitivity of the results to errors in the assumed failure rate was calculated taking a failure rate of $10^{-4}$/y instead of $10^{-5}$/y. The effect of this change is almost to double the risk from LPG operations for the existing installations after the proposed modifications. Thus for an incident involving $>1500$ casualties the frequency is $264 \times 10^{-6}$/y with a contribution of $20 \times 10^{-6}$/y for spontaneous failure of pressure vessels, but the latter rises to $200 \times 10^{-6}$/y if the spontaneous failure rate of pressure vessels is increased from $10^{-5}$/y to $10^{-4}$/y.

It is concluded that a high standard of inspection of the LPG pressure vessels is necessary.

External threats to pressure vessels were also considered. An event tree for the derailment involving overturning of a rail tank car with possible threat to a sphere containing 2000t of anhydrous ammonia is shown in Figure A7.2.

Missile threats are described in Section A7.5.4.

A7.5.2 Failure of pressure piping
Failure of pressure piping is considered as a possible initiating event for releases of LPG and LNG. The report discusses the failure of LPG pressure piping in Part 2, Section 5.3.1.
LPG is piped around the refineries in pressure piping. The pipes mainly contain liquid, but there are some vapour return lines. It was considered that probably if a large pipe were to fail, there would be a vapour plume, the plume would find a source of ignition and would burn back to the pipe and there form a burning jet. In burning back there would be the possibility of semi-confined vapour explosions. If on a 25 cm diameter LPG pipe the fluid burned as a jet, the latter could be over 50 m long, while if, due to obstruction, it burned rather as a hemisphere, the radius of the latter could be over 10 m.

Various effects of such fires and explosions from LPG pipe failure are reviewed. An LPG sphere should withstand a semi-confined explosion beneath it; a horizontal cylinder could be lifted up some tens of centimetres. The principal hazard foreseen, however, is burnback under an LPG storage sphere.

Three cases are treated: (1) failure of a pipe, (2) failure of a pump, and (3) failure of a suction line within about 10 m of a storage sphere. The smallest pipe size considered was 15 cm diameter.

It was estimated that the area of a typical refinery is about 3 km² and that the length of LPG pipe of diameter \( \geq 15 \) cm in such a refinery is about 3 km, of which about 10% is 25 cm diameter pipe. The total frequency of pipe fracture for this length of pipe was assessed from data in the SRS data bank as \( 5 \times 10^{-7} /y \). For a pipe to affect the storage it must be sufficiently near. The hazard ranges of 15 cm and 25 cm diameter pipe were taken as 150 m and 500 m, respectively. The width of a plume would be of the order of 20°, so that the possibility of the plume lying in any particular direction is 5%. Then the frequencies of involvement of an LPG storage vessel due to pipe failures are:

Frequency for 15 cm pipe

\[
2 \times 10^{-2} \times 5 \times 10^{-3} \times 5 \times 10^{-2} = 5 \times 10^{-6} /y
\]

Frequency for 25 cm pipe

\[
1 \times 10^{-1} \times 2 \times 10^{-1} \times 5 \times 10^{-3} \times 5 \times 10^{-2} = 5 \times 10^{-6} /y
\]

Total frequency for all large pipes = \( 10^{-5} /y \).

The number of LPG pumps in a typical refinery was estimated at about 20. The frequency of catastrophic rupture of such pumps was assessed from data in the SRS data bank as \( 10^{-4} /y \). As before, the probability of the plume being in any particular direction is 5%. Then the frequency of involvement of an LPG storage vessel due to a pump rupture is

Frequency for pumps

\[
20 \times 10^{-4} \times 5 \times 10^{-2} = 10^{-3} /y
\]

In addition, there is the possibility that if the pumps are close together (<20 m spacing), a fire at one pump would involve other pumps and would create a large fire regardless of plume direction. Then the frequency for this event is \( 2 \times 10^{-3} /y \).

The proportion of 25 cm diameter LPG pipe within 10 m of a storage vessel was estimated as about 10%. Then the frequency of involvement of an LPG storage vessel due to failure of such pipe is

Frequency for 25 cm pipe beneath vessels

\[
10^{-1} \times 10^{-1} \times 10^{-3} = 5 \times 10^{-5} /y
\]

Thus the frequency of failure of an LPG vessel due to failure of a large LPG pipe or a pump is \( 1.6 \times 10^{-4} /y \). If
interaction between pumps can occur as described above, this figure rises to $2.1 \times 10^{-3}$/y.

The report also discusses the failure of the pipes which carry LNG from the jetty head to the storage tanks in Part 2, Section 6.5.2.

The frequency of failure of these pipes was assessed as $10^{-4} \sim 10^{-3}$/y. The lower rate is more likely during actual transfer pumping and the higher rate during warmup and cooldown when the pumps are not in use.

### A7.5.3 Failure of pipelines
Failure of a pipeline is considered as a possible initiating event for LNG and LPG. The report discusses failure of pipelines in Part 2, Section 15.

There are four methane pipelines leaving the British Gas terminal. One of these is a 35 cm diameter line passing close to the built-up area. A serious failure of this line would lead to a large release of methane, but the gas would be highly buoyant and would undergo turbulent mixing with air, so that there is no chance of the formation of a large vapour cloud heavier than air.

The frequency of a serious failure of the 35 cm pipeline in the built-up area was estimated as not greater than $10^{-4}$/y.

There is a liquid butane pipeline from the British Gas terminal to a point near the Shell refinery. The line is 20 cm diameter for 4 km leaving the terminal and then reduces to 15 cm diameter. The line is not used, but contains some 585 t of liquid butane at a pressure of 4–6 atm. A serious failure of this line could give an initial liquid release rate of 20–30 t/min. If the pressure were sustained by flashing off of propane some 50–100 t could be released in a few minutes. Unless there is a limit on the amount of propane or other volatile component present, the flashing off of the discharging mixture could form a vapour cloud.

The frequency of a serious failure was estimated from data for similar pipelines in the SRS data bank as $3 \times 10^{-4}$/km-y. The distance travelled by the pipeline through populated terrain is 1.5 km. Thus the frequency of a serious failure causing casualties was estimated as $4.5 \times 10^{-5}$/y.

### A7.5.4 Generation of and rupture by missiles
Rupture by a missile is considered as a possible initiating event for releases of LPG, ammonia and hydrogen fluoride. The report discusses the generation of missiles in Appendix 5 and the penetration capability of missiles in Appendix 6.

Some scenarios considered are shown in Table A7.5.

The frequency of a large fire in an oil refinery is, for the USA, 0.2/y obtained from API data and, for the U.K., 0.25/y obtained from FRS data. The API figures indicate that the proportion of these fires which are very large is about one-third. Thus the frequency of a very large fire in a refinery was taken as 0.1/y.

The proportion of such very large fires which involves explosion was estimated from IRI data as 0.5. The proportion of such explosions which generate missiles was estimated as 0.1.

The frequency of a very large fire which involves an explosion and generates missiles was thus estimated as $5 \times 10^{-5}$/y.

It was estimated also that on average such a missile-generating explosion generates some half-dozen missiles.

The frequency of disintegration of the rotor of a rotating machine was estimated as $5 \times 10^{-4}$/y from data in the SRS data bank.

The report gives in Appendix 6 methods for the estimation of the probability of a missile landing in a given area at a known distance from the source and methods for determining whether the missile will penetrate a vessel.

Missiles particularly considered are fragments from process plant and gas cylinders. With regard to the former a case is quoted in the UK in which a fractured vessel produced at least seven missiles of 1 ton capacity.

Reference is also made to the explosion at Whiting, Indiana, where an exploding hydroformer generated some tens of missiles, one of 60 ton, with a velocity of 600 ft/s.

Various empirical formulae for penetration by missiles are given. There is considerable variation in the results obtained from these formulae. When used to determine the penetration thickness for a missile with a velocity of 300 ft/s, the penetration thicknesses given by the formulae ranged from 0.25 in to 2.75 in. One reason for the variation is that some of the formulae are applicable to clamped flat plates rather than spherical or cylindrical vessels.

It is concluded that

1. LPG spheres in excess of $\frac{1}{4}$ in. thick will not be penetrated by flying gas cylinders even at velocities of 300 ft/s, which is a pessimistic upper limit;
2. spheres and cylinders 0.75 in. thick could be penetrated by flying gas cylinders;
3. process missiles can be considerably larger than a gas cylinder and can impact with substantially greater energy – these could penetrate LPG spheres and cylinders.

The report also discusses missile threat to the LNG tanks in Part 2, Section 6.5.4.
Table A7.6  First Canvey Report: some potential aircraft crash accidents at Canvey (after Health and Safety Executive, 1978b)

<table>
<thead>
<tr>
<th>Site</th>
<th>Installation</th>
<th>Frequency of impact (impacts/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell, Mobil, UR, Occidental</td>
<td>LPG</td>
<td>1 x 10^{-6}</td>
</tr>
<tr>
<td>British Gas</td>
<td>Methane</td>
<td>1 x 10^{-6}</td>
</tr>
<tr>
<td>Calor Gas</td>
<td>LPG</td>
<td>2 x 10^{-6}</td>
</tr>
<tr>
<td>London and Coastal Wharves</td>
<td>Oil</td>
<td>7 x 10^{-6}</td>
</tr>
<tr>
<td>Fisons</td>
<td>Ammonia</td>
<td>1 x 10^{-7}</td>
</tr>
<tr>
<td>Shell</td>
<td>Ammonia</td>
<td>1 x 10^{-7}</td>
</tr>
<tr>
<td>Shell, Mobil, UR, Occidental</td>
<td>Process area</td>
<td>2 x 10^{-5}</td>
</tr>
</tbody>
</table>

A7.5.5 Crash of and rupture by aircraft
Rupture by aircraft crash is considered as a possible initiating event for release of all the hazardous materials. The report discusses aircraft crash and vessel rupture in Appendix 8.

The frequency of a fixed-wing aircraft crash at Canvey was assumed to be that for the UK in general and not that for an area near an airport. Canvey is within the Special Rules Zone of Southend airport, but is neither close to the main runway nor beneath the airspace of aircraft waiting to land.

The frequency of an aircraft crash was obtained from UK accident data. Two alternative equations are given for the frequency of an aircraft crash on a target. They are

Method 1 \[ F = A_H F_H + A_V F_V \] [A7.5.1a]
Method 2 \[ F = A_H F_H + A_V F_V \] [A7.5.1b]

where \( A_H \) is the horizontal area of the target, \( A_V \) is the vertical area of the target, \( A_H \) is the horizontal projection of the target area; \( F \) is the frequency of aircraft crash on the target area; \( F_H \) is the frequency of aircraft crash per unit of ground target area; \( F_V \) is the frequency of aircraft crash per unit of vertical area.

In Equation A7.5.1a the value of \( A_V \) was calculated assuming that the impact angle is 15°. In Equation A7.5.1b the value of \( F_V \) was calculated from data on the frequency with which aircraft crash into the National Grid system. The latter was taken as 0.1/y.

Results obtained for the frequency of crashes of aircraft of all types on the total target area at Canvey for each type of hazard were identical by both methods except that, for the refrigerated LPG at British Gas, Method 1 gave a frequency of impact of 6 x 10^{-7}/y and Method 2 one of 4 x 10^{-7}/y. Other results were as given in Table A7.6.

The frequency of a helicopter crash was also considered. Helicopters are used to survey pipelines in the area. It was assumed that data on the frequency of helicopter crashes obtained from NTSB publications are applicable to these helicopters. The frequency of crash obtained from this data is 3 x 10^{-7}/km flown. In such crashes descent is almost vertical.

Frequencies of crash estimated were 2.4 x 10^{-5}/y, 1.4 x 10^{-5}/y and 3.6 x 10^{-6}/y for the Occidental, Shell and Texaco sites. These are not, however, the frequencies of impact on vulnerable targets. These latter frequencies should be very much less, provided the helicopter routes are chosen to avoid such targets.

Helicopters are used by British Gas to survey its gas pipelines. There are about 26 inspection flights per year. The pilots are instructed to avoid flying over industrial complexes and to skirt such locations by about 500yd.

A7.5.6 Ship collision and other accidents
Ship collision is considered as a possible initiating event for release of LNG, LPG and ammonia. The report discusses ship collision in Appendices 11 and 23.

Ship collision may occur while the ship is at sea, is stationary in mid-channel or is moored at a jetty.

At the time of the survey the Port of London Authority (PLA) had just imposed on ships a new speed restriction of 8 knot.

Data on the frequency of ship collisions were obtained from the PLA. These data show that over the 12-year period 1965–76 there were within the scheduled area 592250 harbour movements and 121 accidents, of which 91 were classed as minor. Thus this gives for collisions of at least moderate severity a frequency of 0.5 x 10^{-3}/harbour movement.

Other PLA data were analysed to obtain the frequencies of berthing contact, grounding and fire. Thus the frequencies for collision and for these other accidents are

Frequency of ship–ship collision (moderate severity) \[ = 0.5 \times 10^{-3}/\text{harbour movement} \]
Frequency of berthing contact \[ = 1.5 \times 10^{-4}/\text{harbour movement} \]
Frequency of grounding \[ = 0.3 \times 10^{-4}/\text{harbour movement} \]
Frequency of fire \[ = 0.5 \times 10^{-4}/\text{harbour movement} \]

Further PLA data were analysed to obtain the frequency of ship–ship collision for ships in transit in the estuary. Thus the frequency of collision in transit is

Frequency of ship–ship collision (moderate severity) in transit \[ = 2.3 \times 10^{-5}/\text{movement} \]

The vulnerability of ships to collision damage varies. The LNG carriers are double-hulled ships, whereas the LPG and ammonia carriers were not considered as of comparable strength. The former have much greater cargo protection.
An investigation of the resistance of ships to impact was carried out in 1959 by Minorsky, who correlated his results in terms of the critical impact speed vs. the loaded displacement of the striking ship, and the Minorsky curve method is widely used as a means of assessing impact resistance of ships.

For a typical LPG carrier, data on the relation of the critical impact speed vs. loaded displacement of the striking ship were obtained from Lloyds Register. These data were interpreted as meaning that a striking ship with a loaded displacement of about 4000 ton (2000 GRT) could penetrate an LPG carrier and cause spillage if there is no speed restriction, but that a loaded displacement of about 15,000 ton (7500 GRT) would be necessary if the speed of the striking ship is limited to 8 knot.

Data for another typical LPG carrier were obtained from Norsk Veritas. These data differ from the Lloyds data and indicate that this is an area of uncertainty.

The frequencies of spillage for an ammonia carrier, which in this context is broadly similar to an LPG carrier, were estimated by using the historical data in conjunction with the following assumed probabilities:

Probability of spillage from ship–ship collision = 0.2
Probability of spillage from berthing contact = 0.1
Probability of spillage from grounding = 0.2

Thus for an ammonia carrier the frequencies of spillage due to harbour movements are

Frequency of spillage due to ship–ship collision
= 1 × 10⁻⁵/harbour movement

Frequency of spillage due to berthing contact
= 1.5 × 10⁻⁵/harbour movement

Frequency of spillage due to grounding
= 0.6 × 10⁻⁵/harbour movement

Total frequency of spillage due to harbour movements
= 3.1 × 10⁻⁵/harbour movement

An alternative calculation of the frequency of spillage due to harbour movement based on world data gave a value of 1.45 × 10⁻⁵/harbour movement.

It is concluded that for an ammonia carrier a reasonable estimate of frequency of spillage due to harbour movements is unlikely to exceed

Frequency of spillage due to harbour movements
= 2 × 10⁻⁵/harbour movement

but that this estimate might be significantly reduced if more information were available on cargo protection.

The frequency of spillage for an ammonia carrier due to collision in transit in the estuary was estimated using an assumed probability of spillage due to ship–ship collision of 0.2. Thus for an ammonia carrier frequency of spillage in transit is unlikely to exceed

Frequency of spillage due to ship–ship collision in transit
= 5 × 10⁻⁶/movement

This estimate might be significantly reduced if more information were available on cargo protection.

The frequency of spillage for an LPG carrier was taken as similar to that for an ammonia carrier. Thus for an LPG carrier the frequency of spillage is unlikely to exceed

Frequency of spillage
= 2 × 10⁻⁵/movement

Again this estimate might be significantly reduced given more information on cargo protection.

For an LNG carrier the situation is different, because the vessel is double-hulled. This case was the subject of a special study. From this study a relation was obtained for an LNG carrier between the critical impact speed and the loaded displacement of the striking ship. This relation for an LNG carrier differs considerably from that for an LPG carrier, since the former, being double-hulled, has much greater protection. The relation shows that for an LNG ship stationary in mid-channel a striking ship with a loaded displacement of 100,000 ton (50,000 GRT) would need to have a speed of 9 knot to effect penetration at a 90° impact angle, and that for an LNG ship moored at a jetting striking ships with loaded displacements of 100,000 ton (50,000 GRT) and 20,000 ton (10,000 GRT) would need to have speeds of 7 knot and 13.5 knot, respectively, to effect penetration at a 45° impact angle.

It was assumed, therefore, that only ships with a loaded displacement greater than about 20,000 ton (10,000 GRT) have the potential to cause a spillage from an LNG carrier. This does not include allowance for the new PLA speed restrictions.

It was also concluded that for an LNG carrier spillage due to berthing contact could be disregarded.

The frequency of spillage for an LNG carrier was estimated from the historical data in conjunction with the following assumed probabilities:

Probability of striking ship >20,000 ton (10,000 GRT)
= 0.1

Probability of strike in vulnerable section
= 0.5

Then for an LNG carrier the frequency of spillage is

Frequency of spillage
= 2.5 × 10⁻⁶/movement

This assessment is based on only 4 incidents over the 12-year period.

An alternative calculation of the frequency of spillage for LNG carriers based on world data gave a value of 1 × 10⁻⁶/movement.

It is concluded that for an LNG carrier a reasonable estimate for frequency of spillage is

Frequency of spillage
= 2 × 10⁻⁶/movement

A7.5.7 Flow of a large release of oil
A large release of oil from storage and flow of this oil towards housing is one of the hazard situations considered. The report discusses the methods of calculating
the flow of a large release of oil from the catastrophic failure of a storage tank in Appendix 16.

Equations are given for the flow of a slumping fluid derived from those of van Ulden (1974) assuming that his constants c and Δ have the value of unity. It is assumed that the liquid is initially held in a vertical cylindrical source. The equations are

\[ r = \sqrt{\frac{R^2 + 2t(gV_s/\pi)^{\frac{1}{2}}}{\pi^2}} \]  

\[ h_t = \frac{V_s}{\pi r} \]  

\[ u_t = (gh_t)^{\frac{1}{2}} \]

where \( g \) is the acceleration due to gravity (m/s²); \( r \) the radius of the flooded zone (m); \( R \) the radius of the source cylinder (m); \( t \) the time after initiation of slumping (s); \( u_t \) the slumped liquid velocity (m/s); and \( V_s \) the volume of the source cylinder (m³).

A7.5.8 Temperature of the wall of an LNG tank exposed to an LNG fire in an adjacent bund

The rupture of an LNG tank due to an LNG fire in an adjacent bund is one of the hazard situations considered. The report discusses the effect of an LNG fire in an adjacent bund on the temperature of an LNG tank wall in Appendix 13.

The LNG tanks considered are cylindrical in shape and are 30 m diameter and 20 m high. They stand in a bund of 60 m diameter.

The temperature of the tank wall is determined by the heat balance on the wall. It was assumed that the wall gains heat by radiation and loses it both by radiation and by convection.

For the heat gained by the tank wall use was made of the experimental work of L.E. Brown, Wesson and Welker (1974b). It was assumed that the heat flux from the fire is 44000 BTU/h ft², which is the maximum average value obtained by these workers for liquid pools of up to 30 m diameter. This value is considered reasonably conservative for bund fires with an effective diameter up to 60 m. The flame height calculated from the empirical formula given by these workers is 75 m. The fraction of the radiated heat received by the tank was then calculated by dividing both the flame and tank surfaces into smaller sub-surfaces and determining view factors. The total radiated heat \( Q_t \) received by the tank wall was calculated as 3.11 × 10⁷ W.

For the heat loss by the tank wall the equation used for radiation is

\[ Q_t = \epsilon(\sigma A_V + A_H)\theta_t^4 \]

where \( A_H \) is the area of the tank roof (m²); \( A_V \) the exposed area of the tank vertical sides (m²); \( Q_t \) the heat loss by radiation (W); \( \epsilon \) the emissivity of the tank wall; \( \theta_t \) the absolute temperature of the tank wall (K); and \( \sigma \) the Stefan–Boltzmann constant (W/m² K⁴).

The equation used for convection is

\[ Q_c = (1.76A_V + 2.25A_H)(\Delta \theta)^{1.25} \]

with

\[ \Delta \theta = \theta - \theta_A \]

where \( Q_h \) is the heat loss by convection (W); \( \Delta \theta \) the temperature difference between the tank wall and ambient air (°C); and \( \theta_A \) the absolute temperature of ambient air (K).

The areas \( A_V \) and \( A_H \) of tank surface are the exposed areas and since the whole of the roof but only part of the walls is exposed, \( A_H \) is based on the whole of the roof surface, but \( A_V \) is based on only part of the vertical wall surface.

The equilibrium tank wall temperature \( \theta_t \) was found to be 647 K assuming an emissivity \( \epsilon \) of 0.5 and did not differ by more than 40°C even assuming an emissivity of unity. The tank wall temperature is therefore relatively insensitive to estimates of the emissivity.

The heat loss by radiation is over three times greater than that lost by convection at a tank wall temperature of 650 K.

The time for the temperature of the tank wall to reach steady state was calculated from the unsteady-state equation

\[ mc_p \frac{d\theta_t}{dt} = Q_t - (Q_h + Q_c) \]

where \( c_p \) is the specific heat of the tank wall (J/kg °C); \( m \) the mass of the exposed tank wall (kg); and \( t \) the time (s).

The thermal capacity \( mc_p \) of the exposed tank wall was taken to include half that of the associated perlite insulation.

Equation A7.5.8 is nonlinear and is solved numerically. It was calculated that the time for the temperature of the wall to reach 95% of its equilibrium value is about 42 min.

A7.5.9 Evaporation of LNG and ammonia on water

The spillage and evaporation of LNG and ammonia on water is one of the hazard situations considered. The report discusses the evaporation rates of LNG and of ammonia spilled on water in Part 2, Sections 6 and 7, respectively.

It is stated that for a rapid spill of LNG on water the evaporation time is short and a puff dispersion model is applicable. But for a continuous spill the evaporation rate rapidly reaches the spill rate and this evaporation rate then determines the pool diameter reached. The evaporation rate has been determined by a number of investigators as about 0.19 kg/m² s, which corresponds to a liquid regression rate of 4.7 × 10⁻⁴ m/s.

Similarly, it is stated that for a rapid spill of ammonia on water the evaporation time is short and that all the ammonia will evaporate, except for about 20% which dissolves in the water.

A7.5.10 Dispersion of an LNG vapour cloud

The dispersion of an LNG vapour cloud is one of the hazard situations considered. The report discusses the dispersion of an LNG vapour cloud in Appendix 9.

A cloud of cold LNG vapour tends to behave as a heavy gas cloud. The following elements are identified as particularly important in describing the behaviour of such a cloud: (1) specification of the source, (2) description of the gravitational slumping, (3) description of the air entrainment, and (4) description of the thermal effects.

The model of the source which is assumed can have a significant effect on the results. The release may be instantaneous or continuous. The source may be of fixed...
Figure A7.3  First Canvey Report: hazard ranges for releases of LNG vapour in neutral and stable weather conditions (Health and Safety Executive, 1978b): (a) continuous releases – curve 1 API tests model, 2.5% average, stable condition; curve 2 API tests model, 5% average, stable condition; curve 3 Shell tests model, 5% average, stable condition; (b) instantaneous releases – curve 1 API tests model, 2.5% average, stable condition (Feldbauer et al., 1972); curve 2 API tests model, 5% average, stable condition; curve 3 Shell tests model, 5% average, stable condition (Courtesy of HM Stationery Office)
size or of increasing size, as with LNG spilled on to water. The process of release may or may not involve the entrainment of large amounts of air.

The differences between the various models currently available for the gravitational slumping phase are discussed and it is suggested that these may be due in large part to the extent to which air entrainment is taken into account. The model of R.A. Cox and Roe (1977) is instanced as representative of the new generation of models which take into account air entrainment.

Information is presented on the distance travelled by an LNG cloud before it is diluted to the lower flammability limit, i.e. the hazard range. Experimental work described includes:

<table>
<thead>
<tr>
<th>Source</th>
<th>Release</th>
<th>Weather conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>API</td>
<td>1/3–10 t on sea</td>
<td>Stable (Pasquill stability category E)</td>
</tr>
<tr>
<td>Shell</td>
<td>5–50 t on sea</td>
<td>Relatively stable</td>
</tr>
<tr>
<td>AGA</td>
<td>Spillages in bunds giving vapour releases up to 25 kg/s</td>
<td></td>
</tr>
</tbody>
</table>

The average concentration corresponds to 5% and the peak concentration to 2.5% which, as explained above, allows for localized short-term concentrations of double the latter value.

A7.5.11 Unconfined vapour cloud fire and explosion

An unconfined vapour cloud fire or explosion is considered as one of the possible accidents which could be the cause of fatalities. The report discusses unconfined vapour cloud fire and explosion in Part 2, Sections 4 and 6, and in Appendix 1. The treatment given of unconfined vapour cloud fire and explosion is broadly as follows.

Two standard vapour clouds are considered. The first contains 100t and the second 1000t of hydrocarbons.

Ignition of an unconfined vapour cloud may result in fire or in explosion. The fire and explosion characteristics are given for the two standard vapour clouds just mentioned.

Both complex explosion models and a modified TNT equivalent model were used to estimate the damage effects from an unconfined vapour cloud explosion.

Only the modified TNT equivalent model is described here. This is similar to the usual model, except that the relation between peak overpressure and scaled distance is modified to allow for the fact that the explosion is that of a vapour cloud rather than that of TNT.

For the energy of explosion an equivalence factor \( \alpha \) is defined such that the explosion of a flammable gas cloud of \( W \) t of hydrocarbons with a combustion energy release \( H \) kcal produces the same damage effects as a TNT explosion with an energy release of \( \alpha H \) kcal. The value of \( \alpha \) used is 0.1. In other words, it is assumed that 10% of the hydrocarbons takes part in the explosion.

For the peak overpressure \( \Delta p_m \) and the peak dynamic pressure \( q_m \) at radial distance \( r \) and scaled distance \( r/H^{0.5} \) the relations used are shown in Figure A7.4.

Separate curves of \( \Delta p_m \) are given for TNT explosion, for hydrocarbon detonation and for hydrocarbon deflagration with a deflagration velocity of 170 m/s. Figure A7.4 is for spherical symmetry. Results for explosions with hemispherical symmetry may be obtained by doubling the energy release.
Thus, for example, for a hydrocarbon vapour cloud explosion with an energy release $\alpha H$ where $H = 11.1 \times 10^6$ W kal

$\alpha = 0.1$

Figure A7.4 gives for hemispherical symmetry

<table>
<thead>
<tr>
<th>$\Delta p_m$ (psi)</th>
<th>$r$ (bar)</th>
<th>$r$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.2</td>
<td>69.1 W$^3$</td>
</tr>
<tr>
<td>1</td>
<td>0.07</td>
<td>196 W$^3$</td>
</tr>
</tbody>
</table>

For the two standard hydrocarbon vapour clouds considered the fire and explosion characteristics used are shown in Section A of Table A7.7. The ranges quoted for dilution to the lower flammability limit are for weather conditions of Pasquill stability category D. The overpressures quoted apply only to the cases where an explosion occurs.

The foregoing indicates for the standard hydrocarbon vapour clouds considered the estimated hazard ranges of fire and of explosion, i.e. overpressure effects, where these effects occur.

The probability of ignition of a vapour cloud was taken as 0.1 or 1, depending on whether ignition was regarded as improbable or probable, taking into account the ignition sources between the point of release and the population group.

The probability of deflagration with overpressure in a vapour cloud, given ignition, was taken as 1 for large clouds (>1000) of flammable gas, as 0.1 for smaller clouds of flammable gas other than methane, and as 0.01 for smaller clouds of methane, reflecting the significantly lower probability of explosion of a cloud of methane compared with one of other hydrocarbons.
Table A7.7  First Canvey Report: vapour cloud fire, explosion and casualty characteristics used (after Health and Safety Executive, 1978b)

<table>
<thead>
<tr>
<th>Mass of hydrocarbon (t)</th>
<th>Diameter of stoichiometric hemispherical cloud (m)</th>
<th>Range of stated overpressure (km)</th>
<th>Range for dilution to lower flammability limit (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before burning After burning 0.2 atm (3 psi) 0.07 atm (1 psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>169 323</td>
<td>0.321 0.910</td>
<td>2</td>
</tr>
<tr>
<td>1000</td>
<td>364 696</td>
<td>0.691 1.960</td>
<td>5</td>
</tr>
</tbody>
</table>

B  Casually characteristics of a 1000t hydrocarbon vapour cloud fire and explosion

<table>
<thead>
<tr>
<th>Upper limit</th>
<th>No. of casualties</th>
<th>No. of fatalities</th>
<th>Cumulative probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>750</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>4500</td>
<td>2250</td>
<td>0.14</td>
</tr>
</tbody>
</table>

C  Fire and explosion characteristics of an LNG vapour cloud

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass of hydrocarbon (t)</th>
<th>Burnt cloud radius (m)</th>
<th>Radius of stated overpressure (m)</th>
<th>Probability of overpressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2 atm (3 psi) 0.07 atm (1 psi)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>162</td>
<td>321 910</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>204</td>
<td>404 1147</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>348</td>
<td>691 1960</td>
<td>1</td>
</tr>
</tbody>
</table>

For the 1000t hydrocarbon vapour cloud it was assumed that the whole cloud burns with a fireball approximately equal in volume to that of the cloud formed by the stoichiometric gas-air mixture and further that, where overpressure occurs, the proportion of hydrocarbon taking part in the explosion is 10%.

If the vapour cloud is ignited in situ, the hazard to the public for the situations considered is that of explosion. In accordance with the data given in Table A7.7 it was assumed that the overpressure at the site boundary would not exceed 0.2 atm.

An incidence of 1.1% is quoted for casualties among the population in the areas subject to an overpressure between 0.2 and 0.05 atm, which is approximately the level of overpressure corresponding to the Explosives Acts recommendations.

If the vapour cloud drifts and is ignited off-site, the hazards to the public for the situations considered are those of fireball and explosion. For this case, where the cloud is ignited and burns fully over the populated region, it was assumed that the whole population engulfed in the fireball is killed. For the 1000t hydrocarbon cloud burning fully over a populated region with the average population density of the area, the number of fatalities would be 2000. In addition, it was assumed that in this situation there would be 100 further fatalities and 2000 serious injuries caused by explosion effects out to a radius where the overpressure is 0.075 atm.

The more probable case, however, is ignition when the leading edge of the cloud is just beginning to encroach on the populated region.

It was assumed that if for ignition of the cloud on the edge of the populated region, the number of casualties is \( N \) and the probability is \( P \), then for ignition right over the populated region the number of casualties is \( 4N \) and the probability is \( 0.25P \). It was also assumed that the range of probabilities may be represented by a linear probability distribution function. The corresponding relationships between the numbers of casualties and the probability of these numbers are given in Section B of Table A7.7. The number of fatalities is taken as half the number of casualties.

For a hydrocarbon vapour cloud greater than 1000t it was assumed that the number of casualties would vary with the mass of vapour according to a 2/3 power law.

The report discusses unconfined LNG vapour cloud fire and explosion in Part 2, Section 6.

The following scenarios are among those considered:

Case 1a  Release from storage tank (25 cm diameter hole)

Case 1b  Release from ship's cargo tank at jetty (25 cm diameter hole) – vapour cloud of 100t

Case 2  Failure of storage tank – vapour cloud of 200t

Case 3  Failure of ship's cargo tank – vapour cloud of 1000t

The fire and explosion characteristics of the vapour clouds for these cases are given in Section C of Table A7.7.

The probability of explosion, i.e. overpressure in the vapour cloud, was taken as unity only for the larger clouds. The explosion effects were again calculated assuming that 10% of the hydrocarbons takes part in the explosion.

A7.5.12 Ammonium nitrate explosion

An ammonium nitrate (AN) explosion is considered as one of the possible accidents which could be the cause
Table A7.8  First Canvey Report: some major ammonium nitrate explosions (after Health and Safety Executive, 1978b)

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Mass of ammonium nitrate (t)</th>
<th>Distance for major damage (m)</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1918</td>
<td>Morgan, NJ</td>
<td>500</td>
<td>1600</td>
<td>64</td>
</tr>
<tr>
<td>1923</td>
<td>Oppau, Germany</td>
<td>4500</td>
<td>7000</td>
<td>1100^a</td>
</tr>
<tr>
<td>1947</td>
<td>Brest, France</td>
<td>3000</td>
<td>5000</td>
<td>21</td>
</tr>
<tr>
<td>1947</td>
<td>Texas City, TX</td>
<td>3500</td>
<td>2300</td>
<td>560</td>
</tr>
</tbody>
</table>

^a This value differs from that given by Commentz et al. (1921).

of fatalities. The report discusses ammonium nitrate explosions in Part 2, Sections 4.1.2 and 11, and in Appendix 1.

The ammonium nitrate considered is the storage of 92.5% aqueous solution in two tanks of 5000 and 2000t capacity, respectively. A large spillage from this storage would probably give a mushy heap of ammonium nitrate crystals near the point of release. An escape of 4500t of 92.5% solution was considered as the standard case.

If ammonium nitrate is ignited, the result is normally a fire rather than explosion. The latter is likely to occur only if conditions are favourable for transition from a fire to an explosion.

These conditions have been investigated theoretically and experimentally by van Dolah et al. (BM 1966 RI 6773) and this work is discussed. It is concluded that the work indicates that transition to explosion would be impossible for quantities of ammonium nitrate of tens of tonnes and probably hundreds of tonnes, but that it might occur at the thousands of tonnes level.

The historical record of ammonium nitrate explosions is reviewed and explosions of prilled ammonium nitrate in transport are quoted, one in rail tank cars at Traskwood, Arkansas, in 1960 and one in road tankers in Queensland in 1972.

The only significant possibility foreseen for the occurrence of an ammonium nitrate explosion was the derailment of a train carrying petroleum products which could cause simultaneously the rupture of an ammonium nitrate tank and a liquid petroleum fire.

The frequency of a derailment and overturning was calculated as follows:

Frequency of derailment of rail tank car

\[ = 1 \times 10^{-6} / \text{train km} \]

Number of trains with petroleum products

\[ = 3000 / \text{y} \]

Length of track opposite tanks

\[ \approx 300 \text{ m} \]

Probability of derailment leading to overturning

\[ = 0.2 \]

Probability of overturning on tank side of track

\[ = 0.5 \]

Frequency of derailment and overturning on tank side of track

\[ = 8.5 \times 10^{-5} / \text{y} \]

In view of the many uncertainties and of the omission of other possible accident modes this latter value was also taken as the frequency of an ammonium nitrate explosion. Thus

Frequency of ammonium nitrate explosion

\[ = 8.5 \times 10^{-5} / \text{y} \]

The effect of an ammonium nitrate explosion was assessed by reference to the data on such explosions given by M.A. Cook (1958) and shown in Table A7.8.

These results were interpreted as follows. It was assumed that the predominant reaction in the explosion of ammonium nitrate is

\[ 2\text{NH}_4\text{NO}_3 = 2\text{N}_2 + 4\text{H}_2\text{O} + \text{O}_2 \]

for which the heat of reaction is \(0.35 \times 10^6\) kcal/t. Then using this heat of reaction the values obtained for the group \( r/H^2 \) (m/(kcal)^2) corrected for spherical symmetry for the distance for major damage in the four explosions listed lie in the range 1.72–4.8. This spread indicates a lack of agreement with the 1/3 power scaling relation, which is reduced but not eliminated if a 1/2 power scaling relation is used. The disagreement may be due in part to the relative lack of precision in the term ‘serious damage’. If these results are located on the curve for overpressure \( \Delta P_m \) (TNT) in Figure A7.4, then, as shown by the full line (line 1) in this figure, they correspond to an overpressure of 0.02 bar. This is an extremely low overpressure to cause serious damage. In view of this dilemma, it was decided to locate the ammonium nitrate results at an overpressure of 0.1 bar, as shown by the dotted line (line 2) in Figure A7.4, although they then lie above the TNT curve. It is the further dotted line (line 3) which is used to calculate the damage ranges for explosions of 2250t and 4500t of ammonium nitrate in the report.

A7.5.13 Toxicity of chlorine, ammonia, hydrogen fluoride, and lead additives
The toxicity of chlorine, ammonia, hydrogen fluoride and lead additives is considered. The report discusses the toxicity of chlorine in Appendices 3 and 12, that of ammonia in Appendix 15, that of hydrogen fluoride in Appendix 12 and that of lead additives in Appendix 19.

There is considerable uncertainty about the lethal dosages for all these chemicals and it was necessary, therefore, to make approximate estimates.

Chlorine was not one of the chemicals considered in the study to constitute a hazard at Canvey, but its toxicity is discussed in relation to factors which mitigate
For hydrogen fluoride it is necessary to take care with the units in which concentration is expressed on account of the high degree of association in the vapour phase. Concentrations are therefore expressed in units of mg/m$^3$ rather than of ppm.

Precise information on the lethal dosages of hydrogen fluoride is again lacking. Insofar as it is an irritant gas it appears to have effects similar to chlorine at similar concentrations. The toxicity of hydrogen fluoride was therefore assumed for the purpose of the study to be similar to that of chlorine at a similar concentration, where the concentration units are mg/m$^3$.

In addition, however, hydrogen fluoride in large but sublethal dosages may also have other injurious long-term effects.

The lead additives are the alkyl lead compounds, particularly the methyl and ethyl derivatives.

For lead additives precise information on the lethal dosage is again lacking. The medical evidence is reviewed in some detail. It is concluded that there is a significant probability of fatality at a concentration of 500 mg/m$^3$ for an exposure of 1 h. It is also considered that total dosage is more important than concentration so that the concentration can be scaled inversely with the exposure time for exposure times in the range 15–60 min.

A7.5.14 Dispersion of ammonia and hydrogen fluoride vapour clouds

The dispersion of anhydrous ammonia and hydrogen fluoride gas clouds is one of the hazard situations considered. The report discusses the dispersion of an ammonia gas cloud in Part 2, Section 7, and in Appendices 4 and 14 and that of a hydrogen fluoride gas cloud in Part 2, Section 5.5, and in Appendix 12.

The dispersion of an anhydrous ammonia cloud depends on whether it is lighter or heavier than air. The following conclusions are reached. If an initial fraction of the ammonia released is in the form of suspended droplets, the cloud may become denser than air as it is diluted. There will be a critical value for the initial fraction of droplets such that if the fraction is below this value the cloud will be less dense than air regardless of the humidity of the air. There will be a second critical value such that if the fraction is above this value the cloud will be more dense than air regardless of the humidity of the air. These two critical values are given, respectively, as 4–8% and 16–20% of the total mass of ammonia. Between these critical values the density of the cloud is determined by the degree of dilution and humidity of the air. High values of the air humidity favour low cloud densities and vice versa, since water in the atmosphere will tend to freeze and so liberate latent heat.

The possible chemical reactions of anhydrous ammonia with the water and the carbon dioxide in the air to give ammonium hydroxide and ammonium bicarbonate and carbonate are also reviewed, but it is concluded that it seems unlikely that any such reaction will be a significant effect, although in foggy or rainy conditions it may convert some ammonia to a less toxic form and so effect some reduction in the hazard.

The historical record of anhydrous ammonia releases is reviewed and those at Blair, Conway, Potchefstroom...

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**Figure A7.5** First Canvey Report: lethal exposure time versus concentration for chlorine (Health and Safety Executive, 1978b) (Courtesy of HM Stationery Office)
and Houston are quoted. In all these cases the ammonia cloud appears to have behaved as denser than air.

The emission and dispersion of a release of 1000t of anhydrous ammonia from pressurized storage at 6°C in weather conditions of Pasquill stability category D and wind speed of 3m/s were calculated.

For emission it was assumed that the whole mass of 1000t of ammonia is released virtually instantaneously,
that 20% of the ammonia forms vapour and that the remaining 80% forms liquid droplets, so that the whole amount spilled is airborne.

The escaping ammonia will entrain air. There is little information available on this aspect, although the Potchefstroom accident provides some evidence. There some 40t of ammonia were released and eyewitness accounts stated that the immediate resulting gas cloud was about 150m in diameter and nearly 20m in depth’. This corresponds approximately to an air–ammonia mass ratio of about 10 if all the ammonia was airborne and visible. If it is assumed that in the scenario considered enough dry air is mixed with the ammonia to vaporize all the liquid ammonia, leaving an air–ammonia mixture at the boiling point of ammonia, the corresponding air–ammonia mass ratio is about 20.

The following conditions were taken, therefore, as the source for the dispersion model. The release is 1000t of anhydrous ammonia. This forms a vapour cloud with an air–ammonia mass ratio of 20 at a temperature of \(-33°C\) and with a density of 1.42 kg/m³. This density is greater than that of air at 20°C by a factor of 1.18 so that the cloud is denser than air. Both the radius and height of the cloud are 167m.

For dispersion it was assumed that the behaviour of the vapour cloud is described initially by a heavy gas slumping model and then by a neutral gas dispersion model. This follows the approach developed by van Ulden (1974).

For slumping, van Ulden’s model is used

\[ \frac{dr}{dt} = \left( \frac{(\rho_0 - \rho_a)gh}{\rho_0} \right)^{\frac{1}{2}} \]  

[A7.5.11]

with

\[ h = \frac{V_0}{\pi r^2} \]  

[A7.5.12]

and

\[ r^2 - r_0^2 = 2 \left( \frac{(\rho_0 - \rho_a)gV_0}{\pi \rho_a} \right) t \]  

[A7.5.13]

where \( g \) is the acceleration due to gravity; \( h \) the height of the cloud; \( r \) the radius of the cloud; \( r_0 \) the initial radius of the cylinder; \( t \) the time; \( V_0 \) the initial volume of the cylinder; \( \rho_a \) the density of air; and \( \rho_0 \) the initial density of the cloud.

The termination of slumping depends in this model on the turbulent energy density and hence on the surface roughness length. For a roughness length \( z_0 \) of 10cm the predicted height \( h \) at termination of slumping is 0.15m. For the purposes of this approximate calculation the height \( h \) at termination of slumping was taken as 1m.

The state of the cloud at termination of slumping is then as follows. The radius is 2170m, the height is 1m, the density is 1.42 kg/m³. The time taken is about 12min and the distance travelled with the wind speed of 3 m/s is about 2.6km.

This model predicts, therefore, that the cloud radius becomes very large and that the cloud travels far downwind. The cloud travel distance is regarded as pessimistic, because it is to be expected that at a height of 1m the cloud will be slowed down by various obstacles.

For further dispersion the Pasquill–Gifford model for a neutral buoyancy gas was used

\[ \chi(x, y, t) = \frac{2Q'}{(2\pi)^{\frac{3}{2}}\sigma_x\sigma_y\sigma_z} \times \exp \left[ -\frac{1}{2} \left( \frac{x - u - ut}{\sigma_x^2} \right)^2 - \frac{y^2}{\sigma_y^2} \right] \]  

[A7.5.14]

with

\[ \sigma_x = \sigma_y = \sigma_z \]  

[A7.5.15]

where \( x, y, z \) is the distance in the downwind, crosswind and vertical directions (m); \( Q' \) the mass released instantaneously (kg); \( t \) the time (s); \( u \) the wind speed (m/s); \( \sigma_x, \sigma_y, \sigma_z \) the standard deviations, or dispersion coefficients, in the downwind, crosswind and vertical \( (x, y, z) \) directions (m); and \( \chi \) the concentration (kg/m³).

At the termination of slumping it was assumed that the cloud has a Gaussian concentration distribution with the 10% edges of the cloud equal to the edges of the slumped cloud. Then at transition

\[ r = 2.14\sigma_y \]  

[A7.5.16]

\[ h = 2.14\sigma_z \]  

[A7.5.17]

The maximum concentration on the axis at a downwind distance \( x \) occurs when the centre of the cloud is at that point so that

\[ x = ut \]  

[A7.5.18]

and hence

**Figure A7.7** First Canvey Report: approximate area within which people are at risk from an instantaneous release of 1000t of anhydrous ammonia (Health and Safety Executive, 1978b) (Courtesy of HM Stationery Office)**
Figure A7.8 First Canvey Report: mean concentration, lethal exposure time, time of passage and time to walk out versus distance for a 20t release of chlorine with various release times (Health and Safety Executive, 1978b): (a) release time of 6s; (b) release time of 10min; and (c) release time of 6h (Courtesy of HM Stationery Office)
\[ \chi_{\text{max}}(x) = \frac{2Q^*}{(2\pi \sigma_x \sigma_z)} \]  

[A7.5.19]

The mean concentration \( \chi_{\text{m}}(x) \) along the axis is related to the maximum concentration \( \chi_{\text{max}}(x) \) as follows:

\[ \chi_{\text{m}}(x) = 0.585 \chi_{\text{max}}(x) \]  

[A7.5.20]

The mean concentrations calculated for the release considered are given in Figure A7.6. Figure A7.6(a) shows the mean concentration as a function of downwind distance and Figure A7.6(b) the mean concentration as a function of exposure time.

The distance at which the ammonia cloud is potentially lethal is obtained from Figure A7.6. If it is assumed that the ammonia is potentially lethal at a concentration of 0.002 kg/m\(^3\) for a period of 30–50 min, the range of potential lethality of the cloud is 5 km from the point at which slumping is terminated. This point is itself 2.6 km from the source.

Cloud behaviour was also investigated for other weather conditions.

The approximate area within which people are at risk from an instantaneous release of 1000 t of anhydrous ammonia in weather conditions of Pasquill stability category D and wind speed of 6 m/s is shown in Figure A7.7.

The model just described is a relatively crude one. Further, more sophisticated models were derived which took into account (1) the heating of the cloud and (2) the entrainment of air during the slumping phase. These models indicated that the overall behaviour of the cloud is not greatly altered by these effects and that the original model gave a sufficient representation for approximate calculations.

The dispersion of a hydrogen fluoride gas cloud also depends on whether it is lighter or heavier than air. Hydrogen fluoride monomer has a molecular weight of 20, which suggests that the gas should be lighter than air. But hydrogen fluoride gas is highly associated, forming in particular the hexamer. Although dissociation takes place as the gas is diluted, the process is endothermic so that cooling occurs. Thus the behaviour of a hydrogen fluoride gas cloud is in some ways analogous to that of an ammonia gas cloud.

The approach adopted was to treat the hydrogen fluoride cloud as denser than air.

A7.5.15 Factors mitigating casualties from a toxic release

Large toxic releases are considered as one of the possible accidents which could be the cause of fatalities. Theoretical estimates of large toxic releases tend, however, to give rather large numbers of fatalities and to appear pessimistic compared with the historical record. Considerations was therefore given to the factors mitigating casualties from a toxic release.

The report discusses mitigating factors for a toxic release in Appendix 3.

The historical record of chlorine releases is reviewed. The releases listed by Simmons, Erdmann and Naft (1974) are quoted, as are the releases at Zarnesti, Roumania, in 1939 and at Baton Rouge, Louisiana, in 1976.

The following features are added as factors which may mitigate the effects of a chlorine release:

1. low population density downwind of the source, particularly within the first kilometre or so;
2. favourable weather conditions;
3. low rate of release;
4. escape;
5. shelter.

It is possible to make a quantitative estimate of the effect of these factors. There are other factors such as

6. topography

which may also be important, but which in the present state of knowledge cannot be readily assessed.

A series of calculations was done for a 20 t chlorine release over periods of 6 s, 10 min and 6 h in weather conditions of Pasquill stability category D and with a wind speed of 5 m/s.

The calculations were based on the Pasquill model for short continuous releases, as given in Equation 15.16.31, using the graphs presented by Bryant (1964 UKAEA AHSB(RP) R42 Figure 4). This model may be adapted to the determination of the time of passage and the dosage from a nearly instantaneous release, as follows. The time of passage for an instantaneous release is obtained as the times between the concentration rising to, and subsequently falling back to, one-tenth of its maximum value. This time of passage is corrected for a nearly instantaneous release by adding to it the time of release. For the dosage use is made of the fact that Equation 15.16.31 gives the total dosage for an instantaneous release, as described in Chapter 15. The model applies strictly to short releases of approximately 3 min duration. No account was taken, therefore, of plume broadening with duration of release, but it was believed that this effect would be small for the stability condition considered.

For various points on the downwind axis of the cloud, calculations were made of the dosage and of the time of passage, and by dividing the former by the latter, of the mean concentration. The chlorine toxicity data given in Figure A7.5 were used to determine for each mean concentration the corresponding lethal exposure time. If the lethal exposure time was less than the time of passage, then the cloud was assumed to be fatal to a person remaining in the open air at that point.

The results of the calculations are summarized in Figures A7.8(a–c), which show the mean concentration, the time of passage and the lethal exposure time vs. distance for the three releases studied.

The distances at which the time of passage and lethal exposure time cross over are the lethal distances, or hazard ranges, of the clouds. These distances are 2.7, 1.9 and 0.6 km for release times of 6 s, 10 min and 6 h, respectively. The variation of the lethal range is due entirely to the slope of the line of lethal concentration vs. exposure time in Figure A7.5, which is a log–log plot. If the slope were –1 instead of approximately –2, there would be no variation of distance.

The effects of the mitigating factors are discussed in the light of these results.

For population density the effect of low population density is as follows. In a UK urban area with a population density of about 5000/km\(^2\) the numbers in a 15° sector would be about 650, 2650 and 6000, while in a UK rural area with a population density of about
100/km² the corresponding numbers would be 13, 53 and 120 within distances of 1, 2 and 3 km, respectively. Thus it is estimated that a rapid release of 20 t of chlorine gas could kill up to 6000 in an urban area and up to 120 in a rural area.

The effect of more favourable weather conditions was not calculated. It was considered that, in view of the uncertainties in gas dispersion estimates, calculations for other weather conditions were not justified.

The effect of a lower rate of release is to reduce the estimated number of fatalities. The values may be calculated from the data given.

The effect of escape was estimated by calculating the time for a man to walk out of the cloud. It was assumed that if the axial concentration is lethal for the time of passage of the cloud, the concentration halfway out of the cloud may be considered only injurious and that at the edge of the cloud, defined as 10% of that of the centre, relatively harmless. It was assumed that the man would walk out of the cloud across wind at a speed of 3 mile/h (1.34 m/s). Escape was assumed if the time to walk from the cloud centre to the cloud edge was less than the lethal exposure time at the axial concentration.

The times to walk out are shown in Figures A7.8(a–c). The distances at which the time to walk out and the lethal exposure time curves cross are the lethal distances of the clouds allowing for escape. For the release time of 6 s the lethal range remains 2.7 km, but for the release times of 10 min and 6 h it is reduced to 1.1 km and less than 100 m, respectively.

The effect of shelter was estimated using the equation

$$C = C_0[1 - \exp(-\lambda t)]$$  \[A7.5.21\]

where $C$ is the concentration indoors; $C_0$ the concentration outdoors; $t$ the time; and $\lambda$ the number of air changes per unit time.

The value of $\lambda$ is about one change per hour for a modern centrally heated building, but in general can be two or three changes per hour, particularly if doors or windows are open. Assuming that shelter with one air change per hour is used, for a 6 s release the cloud is lethal at 100 m, but not at 200 m, and for a 10 min release it is lethal at 300 m, but not at 500 m. For a 6 h release the concentration in the building rises to that outside it after 1 h and the cloud is lethal at 0.6 km as before. Thus shelter is very effective for the release time of 6 s and quite effective for the release time of 10 min, but is ineffective for the release time of 6 h. In the latter case, however, escape is relatively easy.

A7.5.16 Road tanker hazards

A road tanker accident is considered as a possible initiating event for release of flammable and toxic materials. The report discusses road tanker accidents in Part 2, Section 14, and in Appendix 18.

The nature of the hazard from a road tanker accident is not discussed in as much detail as that from some of the other hazards. Mention is made of the possibility of a 10 ton spillage of flammable material which could give rise to a fire (p. 96) and of spillage of LPG which could give rise to a 14 ton cloud which could travel 200 m and still remain flammable (p. 178).

The frequency of spillage is estimated from data recorded by HM Inspector of Explosives on accidents resulting in loss of life and personal injury and involving the contents of petrol tankers. These records indicated that over the past five years there were on average 5 accidents per year which led to a spillage. But from statistics published by the DoE (1976) the quantity of petroleum products moved by road is $4.3 \times 10^8$ t/km.

Then since the average tanker load is 14 t

Frequency of petrol tanker accident involving spillage

$$= 1.6 \times 10^{-5} / \text{km}$$

Tankers carrying LPG are stronger than petrol tankers, but the conservative assumption was made that the frequency of accidents involving spillage is the same for LPG tankers as for petrol tankers.

The frequency of spillage from all hazardous materials transported by road from the British Gas Corporation, London and Coastal Wharves, and Texaco was then estimated as $1.4 \times 10^{-5} / \text{y}$. The contribution of flammables to this figure is much the largest, that of toxics being relatively small.

A7.5.17 Evacuation

The mitigating effect of evacuation was also considered. The report discusses evacuation in Part 1, Section 10, and in Part 2, Section 16.

There are two respects in which the evacuation situation at Canvey Island is unusual. There are only two roads leading off the island, and these converge at a single roundabout, and there exist already plans for evacuation in the event of flooding by the sea.

The need for an additional road off the island has been the subject of debate in the area.

The evacuation process was modelled. An exponential model was used in which it was assumed that half the population is moved to safety in the first two hours, half of the remainder in the next two hours and so on.

Evacuation was found to be possibly beneficial in one or two types of emergency. In particular, consideration was given to evacuation in the event of a large release of ammonia from a ship collision or jetty incident. For the majority of emergencies, however, it is suggested that it would be better to remain indoors rather than to attempt evacuation.

Such evacuation would require prior planning. The existing arrangements for evacuation for flooding would not necessarily suffice, since the advance warning from a chemical emergency is likely to be less.

Similarly, the provision of an additional road was seen as beneficial for the same types of incident, but it was considered that the construction of such a road could not be recommended solely for evacuation without further discussion.

A7.6 First Canvey Report: Assessed Risks and Actions

The hazards described in Section A7.3 were assessed using appropriate failure and event data as described in Section A7.4 and hazard models and risk estimates, including those described in Section A7.5.

The accidents which might occur, the nature and frequency of the initiating events and the frequency-number relations for casualties, or societal risks, are shown in Table A7.9.
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<th>Hazardous material</th>
<th>Company</th>
<th>Initiating event</th>
<th>Type of accident</th>
<th>Frequencies in units of $10^{-4}$/y</th>
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<td>Frequency of initiating event</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1235</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shock wave from filling point or process area</td>
<td></td>
<td>230</td>
</tr>
<tr>
<td>Hazardous material</td>
<td>Company</td>
<td>Initiating event</td>
<td>Type of accident</td>
<td>Frequencies in units of $10^{-6}$/y</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Ammonium nitrate</td>
<td>Fisons</td>
<td>Rail accident</td>
<td>Ammonium nitrate explosion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Anhydrous ammonia</td>
<td>Fisons</td>
<td>Spontaneous failure of sphere</td>
<td>Ammonia vapour cloud</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Missile from rotating machine</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Shell</td>
<td>Explosion in process area</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rail accident</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shell</td>
<td>Fire or explosion at jetty</td>
<td>400</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ammonia ship collision</td>
<td>375</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>Shell</td>
<td>Hydrogen fluoride</td>
<td>Hydrogen fluoride vapour cloud</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Missiles from neighbouring plant</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjacent vapour cloud explosion</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mobil (inc. extension)</td>
<td>Intrinsic failure of pressure circuit</td>
<td>100</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Missiles from neighbouring plant</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjacent vapour cloud explosion</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Occidental</td>
<td>Intrinsic failure of pressure circuit</td>
<td>100</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Missiles from neighbouring plant</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shell</td>
<td>Subtotal</td>
<td></td>
<td>464</td>
</tr>
</tbody>
</table>
Table A7.10  First Canvey Report: rank order of societal risks for some principal hazards of existing and proposed installations at Canvey (after Health and Safety Executive, 1978b)

Frequencies in units of $10^{-6}/y$

<table>
<thead>
<tr>
<th></th>
<th>&gt; 10 casualties</th>
<th>&gt; 4500 casualties</th>
<th>&gt; 18000 casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Oil spillage</td>
<td>1366</td>
<td>1 Ammonia vapour cloud</td>
<td>258</td>
</tr>
<tr>
<td>2  LPG vapour cloud (BG)</td>
<td>970</td>
<td>2 HF vapour cloud</td>
<td>246</td>
</tr>
<tr>
<td>3  Ammonia vapour cloud</td>
<td>735</td>
<td>3 Oil spillage</td>
<td>150</td>
</tr>
<tr>
<td>4  LPG vapour cloud (others)</td>
<td>637</td>
<td>4 LPG vapour cloud (other)</td>
<td>96</td>
</tr>
<tr>
<td>5  LNG vapour cloud</td>
<td>497 = 5</td>
<td>LNG vapour cloud</td>
<td>86</td>
</tr>
<tr>
<td>6  HF vapour cloud</td>
<td>464 = 5</td>
<td>HF vapour cloud</td>
<td>80</td>
</tr>
<tr>
<td>7  AN explosion</td>
<td>85</td>
<td>7 AN explosion</td>
<td>17</td>
</tr>
</tbody>
</table>

Table A7.11  First Canvey Report: rank order of societal risks for some principal hazards of existing and proposed installations at Canvey, after improvements suggested (after Health and Safety Executive, 1978b)

Frequencies in units of $10^{-6}/y$

<table>
<thead>
<tr>
<th></th>
<th>&gt; 10 casualties</th>
<th>&gt; 4500 casualties</th>
<th>&gt; 18000 casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  LPG vapour cloud (other)</td>
<td>421</td>
<td>1 Ammonia vapour cloud</td>
<td>71</td>
</tr>
<tr>
<td>2  LNG vapour cloud</td>
<td>396</td>
<td>2 HF vapour cloud</td>
<td>67</td>
</tr>
<tr>
<td>3  Ammonia vapour cloud</td>
<td>240</td>
<td>3 LNG vapour cloud</td>
<td>66</td>
</tr>
<tr>
<td>4  HF vapour cloud</td>
<td>115</td>
<td>4 LPG vapour cloud (other)</td>
<td>63</td>
</tr>
<tr>
<td>5  AN explosion</td>
<td>8</td>
<td>5 AN explosion</td>
<td>2</td>
</tr>
</tbody>
</table>

The results of the risk assessments are presented by the investigators as risks of causing casualties, i.e. severe hospitalized casualties or worse. This is in accordance with established practice (e.g. Department of Defense, n.d.; Glasstone, 1964). It was considered misleading to attempt to distinguish between severe injury and death.

These results have several interesting features. The hazards may be ranked for societal risks in order of descending frequency for accidents of different magnitude as shown in Table A7.9.

The hazard arising from the very large quantities of LNG stored is a serious one, but is no worse than that from the considerably smaller quantities of LPG.

The obvious hazards of LNG, LPG and ammonia are equated by others, such as oil and hydrogen fluoride, which are perhaps less well appreciated.

The relative importance of the hazards changes with the scale of the accident. For the smaller scale accidents oil spillage, flammable vapour clouds and toxic gas clouds are all important. As the scale increases, it is the toxic gas clouds which dominate.

There are a number of interactions identified both within sites and between sites. These include the threat to LPG storage at Mobil from the Calor Gas site, to the oil storage at Texaco from explosives barges, to the ammonia sphere at Fisons from rotating machinery and from the ammonium nitrate plant at Fisons, to various installations from process and jetty explosions, and possibly to the ammonia storage tank at Shell from explosion in the Shell refinery.

The relative hazard of the pressure storage of anhydrous ammonia at Fisons is much greater than that of the refrigerated storage of the same chemical at Shell. The risk for the latter was assessed as negligible with the possible exception of rupture by an explosion.

The assessed societal risks are shown in Table A7.9 and in Figure A7.9. Figure A7.9(a) gives the societal risks for all the existing installations. It shows that the risk of an accident causing more than 10 casualties is $31 \times 10^{-4}/y$. Figure A7.9(b) gives the societal risks for all the proposed developments. It shows that the risk of an accident causing more than 10 casualties is $16 \times 10^{-4}/y$.

The assessed individual risks are given for all the existing installations. These range from $13 \times 10^{-4}/y$ in region A to less than $1 \times 10^{-4}/y$ in region G of the area. The individual risks are also given for all the existing installations and proposed developments. These range from $26.3 \times 10^{-4}/y$ in region A to less than $2 \times 10^{-4}/y$ in region G.

The investigators made a number of recommendations for the reduction of the hazards. These included:

1. oil spillage – construction of a simple containing wall around the London and Coastal Wharves and Texaco sites and the proposed Occidental and UR refinery sites;
2. LNG tank flooding – construction of a dike;
3. spontaneous failure of LPG spheres – high standard of inspection;
4. LPG vessel rupture by missile (Mobil) – measures including fitting of pressure relief valves on cylinders at Calor Gas depot;
5. LPG tank failure at BG jetty – improvement of bund;
Figure A7.9  First Canvey Report: societal risks for existing installations and proposed developments (Health and Safety Executive, 1978b): (a) all existing installations; and (b) all proposed developments (Courtesy of HM Stationery Office)

(6) LPG pipeline failure (BG) – removal of pipeline;
(7) spontaneous failure of ammonia sphere – high standard of inspection, control of ammonia purity;
(8) ammonia release at Shell jetty – provision of water sprays at jetty;
(9) HF plant rupture (Mobil, Occidental) – provision of water sprays;
(10) ship collision – strict enforcement of the speed restriction of 8 knot;
(11) road tanker hazards – road tanker traffic restriction to new road only (if road built).

The assessed effect of the proposed modifications is to eliminate the hazards from oil spillage, from LPG vapour cloud due to explosion at the jetty and pipeline failure at British Gas, and from vessel rupture at Mobil due to missiles from Calor Gas, and to reduce greatly many of the other hazards.

The rank order for societal risk of the hazards assuming that the proposed modifications are carried out is then as shown in Table A7.11. Oil spillage and LPG vapour cloud (BG) are eliminated.
There are some hazards, however, which remain relatively difficult to eliminate. In particular, spontaneous failure of storage vessels, jetty incidents and ship collisions make large contributions to the residual risks.

The effect of the proposed modifications on the societal risks for the existing and proposed installations is given in Figure A7.9. This shows that the risk of an accident causing more than 10 casualties is \(9 \times 10^{-4}/y\) for the existing installations and \(2 \times 10^{-4}/y\) for the proposed developments.

The assessed individual risks are given for all the existing installations after the proposed modifications. These range from \(6 \times 10^{-5}/y\) in region A to less than \(1 \times 10^{-4}/y\) in region G. The individual risks are also given for all the existing installations and proposed developments, after the proposed modifications. These range from \(9 \times 10^{-5}/y\) in region C to less than \(1 \times 10^{-4}/y\) in Region G.

The risk to an individual member of the public at Canvey may be compared with the average risk to workers in British industry. For the latter the FAR, or fatal accident rate per 10\(^6\) exposed hours, is 4. If it is assumed that a man works 2000 hours per year, then the FAR is equivalent to an individual risk of \(0.8 \times 10^{-4}/y\).

A7.7 First Canvey Report: Responses to Report
A7.7.1 Response of HSE
The HSE accepted the report as a significant step forward in quantitative risk assessment, while acknowledging that there were some deficiencies.

It concluded that provided certain improvements were carried out, none of the existing installations need cease operations and the proposed developments could take place.

A7.7.2 Response of other parties
An account of some of the other responses to the report is given by the HSE in the Second Canvey Report, described below.

Publication of the report led to a surge of interest both locally and at national and international level. HSE attended a public meeting at Canvey and explained the report. While the determination of the risks was welcomed, there was criticism of HSE’s decision to allow continued operation of the existing installations, subject to the modifications.

The HSE give a summary of some criticisms made of the report by various parties. One was that the report overestimates the risks. The assessors were required by HSE not to err on the side of optimism. Many in the industry, however, considered that it is preferable to adopt a 'best estimate' approach and that a conservative method which involves making a pessimistic estimate at each stage where there is doubt is liable to give a gross overestimate of the risks.

The HSE was also criticized in appearing to acquiesce in risks, some of which had been assessed as relatively high. On this the HSE draws attention to its requirement that improvements be made. It goes on

HSE strongly believes that it has a duty, as the body charged with enforcing health and safety legislation, to express opinions about what may be required by that legislation. In HSE’s view it is not sufficient merely to identify the risk to health and safety without also recommending a course of action.

A critique of the First Canvey Report was published by Cremer and Warner (1980).

A7.7.3 General comments
An investigation of the kind described has perhaps an inevitable tendency to suggest that the hazards revealed were previously unappreciated. In fact companies involved in such a survey are generally very well aware of the hazards and have taken the measures which they consider appropriate.

The report itself expresses some reservations on the risk estimates and states: ‘Practical people dealing with industrial hazards tend to feel in their bones that something is wrong with risk estimates as developed in the body of the report…’.

At the time, the industry in the UK was conscious particularly of the Flixborough explosion. This has been dwarfed by subsequent disasters such as those at Mexico City, Bhopal, Ufa and Piper Alpha.

A7.8 Second Canvey Report
In 1981 there appeared the Second Canvey Report entitled Canvey: A Review of Potential Hazards from Operations in the Canvey Island/Thurrock Area Three Years after Publication of the Canvey Report (HSE, 1981a). This again was in two parts, with Part 1 an introduction by the HSE and Part 2 the SRD study.

In Part 1 HSE outlines the criticism of the first report, as just described, and gives its conclusions concerning the reviewed assessment.

In the next two sections, accounts are given of the reassessed risks and actions and of some technical aspects of the second report.

A7.9 Second Canvey Report: Reassessed Risks and Actions
The risks assessed in the Second Canvey Report are generally less than those in the first report. Thus, for example, at Stanford-le-Hope the individual fatality risk is given as \(0.6 \times 10^{-4}/y\), as opposed to \(5 \times 10^{-4}/y\) in the first report, a reduction by a factor of 8.

The HSE in Part 1 adduce the following reasons for this: (1) physical improvements already carried out; (2) changes in operation; (3) detailed studies by companies; (4) changes in assessment techniques; (5) correction of errors; and (6) further changes firmly agreed but yet to be made.

One major change in operation was the cessation of ammonia storage at Shell.

In a number of cases in the first report, estimates of the risks had to be made without benefit of detailed studies. Subsequent studies by the companies involved showed that in some cases the risks had been overestimated. A case in point was the limited ammonia spill at Fisons.

In a large proportion of cases the effect of the use of improved models for heavy gas dispersion was to reduce the travel distance of the cloud and hence the risks.
The HSE describe a number of further actions taken or pending to reduce the risks.

A7.10 Second Canvey Report: Technical Aspects

The Second Canvey Report revisits some of the frequency estimates and gives a revised set of hazard models and injury relations, covering the following aspects: (1) emission; (2) gas dispersion; (3) ignition; (4) fire events (5) vapour cloud explosions; and (6) toxic release.

A7.10.1 Pressure vessel failure

The report reviews the frequency of spontaneous failure of pressure vessels, in the light of a further survey of the failure rate of such vessels by T.A. Smith and Warwick (1978) (see also Smith and Warwick 1981 SRD R203). The use of a failure rate of 10⁻⁷/y is reaffirmed.

A7.10.2 Emission models

The set of emission models given covers the following cases:

(1) rupture of a pressure vessel;
(2) flow from a pipe:
   (a) non-flashing liquid;
   (b) flashing liquid;
   (c) gas.

The model for emission following rupture of a pressure vessel containing liquefied gas is the adiabatic flash.

A7.10.3 Vaporization model

Vaporization of a pool of liquefied gas is treated using the SRD code SPI LL, which can be applied to instantaneous or continuous releases.

A7.10.4 Gas dispersion models

Most of the liquefied gases studied exhibit heavy gas behaviour on release. For these use is made of the SRD codes DENZ and CRUNCH for instantaneous and continuous releases, respectively.

The report gives some results from these models in the form of tables of distance to the LFL and 1/2 LFL for releases of propane and butane. As described in Chapter 15, a correlation model for heavy gas dispersion based on such tables has been developed by Considine and Grint (1985).

A7.10.5 Ignition models

The report gives several sets of ignition probabilities. It distinguishes three distinct cases of gas cloud dispersion: Ignition may occur (1) at source, which may be (a) on site or (b) at a jetty; (2) in transit; or (3) over a populated area. Table A7.12 shows some of the ignition probabilities given for a flammable gas cloud in these situations. The values are based partly on data on the proportion of releases ignited given by Science Applications Inc. (SAI) (1974) and D.C. Wilson (1980) and partly on judgement.

Table A7.12 Second Canvey Report: some ignition probabilities for a flammable vapour cloud (after Health and Safety Executive, 1981a)

<table>
<thead>
<tr>
<th>A</th>
<th>Ignition on site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources of ignition</td>
<td>Ignition probability</td>
</tr>
<tr>
<td>‘None’</td>
<td>0.1</td>
</tr>
<tr>
<td>Very few</td>
<td>0.2</td>
</tr>
<tr>
<td>Few</td>
<td>0.5</td>
</tr>
<tr>
<td>Many</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>Ignition at jetty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay before ignition</td>
<td>Probability of ignition following:</td>
</tr>
<tr>
<td></td>
<td>Fire/explosion</td>
</tr>
<tr>
<td>Immediate ignition (within 30 seconds)</td>
<td>0.6</td>
</tr>
<tr>
<td>Delayed ignition (delay 1/2 to several minutes)</td>
<td>0.3</td>
</tr>
<tr>
<td>No ignition (within a few minutes)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C</th>
<th>Ignition in transit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain</td>
<td>Ignition probability</td>
</tr>
<tr>
<td>Open land</td>
<td>0</td>
</tr>
<tr>
<td>Industrial site</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D</th>
<th>Ignition over populated area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of ignition</td>
<td>Ignition probability</td>
</tr>
<tr>
<td>Edge/edge: edge of unignited cloud just reaches edge of populated area when ignition occurs</td>
<td>0.7</td>
</tr>
<tr>
<td>Central: unignited cloud right over population when ignition occurs</td>
<td>0.2</td>
</tr>
<tr>
<td>No ignition</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Likely consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire burning around edge of cloud (possibly leading to a fireball)</td>
</tr>
<tr>
<td>Flash fire or explosion</td>
</tr>
<tr>
<td>Hazard unlikely, though some flammable gas pockets possible</td>
</tr>
</tbody>
</table>
A7.10.6 Fire models and injury relations
The report gives a set of models for the following fire events: (1) pool fires; (2) fireballs; (3) BLEVEs; (4) flash fires.
The event which occurs will depend on the delay before ignition. The behaviour assumed is as follows:

<table>
<thead>
<tr>
<th>Delay before ignition</th>
<th>Liquefied gas release</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Refrigerated</td>
</tr>
<tr>
<td>Immediate ignition</td>
<td>Pool fire</td>
</tr>
<tr>
<td>(within seconds)</td>
<td></td>
</tr>
<tr>
<td>Slight delay</td>
<td>Diffusion flash</td>
</tr>
<tr>
<td>(up to 30 seconds)</td>
<td>fire</td>
</tr>
<tr>
<td>Longer delay</td>
<td>Premixed flash</td>
</tr>
<tr>
<td>(minutes)</td>
<td>fire/exlosion</td>
</tr>
</tbody>
</table>

For the various fire models the report refers to work by Considine (1981), evidently an early version of the paper by Considine and Grint (1985), which gives a similar set of models, as described in Chapter 16.

A7.10.7 Vapour cloud explosion model and injury relations
The vapour cloud explosion model covers both the probability that an explosion occurs given ignition and the effects of such an explosion. For the former the probabilities used are

<table>
<thead>
<tr>
<th>Size of cloud (te)</th>
<th>Explosion probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&gt;0</td>
<td>0.1 (LNG = 0.01)</td>
</tr>
<tr>
<td>&gt;100</td>
<td>1</td>
</tr>
</tbody>
</table>

For the effects of such an explosion use is made of the following relations based on the work of the ACHM:

\[ p_o = k M^2 \]  

\[ R = 30 M^4 \]  

\[ p_o = k' R \]

where \( M \) is the mass released (te), \( p_o \) the peak side-on overpressure (kPa), \( R \) the radius of the cloud (m) and \( k, k' \) are constants. Relationships are given as follows:

<table>
<thead>
<tr>
<th>Overpressure (kPa)</th>
<th>Hazard range (m)</th>
<th>Casualty probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.25R</td>
<td>0</td>
</tr>
<tr>
<td>7–21</td>
<td>(2–4.25)R</td>
<td>0.1</td>
</tr>
<tr>
<td>21–34</td>
<td>(1.35–2)R</td>
<td>0.25</td>
</tr>
<tr>
<td>34–48</td>
<td>(1.1–1.35)R</td>
<td>0.70</td>
</tr>
<tr>
<td>&gt;48</td>
<td>&lt;1.1R</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Further the authors quote the estimates of the ACMH that the overpressure at the centre of the cloud is likely to be about 103 kPa and at the edge about 69 kPa.

A7.10.8 Toxic injury relations
Injury relations are given for ammonia and for hydrogen fluoride. For these gases the authors state that the best information available to them on the LC\(_{50}\), the concentration lethal at the 50% level, is as follows:

<table>
<thead>
<tr>
<th>Time ( t ) (min)</th>
<th>Lethal concentration LC(_{50})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ammonia (kg/m(^3))</td>
</tr>
<tr>
<td>1</td>
<td>( 7 \times 10^{-3} )</td>
</tr>
<tr>
<td>5</td>
<td>4 \times 10^{-4}</td>
</tr>
<tr>
<td>10</td>
<td>3.5 \times 10^{-3}</td>
</tr>
<tr>
<td>30</td>
<td>1.2 \times 10^{-3}</td>
</tr>
<tr>
<td>60</td>
<td>5 \times 10^{-4}</td>
</tr>
</tbody>
</table>

They further state that these data may be fitted to the relation

\[ LC_{50} = k C^{0.9} \]  

where \( C \) is the concentration, \( LC_{50} \) the dose lethal at the 50% level and \( t \) time.

A7.11 Notation

Section A7.5

Subsection A7.5.5

\( A_H \) horizontal area of target  
\( A_t \) vertical area of target  
\( A' \) horizontal projection of vertical area of target  
\( F \) frequency of aircraft crash on target area  
\( F_H \) frequency of aircraft crash per unit of ground area  
\( F_v \) frequency of aircraft crash per unit of vertical area  

Subsection A7.5.7

\( g \) acceleration due to gravity (m/s\(^2\))  
\( h_l \) slumped liquid depth (m)  
\( r \) radius of flooded zone (m)  
\( r_s \) radius of source cylinder (m)  
\( t \) time after initiation of slumping (s)  
\( u_l \) slumped liquid velocity (m/s)  
\( V_s \) volume of source cylinder (m\(^3\))

Subsection A7.5.8

\( A_{HI} \) area of tank roof (m\(^2\))  
\( A_v \) exposed area of tank vertical sides (m\(^2\))  
\( c_p \) specific heat of tank wall (J/kg\(^\circ\)C)  
\( m \) mass of exposed tank wall (kg)  
\( Q_i \) heat input to tank (W)  
\( Q_c \) heat loss by convection (W)  
\( Q_r \) heat loss by radiation (W)  
\( t \) time (s)  
\( \epsilon \) emissivity of tank wall  
\( \theta_A \) absolute temperature of ambient air (K)  
\( \theta_T \) absolute temperature of tank wall (K)  
\( \Delta \theta \) temperature difference between tank and ambient air (°C)  
\( \sigma \) Stefan–Boltzmann constant (W/m\(^2\) K\(^4\))
Subsection A7.5.11

\( H \) heat of combustion of hydrocarbons (kcal)
\( \Delta p_m \) peak overpressure (bar)
\( q \) peak dynamic pressure (bar)
\( r \) distance (m)
\( W \) mass of hydrocarbons (t)
\( \alpha \) equivalence factor

Subsection A7.5.13

\( a, b \) constants
\( C \) concentration (g/m\(^3\))
\( D \) dosage ((g/m\(^3\))\(^{0.75}\) min)
\( \text{Pr} \) probit
\( t \) time (min)

Subsection A7.5.14

Equations A7.5.11–A7.5.13
\( g \) acceleration due to gravity
\( h \) height of cloud
\( r \) radius of cloud
\( r_o \) initial radius of cylinder
\( t \) time
\( V_o \) initial volume of cylinder
\( \rho_o \) density of air
\( \rho_o \) initial density of cloud

Equations A7.5.14–A7.5.20
\( h \) height of cloud (m)
\( Q^* \) mass released instantaneously (kg)
\( r \) radius of cloud (m)
\( t \) time (s)
\( u \) wind speed (m/s)

\( x, y \) distances in downwind, cross-wind directions (m)
\( \sigma_x, \sigma_y, \sigma_z \) dispersion coefficients in downwind, crosswind and vertical directions (m)
\( \chi \) concentration (kg/m\(^3\))
\( \lambda_{av} \) mean concentration along axis (kg/m\(^3\))
\( \lambda_{max} \) maximum concentration along axis (kg/m\(^3\))

Subsection A7.5.15

\( C \) concentration indoors
\( C_o \) concentration outdoors
\( t \) time
\( \lambda \) number of air changes per unit time

Section A7.10

Subsection A7.10.7
\( k, k' \) constants
\( K \) constant
\( M \) mass released (t)
\( p_o \) peak side-on overpressure (kPa)
\( R \) radius of cloud (m)

Subsection A7.10.8
\( C \) concentration
\( k \) constant
\( LCT_{50} \) dose lethal at 50% level
\( t \) time
Appendix Rijnmond Report

Contents
A8.1 The Investigation A8/2
A8.2 Installations and Activities A8/4
A8.3 Event Data A8/6
A8.4 Hazard Models A8/6
A8.5 Injury Relations A8/6
A8.6 Population Characteristics A8/6
A8.7 Mitigation of Exposure A8/8
A8.8 Individual Assessments A8/8
A8.9 Assessed Risks A8/18
A8.10 Remedial Measures A8/18
A8.11 Critiques A8/21
Another comprehensive hazard assessment is the Rijnmond study carried out for the Rijnmond Public Authority by Cremer and Warner.

This work is described in *Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, a Pilot Study* issued by the Rijnmond Public Authority (1982) (the *Rijnmond Report*).

The Rijnmond is the part of the Rhine delta between Rotterdam and the North Sea. Within the Rijnmond area of 15 x 40 km are located some one million people and a vast complex of oil, petrochemical and chemical industries as well as the largest harbour in the world. A description of the industrial complex at Rijnmond has been given by Molle and Wever (1984). A map of the Rijnmond showing the principal plant areas is given in Figure A8.1 and a diagram of the petrochemical complex in Figure A8.2. There are five oil refineries with a refining capacity of some 81 Mt/year, including the large refineries of Shell at Pernis and BP near Rozenburg, and major petrochemicals complexes operated by Shell, Gulf and Esso. Some of the other plants are described below.

A first note on the industrial hazards issued in 1976 by the Rijnmond Authority was strongly criticized by industry. Accordingly a commission, COVO, was set up with representatives of the Labour Inspectorate of the Ministry of Social Affairs, the Rijnmond Authority and industry. COVO decided to carry out a pilot study of six industrial installations in the Rijnmond in order to evaluate the applicability of risk assessment to decision-making on safety and commissioned Cremer and Warner to carry out the study. A steering committee was formed and the work was done to the requirements of this committee.

**A8.1 The Investigation**

The aim of the work was to evaluate the methods of risk assessment for industrial installations and to obtain experience in the practical application of these methods. Such evaluation was considered to be essential before any decision could be made on the role of such methods in the formulation of safety policy.

The objectives of the study were formulated so as to give an answer to the following questions:

1. What is the reliability of the assessment of the consequences and probabilities of possible accidents with industrial installations when the procedures and methodology of risk analysis are carried out to their full extent?
2. What problems and gaps in knowledge exist in the field of risk analysis?
3. How can the results of a risk analysis be presented conveniently, without losing important details, so that it may be used for safety policy decisions?
4. How well can the influence of risk reducing measures on the consequences and probabilities be calculated?
5. What resources are required, in time and money, to assess the risk with sufficient accuracy to be useful for safety policy decisions?

![Figure A8.1 Rijnmond harbour area (Molle and Wever, 1984)](image-url)
Figure A8.2 Petrochemical complex in the Rijnmond harbour area (Molle and Wever, 1984)
The COVO steering committee was reinforced with experts from industry. The committee also included representatives of the Battelle Institute who were charged with the task of scrutinizing the methodology and models used.

The overall approach taken in the investigation was

(1) to collect basic data and define the boundary limits of the installation;
(2) to identify the potential failure scenarios;
(3) to select and apply the best available calculation models for physical phenomena;
(4) to collect and apply the best available basic data and models to calculate the probabilities of such events;
(5) to choose and develop different forms of presentation of the final results;
(6) to investigate the sensitivity of the results for variations in the assumptions used and to estimate the accuracy and reliability of these results;
(7) to investigate the influence of risk reducing measures.

The investigation involved the identification of the principal hazards of the installation in the area, the assessment of the associated individual and societal risks, and the proposal of remedial measures to reduce the risks.

The project was planned to last one year but in fact took two and a half years and it cost some 2.5 m. guilders. A supplementary contract was placed with the consultants to study methods of presenting the results.

The report was published in 1982. It is in five parts. Part 1 is the report of the steering committee; Part 2 is the main Cremer and Warner study; Part 3 the supplementary Cremer and Warner study; Part 4 is the Battelle review; and Part 5 contains the industrial and other comments.

### A8.2 Installations and Activities

The six installations studied were as follows:

(1) Acrylonitrile storage (Paktank)
(2) Ammonia storage (UKF)
(3) Chlorine storage (AKZO)
(4) LNG storage (Gasunie)
(5) Propylene storage (Oxirane)
(6) Hydridesulphurizer (Shell)

The storages of acrylonitrile and LNG were at atmospheric pressure and those of ammonia, chlorine and propylene were all liquids under pressure. The acrylonitrile, ammonia and chlorine represented toxic materials and the LNG and propylene flammable materials. The hydridesulphurizer represented part of a process plant, the section studied being the diethanolamine stripper.

### Table A8.1 Rijnmond Report: summary of entries for the six installations (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Page</th>
<th>Acrylonitrile</th>
<th>Ammonia</th>
<th>Chlorine</th>
<th>LNG</th>
<th>Propylene</th>
<th>Hydrodesulphurizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main entry</td>
<td>81</td>
<td>111</td>
<td>151</td>
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<tr>
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<td>181, 355</td>
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<td>223, 362</td>
<td>240, 370</td>
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<tr>
<td>Release scenarios</td>
<td>91</td>
<td>113</td>
<td>154</td>
<td>187</td>
<td>203</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>Undesired events:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Events key</td>
<td>89</td>
<td>133</td>
<td>157</td>
<td>188</td>
<td>203</td>
<td>229</td>
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<tr>
<td>Event frequency</td>
<td>101</td>
<td>146</td>
<td>171</td>
<td>196</td>
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<tr>
<td>Failure data</td>
<td>97, 446</td>
<td>122, 462</td>
<td>170, 480</td>
<td>194, 497</td>
<td>209, 513</td>
<td>235</td>
<td></td>
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<tr>
<td>Other data</td>
<td>438</td>
<td></td>
<td>191</td>
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<tr>
<td>Fault trees</td>
<td>451</td>
<td>468</td>
<td>491</td>
<td>507</td>
<td>527</td>
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<td></td>
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<tr>
<td>Hazard models</td>
<td>96</td>
<td>115</td>
<td>156</td>
<td>189</td>
<td>205</td>
<td>228</td>
<td></td>
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<td>Injury relations:</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fire/explosion</td>
<td>319, 331</td>
<td>319, 331</td>
<td>319, 331</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Toxic effects</td>
<td>93, 340</td>
<td>145, 340</td>
<td>340</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Consequence results:</td>
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<td></td>
<td></td>
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<td></td>
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<td>Summary table</td>
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<tr>
<td>Fire/explosion</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toxic effects</td>
<td>93</td>
<td>135, 397</td>
<td>161</td>
<td>419</td>
<td>422</td>
<td>413</td>
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<td>Hazard ranges:</td>
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<td>Fire/explosion</td>
<td>96, 102</td>
<td>135, 102</td>
<td>161</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Toxic effects</td>
<td>95, 102</td>
<td>135</td>
<td>161</td>
<td></td>
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<td>Risk results:</td>
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<tr>
<td>Tables</td>
<td>102</td>
<td>135, 578</td>
<td>161</td>
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<td>Risk contours</td>
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<tr>
<td>FN tables</td>
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<td>596</td>
<td>603</td>
<td>604</td>
<td>608</td>
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<tr>
<td>FN curves</td>
<td>562</td>
<td>563</td>
<td>564</td>
<td>565</td>
<td>566</td>
<td>567</td>
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<tr>
<td>Evaluation</td>
<td>250</td>
<td>250</td>
<td>251</td>
<td>251</td>
<td>252</td>
<td>252</td>
<td></td>
</tr>
<tr>
<td>Remedial measures</td>
<td>107</td>
<td>130</td>
<td>180</td>
<td>199</td>
<td>213</td>
<td>238</td>
<td></td>
</tr>
</tbody>
</table>
Table A8.2  Rijnmond Report: some failure and event data used (after Rijnmond Public Authority, 1982)

A Data sources

| 4. Lees (1976b) | 13. SRS data bank |

B Event data

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Failure rate$^{a,b}$</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tanks and vessels</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure vessels:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>serious leakage</td>
<td>$1 \times 10^{-5}$/year</td>
<td>$6 \times 10^{-6}$-$2.6 \times 10^{-3}$/year</td>
<td>7, 9, 10</td>
</tr>
<tr>
<td>catastrophic rupture</td>
<td>$1 \times 10^{-6}$/year</td>
<td>$4.6 \times 10^{-5}$-$6.3 \times 10^{-7}$/year</td>
<td>12, 15</td>
</tr>
<tr>
<td>Atmospheric storage tanks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>serious leakage</td>
<td>$1 \times 10^{-4}$/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>catastrophic rupture</td>
<td>$6 \times 10^{-6}$/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerated storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tanks (double wall, high integrity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>serious leakage from inner tank</td>
<td>$2 \times 10^{-5}$/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>catastrophic rupture from both containments</td>
<td>$1 \times 10^{-6}$/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pumps, pipework, etc.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>failure to start</td>
<td>$1 \times 10^{-3}$/d</td>
<td>$5 \times 10^{-5}$-$5 \times 10^{-3}$/d</td>
<td>1</td>
</tr>
<tr>
<td>failure to run normally</td>
<td>$3 \times 10^{-5}$/h</td>
<td>$1 \times 10^{-2}$-$1 \times 10^{-4}$/h</td>
<td>1</td>
</tr>
<tr>
<td>failure to stop catastrophically</td>
<td>$1 \times 10^{-4}$/d</td>
<td>$4 \times 10^{-5}$-$1 \times 10^{-3}$/d</td>
<td>1, 11</td>
</tr>
<tr>
<td>Pipework</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt;50$ mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>significant leakage</td>
<td>$1 \times 10^{-8}$/sect. h</td>
<td></td>
<td>1, 9, 13, 15</td>
</tr>
<tr>
<td>catastrophic rupture</td>
<td>$1 \times 10^{-9}$/sect. h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;50$ mm, $&lt;150$ mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>significant leakage</td>
<td>$6 \times 10^{-9}$/sect. h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>catastrophic rupture</td>
<td>$3 \times 10^{-10}$/sect. h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;150$ mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>significant leakage</td>
<td>$3 \times 10^{-9}$/sect. h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>catastrophic rupture</td>
<td>$1 \times 10^{-10}$/sect. h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>heavily stressed</td>
<td>$4 \times 10^{-5}$/h</td>
<td></td>
<td>11, 14</td>
</tr>
<tr>
<td>lightly stressed</td>
<td>$4 \times 10^{-6}$/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading arms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>leakage</td>
<td>$3 \times 10^{-6}$/h</td>
<td>$1 \times 10^{-7}$-$1 \times 10^{-4}$/h</td>
<td>1, 11</td>
</tr>
<tr>
<td>catastrophic rupture</td>
<td>$3 \times 10^{-8}$/h</td>
<td>$1 \times 10^{-8}$-$1 \times 10^{-5}$/h</td>
<td></td>
</tr>
<tr>
<td><strong>Valves</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure relief valves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fails dangerously blocked</td>
<td>0.001/year</td>
<td>0.001-0.01/year</td>
<td>5, 7, 13</td>
</tr>
<tr>
<td>lifts heavy</td>
<td>0.004/year</td>
<td>(1.4 $\times 10^{-5}$-$3.6 \times 10^{-5}$/d)</td>
<td>1</td>
</tr>
<tr>
<td>lifts light/leakage</td>
<td>0.06/year</td>
<td>0.02-0.09/year</td>
<td>1, 5, 7</td>
</tr>
<tr>
<td>Vacuum relief valves</td>
<td>0.005/year</td>
<td>($1 \times 10^{-5}$-$1 \times 10^{-4}$/d)</td>
<td>1</td>
</tr>
<tr>
<td>Other data taken from references 1, 5, 6, 7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Instrumentation
Data taken from references 1, 5, 6, 7, 13, 16, 17

Electrical equipment
Battery supply
failure to provide  $1 \times 10^{-6}$/h  $1 \times 10^{-7-6} \times 10^{-6}$/h  1, 7
proper output (in standby mode)
Electric motors
failure to start  $3 \times 10^{-4}$/d  $7 \times 10^{-5-3} \times 10^{-3}$/d  1
failure to run  $7 \times 10^{-6}$/h  $5 \times 10^{-7-1} \times 10^{-4}$/h  1, 7
Emergency diesel system (complete)
failure to start  $3 \times 10^{-2}$/d  $1 \times 10^{-3-1} \times 10^{-1}$/d  1
failure to run  $3 \times 10^{-3}$/h  $1 \times 10^{-4-1} \times 10^{-3}$/h  1

* The unit d in this table stands for demand.
* The failure rates taken from the Rasmussen Report correspond to the median values there quoted.
* Values per metre run are also given and are one tenth of those per section.
* Following data are given for range:

<table>
<thead>
<tr>
<th>Industry</th>
<th>Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 75 mm</td>
<td>$2 \times 10^{-8-5} \times 10^{-6}$/sect. h</td>
</tr>
<tr>
<td>&gt; 75 mm</td>
<td>$1 \times 10^{-10-5} \times 10^{-9}$/sect. h</td>
</tr>
</tbody>
</table>

The context of these installations is described by Molle and Wever and accounts of the individual installations are given below.
The report is organized partly by installation and partly by themes and material on a particular installation is therefore given dispersed. Table A8.1 gives a summary of the entries for each installation.

A8.4 Hazard Models
The principal hazard models used are given in Table A8.4 and their application is described in the sections on particular installations.

A8.5 Injury Relations
The injury relations used are given in Table A8.5 and their application is described in the sections on particular installations.

A8.6 Population Characteristics
The study covered the risks both to employees and to the public. For the off-site population a grid was used showing the number of people over an area of some 75 km², which covered the whole of the Rijnmond. Populations were estimated for each 500 m square using data from the 1971 census, updated in 1975.

A8.3 Event Data
The event data used in the study were a mixture of generic data, plant data and estimates. Some failure and event data and some external event data used are given in Tables A8.2 and A8.3, respectively. Other data are given in the sections on particular installations.

Table A8.3  Rijnmond Report: some external events data used (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency&lt;sup&gt;a&lt;/sup&gt; (events/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Generic</td>
</tr>
<tr>
<td>Earthquake</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Subsidence</td>
<td>$2 \times 10^{-9}$</td>
</tr>
<tr>
<td>Flooding</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Vehicular intrusion</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>Mechanical impact</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Major fire</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>

<sup>a</sup> Frequencies for these events are not given for the hydrodesulphurizer.
<sup>b</sup> Estimate based on fact that major fire would cause immediate ignition, not a vapour cloud.
<sup>c</sup> Estimate towards higher end of range due to flammable nature of products stored.
Table A8.4 Rijnmond Report: some hazard models used

<table>
<thead>
<tr>
<th>Event</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fauske–Cude (Fauske, 1964; Cude, 1975)</td>
</tr>
<tr>
<td>A. Emission</td>
<td>Fauske–Cude (Fauske, 1964; Cude, 1975)</td>
</tr>
<tr>
<td>A. Vessel containing liquid at atmospheric pressure</td>
<td>Fauske–Cude (Fauske, 1964; Cude, 1975)</td>
</tr>
<tr>
<td>A. Vessel containing liquid above atmospheric boiling point</td>
<td>Fauske–Cude (Fauske, 1964; Cude, 1975)</td>
</tr>
<tr>
<td>A. Vessel containing gas only</td>
<td>Fauske–Cude (Fauske, 1964; Cude, 1975)</td>
</tr>
<tr>
<td>Two-phase flow</td>
<td>Fauske–Cude (Fauske, 1964; Cude, 1975)</td>
</tr>
<tr>
<td>B</td>
<td>Shaw and Briscoe (1978 SRD R100)</td>
</tr>
<tr>
<td>B. Vaporization</td>
<td>Shaw and Briscoe (1978 SRD R100)</td>
</tr>
<tr>
<td>B. Spreading of liquid spill</td>
<td>Shaw and Briscoe (1978 SRD R100)</td>
</tr>
<tr>
<td>B. Vaporization of cryogenic liquid</td>
<td>Shaw and Briscoe (1978 SRD R100); AGA (1974)</td>
</tr>
<tr>
<td>B. on water</td>
<td>Shaw and Briscoe (1978 SRD R100); AGA (1974)</td>
</tr>
<tr>
<td>B. on land</td>
<td>Shaw and Briscoe (1978 SRD R100); AGA (1974)</td>
</tr>
<tr>
<td>B. Combined spreading and vaporization of cryogenic liquid on land</td>
<td>Shaw and Briscoe (1978 SRD R100); AGA (1974)</td>
</tr>
<tr>
<td>B. Vaporization from spill into complex bunds</td>
<td>Shaw and Briscoe (1978 SRD R100); AGA (1974)</td>
</tr>
<tr>
<td>B. Evaporation of volatile liquid</td>
<td>Shaw and Briscoe (1978 SRD R100); AGA (1974)</td>
</tr>
<tr>
<td>C</td>
<td>Pasquill (1943), Opschoor (1978)</td>
</tr>
<tr>
<td>C. Gas dispersion</td>
<td>Pasquill (1943), Opschoor (1978)</td>
</tr>
<tr>
<td>C. Neutral density gas dispersion</td>
<td>Pasquill–Gifford</td>
</tr>
<tr>
<td>C. Dense gas dispersion</td>
<td>Pasquill–Gifford</td>
</tr>
<tr>
<td>C. Dispersion of jet of dense gas</td>
<td>Pasquill–Gifford</td>
</tr>
<tr>
<td>D</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>D. Vapour cloud combustion</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>D. Initial dilution with air</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>D. continuous release</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>D. instantaneous release</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>D. Ignition sources</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>D. Fire vs explosion</td>
<td>Empirical relation</td>
</tr>
<tr>
<td>E</td>
<td>TNO (Wiekema, 1980)</td>
</tr>
<tr>
<td>E. Vapour cloud explosion</td>
<td>TNO (Wiekema, 1980)</td>
</tr>
<tr>
<td>E. Vapour cloud explosion</td>
<td>TNO (Wiekema, 1980)</td>
</tr>
<tr>
<td>F</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. Pool fire</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. Flame emissivity</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. Liquid burning rate</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. Flame length</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. Flame tilt</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. Fraction of heat radiated</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>F. View factor</td>
<td>Ooms, Mahieu and Zelis (1974)</td>
</tr>
<tr>
<td>G</td>
<td>Reim, Slipecevich and Welker (1970)</td>
</tr>
<tr>
<td>G. Jet flame</td>
<td>Reim, Slipecevich and Welker (1970)</td>
</tr>
<tr>
<td>G. Flame length</td>
<td>Reim, Slipecevich and Welker (1970)</td>
</tr>
<tr>
<td>G. Deflection effect</td>
<td>Reim, Slipecevich and Welker (1970)</td>
</tr>
<tr>
<td>G. Buoyancy and liquid effects</td>
<td>Reim, Slipecevich and Welker (1970)</td>
</tr>
<tr>
<td>G. View factor</td>
<td>Reim, Slipecevich and Welker (1970)</td>
</tr>
<tr>
<td>H</td>
<td>R.W. High (1968)</td>
</tr>
<tr>
<td>H. Fireball</td>
<td>R.W. High (1968)</td>
</tr>
<tr>
<td>H. Fireball dimensions</td>
<td>R.W. High (1968)</td>
</tr>
<tr>
<td>H. radius</td>
<td>R.W. High (1968)</td>
</tr>
<tr>
<td>H. duration</td>
<td>R.W. High (1968)</td>
</tr>
<tr>
<td>H. View factor</td>
<td>R.W. High (1968)</td>
</tr>
<tr>
<td></td>
<td>McGuire (1953)</td>
</tr>
</tbody>
</table>

Both day and night time populations were determined, day being defined as the working week of 45 hours and night as the remaining 123 hours.

Outside the population grid average population densities were used. These were required only in cases where an exceptionally large cloud occurred.
Table A8.5 Rijnmond Report: some injury relations used

<table>
<thead>
<tr>
<th>Incident thermal radiation (kW/m²)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>Level insufficient to cause discomfort for long exposures</td>
</tr>
<tr>
<td>4.5</td>
<td>Level sufficient to cause pain if subject does not reach cover in 20 s; blistering of skin likely (first degree burns)</td>
</tr>
<tr>
<td>12.5</td>
<td>Minimum level for piloted ignition of wood, melting of plastic tubing, etc.</td>
</tr>
<tr>
<td>25</td>
<td>Minimum level for unpiloted ignition of wood at infinitely long exposures</td>
</tr>
<tr>
<td>37.5</td>
<td>Level sufficient to damage process equipment</td>
</tr>
</tbody>
</table>

B Fire: Unsteady state

<table>
<thead>
<tr>
<th>Incident thermal radiation dose threshold (kJ/m²)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>Threshold of pain; no reddening or blistering of skin</td>
</tr>
<tr>
<td>125</td>
<td>First degree burns</td>
</tr>
<tr>
<td>250</td>
<td>Second degree burns</td>
</tr>
<tr>
<td>375</td>
<td>Third degree burns</td>
</tr>
</tbody>
</table>

C Explosion

<table>
<thead>
<tr>
<th>Blast overpressure (bar)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>Window breakage, possibly causing some injuries</td>
</tr>
<tr>
<td>0.1</td>
<td>Repairable damage; light structures collapse; pressure vessels remain intact</td>
</tr>
<tr>
<td>0.3</td>
<td>Major structural damage (assumed fatal to people inside buildings or other structures)</td>
</tr>
</tbody>
</table>

D Toxic effects

Data given in terms of constants in probit equation for fatalities

\[ Y = k_1 + k_2 \ln \Sigma C^m T \]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Constants</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( LTL_{50} ) (ppm²·min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile</td>
<td>1</td>
<td>-30.57</td>
<td>1.385</td>
<td>( 8.15 \times 10^3 )</td>
</tr>
<tr>
<td>Ammonia</td>
<td>2.5</td>
<td>-17.1</td>
<td>1.69</td>
<td>( 1.22 \times 10^{10} )</td>
</tr>
<tr>
<td>Chlorine</td>
<td>2.75</td>
<td></td>
<td></td>
<td>( 5.46 \times 10^4 )</td>
</tr>
<tr>
<td>Hydrogen sulphide</td>
<td>2.75</td>
<td></td>
<td></td>
<td>( 1.6 \times 10^8 )</td>
</tr>
</tbody>
</table>

For the particular installations studied data were obtained on the numbers of employees present during day and night and on their locations. The on-site population \( N_c \) was estimated from the relation

\[ N_c = \frac{(5N_d + 16N_h) \times 52}{(5 \times (52 - n_h))} \]

where \( n_h \) is the number of weeks off for holidays, sickness, etc., \( N_d \) the numbers present during the working day and \( N_h \) the numbers present at all other times.

For toxic gas hazard it was assumed that 1% of the population are indoors. This estimate includes an allowance for people taking shelter. For explosion hazard it was assumed that 10% are outdoors.

A8.8 Individual Assessments

A8.8.1 Acrylonitrile storage (Paktank)

The acrylonitrile storage is one of a number of storages at the Botlek terminal of Paktank, a tank storage company providing bulk storage and associated services to the oil and chemical industries.

There are normally two or three tanks containing acrylonitrile (AN). The study was confined to a single tank and associated transfer systems which had been dedicated to handling AN for some years. This AN tank is one of a number of fixed roof tanks located in a tank bund which is at the centre of the site.

The tank has a capacity of 3700 m³. It is designed to withstand small variations of internal pressure, the
### Table A8.6 Rijnmond Report: summary of assessment of acrylonitrile storage (Paktank) (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency</th>
<th>Mass flow or mass</th>
<th>Duration</th>
<th>Average no. of fatalities to public(b,c) (deaths/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(events/year)</td>
<td>(kg/s or kg)</td>
<td>(s)</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>4.3 \times 10^{-5}</td>
<td>1.85 \times 10^{6}</td>
<td></td>
<td>7.6 \times 10^{-6}</td>
</tr>
<tr>
<td>P2</td>
<td>2.0 \times 10^{-4}</td>
<td>1.85 \times 10^{6}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>1.8 \times 10^{-4}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>1.0 \times 10^{-4}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>1.5 \times 10^{-3}</td>
<td></td>
<td>200 m³/h</td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td>5 \times 10^{-6}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P7</td>
<td>2 \times 10^{-5}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P8</td>
<td>9 \times 10^{-7}</td>
<td>1.85 \times 10^{6}</td>
<td></td>
<td>3.2 \times 10^{-7}</td>
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<tr>
<td>P9</td>
<td>5.2 \times 10^{-5}</td>
<td></td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>P10</td>
<td>2.6 \times 10^{-3}</td>
<td></td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>P11</td>
<td>8.8 \times 10^{-6}</td>
<td></td>
<td>900</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.9 \times 10^{-6}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event</th>
<th>Mass flow or mass</th>
<th>Duration</th>
<th>Average no. of fatalities to public (deaths/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg/s or kg)</td>
<td>(s)</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>1.85 \times 10^{6}</td>
<td></td>
<td>7.6 \times 10^{-6}</td>
</tr>
<tr>
<td>P2</td>
<td>1.85 \times 10^{6}</td>
<td></td>
<td></td>
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<tr>
<td>P3</td>
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<tr>
<td>P4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td></td>
<td></td>
<td>200 m³/h</td>
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<tr>
<td>P6</td>
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<td>P7</td>
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<td></td>
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<tr>
<td>P8</td>
<td></td>
<td></td>
<td>1.85 \times 10^{6}</td>
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<tr>
<td>P9</td>
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<tr>
<td>P10</td>
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<td>P12</td>
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<td>900</td>
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<td></td>
</tr>
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<td>P28</td>
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</tr>
</tbody>
</table>

### B Hazard scenarios
- Spillage into bund
- Evaporation from bund
- Gas dispersion (from continuous source)
- Pool fire in bund
- Flash fire in vapour cloud

### C Fault trees
- P1 Catastrophic rupture of tank
  - P1.1 Severe overpressurization of tank
    - P1.1.1 Pressurization of tank with nitrogen
    - P1.1.2 Severe polymerization within tank
    - P1.2 Severe tank depressurization
  - P1.4 Severe polymerization in tank
- P5 Tank overfilled up to breather valve level
  - P5.1 High level detected, incorrect action taken

---

\(a\) There are 15 further events:

- P12 Transfer line leakage
- P15 Transfer hose leakage
- P16 Transfer line rupture
- P17 Transfer hose rupture
- P18 Transfer line/hose rupture
- P19 Transfer line/hose rupture
- P20 Transfer line/hose leakage
- P21 AN transfer line/hose leakage

None of these events causes an average number of fatalities to the public > 10^{-5}/year.

\(b\) For both cases P1 and P8 the typical hazard distances to the LTL\(_{90}\) are 76 m and to the LTL\(_{95}\), 126 m. These are the greatest hazard distances quoted.

\(c\) For all cases the typical hazard distances for fatal effects from fire are < 10 m. No hazard distances for fatal effects from explosion are quoted.

\(d\) Maximum rate (pump rate).

breather valves were being designed to open at an over-pressure of 200 mmHg and a vacuum of 50 mmHg.

Operation at the site is flexible, but in the preceding two years only six modes of transfer had been recorded, these being loading of coastal barges; loading of road tankers; loading of rail tank cars; filling from coastal barges and chemical tankers; filling from sample tanks; and transfer between this tank and others at the site.

A summary of the risk assessment for the AN storage is given in Table A8.6. Section A of the table lists the undesired events considered, Section B the hazard scenarios and Section C the main fault trees.
Figure A8.3 Rijnmond Report: fault trees for release from the acrylonitrile storage (Rijnmond Public Authority, 1982. Reproduced by permission.): (a) head of tree for top event 'catastrophic rupture of tank'; (b) sub-tree for 'tank overpressurization'; and (c) sub-tree for 'tank depressurization'
Figure A8.3 continued
Figure A8.3 continued
Table A8.7 Rijnmond Report: summary of assessment of ammonia storage (UKF) (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency (events/year)</th>
<th>Mass flow or mass (kg/s or kg)</th>
<th>Duration (s)</th>
<th>Average no. of fatalities to publica (deaths/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U0</td>
<td>$2.3 \times 10^{-7}$</td>
<td>682000</td>
<td>1</td>
<td>$54 \times 10^{-6}$</td>
</tr>
<tr>
<td>U1</td>
<td>$1.8 \times 10^{-6}$</td>
<td>250000</td>
<td>1</td>
<td>$67 \times 10^{-6}$</td>
</tr>
<tr>
<td>U2.1</td>
<td>$5.6 \times 10^{-7}$</td>
<td>166</td>
<td>1200</td>
<td>$27 \times 10^{-6}$</td>
</tr>
<tr>
<td>U2.3</td>
<td>$2.1 \times 10^{-7}$</td>
<td>83</td>
<td>3000</td>
<td>$11 \times 10^{-6}$</td>
</tr>
<tr>
<td>U2.4</td>
<td>$1.9 \times 10^{-4}$</td>
<td>83</td>
<td>86</td>
<td>0</td>
</tr>
<tr>
<td>U3</td>
<td>$4.2 \times 10^{-6}$</td>
<td>36</td>
<td>6950</td>
<td>$38 \times 10^{-6}$</td>
</tr>
<tr>
<td>U4</td>
<td>$4.4 \times 10^{-6}$</td>
<td>39</td>
<td>6400</td>
<td>$9 \times 10^{-6}$</td>
</tr>
<tr>
<td>U5</td>
<td>$1.0 \times 10^{-5}$</td>
<td>9.2</td>
<td>&gt; 10000</td>
<td>$40 \times 10^{-6}$</td>
</tr>
<tr>
<td>U7</td>
<td>$1.4 \times 10^{-5}$</td>
<td>22</td>
<td>300</td>
<td>$56 \times 10^{-6}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>$197 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

B Hazard scenarios
Sphere catastrophic failure: instantaneous release
Pipeline rupture: continuous release

C Fault trees
U1 Sphere rupture
  U1.1 Support failure
  U1.2 Excess external heat
  U1.3 Excess of pressure
  U1.3.1 Overfilling with liquid
  U1.3.2 Chemically incompatible material introduced
  U1.4 Mechanical defect
  U1.4.1 Stress corrosion cracking
  U1.4.2 Corrosive material introduced from rail cars

a For these 9 cases the typical hazard distances to the LTL90 are 2308, 1497, 671, 575, 241, 374, 23, 63, 87 m and to the LTL05, 2775, 1819, 893, 755, 327, 501, 100, 103 and 142 m, respectively.
b Equivalent to a hypothetical 50 mm hole.

An escape from the tank into the bund, though instantaneous, gives rise to a constant evaporation rate and hence acts as a continuous source. Releases from the pipework are also continuous sources.

The frequency of the releases is estimated using the seven fault trees listed as shown in Figure A8.3. The table giving the frequency and event data for these trees contains 81 entries. Of these some 30 are derived from the generic data given in Tables A8.2 and A8.3 and the rest from other sources, mainly company data, meteorological data or judgement.

For fire hazard it was assumed that 10% of all major spillages or resulting vapour clouds and 5% of significant spillages ignite and that an operator present at the release or ignition source receives fatal burns in 80% of cases. The hazard distances obtained are shown in the table as < 10 m.

For toxic gas hazard the exposure is continuous. In most cases only employees were at risk. A 10 min exposure was assumed for employees, who are alert to the hazard.

It was found, however, that serious toxic effects were possible to the public from a major spill (P1) if the exposure time was 30 min.

For the public credit was given for evacuation, usually 90-100%, depending on the warning time.
### Table A8.8 Rijnmond Report: summary of assessment of chlorine storage (AKZO) (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Eventa</th>
<th>Frequency</th>
<th>Mass flow or mass (kg/s or kg)</th>
<th>Duration (s)</th>
<th>Average no. of fatalities to publicb (deaths/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.1 Catastrophic burst, full</td>
<td>$0.93 \times 10^{-7}$</td>
<td>100 000</td>
<td>1</td>
<td>$2.59 \times 10^{-5}$</td>
</tr>
<tr>
<td>A1.2 Catastrophic burst, half full</td>
<td>$0.74 \times 10^{-6}$</td>
<td>50 000</td>
<td>1</td>
<td>$7.47 \times 10^{-5}$</td>
</tr>
<tr>
<td>A2.1 Split below liquid, $\Delta p = 6.5$ bar</td>
<td>$0.83 \times 10^{-6}$</td>
<td>63</td>
<td>790</td>
<td>$1.03 \times 10^{-4}$</td>
</tr>
<tr>
<td>A2.2 Split below liquid, $\Delta p = 9$ bar</td>
<td>$0.83 \times 10^{-6}$</td>
<td>76</td>
<td>660</td>
<td>$1.03 \times 10^{-4}$</td>
</tr>
<tr>
<td>A3.1 Split above liquid level, $\Delta p = 6.5$ bar</td>
<td>$0.83 \times 10^{-6}$</td>
<td>14</td>
<td>3500</td>
<td>$0.82 \times 10^{-4}$</td>
</tr>
<tr>
<td>A3.2 split above liquid level, $\Delta p = 9$ bar</td>
<td>$0.83 \times 10^{-6}$</td>
<td>26</td>
<td>1900</td>
<td>$0.82 \times 10^{-4}$</td>
</tr>
<tr>
<td>A4.1h Fracture of connection, full bore, $\Delta p = 6.5$ bar, angled horizontally</td>
<td>$3 \times 10^{-7}$</td>
<td>94</td>
<td>530</td>
<td>$3.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>A4.1d Fracture of connection, full bore, $\Delta p = 6.5$ bar, angled down</td>
<td>$3 \times 10^{-7}$</td>
<td>300</td>
<td>166</td>
<td>$3.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>A4.2h Fracture of connection, full bore, $\Delta p = 9$ bar, angled horizontally</td>
<td>$3 \times 10^{-7}$</td>
<td>110</td>
<td>450</td>
<td>$3.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>A4.4h Fracture of connection, small leak $\Delta p = 6.5$ bar, angled horizontally</td>
<td>$6 \times 10^{-6}$</td>
<td>5.8</td>
<td>3600</td>
<td>$9.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>A4.3d Fracture of connection, small leak, $\Delta p = 9.5$ bar, angled down</td>
<td>$6 \times 10^{-6}$</td>
<td>2.2</td>
<td>3600</td>
<td>$4.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>A4.4h Fracture of connection, small leak, $\Delta p = 9$ bar, angled horizontally</td>
<td>$6 \times 10^{-6}$</td>
<td>6.9</td>
<td>3600</td>
<td>$9.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>A4.4d Fracture of connection, small leak, $\Delta p = 6.5$ bar, angled down</td>
<td>$6 \times 10^{-6}$</td>
<td>2.6</td>
<td>3600</td>
<td>$4.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>A7.3 Full bore fracture of liquid line, valve open</td>
<td>$2.4 \times 10^{-6}$</td>
<td>64/32</td>
<td>56/1500</td>
<td>$9 \times 10^{-5}$</td>
</tr>
<tr>
<td>A7.4 Full bore fracture of liquid line, valve open, later shut</td>
<td>$7.4 \times 10^{-6}$</td>
<td>64/32</td>
<td>56/44</td>
<td>$5.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>A11.5 Full bore fracture of liquid line, at end, valve open, later shut</td>
<td>$5.9 \times 10^{-5}$</td>
<td>160/100</td>
<td>60/240</td>
<td>$4.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>A11.6 Full bore fracture of liquid line, small leak</td>
<td>$1.2 \times 10^{-3}$</td>
<td>3.6/1.3</td>
<td>300/2300</td>
<td>$1.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>A15.1 Full bore fracture of vapour line, valves open, later shut</td>
<td>$6.6 \times 10^{-6}$</td>
<td>15</td>
<td>300</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>A17.2 Full bore fracture of liquid line, at end, valves open, later shut</td>
<td>$8 \times 10^{-6}$</td>
<td>64/32</td>
<td>23/280</td>
<td>$6.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total (37 events)</td>
<td></td>
<td></td>
<td></td>
<td>$3.57 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

B Hazard scenarios
- Tank catastrophic failure: instantaneous release
- Tank leak: mixed and continuous release
- Pipework leak: mixed and continuous release

C Fault trees
- A1 Tank rupture
  - A1.2 Pressure of water in tank
  - A1.3 Internal explosion in tank
  - A1.4a Bursting disc does not relieve
  - A1.4b Source of overpressure potential
  - A1.5 Overpressure due to liquid overfilling

---

*a* There are 17 further events. None of these events causes an average number of fatalities to the public greater than $10^{-5}$/y.

*b* For these 20 cases the typical hazard distances to the LTL_{50} are 6500, 4900, 3400 (× 2), 2200 (× 2), 4700 (× 4), 1100 (× 4), 2100, 1600 (× 2), 1100 and 1600 m and to the LTL_{50} 8600, 6400, 4200 (× 2), 2800 (× 2), 6000 (× 2), 1400 (× 4), 2600, 2000 (× 2), 1400 and 2000 m, respectively.
Table A8.9  Rijmond Report: summary of assessment of LNG storage (Gasunie) (after Rijmond Public Authority, 1982)

A Undesired events

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Mass flow or mass</th>
<th>Duration</th>
<th>Average no. of fatalities to public&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(events/year)</td>
<td>(kg/s or kg)</td>
<td>(s)</td>
<td>(deaths/year)</td>
</tr>
<tr>
<td>G1 Catastrophic failure of tank</td>
<td>0.8 x 10^-6 0.126</td>
<td>19 x 10^6</td>
<td>1</td>
<td>6.3 x 10^-10</td>
</tr>
<tr>
<td>G2 Failure of tank into earth bund</td>
<td>1 x 10^-9 0.144</td>
<td>19 x 10^6</td>
<td>1</td>
<td>3.5 x 10^-12</td>
</tr>
<tr>
<td>G3.1 Fracture of line (no pumping)</td>
<td>2.5 x 10^-7 0.051</td>
<td>60</td>
<td>35</td>
<td>4.5 x 10^-11</td>
</tr>
<tr>
<td>G3.2 Fracture of line, other place (no pumping)</td>
<td>8.1 x 10^-7 0.027</td>
<td>60</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>G4.1 Fracture of line (pumping)</td>
<td>1.5 x 10^-8 0.06</td>
<td>100</td>
<td>600</td>
<td>4.1 x 10^-12</td>
</tr>
<tr>
<td>G4.2 Fracture of line, other place (pumping)</td>
<td>4.8 x 10^-8 0.0585</td>
<td>100</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>6.8 x 10^-10</td>
</tr>
</tbody>
</table>

B Hazard scenarios

Inner tank failure: instantaneous release
Concrete containment failure: instantaneous release
Pipe failure: rupture: continuous release (short)
Spreading of liquid
Vaporization of liquid
Pool fire
Flash fire

C Fault trees

G1 Tank rupture
  G1.1 Other sources of overpressurization
  G1.2 Excessive underpressurization
  G1.3 Internal explosion

<sup>a</sup> For each case the probability of immediate ignition is 0.1 and that of ignition when dispersed is given by the second entry in the column.

<sup>b</sup> For these six cases the typical hazard distances for fatal effects from fire are 211, 174, 152, 210, 151 and 199 m, respectively. No hazard distances are quoted for fatal effects from explosion.

Typical hazard distances to the LTI<sub>50</sub> of 76 m are given in Table A8.6. The distances are greater for adverse weather conditions, being on the centreline for 2.0/F and 1.5/D conditions 575 and 260 m to the LTI<sub>50</sub> and 879 and 365 m to the LTI<sub>450</sub>, respectively.

A8.8.2 Ammonia storage (UKF)

The ammonia storage is part of a complex of plants producing ammonia, nitric acid, ammonium nitrate, urea and other fertilizers at the Pernis site of UKF.

The ammonia is stored in a sphere under pressure at atmospheric temperature. The capacity of the sphere is 1000 m<sup>3</sup>, but the average inventory is only 40% of this. The ambient temperature was taken in the study as 15°C which corresponds to a pressure of 7.1 bar.

Ammonia is transferred to the sphere from rail tank cars or from the ammonia plant. Transfer of the liquid ammonia from the rail tank car is effected by pressurizing the tank car with ammonia vapour from the sphere and from the ammonia plant by pumps. Ammonia is transferred from the sphere to the downstream plants by pumps.

An escape from a sphere may constitute an instantaneous or a continuous source. Catastrophic rupture of a sphere was taken as equivalent to an instantaneous release, other escapes to continuous releases.

A summary of the risk assessment for the ammonia storage is given in Table A8.7. Sections A-C list the undesired events, the hazard scenarios and the main fault trees.

Ammonia constitutes both a flammable and toxic hazard, but since the toxic effects can occur at concentrations one hundredfold less than the flammable effect, only the former were considered.

A8.8.3 Chlorine storage (AKZO)

The chlorine storage consists of five spheres associated with chlorine cellrooms at the Botlek site of AKZO.

The chlorine is stored in the spheres in two separate tanks. Each sphere has a capacity of 90 m<sup>3</sup> and can therefore hold 100 te, but at any given time one of the spheres is used as a dump tank, so that the capacity of the storage is 400 te. At ambient temperature the sphere pressure is 6.5 bar, but pressure...
Table A8.10 Rijnmond Report: summary of assessment of propylene storage (Oxirane) (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency</th>
<th>Mass flow or mass</th>
<th>Duration</th>
<th>Average no. of fatalities to public</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(events/year)</td>
<td>(kg/s or kg)</td>
<td>(s)</td>
<td>(deaths/year)</td>
</tr>
<tr>
<td>O.01 Failure of full sphere</td>
<td>0.028 × 10^-6</td>
<td>600 000</td>
<td>I</td>
<td>1.43 × 10^-7</td>
</tr>
<tr>
<td>O.02 Failure of sphere containing 300 te</td>
<td>0.233 × 10^-6</td>
<td>300 000</td>
<td>I</td>
<td>1.52 × 10^-6</td>
</tr>
<tr>
<td>O.03 Full rate from sphere relief valve</td>
<td>2.0 × 10^-5</td>
<td>0.001</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>O.04 Failure of connection</td>
<td>3.5 × 10^-7</td>
<td>455</td>
<td>1300</td>
<td>2.2 × 10^-7</td>
</tr>
<tr>
<td>O.05 Failure of liquid line</td>
<td>1.3 × 10^-6</td>
<td>233</td>
<td>2570</td>
<td>5.3 × 10^-7</td>
</tr>
<tr>
<td>O.06 Failure of connection</td>
<td>33</td>
<td>202</td>
<td>C</td>
<td>3.6 × 10^-7</td>
</tr>
<tr>
<td>O.09 Failure of liquid line</td>
<td>5.8 × 10^-6</td>
<td>104</td>
<td>C</td>
<td>1.5 × 10^-6</td>
</tr>
<tr>
<td>O.20 Failure of liquid line</td>
<td>2.4 × 10^-5</td>
<td>230</td>
<td>C</td>
<td>13.2 × 10^-6</td>
</tr>
<tr>
<td>O.21 Failure of liquid line</td>
<td>1.4 × 10^-5</td>
<td>230</td>
<td>C</td>
<td>9.0 × 10^-6</td>
</tr>
<tr>
<td>O.25 Failure of liquid line</td>
<td>3.6 × 10^-6</td>
<td>280</td>
<td>C</td>
<td>1.04 × 10^-6</td>
</tr>
<tr>
<td>O.26 Failure of liquid line</td>
<td>2.0 × 10^-5</td>
<td>104</td>
<td>C</td>
<td>2.1 × 10^-6</td>
</tr>
<tr>
<td>O.30 Failure of liquid line</td>
<td>1.1 × 10^-5</td>
<td>230</td>
<td>C</td>
<td>6.2 × 10^-6</td>
</tr>
<tr>
<td>Total (31 cases)</td>
<td></td>
<td></td>
<td></td>
<td>3.66 × 10^-5</td>
</tr>
</tbody>
</table>

B Hazard scenarios
- Sphere failure: instantaneous release
- Vaporizer shell failure: instantaneous release
- Pipework failure: continuous release
- Gas dispersion
- Ignition probability
- Flash fire
- Explosion

C Fault trees
- O1 Sphere rupture
  - O1.1 Gross overstressing of shell
  - O1.1.1 Gas phase pressurization of sphere
  - O1.1.1.1 High temperature and pressure from jetty vaporizer
  - O1.1.1.2 Manual and power valves in circuit round spheres/vaporizer liquid and vapour lines all open
  - O1.1.2 Internal explosion in sphere
  - O1.1.3 Wrong material loaded
  - O1.1.4 Liquid overfilling
  - O1.1.4.1 Overfilling from ship
  - O1.1.4.2 Overfilling from rail car
  - O1.2 Mechanical defect in sphere shell
  - O1.2.1 Wrong material loaded (see tree for O1.1.3)

\* There are 19 further cases. None of these events causes an average number of fatalities to the public > 10^-6/year.

\* For each case the probability of immediate ignition is 0.1 and that of ignition when dispersed is given by the second entry in the column.

\* For these 12 cases the typical hazard distances for fatal effects from fire are 353, 338, 47, 125, 154, 105, 110, 138, 218, 268, 118 and 147 m, respectively. The hazard distances for explosion are given for overpressures of 0.3, 0.1 and 0.03 bar. For the former the distances are 207, 164, 28, 62, 74, 51, 56, 68, 88 and 102 m, respectively.
Table A8.11  Rijnmond Report: summary of assessment of hydrodesulphurizer (Shell) (after Rijnmond Public Authority, 1982)

A  Undesired events

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency (events/year)</th>
<th>Mass flow or mass (kg/s or kg)</th>
<th>Duration (s)</th>
<th>Average no. of fatalities to public (deaths/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1.1 Major failure H₂S line, elevated, 1 min duration</td>
<td>3.2 × 10⁶</td>
<td>1.21</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>S1.2 Major failure H₂S line, elevated, 10 min duration</td>
<td>3.2 × 10⁶</td>
<td>1.21</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>S1.3 Major failure H₂S line, elevated, extended duration</td>
<td>7.2 × 10⁷</td>
<td>1.21</td>
<td>long</td>
<td>0</td>
</tr>
<tr>
<td>S2.1 Major failure H₂S line, low level, 1 min duration</td>
<td>3.2 × 10⁶</td>
<td>1.21</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>S2.2 Major failure H₂S line, low level, 10 min duration</td>
<td>3.2 × 10⁶</td>
<td>1.21</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>S2.3 Major failure H₂S line, low level, extended duration</td>
<td>7.2 × 10⁷</td>
<td>1.21</td>
<td>long</td>
<td>0</td>
</tr>
<tr>
<td>S5 Major failure at DEA line</td>
<td>1.6 × 10⁶</td>
<td>0.49</td>
<td>long</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

B  Hazard scenarios
Pipework failure: continuous release
Gas dispersion

C  Fault trees
None

¹ For these 7 cases the typical hazard distances to the LTL₅₀ are 0, 19, 59, 81, 144, 153 and 64 m and to the LTL₀₅ 0, 85, 96, 99, 173, 181 and 81 m, respectively.

is taken up to 9 bar when the sphere is discharging to consumer plants. The spheres are located in a bund.

Chlorine is received only from the associated production plant, but is sent out to a variety of consumers.

There is a chlorine gas disposal plant consisting of caustic soda scrubbers.

An escape from a sphere may constitute an instantaneous or a continuous source. Catastrophic rupture of a sphere was taken as equivalent to an instantaneous release, other escapes to continuous releases or mixed releases.

A summary of the risk assessment for the chlorine storage is given in Table A8.8. Sections A–C list the undesired events, the hazard scenarios and the main fault trees.

A8.8.5 Propylene storage (Oxirane)
The propylene storage is associated with the propylene oxide plant of Oxirane at Seinehaven.

There are two spheres each with a capacity of 600 te. The ambient temperature was taken in the study as 15°C, which corresponds to a gauge pressure of 8 bar.

Propylene is transferred to the spheres by pipeline, ship and rail tank cars. It is transferred from the spheres to the downstream plants.

An escape from a sphere may constitute an instantaneous or a continuous source. Catastrophic rupture of a sphere was taken as equivalent to an instantaneous release, other escapes to continuous releases.

A summary of the risk assessment for the propylene storage is given in Table A8.10. Sections A–C list the undesired events, the hazard scenarios and the main fault trees.

A8.8.6 Hydrodesulphurizer (Shell)
The section of the hydrodesulphurizer studied is the diethanolamine (DEA) regenerator. The latter is part of an absorber–regenerator unit which removes hydrogen
sulphide from sour gas. The hydrogen sulphide is absorbed into DEA in the absorber and the fat DEA passes to the regenerator where a reversible reaction occurs releasing the hydrogen sulphide again.

The escapes which can occur from this unit are of two types. There may be a direct release of hydrogen sulphide gas. Alternatively, the release may be by evolution of the gas from the fat DEA liquid.

Hydrogen sulphide presents both a flammable and a toxic gas hazard. On review the flammable hazard was discounted. However, the flammability of the gas remains relevant in that in a proportion of cases the gas cloud would burn and would then not constitute a toxic hazard.

A summary of the risk assessment for the regenerator section of the hydrosulphurizer is shown in Table A8.11. Section A lists the undesired events and Section B the hazard scenarios. As indicated in Section C there are no fault trees.

For cases S1–S2, which involve direct release of hydrogen sulphide, it was found that the inventory of gas, which is at a gauge pressure 0.5 bar, was too small to sustain a release of any significant duration and that for these cases the limiting flow was determined by the rate of evolution of the gas, which was 4370 kg/h. This is equivalent to discharge from hole of a 75 mm diameter.

All the emissions are continuous sources.

An ignition probability of 0.2 on release was assumed.

For toxic gas hazard, therefore, the exposure is continuous. In all cases only employees were at risk.

Typical hazard distances to the LTL50 are given in Table A8.11, the greatest distance there quoted being 153 m. The distances are greater for adverse weather conditions, being for case S2.3 on the centreline for 2.0/F conditions 395 m.

### A8.9 Assessed Risks

The results of the assessment are presented in a number of ways. These include

- Risk contours
- Risk to employees:
  - Individual risk
  - Societal risk
- Risk to public:
  - Individual risk
  - FN tables
  - FN curves
- Average annual fatalities

The individual risks and average annual fatalities are shown in Table A8.12.

The use of risk contours is illustrated here by one of those for the ammonia storage shown in Figure A8.4, while that of FN tables and of FN curves is illustrated by those for the chlorine storage shown in Table A8.13 and Figure A8.5, respectively.

### A8.10 Remedial Measures

For each installation recommendations were made for remedial measures to reduce the risks. In accordance with the remit of the study the proposals made were

### Table A8.12 Rijnmond Report: individual and average annual risk for six installations (Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>Installation</th>
<th>Average annual fatalities</th>
<th>Public</th>
<th>Individual risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Employees</td>
<td>Public</td>
<td>Employees</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>$2.1 \times 10^{-3}$</td>
<td>$7.9 \times 10^{-6}$</td>
<td>$6.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ammonia</td>
<td>$2.1 \times 10^{-3}$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>Chlorine</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$3.6 \times 10^{-3}$</td>
<td>$5.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>LNG</td>
<td>$1.5 \times 10^{-7}$</td>
<td>$6.8 \times 10^{-10}$</td>
<td>$5.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>Propylene</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$3.7 \times 10^{-5}$</td>
<td>$7.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>Hydrodesulphurizer</td>
<td>$1.0 \times 10^{-6}$</td>
<td>0</td>
<td>$2.1 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

### Table A8.13 FN table for public for chlorine storage in Rijnmond Report (after Rijnmond Public Authority, 1982)

<table>
<thead>
<tr>
<th>No. of deaths</th>
<th>Cumulative frequency</th>
<th>No. of deaths</th>
<th>Cumulative frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$4.00 \times 10^{-4}$</td>
<td>125</td>
<td>$2.09 \times 10^{-6}$</td>
</tr>
<tr>
<td>10</td>
<td>1.07</td>
<td>151</td>
<td>1.62</td>
</tr>
<tr>
<td>20</td>
<td>$3.70 \times 10^{-5}$</td>
<td>200</td>
<td>$9.86 \times 10^{-7}$</td>
</tr>
<tr>
<td>30</td>
<td>1.50</td>
<td>304</td>
<td>3.06</td>
</tr>
<tr>
<td>40</td>
<td>$9.46 \times 10^{-6}$</td>
<td>404</td>
<td>2.34</td>
</tr>
<tr>
<td>50</td>
<td>7.32</td>
<td>518</td>
<td>1.26</td>
</tr>
<tr>
<td>60</td>
<td>6.34</td>
<td>738</td>
<td>$4.85 \times 10^{-8}$</td>
</tr>
<tr>
<td>70</td>
<td>5.23</td>
<td>1027</td>
<td>3.40</td>
</tr>
<tr>
<td>80</td>
<td>4.31</td>
<td>1697</td>
<td>$7.50 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
Figure A8.4 Rijnmond Report: risk contours for ammonia storage (Rijnmond Public Authority, 1982. Reproduced by permission.)

illustrative rather than exhaustive and are suggestions for further evaluation.

For the AN storage the main measure proposed is nitrogen blanketing to prevent internal explosion. It is recognized, however, that there is a contrary view that lack of oxygen may make spontaneous reaction more likely. It was estimated that inerting would reduce the frequencies of events P1 and P3 to $0.1 \times 10^{-5}$ and $0.4 \times 10^{-5}$/year, respectively. Some 17 other measures are also listed, including hose support, tanker earthing, and changes to sampling methods.

For the ammonia storage the principal measure suggested is the provision of a bund. This would do little to retain material released in a catastrophic failure of the sphere, but it might well mitigate the effect of failure of a bottom connection.

Another proposal made is the provision of an emergency air supply at the control room to allow the operators time to close emergency isolation valves.

For the chlorine storage the main recommendations are directed to reduction of the size of escapes from pipework by the use of excess flow valves.

For the LNG storage the main measure proposed is directed towards the prevention of escalation due to brittle fracture of carbon steel from a small release of cold liquefied gas. It is suggested that baffles on the tank roof would reduce this risk. It was estimated that this would reduce the total risk by 5.6%.
Figure A8.5  Rijnmond Report: FN curve for chlorine storage (Rijnmond Public Authority, 1982. Reproduced by permission.)
For the propylene storage the installation of remote isolation valves is the principal measure proposed. It was estimated that this would reduce the total risk by half. Proposals are also made for modifications to the vapour return system.

For the hydrodesulphurizer the measures proposed are minor. It is suggested that there should be monitoring of hydrogen sulphide in the control room and that the hazard of spread of DEA through the drain system be investigated.

A8.11 Critiques

As indicated, the Rijmond Report itself contains its own critique in the form of a review by outside consultants and industrial comment. Much of this relates to the failure and event data, the hazard models and the injury relations, and particularly to the models.

**Notation**

- \(n_h\) number of weeks off for holidays, sickness, etc.
- \(N_d\) number of persons on site during day
- \(N_e\) number of persons on site
- \(N_{n}\) number of persons on site at other times
Appendix

9

Laboratories

Contents

A9.1  Legal Requirements  A9/2
A9.2  Laboratory Management Systems  A9/2
A9.3  Laboratory Personnel  A9/3
A9.4  Laboratory Codes  A9/3
A9.5  Laboratory Hazards  A9/4
A9.6  Laboratory Design  A9/5
A9.7  Laboratory Equipment  A9/6
A9.8  Laboratory Services  A9/6
A9.9  Laboratory Storage and Waste Disposal  A9/7
A9.10 Laboratory Operation  A9/8
A9.11 Laboratory Fire and Explosion Protection  A9/9
A9.12 Emergency Planning  A9/10
Laboratories are an integral part of the activities of the process industries. They include not only analytical laboratories and laboratories carrying out research and development work in industry but also university teaching laboratories where future industrial managers are trained. The account here is concerned with chemical engineering rather than chemistry laboratories. Pilot plants are considered in Appendix 10.


A Code of Practice for Chemical Laboratories (the RIC Laboratories Code) has been published by the Royal Institute of Chemistry (RIC) (1976).

Activities in a chemical engineering laboratory are distinguished from those on industrial plant above all by their small scale. This certainly reduces the hazards. There are, however, factors which may increase the risk of a hazardous initial event, such as the use of inexperienced and untrained personnel, and of escalation of that event, such as the enclosed space and the close proximity of personnel. Further, if the small scale of the hazard leads to general complacency and poor practice, the risk that it will be realized is augmented.

Despite the lesser scale of the hazard, the approach to hazard control used for full-scale plants is applicable in large part to activities in the chemical engineering laboratory. An accident in the laboratory can give rise to considerable personal injury or loss of life and direct damage loss, because the density of personnel and of expensive equipment which are at risk is relatively high. There may also be serious consequential loss due to interruption of the facilities which the laboratory provides for production plants or of research and development activities.

Moreover, where a laboratory, whether in the university or industry, has a training function, it is essential to adhere to, and instil, good practice in hazard control.

Many of these topics touched on here have already been discussed, albeit not specifically in relation to laboratories, in previous chapters, in particular those on legislation (Chapter 3), management and management systems (Chapter 6), hazard identification (Chapter 8), process design (Chapter 11), fire, explosion and toxic release (Chapters 16–18), personal safety (Chapter 25) and safety systems (Chapter 28).

Selected references on laboratory safety are given in Table A9.1.

### Table A9.1 Selected references on laboratory safety

<table>
<thead>
<tr>
<th>Reference</th>
<th>Details</th>
</tr>
</thead>
</table>

### Fume cupboards, enclosures

Walls and Metzner (1962); BOHS (1980 Monogr. 4, 1987); J. Grant and Rimmer (1980); ASHRAE (1985 ASHRAE 110); OSHA (1990/6); V.C. Marshall and Townsend (1991); AIHA (1993 Z95) | BS 7258: 1990– |

1974 applies to all places of work and thus extends coverage to university as well as industrial laboratories. Chapter 3 gives an account of these acts and also of other legislation relevant to laboratories such as that on the workplace, including management, work equipment and incident reporting; pressure systems; toxic substances and occupational hygiene; flammable and explosive materials; fire; ionizing radiations; electricity; and personal safety, including safety signs, machine guarding, compressed air and compressed gases, manual handling, protective equipment, eye protection and first aid.

A review of legislation applicable to chemical engineering laboratories is given in the IChemE Laboratories Guide.

### A9.2 Laboratory Management Systems

The management approach used for the control of hazards in industry is in large part applicable in
chemical engineering laboratories. In particular, use should be made of formal systems and procedures as described in Chapter 6.

The laboratory should have a management system with suitable organization and competent people, systems and procedures, standards and codes of practice, and documentation. There should be a clear chain of command and separation of executive, or line, from advisory, or staff functions. There should be a safety officer and a safety committee, and safety audits should be conducted.

Some principal systems are described below, and others in later sections.

A9.2.1 Hazard reviews
There should be a system of hazard reviews for experimental work. A review should give a statement of the hazards involved and of the means by which they will be controlled.

A9.2.2 Permit systems
Hazardous activities should be covered by a permit system. Permits may be required for general maintenance activities, for hot work and for vessel entry.

The IChemE Guide gives specimen permit forms.

A9.2.3 Incident reporting
There should be a system for the reporting of incidents. As a minimum this should meet the legal requirements given in RIDDOR 1985, but in addition there should be a general requirement for the reporting of unintended events.

A9.2.4 Safety audits
The system of safety audits should cover the management systems for the laboratory, the equipment, the services, the storage and waste disposal, and the operations.

The conduct of safety audits is discussed in the IChemE Guide and by Bretherick (1986) and J.A. Young (1987b).

A9.3 Laboratory Personnel
There tend to be wide variations in the capability of the personnel who work in laboratories, ranging from well-trained and experienced permanent staff to relatively inexperienced research workers and students. A discussion of people in laboratories is given by Buttolph (1980 LPB 32).

A9.3.1 Training
It follows from the above that for laboratory personnel training assumes particular importance. This training needs to cover the hazards, the equipment, the procedures and the systems. As with all training, it should aim to motivate as well as to inform.

Personnel who use the laboratory should be trained in good laboratory practice. The training should include such aspects as action to take in case of fire and other accidents, methods of eye irrigation and use of fire extinguishers.

The laboratory should have the appropriate number of persons trained in first aid.

Where the personnel concerned are prospective managers of industrial plants, experience in a well-conducted laboratory provides a good foundation.

Accounts of the content of, and techniques for, laboratory training are given by Bretherick (1986), Armour (1987) and Redden (1987).

A9.4 Laboratory Codes

A9.4.1 RIC Laboratories Code
The RIC Laboratories Code covers the following aspects:

(1) Laboratory services
   (a) electricity
   (b) gas for heating
   (c) water
   (d) steam
   (e) ventilation
   (f) compressed air
   (g) brine circulation
   (h) hot plates, ovens and furnaces
   (i) drainage

(2) Hazardous chemicals
   (a) flammable substances
   (b) explosive substances and mixtures
   (c) corrosive chemicals
   (d) irritant chemicals, dusts, gases and vapours
   (e) toxic chemicals
   (f) radiation and radioactive materials
   (g) cylindered gases
   (h) cryogenic fluids and systems

(3) Hazardous techniques
   (a) pressure reactions
   (b) vacuum techniques
   (c) glass handling
   (d) heating of chemical apparatus
   (e) centrifugation

(4) Organization
   (a) safety officers and safety committees
   (b) appointment and functions of a safety committee
   (c) fire prevention
   (d) personal protection
   (e) rescue
   (f) first aid and medical services
   (g) housekeeping and safety audits
   (h) labelling
   (i) storage
   (j) waste disposal
   (k) noise
   (l) unattended experiments and working alone
   (m) documentation of procedures

(5) Legal responsibility
   (a) legal responsibility
   (b) legislation

The code is intended primarily for chemical laboratories, but, as the summary indicates, it is in large part applicable to chemical engineering laboratories also.

A9.4.2 NFPA 45
Guidance on fire protection is available in NFPA 45: 1986 Fire Protection for Laboratories using Chemicals.

The standard covers (1) general topics, (2) laboratory unit hazard classification, (3) laboratory unit design and
construction, (4) fire protection, (5) explosion hazard protection, (6) laboratory ventilating systems and hood requirements, (7) chemical storage, handling and waste disposal, (8) compressed and liquefied gases, (9) laboratory operations and apparatus, and (10) hazard identification.

The classification divides laboratories into high, intermediate and low hazard according to the maximum densities of materials held. For flammable or combustible liquids Class I, II or IIIA, these densities are

<table>
<thead>
<tr>
<th>Laboratory unit</th>
<th>Flammable or combustible liquid class</th>
<th>Maximum quantity/100 ft² of unit (US gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A High hazard</td>
<td>I, II and IIIA</td>
<td>Excluding storage: 10 Including storage: 20</td>
</tr>
<tr>
<td>B Intermediate</td>
<td>I, II and IIIA</td>
<td>Excluding storage: 5 Including storage: 10</td>
</tr>
<tr>
<td>C Low hazard</td>
<td>I, II and IIIA</td>
<td>Excluding storage: 2 Including storage: 4</td>
</tr>
</tbody>
</table>

The storage referred to is storage in cabinets and cans. The standard states that Class A laboratory units should not be used as instructional laboratories and that for Class B and C instructional laboratories the maximum quantities should be half those given above.

An account of the use of NFPA 45 in laboratory design is given by Le, Santay and Zabrenski (1988).

A9.4.3 IChemE Laboratories Guide

The IChemE Laboratories Guide has the following coverage: (1) introduction, (2) safety management of laboratories, (3) the law and process laboratories, (4) hazards in chemical engineering laboratories, (5) designing process research and development facilities, (6) services, (7) storage of materials and disposal of waste, (8) design of experiments, (9) operating procedures and safety, (10) emergency procedures, (11) maintenance and modifications, and (12) relevant publications.

A9.5 Laboratory Hazards

Reviews of hazards in chemical engineering laboratories are given in the RIC Code and the IChemE Guide and in most texts of laboratory safety such as those of Steere (1971), Bretherick (1986) and J.A. Young (1987a). The list quoted from the RIC Code in Section A9.4 is typical.

In addition to the specific treatments mentioned below, a general account of the handling of hazardous research chemicals is given by Prokopetz and Walters (1987) and one of hazards other than those from chemicals by Bulloff (1987).

Further treatments of the hazards of flammable substances are given in Chapter 16, of toxic substances in Chapter 18 and of others such as radiation, electrical and mechanical hazards in Chapter 25.

A review of the causes of incidents in laboratories is given by J.A. Young (1987c), who utilizes the following heads: (1) management responsibilities inadequate, (2) lack of communication, (3) lack of personal responsibility, (4) lack of proper ventilation, (5) lack of protective equipment, (6) personal hygiene problems, (7) electrical hazards, (8) storage problems and (9) inadequate emergency procedures and equipment.

A9.5.1 Reactive substances

Where reactive substances are handled or processed, every effort should be made to obtain the fullest information on their behaviour. Texts such as Handbook of Reactive Chemical Hazards by Bretherick (1990b) and Hazardous Chemicals Handbook by Carson and Mumford (1994) are an essential point of departure.

Bretherick (1987) has also given a review of chemical reactivity in the laboratory context.

A9.5.2 Flammable substances

Many of the liquids and gases handled in laboratories are flammable. Each phase presents its characteristic hazards.

Accounts of the hazards of flammable and combustible materials are given in the various NFPA codes, including for laboratories NFPA 45 and by Steere (1971), Bretherick (1986) and Gerlach (1987).

Where flammable liquids are handled, one hazard is release followed by ignition. Factors which need to be considered are the integrity of the containment, the flow of liquid if it does escape and any sources of ignition.

Another hazard is overheating of the liquid, leading to its escape, either as a liquid following rupture of the containment or as vapour from an open vent.

A frequent cause of bench fires is loss, or under-circulation, of cooling water.

Flammable liquids should not be handled near, or heated on, naked flames.

Where flammable gases or vapours are handled, the most common hazard is a leak which allows a flammable atmosphere to build up in the enclosed laboratory space. Unless there is a high level of ventilation, this can occur even with a relatively small leak rate.

Another cause of bench fires is contact between water and reactive metals such as sodium.

Oxygen should not be used in such a way as to create the hazard of an oxygen-enriched atmosphere. Oxygen is liable to oxidize and then rupture rubber tubing.

A9.5.3 Toxic substances

Where toxic substances are handled, it is necessary to consider all three modes of entry into the body and both short- and long-term toxic effects.

For entry, inhalation may well be the principal mode, but in laboratory work in which chemicals are ‘handled’ to a much greater extent the ingestion and skin modes may be more significant than is usually the case. High standards of hygiene therefore assume greater importance.

With regard to inhalation, there may be a hazardous short-term effect if the substance is highly toxic and circumstances can be foreseen in which a concentration sufficiently high to cause acute poisoning can occur. This is rather more likely in the enclosed space of a laboratory.

More commonly, however, the hazard arises from exposure to low concentrations over a relatively long period.

Where a toxic hazard exists, the requirements of the COSHH Regulations 1988 apply.
The design countermeasures are primarily a high standard of containment. Other measures are described in the next section.

Accounts of the effects of toxic chemicals in the laboratory context are given by Steere (1971), Bretherick (1986) and Springer (1987).

A9.5.4 Radiation hazards
There are a variety of radiation hazards, most of which may be found on occasion in laboratories. They include both ionizing and non-ionizing radiations as described in Chapter 25.

With regard to ionizing radiation, some devices containing radioactive sources instanced in the IChemE Guide are certain liquid level gauges, gas chromatograph detectors, leakage detectors, anti-static devices on balances, and fire detectors.

Certain apparatus producing voltages above 5 kV may be a source of X-rays.

Non-ionizing radiation sources include lasers, microwaves and UV and IR devices.

A9.5.5 Electrical hazards
The electrical hazards are little different from those in industrial situations generally, but unless good practice is observed a laboratory tends to be especially vulnerable to them.

Personnel may be at risk of electrocution from temporary lashups and repairs, defective and damaged cabling, unearthed components and poor earthing. This may be aggravated by handling equipment with wet hands.

Short circuits due to worn cabling, wrong wiring or over-rated fuses can lead to a fire.

A9.5.6 Mechanical hazards
The mechanical hazards likewise are such as may be found in other industrial situations, but again laboratory personnel may be especially vulnerable unless strict controls are observed.

These mechanical hazards include those associated with rig equipment, workshop machinery, hand and power tools, and lifting equipment.

Accidents are liable to occur where laboratory personnel use equipment with which they are unfamiliar in order to progress the job.

A9.5.7 Operating condition hazards
Equipment operating at high or low temperature constitutes a contact hazard. Contact with a very cold surface can cause a ‘cold burn’ not unlike the burn from a very hot surface.

A cryogenic fluid also involves the hazard that it will vaporize by heat transfer from the atmosphere unless this is positively prevented. Depending on the nature of the fluid, such vaporization may give rise to an atmosphere enriched with a flammable or toxic material or oxygen.

A laboratory usually contains a number of sources of high pressure such as compressed air, steam, compressed gas in cylinders and so on. Water also may act as a high pressure source. Rupture of equipment may occur either because the pressure to which it is subjected is above the design conditions, or because the equipment is weaker than designed. Overpressure can occur if a valve is open or fails, weakening if metal equipment is exposed to extremes of heat or cold.

Failure may also be caused by vacuum, which may occur not just by connection to a vacuum supply but by rapid cooling of a vapour in the apparatus.

A9.5.8 Water release hazards
Another hazard is the escape of water, particularly in the form of a jet. Some potential effects of such a jet are short circuiting, thermal shock, extinction of gas jets and reaction with water-reactive chemicals.

A9.6 Laboratory Design
Laboratory design and layout is discussed in the IChemE Guide and by Steere (1971), Everett and Hughes (1975) and Baum and Diberardinis (1987).

A checklist for laboratory design is given by Everett (1980 LPB 32) and a case study in such design by Martin (1980 LPB 32).

A9.6.1 Laboratory layout
The design and layout of a laboratory should proceed on principles broadly similar to those described in Chapter 10. This is the approach taken in the IChemE Guide.

The method described in the guide is to analyse the needs of the experimental activities using a flow diagram showing the flow of materials between the experimental rigs, the workshops, stores, analytical services, waste disposal facilities, etc., and to develop layout diagrams in which the low and high hazard features are separated, with minimization of exposure near the latter. In this method layout features which bulk large are the supplies of materials and of services.

A9.6.2 Toxic chemicals
The hazard from toxic chemicals has been described in the previous section.

Where toxic chemicals are handled, the design should aim to keep the concentration in the laboratory atmosphere below the relevant exposure limit. The prime means of ensuring this is to prevent leaks through a high standard of containment.

For toxic chemicals the COSHH Regulations 1988 apply as described in Chapter 25. These regulations include provisions for monitoring the workplace atmosphere.

Means of keeping down the concentration of contaminants which do escape include use of ventilation and of fume cupboards.

A9.6.3 Ventilation
The most common method of controlling the concentration of contaminants in the workplace is ventilation. The basic methods are local exhaust ventilation and general ventilation. Ventilation of the workplace is described in Chapter 25.

The exhaust from the ventilation should pass to a safe place.

A9.6.4 Fume cupboards
For some toxic or noxious chemicals use is made of a fume cupboard. An account of fume cupboards is given in Chapter 25.
The resort to fume cupboards has been criticized, however, by V.C. Marshall (1981 LB 37) as outmoded. He argues that in the laboratory the release of noxious chemicals has become too readily accepted. The proper approach is higher standards of containment which avoid such emissions.

A9.6.5 Laboratory support
There are a number of facilities which may be needed to support the laboratory. They include (1) workshop, (2) stores, (3) receipt bays, (4) analytical services and (5) staff facilities. These are essentially self-explanatory.

The storage needs should be examined to identify the extent to which segregation is required. It is normal to devote one store to the materials required for the fabrication of rigs and another to process materials such as flammable and toxic liquids, but further segregation may be required.

The IChemE Guide suggests, for example, that separate stores are normally required for solvents, chemicals, explosives, gas cylinders and cryogenic materials.

Eating and drinking should not be permitted in laboratories. There need to be adequate staff facilities provided.

A9.7 Laboratory Equipment

A9.7.1 Glassware
Much laboratory apparatus is constructed in glass. Glass has a number of advantages such as resistance to corrosion, flexibility in use and visibility of contents. It can be used with a high degree of safety. For this it is necessary that its limitations be respected, that it be used only in suitable applications and that manufacturers guidance be consulted.

A9.7.2 Hotplates, ovens and furnaces
Hotplates, ovens and furnaces involve the hazard that an item being heated, or the heating element itself, becomes overheated.

The use of ovens is frequently not subject to the same degree of formal control as other apparatus, and different people may put in items which are incompatible or may alter the controls, with undesirable results.

A9.7.3 Centrifuges
Laboratory centrifuges are a recognized hazard. They are the subject of BS 4402: 1982 Specification for Safety Requirements for Laboratory Centrifuges and are treated in Appendix 6 of the IChemE Guide. This is in addition to BS 767 and a further IChemE guide both of which apply to industrial centrifuges.

A laboratory centrifuge should be properly balanced. The buckets should be well fitting and with rubber pads in place. The machine should be cleaned and dried after use to prevent corrosion which is a common cause of mechanical failure.

In use the lid should be closed and locking devices secured before start-up. The machine should be brought up to speed gradually. It should be stopped using the controls, not simply switched off. The lid should not be opened until the machine has come to rest.

Centrifuges are discussed further in Chapter 11.

A9.8 Laboratory Services
Laboratories use a wide range of services. The most common are (1) water, (2) steam, (3) compressed air, (4) fuel gas and (5) electrical power. Others include refrigerated coolants, vacuum, oxygen and other piped gases.

A9.8.1 Water
Water is used as process water and as coolant.

Where the cooling load is larger enough to justify it, an external cooling water system may be provided which is a smaller-scale version of an industrial system with the water pumped through cooling towers.

The use of water in laboratories involves several hazards. The first is the potential for reverse flow of liquid from a laboratory process into a water supply main. Where such a possibility exists, some safeguard is required. A break tank provides a barrier more dependable than a non-return valve.

Another hazard is loss of cooling water. Generally this occurs on a single rig due to a leak at that point.

A third hazard is the escape of water into the laboratory. A typical situation might be failure of a cooling water connection on apparatus in a fume cupboard where the drains are blocked, so that the water flows into the laboratory. If the equipment is running unattended, a large quantity of water can escape, perhaps damaging equipment such as computers on the floor below.

There is usually a requirement for demineralized water, which is supplied by a stand-alone unit.

A9.8.2 Steam
Steam is required in the laboratory for heating on larger rigs. It is typically provided by an external boiler system, but for small quantities may be generated by a small electrically heated, or less commonly, gas-fired, unit.

The pressure of steam for laboratories is typically in the range 4–10 barg. Measures should be taken to ensure that equipment supplied with such steam cannot be overpressured and that, where loss of coolant with steam still on could be hazardous, steam is shut off.

The use of steam implies the use of steam traps. These devices need regular maintenance.

A9.8.3 Compressed air
Compressed air for laboratories is generally provided by a fixed piped system supplied from an external air receiver charged by a compressor.

The air should be free of oil, which may be achieved either by use of an oil-free compressor or by oil removal equipment. Regular maintenance is required for the latter.

Compressed air is potentially hazardous and the supply pressure should be limited to that required for the purposes of the laboratory.

Like steam, compressed air is a potential source of overpressure and measures are needed to safeguard against this.

A9.8.4 Fuel gas
Fuel gas is another service which is usually provided in a laboratory by a fixed pipe system.
A9.8.5 Refrigerated coolants
Cooling to lower temperature that can be achieved by cooling water may be provided using refrigeration, either by circulation of a refrigerant or by the use of an intermediate fluid such as brine or ethylene glycol.

The normal practice is to house the refrigeration set in a separate room.

A9.8.6 Vacuum
In some laboratories a piped system is provided to supply vacuum. Collapse of equipment under vacuum is not unlike an explosion and may generate missiles. Measures are required to ensure that equipment connected to vacuum is not underpressured.

A9.8.7 Oxygen
Another gas which may be provided as a fixed piped supply is oxygen, but where this is done special care is needed.

Hazards arising from the use of oxygen are attack and rupture of rubber tubing and creation of an oxygen-enriched atmosphere, which can result in a dramatic enhancement of the flammability of clothing.

A9.8.8 Other piped gases
Laboratory requirements for gases other than air vary greatly. In principle, where the usage is high, a fixed piped system has the very considerable advantage of eliminating the use of gas cylinders. However, frequently what is required is moderate quantities of a relatively large number of gases, so that a piped supply for any one is difficult to justify. In some instances pipes are used for different gases, with suitable precautions.

Where a piped supply is installed, the gas is usually piped from gas cylinders located at a protected shelter on the outside of the building.

Piped systems for hydrogen require special care.

A9.8.9 Compressed gas cylinders
For the reasons just given, supply of many of the gases used is often taken from gas cylinders brought into the laboratory. The use of gas cylinders requires a number of precautions.

The contents of the cylinder should be identified by labelling and colour coding. In use the cylinder should be fitted with a regulator and both valve and regulator should be kept clean and free of grease and oil. The valve should be closed when the cylinder is not in use. The cylinder should be transported in a wheeled carrier and when in use supported in a vertical position.

A more detailed treatment of precautions in the use of gas cylinders is given in Appendix 4 of the IChemE Guide.

A9.9 Laboratory Storage and Waste Disposal

A9.9.1 Materials storage

The main inventory of hazardous chemicals is, or should be, in the chemical storages. General principles governing such storage concern (1) segregation of incompatible materials, (2) types of container, (3) receipt points, (4) acquisition, stock-taking and disposal, (5) minimization of inventory and (6) identification and labelling.

With regard to segregation, some relevant categories of chemical are (1) flammables, (2) toxics, (3) oxidizing agents, (4) corrosive substances, including strong acids and alkaloids, (5) cryogenic substances and (6) pyrophoric substances. Toxics should be segregated from flammables and oxidizing agents from flammables, organic chemicals, reducing or dehydrating agents. Categories which should be held in separate stores include corrosive substances, cryogenic substances and pyrophoric substances.

Types of container used are small containers, large containers, bulk containers and gas cylinders. Aspects of good practice with small containers include the use of bottle carriers, non-spill containers and controlled dispensing. Good practice in the storage of large containers, essentially drums, and bulk containers is discussed in Chapter 22.

The receipt points for chemicals should be designed to facilitate handling of incoming loads. Vehicles carrying gas cylinders generally have their own lifting gear, but those carrying drums often do not.

The control of materials in storage is exercised through the processes of acquisition, stock-taking and disposal. It is common for an experimenter to order an appreciable quantity of a chemical, use only a portion of it and then forget about it. Unless close control is exercised, there can build up in the stores a large quantity of chemicals, much without ‘ownership’. It is necessary to keep the situation under control by taking stock periodically and by disposal of unwanted material.

Carefully connected with this is the minimization of inventory. The inventory held in the laboratory itself should be the minimum necessary, and that in the storage likewise.

The number of chemicals used in a laboratory can be large and the conditions of use vary. It is essential to ensure that all materials are identified and labelled. There should be a materials safety data sheet for each chemical. Reale and Young (1987) give an account of labelling and MSDSs in the laboratory context.

The Poison Rules 1982 give in Schedule 1 a list of substances which must be stored in a locked cupboard under the supervision of a registered keeper and the usage of which must be entered in a register.

A9.9.2 Waste disposal
A laboratory usually generates gaseous, liquid and solid wastes, all of which need to be disposed of. The problems of waste disposal are not trivial and have become increasingly severe as environmental standards have risen.


A distinction is generally made between domestic and chemical wastes. The former category includes paper and broken glass. The latter should be segregated both from paper and from unbroken bottles.

Flammable solvents generally constitute a large proportion of the chemical wastes. Other liquids which are incompatible with such solvents should be collected
separately. Separate collection is also required for oil-soaked rags. On no account should chemical wastes be put down the drains.

Separate, clearly labelled receptacles are required for each category of waste. For some categories, such as for flammable solvents, receptacles with appropriate safety features should be used.

Options for the disposal of laboratory wastes are listed by Pitt and Pitt, who give some 13 choices, although many are applicable only to small quantities.

The disposal of wastes has to be formally managed by identifying disposals and obtaining the necessary licences.

Specialist contractors are used by most laboratories for disposal of at least some of their wastes. This is one of the options discussed by Pitt and Pitt.

A9.10 Laboratory Operation

A9.10.1 Information requirements
It is essential to have the fullest information on the chemicals being handled and on the associated hazards. This applies particularly to chemicals which are highly reactive or which have toxic effects at low concentrations over long periods.

Sources of such information are discussed in Chapter 8.

A9.10.2 Design of experiments
Laboratory experiments are undertaken for different purposes and these necessarily influence their design. In all cases inherently safer design should be a prime aim, but the extent to which it can be achieved will vary. Facets of inherent safety include scale, operating conditions and materials. Where the objective is the pedagogical one of demonstrating a principle, it may be possible to operate on a small scale, at atmospheric pressure and temperature and using less hazardous materials such as air, water and inert solids.

The purposes of the experiment should be well defined. It should not be too ambitious, and if necessary should progress in stages. Information on the materials handled and their potential hazards should be as complete as practical. The basis of safety should be defined. The design should cover the equipment and its operation, and should be to applicable standards and codes.

The design should be subject to a hazard review, utilizing hazard identification techniques such as checklists and hazop studies.

Laboratory equipment should be fit for purpose. The standard of construction of the apparatus should match the degree of hazard and its expected life.

It is not uncommon to build a ‘temporary’ rig with connections made to certain services by hose rather than by fixed piping. If this is accepted in certain applications, care is still needed to ensure that the practice does not extend to unsuitable cases or to operation over extended periods.

Another common practice is the use in a new experiment of a rig ‘inherited’ from an earlier one. The suitability of the equipment for the new purpose needs careful scrutiny.

For critical features consideration should be given to the provision of automatic protective devices. Trips may be required to guard against loss of cooling and excessive heating and deviations of pressure, temperature, flow, level and composition.

Full instructions should be prepared for operating procedures and emergency procedures. Consideration should be given to the requirements of unattended operation if this is planned.

Certain activities require special enclosures. These include the use of a fume cupboard where the materials are toxic and of explosion cubicles where the process involves hazardous reactions or high pressures.

The planning of safe experiments is discussed by Fowler (1989 LPB 32).

A9.10.3 Hazard assessment
If an experiment has the potential to cause serious injury, it may be appropriate to carry out a hazard assessment. Case studies of the application of hazard assessment in the laboratory have been described by Le, Santay and Zabrenski (1988).

One example given is a review of the situations involving release of toxic gas sufficient to pose an acute toxic threat. The gases in question were arsine, diborane and phosphine, all in hydrogen. A tabulation was made of the various release scenarios, showing the expected toxic loads and candidate scenarios were then investigated. Fault tree analysis was used to determine the failure paths.

Another case study described by these authors involved fault tree analysis where the top event considered was the formation of a detonable hydrogen–air mixture from a gas phase reactor system.

A9.10.4 COSHH assessment
A COSHH assessment should be made for any laboratory activity which attracts such an assessment under the COSHH Regulations 1988, as described in Chapter 18.

A9.10.5 Operating procedures
Operating procedures may be classified in two ways. One distinction is between general laboratory procedures and procedures specific to a particular rig. Another is between those which concern safety and those which do not.

For the laboratory as a whole, general operating instructions relating to safety are usually set down in a laboratory safety manual.

For the particular rig, it is advisable to separate the procedures which have safety implications from those which do not. Where operating instructions are imported, as with equipment bought from a manufacturer, it may be necessary to rewrite them, abstracting the safety-related parts.

The operating instructions for a rig should cover startup, running and shut down, and should indicate the hazards and the countermeasures to be taken. They should not duplicate the general instructions. They should be clear and simple, and should preferably extend to no more than two pages.
A9.10.6 Emergency procedures
The operating procedures for each rig should cover action to be taken in the event of an emergency (1) on that rig and (2) in the laboratory as a whole.

It is an accepted principle that a laboratory fire should be fought if it can be done without undue risk. The same principle may be extended to other actions in an emergency which threatens to escalate.

Emergency planning is discussed in Section A9.12.

A9.10.7 Equipment maintenance
The general approach to maintenance of equipment in a laboratory is similar to that on plant. It involves identification of the equipment to be worked on; planning of the work and shut down of the equipment; electrical and mechanical isolation of the equipment; and preparation for the work by removing fluids and solids and by cleaning. The principles are as outlined in Chapter 21.

A9.10.8 Equipment and procedure modification
Similarly, control should be exercised over modifications to the equipment or the activities analogous to those over plant and process modification on full-scale plant described in Chapter 21.

The IChemE Laboratories Guide gives detailed guidance on what, in a laboratory context, constitutes a modification and contains in Appendix 14 a specimen form for control of modifications.

A9.10.9 Permit systems
The scope of the permit system, defining which activities need to be so covered and which do not, should generally be agreed between the laboratory superintendent and the rig supervisor.

The activities which require permits and the parties responsible for issuing and receiving them should be listed in the general laboratory instructions or the rig instructions.

Hazardous activities such as maintenance and vessel entry should be covered by a permit system. The principles are similar to those for industrial plant as described in Chapter 21.

One of these principles is formal handover from operations to maintenance personnel and then backhand in the reverse direction. In a laboratory these responsibilities may sometimes be less clear than on plant and, as just stated, they need therefore to be clearly defined. The effectiveness of the permit system depends on formal observance of such handovers.

A9.10.10 Housekeeping
There should be a high standard of housekeeping. Facilities should be provided for disposal of broken glass and of waste materials. Equipment not in use should be removed or arranged tidily. Spillages should be cleaned up at once.

A9.10.11 Out-of-hours working
Personnel working out of hours should be required to sign in and sign out.

Working alone in the laboratory should be permitted only where the hazard is low and is best kept to a minimum. Anyone who does work alone should be in contact with, or should be visited by, the security guard at regular intervals.

A9.10.12 Unattended operation
Unattended operation of equipment may present a hazard, especially if flammable or toxic materials are involved. There will be some experiments where such operation is not permissible. When unattended operation is practised, arrangements should be made for the apparatus to be visited by a trained security guard, who should be given full instructions on the action to be taken in case of accident or doubt and should be able to make telephone contact with the experimenter.

A9.10.13 Access
Access to the laboratory should be subject to control and unauthorized persons should be excluded. The extent of the measures necessary depends on the nature of the hazards and the confidentiality of the work.

A9.11 Laboratory Fire and Explosion Protection

A9.11.1 Fire protection
The laboratory should be designed for fire protection, in accordance with building and fire protection codes and with advice from the fire authorities.

Some basic elements of design for fire protection include the fire resistance of the laboratory envelope, including doors; internal layout; hazardous area classification; mechanical ventilation; and a fire alarm system.

It is desirable that there be constructional features with a minimum fire resistance between the laboratory and any adjoining section of the building and that the doors be to a fire resistant standard. Measures should be taken to prevent fire spread through openings in walls and voids in the roof.

It should be a principal aim of the laboratory layout to minimize both the occurrence and escalation of fire. Hazardous area classification should be applied to effect control of ignition sources. It is suggested in the IChemE Guide that for a well ventilated laboratory classification as Zone 2 should be sufficient. The guide states that ideally the whole space should be so classified, but if this is not practical, the Zone 2 should extend at least 2 m around any potential leak source.

The risk of buildup of a flammable atmosphere may be minimized by the use of mechanical ventilation. The guide recommends that where flammable liquids are in use, the ventilation fan should be operated for the period of use and for five minutes thereafter.

There should be a fire alarm system with alarm points inside the exits and at other strategic points.

A9.11.2 Fire fighting
The laboratory should be equipped with suitable fire extinguishers, fire blankets, etc. An account of fire extinguishers in general is given in Chapter 16 and in the laboratory context in the IChemE Guide.

A9.11.3 Explosion protection
Where there is to be operation of equipment such as an experimental reactor with a significant risk of vessel rupture, a separate cubicle should be provided in which the work can be conducted. Such arrangements are
perhaps more commonly found in pilot plants, but may find place in a laboratory.

The cubicle should be designed to contain both blast and missiles. Accounts of such explosion-proof cells are given in Chapter 17 and Appendix 10.

A9.11.4 High pressure plant
A similar arrangement may be used where it is proposed to operate high pressure equipment, with or without reaction.

A9.12 Emergency Planning
Emergency planning should be undertaken to identify the potential causes and types of emergency and their consequences, and the countermeasures required. The principles are similar to those outlined in Chapter 24.

Planning should cover not only the laboratory and the rigs but also storages and services. The plan should be formulated by conducting audits during design and at commissioning and should be updated by audits at regular intervals thereafter.

The purposes of emergency planning are to protect life and property. They are achieved by early recognition of the problem, rapid raising of the alarm and prompt action to bring the incident under control and to separate the people from the hazard.

Functions which need to be performed in an emergency are to deal with the emergency, to evacuate people and to liaise with the emergency services. The personnel who will perform these functions should be identified and their tasks defined.

The range of situations in laboratories tends to be particularly wide and the emergency plan should aim for flexibility.

Laboratory personnel responsible for emergency response should understand the statutory duties and likely priorities and needs of the external services.

There are certain typical problems faced by the external fire services coming into laboratory situations. Steps should be taken to find out what information the fire brigade is likely to need and to ensure as far as is practical that it can be provided. This means having the information available and appointing someone to communicate it in the actual event. Frequently fire brigades are hampered by hazards from gas cylinders and radioactive materials and by lack of information on the chemicals present and their hazards.

There should be regular fire drills, including joint exercises with the external services.

A detailed account of laboratory emergency planning is given in the IChemE Guide.
Contents

A10.1 Pilot Plant Uses, Types and Strategies A10/2
A10.2 Pilot Plant Features and Hazards A10/3
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A10.5 Pilot Plant Operation A10/7
A10.6 Pilot Plant Safety A10/7
A10.7 Pilot Plant Programmes A10/7
Pilot plants are intermediate in scale between the laboratory bench and the full-scale plant. They are used for a variety of purposes, essentially to obtain information on process design and operation and on products, including information relevant to safety. Some hazards are liable to show up first at the pilot plant stage and the pilot plant is therefore an important tool for hazard identification, as described in Chapter 8. Here consideration is given to the more general aspects of pilot plants and particularly to their characteristic features and hazards, and to safety in pilot plants.


A number of authors on pilot plants give checklists, often as tables. These checklists include the following: justification for use (J. Jones et al., 1993b); overall programme (Lesins and Moritz, 1991; J. Jones et al., 1993a); chemical and process information (Dore, 1988); scale-up issues (Lo and Oakes, 1993); project review (J. Jones et al., 1993a); flowsheet review (Lesins and Moritz, 1991); hazard identification—what-if review (Lesins and Moritz, 1991); plant construction (Dore, 1988); staffing requirements (J. Jones et al., 1993a); operating and safety aspects (Dore, 1988); operating manual (J. Jones et al., 1993a); operator training manual (Chaty, 1985); and computer control systems (J. Jones et al., 1993a). Many of the entries in the AIChE Pilot Plant Safety Manual may be used as checklists for pilot plant safety.

In general, the principles of laboratory safety, discussed in Appendix 9, are applicable to pilot plants also. Selected references on pilot plants are given in Table A10.1.

Table A10.1 Selected references on pilot plants

<table>
<thead>
<tr>
<th>Process</th>
<th>Product</th>
<th>Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>Existing</td>
<td>Existing</td>
</tr>
<tr>
<td>New</td>
<td>New</td>
<td>Existing</td>
</tr>
<tr>
<td>New</td>
<td>New</td>
<td>New</td>
</tr>
</tbody>
</table>

A10.1 Pilot Plant Uses, Types and Strategies

A10.1.1 Uses of pilot plants

The purposes for which pilot plants are built are the development of (1) a new product, (2) a new process, or (3) an existing process. For a new product small quantities may be required for testing and for market development. For a new process information is required to prove feasibility, specify operating conditions, resolve scale-up issues, provide design data, identify problems, develop operating procedures and provide experience and training. For an existing process work may be required to check the suitability of different raw materials, improve product quality, explore modified operating conditions, improve the treatment of the effluents and effect cost reductions and other optimizations.

Frequently it is information on reaction kinetics and yield which is lacking and which the pilot plant is required to provide. Other information typically obtained from a pilot plant is data on heat transfer and pressure drops; on mixing effects; on impurities, foams and emulsions; and on fouling and corrosion.

The justification for pilot plants is discussed by J. Jones et al. (1993a). They discuss the following situations, in increasing order of difficulty:

A10.1.2 Types of pilot plant

Pilot plants differ in both type and scale. There are three principal types: (1) the general-purpose pilot plant; (2) the specific-purpose pilot plant; and (3) the multi-purpose pilot plant. The merits of these different types of pilot plant are discussed by Palluzzi (1991, 1992). Representative capacities for different scales of operation are given by J. Jones et al. (1993b) as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Product</th>
<th>Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>Existing</td>
<td>Existing</td>
</tr>
<tr>
<td>New</td>
<td>New</td>
<td>Existing</td>
</tr>
<tr>
<td>New</td>
<td>New</td>
<td>New</td>
</tr>
</tbody>
</table>
Some pilot plants currently in use are quite old and over the years have been modified and adapted. Accounts of particular pilot plants include those of Chaty (1985), P. Dawson (1986), Siminski (1987), Carr (1988), Capraro and Strickland (1989) and Lesin and Moritz (1991).

### A10.1.3 Strategies for development utilizing pilot plants

It need not be assumed that a pilot plant necessarily has to be designed and located in-house; there are other options. The main options are (1) design and location in-house; (2) location in-house but with design by a design contractor; (3) hiring of outside pilot plant facilities; and (4) contracting out of the pilot plant work. The merits of these options are discussed by Palluzzi (1991).

### A10.2 Pilot Plant Features and Hazards

While the hazards encountered on pilot plants are essentially similar to those on full-scale plants, the characteristics of pilot plants are such that the hazard profile is somewhat rather different. The specific features and hazards of pilot plants are discussed by a number of authors, including Carr (1988) and Capraro and Strickland (1989).

Some features characteristic of pilot plants include (1) gaps in knowledge; (2) novelty of chemicals, process, equipment and operations; (3) scale effects; (4) extent of manual activities; (5) frequency of modification; (6) multiplicity of tasks; (7) materials storage and transfer; (8) flow features; (9) recycles; (10) utilities features; (11) frangible elements; (12) plant layout features; (13) location in a building; and (14) research staff involvement.

The process reaction may involve a number of potential hazards. Most frequently mentioned is the unidentified reaction exotherm which could lead to a reaction runaway. There should be a formal system of screening to identify any exotherms. However, this is by no means the only hazard which may be present. The raw materials may contain impurities. The ratio and flow rate of the reactants may vary. There may be inhomogeneities due to poor mixing which affect reaction rate and temperature measurement. Features of the reaction such as induction time may assume greater significance. The handling of the catalyst may pose problems.

There are a number of equipment problems which can occur on pilot plants. One is the use of unfamiliar equipment. Another is the reactivation of idled equipment. When this is in prospect, a check on the integrity of the equipment is advisable; it may have been ‘cannibalized’. Another problem can be the use of equipment which differs from that used on the full scale and for which, in consequence, operating procedures may be deficient. An example is an oven used by a number of different users with no formal control over its contents and settings.

A principal reason for building a pilot plant is to fill the gaps in the information necessary for the design and operation of the full-scale plant. This implies that there will be gaps also in the information which ideally would be available for the design of the pilot plant.

A pilot plant is on a scale intermediate between those of the laboratory and of the full-size plant. Relative to the laboratory, the larger scale of the pilot plant means that hazards may become apparent which were obscured at the laboratory scale. Operation on the laboratory scale has some of the features of an inherently safer design. The most obvious is the limited inventory, but there are also others such as good ventilation. In some cases the problem may be that the change in scale is accompanied by other changes, such as the use of less pure raw materials. In others it may simply be that features always present become more obvious with scale such as the need to dispose of toxic effluents. Moreover, the pilot plant is the stage at which the process is first carried out in process plant as opposed to laboratory equipment and thus the stage at which difficulties of processing, of equipment or of measurement will show up.

Relative to the full-scale plant, the smaller scale of the pilot plant is beneficial in reducing the scale of the hazard, but can lead to problems of flow control, blockage and so on.

The balance between manual and automatic functions tends to be different in a pilot plant from that on the full scale. There are several reasons for this. Foremost reasons are economics and flexibility; others include factors such as measurement problems.

It is a normal, and expected, feature of pilot plant operation that both the process and the plant are subject to frequent modification. A system for the control and documentation of modifications of both types is required, both as a record of the learning process and to assure safety.

Work in a pilot plant is liable to involve tasks which are more numerous, varied and novel-features which can increase the probability of error.

The problems of containers for materials and the identification of the materials and containers can be a significant problem in pilot plants. The number of materials used may be appreciable, creating much greater scope for error than on a regular plant. It is necessary, therefore, that raw materials, intermediates, products and effluents be fully identified. Where common containers are used, as sometimes with effluents, controls need to be established to prevent mixing of incompatible materials.

Flow problems associated with features such as highly viscous fluids, gas locks, lutes, siphons, water hammer, cavitation and so on are features commonly encountered on process plants, but it is on the pilot plant that they may be first experienced and will have to be solved.

Another feature which may well be novel at the pilot stage is recycling with its characteristic problems of positive feedback and build-up of impurities.

Some pilot plants, particularly the larger ones, are on a works site and are served by the works utilities. It is
normal practice to give advance warning to the main production plants of an expected change in the status of such utilities, but the Cinderella status of the pilot plant may result in its being overlooked, and suffering unexpected loss of a utility.

Frangible pipework and vessels made of glass or plastic and other features, such as rotameters and sightglasses are common in pilot plants, and make the plant more vulnerable to damage and leaks.

Plant layout in pilot plants tends to be more congested. Such congestion can increase the risk of damage to plant or inadvertent movement of controls. An example of the latter is movement of a control such as a valve as an operator brushes against it. This danger is increased by the fact that the valve is much lighter and more readily moved than its equivalent on the full scale. Similar points apply to damage to plant, which is more vulnerable on the small scale.

In contrast to most large-scale plants, which are in the open, many pilot plants are in buildings, and this has a number of implications. There is often a more congested layout. There is an increased hazard from accumulation of gases or vapours. These may be flammable or toxic vapours, whether from open vessels or from leaks and spillages. Or they may be asphyxiants, such as nitrogen, or flammability-enhancing gas, such as oxygen. Likewise, there may be occupational hygiene problems because fugitive emissions disperse less readily.

Research staff involved in pilot plant work are likely to be less attuned than those familiar with plant operation to the disciplines necessary, and specific steps may need to be taken to rectify this.

A10.3 Pilot Plant Scale-up

Historically, a basic reason for the use of a pilot plant has been the difficulty of scaling up from the laboratory bench to the full scale. To a considerable extent, such scale-up is what chemical engineering is all about, and progress in the discipline has made this reason seem rather less cogent.

Despite this, operation on the pilot scale may still be desirable even in respect of fundamental features such as reactor heat transfer, mixing, runaway and venting.

However, even in terms of scale-up, there is more to pilot plant operation than the scale effects typically expressed in terms of dimensionless numbers and engineering models. As already indicated, there are other effects of scaling up such as the use of less pure raw materials; the occurrence of poor mixing; the build-up of impurities due to recycling; the need to dispose of noxious effluents; and so on.

The process of scale-up is frequently envisaged as a linear one, progressing to successively larger scales. An alternative model, however, is one in which the process is iterative, passing to and fro between the smaller and larger scales.

The pilot plant stage is the first at which the process is operated in the form of a plant. It therefore provides the first opportunity to examine all those features which are new in passing from laboratory bench to plant. This is so whether the pilot plant is small or large.

A10.4 Pilot Plant Design

There are a number of features which are characteristic of, or tend to bulk large in, the design of pilot plants. Some of these are now considered.

A10.4.1 Some design objectives

The pilot plant should be utilized to design the full-scale plant using recognized engineering methods of scale-up.

The design should accommodate a sufficiently wide range of operating variables, such as pressure and temperature, to allow the effect of these variables to be determined with some confidence.

The purpose of the pilot plant is to provide information for the design of the full-scale plant. The plant should be designed and operated so as to yield information in which confidence can be placed and which is conformable to established design methods. As far as practicable, the process should be modelled and the experimental results compared with the model as they are obtained. Important features of such a model are the mass and heat balance and pressure drop relations, the reaction kinetics and the unit operations models.

A10.4.2 Design standards and codes

A particular problem in pilot plant design is the application of standards and codes. In general, these are formulated with full-scale plant in mind, and can sometimes pose difficulties for the pilot plant designer.

The standards to be applied should be declared at an early stage and any potential conflict identified, whether between different standards or between a standard and the design.

The application of standards to pilot plants is discussed by Siminski (1987), who describes the particular case of the standards covering an engine test facility. The approach which he describes is to assess the impact of standards on the safety, industrial hygiene and environmental aspects of the plant, to assess the risks and develop alternative strategies, to seek independent review and to test design concepts early on, to examine the specification to check whether features causing conflict with standards are strictly necessary, and to negotiate with the parties to achieve solutions.

A10.4.3 Flexibility and multiple use

Since the purpose of a pilot plant is to extend knowledge and deal with novel issues, it needs to be flexible. Methods of providing such flexibility are discussed by P. Dawson (1986). They include the provision of inherently flexible equipment, a range of equipments and materials of construction and a layout which groups together items which most frequently need to be connected, thus avoiding long pipe runs.

A10.4.4 Plant layout

The basic principles of plant layout apply to pilot plants also, but some features assume particular importance.

One feature just mentioned is layout to minimize the length of pipework and to ensure a convenient arrangement of principal items of equipment.

Another feature is to ensure good access, which includes both access to items of equipment but also minimization of the likelihood of inadvertent damage to plant or operation of controls as personnel move about
congested passages. Closely related is minimization of damage by dropped objects.

Another feature is clear identification of equipment. One aspect is the labelling of tanks and vessels holding process materials, since misidentification of materials is an error characteristic of pilot plant operation Another aspect is labelling and coding of equipment which may need to be worked on and which may contain noxious materials.

Another feature is provision for collecting and disposing of liquid leaks.

A fifth feature is the provision of protective barricades against missiles. In some cases this leads to a design in which the pilot plant space is divided up into separate cells.

A10.4.5 Protective barricades
If the process carried out involves high pressures, and particularly high pressure reactions, protective barricades may be provided.

Some practical aspects of barricades are discussed by Carr, who describes methods of protection against missiles such as valve stems and reactor fragments, as well as high pressure steam jets, which can be almost as damaging.

Missiles from an exploding reactor may be stopped by a barricade in the form of a sand bath protected by a pressure relief valve. This reduces the need to house the whole plant in a barricade.

For barricade design in general, design case missiles are specified and the barricade is designed to withstand these missiles, using methods such as those outlined in Chapter 17. It is on pilot plants that the provision of such barricades is most common, and thus where most of the expertise resides.

A10.4.6 Pressure systems
The combination of the facts that a pilot plant is usually in a building and that it is subject to continuous experimentation and modification means that it is necessary to give particular attention to the integrity of the pressure system. Procedures should be laid down for the proof testing and leak testing of the plant.

A10.4.7 Pressure relief
It is common practice in pilot plants to put a safety valve on a vessel. The lines to and from such valves tend to be small diameter and liable to fill with liquid which then solidifies. Countermeasures include design of lines so that the liquid drains away and use of heated lines.

A10.4.8 Frangible elements
Pilot plants are frequently constructed in part or in whole in glass or plastic. They also tend to contain vulnerable features such as rotameters and sightglasses.

The protection of the latter devices is described by Carr. Use is made of protective shields with adequate pressure-relief space between the shield and the device. Specific designs have been developed and tested for most types of device used.

A10.4.9 Gas cylinders
Another hazard discussed by Carr is gas cylinders. Rupture of a line supplied by a high pressure cylinder can result in a large jet of gas. He describes arrangements involving the use of a limiting orifice just downstream of the regulator.

A10.4.10 Ignition source control
Another aspect of the design is the control of ignition sources. The importance of this is enhanced in a pilot plant by the fact that the probability of a leak tends to be higher, that in a building gas or vapour accumulates more readily and that the probability of personnel being present is relatively high.

Since it is necessary to exclude all ignition sources, the proper approach is to make a formal examination of the plant to identify possible sources of release. These sources include activities, both operations and maintenance, as well as fixed plant. Such ignition hazard identification provides a basis for the design both of layout and equipment and of operating controls.

The application of the methods of hazardous area classification is one necessary aspect of this. The principal options are classification as Zone 1 or as Zone 2. Classification as Zone 1 puts constraints on the equipment, particularly instrumentation, which can be used, while classification as Zone 2 requires the elimination of leaks and a good level of ventilation.

An account of practical measures for an area classified as Class 1, Division 2, in the US system is given by Carr.

Other features typically include liquid catchment and disposal arrangements, gas detectors and mechanical ventilation.

Multipurpose plant places particularly severe requirements on ignition control.

These hardware measures need to be complemented by a system of operational controls to eliminate ignition sources. Failure to do this largely negates the value of the hardware.

A10.4.11 Plant classification
A systematic approach to the design of pilot plants is to use a formal method of classification.

Carr describes the method which is used in one company for classifying pilot plants for the purposes of design and operation and of personnel protection and which utilizes four operating categories:

<table>
<thead>
<tr>
<th>Category</th>
<th>Hazard potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Detonation reactions</td>
<td>High potential for detonation or massive rupture and large, extremely rapid release</td>
</tr>
<tr>
<td>2. Rupture and fires</td>
<td>High potential for large rupture and large fire</td>
</tr>
<tr>
<td>3. Leaks and small fires</td>
<td>Low potential for leaks and, at worst, only leaks and fires of limited size</td>
</tr>
<tr>
<td>4. Low hazard operations</td>
<td>Near ambient temperatures and low pressures with very low potential for either ruptures or fires</td>
</tr>
</tbody>
</table>

The corresponding protection requirements are given in Table A10.2.
### Table A10.2. Protection requirements scheme for pilot plants (after Carr, 1988) (Courtesy of the American Institute of Chemical Engineers)

<table>
<thead>
<tr>
<th>Typical hazard</th>
<th>Category 1 Detonating reactions</th>
<th>Category 2 Rupture and fire hazards</th>
<th>Category 3 Leaks and small fires</th>
<th>Category 4 Low hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hazard potential</td>
<td>Protection device</td>
<td>Hazard potential</td>
<td>Protection device</td>
</tr>
<tr>
<td>Detonation (internal) Shrapnel</td>
<td>High</td>
<td>Barricade</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Blast relief</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Explosive atm. (external)</td>
<td>High</td>
<td>Barricade</td>
<td>Moderate</td>
<td>Baffle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blast relief Ventilation</td>
<td></td>
<td>Ventilation Cubicle size</td>
</tr>
<tr>
<td>Fire Pressure leaks</td>
<td>High</td>
<td>Baffle (barricade)</td>
<td>High</td>
<td>Baffle</td>
</tr>
<tr>
<td></td>
<td>Possible</td>
<td>Baffle (barricade)</td>
<td>Possible</td>
<td>Baffle</td>
</tr>
<tr>
<td>Skin toxic</td>
<td>Possible</td>
<td>Baffle (barricade)</td>
<td>Possible</td>
<td>Baffle</td>
</tr>
<tr>
<td>Lung toxic</td>
<td>Possible</td>
<td>Ventilation Excluded</td>
<td>Possible</td>
<td>Ventilation Limited</td>
</tr>
<tr>
<td>Permitted access to operating areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summary of protective devices</td>
<td></td>
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</tbody>
</table>

#### A10.4.12 Extent of automation and protective systems
The operations to be performed on a pilot plant are on a small scale and are required for a limited period, relative to the equivalent operations on the full-scale plant. Further, their automation may well require the development of measuring instrumentation. Hence it will generally not be appropriate to seek to automate these operations to the extent that will pertain on the full-scale plant.

Somewhat similar considerations apply to the provision of protective systems such as trips and interlocks. These definitely have their place in pilot as in full-scale plants, but the particular mix appropriate to the full scale may not suit the pilot scale.

#### A10.4.13 Control systems
The pilot plant should be provided with instrumentation sufficient not only to obtain design data but to ensure safety. The same principles should be applied as to the design of full-scale plant, such as the use of trips and interlocks, subject to the comments made above on the extent of automation and of protective systems.

The use of computers, mainly PCs, for data acquisition and control of experiments is routine in pilot plants. In some cases the flexibility of such computers has also been exploited to provide alarms and trips.

Control schemes for pilot plants are discussed by Uitenham and Munjal (1991) and Palluzzi (1992).

The effectiveness of any protective systems depends on the training of the operators.

#### A10.4.14 High pressure plants
Some pilot plants involve high pressure equipment. The AIChE Pilot Plant Safety Manual contains sections on the design of pilot plants for high pressure and for high temperature operation. For the former further guidance is given in the High Pressure Safety Code by B.G. Cox.

At the pilot plant scale it is quite common to provide blast-proof cubicles and barricades against missiles, which tend to be impractical on the full-scale plant.

A10.5 Pilot Plant Operation

A10.5.1 Suitability of plant
If the pilot plant is a multipurpose one and is thus used to investigate a number of different processes, a particularly careful check should be made that it is fully suitable for the proposed process.

A10.5.2 Personnel and training
The magnitude of the hazard on a pilot plant is less than on the full scale, but in other respects the operations tend to be more demanding. The materials, the process, the equipment, the plant and the procedures are all relatively unfamiliar. The operating team needs strong leadership and experienced personnel.

As with plant operation generally, training is critical. Many of the topics mentioned in this appendix imply the need for training.

Training is required for management and research personnel also. The latter may well be used to laboratory rather than plant situations, and need to become familiar with plant disciplines.

A10.5.3 Operating and emergency procedures
The operations to be performed should be identified and for each a suitable operating procedure should be developed, and should include any safety viewpoint. Operations which are likely to bulk large in pilot plant work include manual operations, reactor operations, sampling and measurement activities.

There need also to be suitable emergency procedures.

A10.5.4 Specifications and documentation
Despite the small scale, it is desirable to adhere to a certain normality in pilot plant operation. Some aspects of this are discussed by J. Jones et al. (1995a).

There should be formal specification for the raw materials, intermediate and products, for yield and throughput, for cost targets and for the completion date.

Records should be kept of the progress of the project during the pilot plant stage, of problems and hazards encountered, and of the steps taken to solve the problems and to eliminate or control the hazards.

The data needed for the design of the full-scale plant should be documented and the information gathered and recorded.

The operating procedures evolved, including the emergency procedures should be properly documented. Again, this should include any problems and hazards encountered and the response made.

A10.5.5 Mothballing
By its nature a pilot plant is liable to be subject to intermittent operation, with periods when it is not in use. Often a pilot plant is shut down and ‘mothballed’ for an extended period. If this is a possibility, it should be taken into account in the design. At the start of such a shutdown measures should be taken to prevent deterioration, including cleaning and flushing of the plant. On recommissioning care should be taken to identify hazards which may arise from the prolonged shutdown.

A10.6 Pilot Plant Safety

An accident in a pilot plant, like one in a laboratory, is generally on a much smaller scale than one on a full-scale plant, but again it can give rise to considerable direct and consequential loss.

Safety in pilot plants is treated in the AICHe Pilot Plant Safety Manual. This deals with procedures, including transfer of information from the chemist, hazard identification, process design, mechanical design and design review; scale-up from pilot to full scale; engineering standards for flammable, explosive, corrosive and toxic materials and for radiation protection; maintenance procedures; and high pressure and high temperature processes.

In general, the same approach should be taken to the design and operation of a pilot plant as is adopted for a full-scale plant. Many of the topics already discussed are equally relevant to pilot plants, including management and management systems (Chapter 6), hazard identification (Chapter 8), process, pressure system and control system design (Chapters 11–13), fire, explosion and toxic release (Chapters 16–18), plant operation and maintenance (Chapters 20 and 21), personal safety (Chapter 25) and safety systems (Chapter 28). On the other hand there are certain features which are characteristic of pilot plants.

A10.6.1 Project safety reviews
There should be a system of project safety reviews adapted to pilot plant design and operation. These should be the subject of a formal requirement and should be documented.

The general methods of hazard identification should be used to discover potential hazards in plant design and operation. In addition, there are hazard identification procedures which are particularly relevant to pilot plants.

The information on the chemicals handled, the reactions involved, and the materials of construction for the plant should be as complete and as well documented as practical.

The transfer of information from the chemist to the engineer should be regulated by formal procedures. The chemist should give a full description of the process, including the reaction kinetics and heats of reaction, limits of operating parameters such as pressure and temperature, and procedures and precautions adopted. The engineer should study the research reports to envision problems which may arise in scale-up to the pilot plant.

The process reaction(s) should be screened to identify any reaction exotherm which might lead to a runaway reaction.

A10.7 Pilot Plant Programmes

Accounts of pilot plant programmes emphasise a number of themes. They include keeping attention focused on the basic chemistry; keeping the programme simple, first establishing feasibility, before getting involved in matters such as yield, effluents, etc., applying lateral thinking and
seeking alternative approaches; being prepared to take the calculated risk that the process may not work, although taking no risks with safety; and making use of expert advice from other sources.

A10.7.1 Handover and decommissioning
The pilot plant operation must recognize the point at which the baton should be handed over the next stage. However, it is advisable not to be in too much of a hurry to decommission a pilot plant. The purpose of the plant is to provide information and/or products to other users. Once they have received these, they too will have to undergo a learning process, and are likely to come back with queries, some of which may require further plant trials. This is true particularly with new products, where the queries may be directed to improving quality or reducing cost and meeting regulatory requirements and environmental constraints.
Appendix

Safety, Health and the Environment

Contents

Safety, Health and the Environment
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Although the problems of environmental protection (EP) are basically beyond the scope of this book, they cannot be completely neglected, because there are a number of ways in which they are closely linked to safety and loss prevention (SLP).

Selected references on the environment and pollution are given in Table A11.1.

Safety, Health and the Environment

These links are recognized in the common practice of coupling health, safety and environment (HSE) or safety.

Table A11.1 Selected references on pollution, effluents and waste disposal

<table>
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<th>Name</th>
<th>Reference Details</th>
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<td>Clementor</td>
<td>(Table A1.4): EPA (n.d., 1988/2); MCA (SG-9, n.d., 11); RCEP (Appendix 28); Mohlman (1950); Brady (1950); Cross (1962); Carson (1963); Byrd (1968); Chem. Eng. (1968-); Chieffe and McLean (1989); Marshal (1968); AICHE (1989-120); Bond and Straub (1972, 1973); Cecil (1972); Levine (1972); Nilsen (1972); Prober (1972-3); Racine (1972); Ripley (1972); S.S. Ross and White (1972); G.F. Bennett (1973); DoE (1973 Poll. Pap. 4, 1974 Poll. Pap. 1, 1976 Poll. Pap. 9); R.D. Fox (1973); Vervain (1973), c, 1979; Barnes, Forster and Hruday (1984-); Mabey (1974); McQuate, Marstrad and Sinclair (1974); Napier (1974a); Rudolph (1974); Sax (1974); Strahler and Strahler (1974); Jaffe and Walters (1975); Rouller, Landreth and Carnes (1977); Singer (1977); Yamaguchi (1975); Boyd and Leotta (1976); CONCAWE (1976-76, 1977-277, 1979-579); R.W. James (1976); Warner (1976, 1979); Anon. (1977); Allaby (1977); Ashby (1977, 1979); E.B. Harrison (1977); Hillman (1977); Holm (1977); P. Sutton (1977b); Boyd (1978); G. Parkinson (1978, 1980, 1987); Pier et al. (1978); Pocock and Docherty (1978); Ricci (1978a); Schneiderman (1978); Bridgewater and Mumford (1979); Golden et al. (1979); Harwell (1979); Baasal, McCullister and Kingsbury (1980); Bakshi and Naveh (1980); Dix (1980); Eggington (1980); Moss (1980); Anon. (1980); Kletz (1981), 1993e, 1994 LPB 110; Portman and Norton (1981); Bennett, Feates and Wilder (1982); Trevith (1982); API (1983/7); ASME (1983/194); R.M. Harrison (1983); Macready (1983); Tan (1983); D. Clarke (1984); Jalees (1985); Neely and Blau (1985); Pitt and Pitt (1985); D. Williams (1985); APCA (1986); Hollowood (1986); Vervain (1986a); Anon. (1987); Anon. (1988c); C. Butcher (1988c); CIA (1989 CE23, 1991 BT23); Hoover et al. (1989); Penkett (1989); Veselind, Peice and Weiner (1990); IBC (1991, 1992, 1993); Jackman and Powell (1991); Shillito (1991); Anon. (1992 LPB 108); Diepolder (1992); Goldsmith (1992a); Parfitt and Andreasen (1992); Reid (1992); Wainwright (1992); Anon. (1993a, f); API (1993 Publ. 311, 317); Doerr (1993); Englehardt (1993); Hydrocarbon Processing (1993b); Karrh (1993); Anon. (1994 LPB 120, p. 13); Agra Europe (1994a); Debeil and Myren (1994 LPB 119); Shillito (1994 IChemE/110) BS 7750: 1992</td>
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Waste minimization, inherently cleaner design

Mencher (1967); Kohn (1978b); Duffy (1983); Tavlarides (1985); Goodfellow and Berry (1986); Koenigsberger (1986); EPA (1987b, 1988, 1988a, b); Gardner and Huisingsh (1987); ACGIH (1989/34); CIA (1989 CE1, 1990 CE2); Higgins (1989); Redman (1989c); H.M. Freeman (1990); Hethcoat (1990); Hunter and Benford (1990); API (1991 Publ. 302); Berglund and Lawson (1991); R. Smith and Petela (1991- ); Crittenden and Kolarzewski (1992); Curran (1992); IBC (1992/88); Chaplin and Parmelee (1993); IChemE (1993/106, 1994/111); Rossiter, Spriggs and Klee (1993)

AICHe Center for Waste Reduction Technologies

L.L. Ross (1991)

Pilot plants

Gundzik (1983); d’Aco, Campbell and Stone (1984); Pitt and Pitt (1985); Gurvitch and Lowenstein (1990)

Chemicals in the environment, inc. physical and chemical properties

ASTM (Appendix 28); Sax (1957); MCA (1966–13, 14); CONCAWE (1970-70, 1971-71, 1971-75, 1985-85); Heck, Daines and Hindawi (1970); AICHE (1971-132, 1975/138, 1980/147); Walker (1971); A. Tucker (1972); NAS (1975); Curtis, Copeland and Ward (1978); Mackenthun and Guarria (1978); SCI (1978); S.D. Lee and Mudd (1979); Tinsley (1979); Aghian and Mackay (1980); Alexander (1980); Blair (1980); Bungay, Dredick and Matthews (1980); Freed (1980); Hanson (1980); Haque (1980a, b); Haque et al. (1980); Keith (1980); Khan (1980); Kimerle (1980); Ljinsky (1980); Mackay, Shiu and Sutherland (1980); Mill (1980); Moein, Smith and Stewart (1976); Murphy (1980); Neeley (1976, 1980); Riordan (1980); M.E. Stephenson (1980); Stern (1980); Weber et al. (1980); Zepp (1980); Jorgensen and Johnson (1981); N.J. King and Hinchcliffe (1981); Neeley (1981); API (1982 Publ. 4434); P.R. Edwards, Campbell and Milne (1982); Kullenberg (1982); Versino and Ott (1982); Rowe (1983); Dragun, Kuffner and Schneider (1984); Iyengar (1984); Jorgensen (1984); Okouchi and Sasaki (1984); Piver (1984); Greenland (1985); Neeley and Blau (1985); CEFC Workshop (1986); Donkin and Widdows (1986); Moriarty (1986); Coughtrey, Martin and Unsworth (1987); Ashworth et al. (1988); Valsaraj and Thibodeaux (1988); Pagna and Ottar (1989); Barton, Clark and Seeker (1990); Lyman, Reehl and Rosenblatt (1990); Manahan (1991, 1993); Wakoh and Hirona (1991); Bruseau (1992); Thoma et al. (1992); Gentile et al. (1993); Kollig, Kitchins and Hanrigr (1993); Marple and Throp (1993); Larson and Weber (1994)

Environmental limit values, indices

Ott (1978); Sittig (1994)

Particular chemicals

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Pollution and human health

Howe (1970); Waldibott (1973); Chementator (1975 May 12, 40; Aug. 4, 38; 1977 Jan. 3, 36); Trevethick (1976); Lave and Siskin (1977,a,b); Doll and McLean (1979); Moghissi et al. (1980); Bolten (1985); BMA (1991)

Environmental management, environmental risk management

Cecil (1969); Vervalin (1979); IBC (1981/10); APCA (1980); J.J. Stevens (1988); Kolluru (1991); Harwell, Cooper and Flack (1992); Kraft (1992); Ormon and Isherwood (1992); Welsh (1992, 1993); S. Wilson (1992); Callahan and McCaw (1993); Turney (1993); Petts and Eduljee (1994)

BS 7750: 1992

Environmental planning

D.C. Wilson (1981); Barclay (1987); DoE (1988 Circ. 15/88); Hassan (1993); Petts and Eduljee (1994)

Environmental hazard identification, assessment

Fuquay (1968); Friedl, Hiltz and Marshall (1973); EPA (1984d); Onishi et al. (1985); Keller and Lamb (1987); B.P. Smith (1987); NSW Govt (1989b); Paustenbach (1989); Cassidy (1990); Picciolo and Metzger (1992); Rouhianen (1992); IBC (1993/98); Petts and Eduljee (1994)

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Environmental modelling

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EPA compliance, inspections


Cost of pollution, pollution control

RCEP (Appendix 26); Eckenfielder (1969); Popper (1971); Chementator (1975 May 26, 58; Sep. 1, 92; 1977 Jan. 31, 55); E.P. Austin (1977); Isaac (1978); Marion (1987c); Martindale (1979); Vatavak and Neveril (1980); Anon. (1991b)

Environmental analysis, monitoring

Ottmers et al. (1972); Nemerow (1974); Sittig (1974); McKee (1976); R.G. Thompson (1976); R.M. Harrison and Perry (1977); Cornish (1978a); R. Briggs (1980); Hinchcliffe (1980); Simpson (1980); Hwang and Koerner (1983); Weston (1984); McMorris and Gravelye (1993)

Airborne effluents

HSE (Appendix 28 Best Practicable Means LFLs, Emission Test Methods); ASTM (STP 281); HM Chief Alkali Inspector (annual report); MCA (n.d.6/10); WHO (EHC4, EHC7); J.E. Pearson, Nonhebel and Ulander (1935); Hawson (1951); Magill, Holden and Ackley (1956); Dept of Health, Education and Welfare (1960); Lapple (1962); Stern (1962-7); Yocom and Wheeler (1962); Hughson (1967); Squire (1967); Brewer (1968); Carlson-Jones and Schneider (1968); Chiefio and McLean (1968b); Imperato (1968); Meetham (1968); Munson (1968); Rossano and Cooper (1968); Scorer (1968, 1973); Sickles (1968); Fay and Hoult (1969); Constanze (1970, 1972a); Ernem (1970); Weismantel (1970); Anon. (1971a); AlChE (1971/132, 1972/133, 1974/136, 1975/139, 140, 1976/142, 1979/145, 1980/146, 147, 1981/149); Strauss (1971-75); Anon. (1972a); CONCAWE (1972/171); Crowley (1973); Elkin and Constable (1972); Iya (1972); Morrow, Brief and Bartrnd (1972a,b); Nonhebel (1972); S.S. Ross (1972a); R.S. Smith (1972); Swinchenbank (1972); Teller (1972); ASME (1973/32); Cross and Schaff (1973); DoE (1973/3, 1974/4); EPA (1973, 1978a); HIWE (1973); Lazorko (1973); Peters (1973); Stern et al. (1973); Vandegeff, Shannon and Gorman (1973); Wiley (1973); Dorman (1974); Pfeifer (1974); Ring and Fox (1974); Driscoll (1975); Ecke and Dreyhaupt (1975); Marchello and Kelly (1975); Open Univ. (1975a); Parekh (1975); Rymarz and Klipstein (1975); Schneider et al. (1975a,b); Seinfeld (1975); Crawford (1976); Gammell (1976); O’Connell (1976); RCEP (1976 Rep. 5); Theodore and Buonicro (1976, 1982); API (1977 Waste Manual, vol. 2); M.L. Barker (1977); E. Briggs (1977); Bump (1977); S.K. Friedlander (1977); N. Kaplan and Maxwell (1977); Kohn (1977b); Lasater and Hopkins (1977); Lave and Siskin (1977a); Perry and Young (1977); Preussner and Broz (1977); R.D. Reed (1977); Ricci (1977b); Rosebrook (1977); Straitz (1977); Dunlap and Deland (1978); Freitag and Packbier (1978); A.F. Friedlander (1978); McCarthy (1978); NSCA (1978); A. Parker (1978); Parrish and Seide (1978); Bochinski, Schoutz and Gideon (1979); Downey and Ni Uid (1979); Hesketh (1979); Parmele, O’Connell and Basdeks (1979); Stockham and Fochtman (1979); Storch (1979); D.P. Wallace (1979); Buonicro (1980); England, Heap and Pershing (1980); Kenson and Holland (1980); Licht (1980); Marzo and Fernandez (1980); Niess (1980); Parungo, Pueschel and Wellman (1980); Theodore, Sosa and Fajardo (1980); Wheeler (1980); Ireland (1981, 1984, 1987); Keene (1981); Lallande (1981, 1982); SCI (1981b); de Wispelaere (1981, 1983, 1984, 1985); Holland and Fitzsimmons (1982); Keith (1982); Record, Bubenick and Kindya (1982); Theodore and Buonicro (1982); E. Weber (1982); Elliot (1983); J.D. Daniels (1984); R.W. Lee (1984); Ogawa (1984); D.D. Adams and Page (1986); APCA (1986);
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Liquid effluents
ASTM (STP 130, 148, 1481, 207, 337, 442, 573); CONCAWE (Appendix 28, 1970 3/70, 1975 3/75, 1975 3/79); IP (Appendix 28 Oil Loss Cond.); MCA (n.d/12, 1966–/13, 14); Eckenfelder and O’Connor (1961); Gurnham (1963, 1965); Busch (1965); Eckenfelder (1966, 1969); Fair, Geyer and Okun (1966); ArChE (1967–71/127–129, 1968/130, 1969/131, 1972/135, 1974/137, 1975/141, 1977/143, 1981/148); Beychock (1967, 1971); Jaeschke and Trobisch (1967); D.R. Montgomery (1967); SCI (1967); Cross (1969); Mziałowski (1969); Dytycher and Michel (1968); Eliasen and Tchobanoglous (1968); Geinopolos and Katz (1968); Kemmer and Oland (1968); Lesperance (1968); Sebastian and Cardnal (1968); A.R. Thompson (1968); API (1969 Waste Manual, vol. 1); Cecil (1969); Chopey (1970); Hiser (1970); Min. of Housing and Local Govt (1970); Anon. (1971h); Nemerow (1971, 1974); Characklis and Busch (1972); Moores (1972); Newsom and Sherrat (1972); Nogaj (1972); McLaughlin (1973); Reiter and Sobel (1973); Helliwell and Bosanyi (1975); Huber (1975); IChemE (1975/88); Lash and Kominek (1975); Open Univ. (1975b); H.W. Parker (1975); Bush (1976); Mulligan and Fox (1976); Thompson (1976); Cope (1976); Finelt and Crump (1977); Ford and Tischler (1977); Lederman (1977); Lewin (1977); McDowell and O’Connor (1977); Moss (1977); Paulson (1977); B.A. Bell, Whitmore and Cardenas (1978); Culp, Webster and Culp (1978); IBC (1978/3, 1993/100); Nathan (1978); Ramalho (1978, 1979); C.R. Fox (1979); Freeze and Cherry (1979); Martindale (1979); Sundstrom and Klei (1979); Afghan and Mackay (1980); Brewin and Hellawell (1980); R.A. Freeman (1980); Glaubinger (1980); J.H. Robertson. Cowen and Longfield (1980); D.L. Russell (1980); G.K. Anderson and Duarte (1981); Arceivala (1981); Ailing and Castrantas (1981); Chalmers (1981); Howie, Howe and Howe (1981); Iddledien (1981); Sidwick (1981); Walters and Wint (1981); Askew (1982); Olofsson and Oleskiewicz (1982); Selby (1982); Vernick and Walker (1982); Wheatley (1982); Barrs (1983); Langer (1983); Cushie (1984); A.E. James (1984); R.A. Mills (1984); Eckenfelder, Patoczka and Watkin (1985); Crossland (1986); J. Lawrence (1986); NFPA (1990 NFPA 820); Veselind, Peirce and Weiner (1990); Metcalfe and Eddy (1991); G. Parkinson and Basta (1991); RCEP (1992 Rep. 16). Deep well disposal: Selim and Hulse (1960); Talbot and Beardon (1964); D.L. Warner (1965); Talbot (1968); Sheldrick (1969); M.E. Smith (1979); Hydraulic dispersal: Abbott (1961); Fisher et al. (1979); Lloyd, O’Donnell and Wilkinson (1979); Cunge, Holly and Verney (1980); Kubus (1981); R.E. Lewis (1981); Novak and Cabelka (1981); Komar (1983); ASCE (1986/28); Oil-water separators: API (1990 Publ. 421); Stream dispersal, pollution, renewal: Streeter and Phelps (1925); H.A. Thomas (1948); Churchill and Buckingham (1956); Hwag (1980); Nusser (1982); Velz (1984); Wet air oxidation: Flynn (1979); Wilhelmi and Knopp (1979); Laughlin, Gallo and Robey (1983); Baillol, Lamparter and Barna (1985); Heimbuch and Wilhelmi (1985)

Spills, spill control
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Oil spills

Marine

Torrey Canyon
Cowan (1969)

Hazardous and solid wastes
MCA (SG-9, 1974 SW1–SW3); Mohlman (1950); SCI (1957); Rickles (1965); FPA (S3, 1971/15); Key (1970); Novak (1970, 1972); Anon. (1971b); IChemE (1971/51); Witt (1971b, 1972); AIChE (1972/134); Baum and Parker (1973); Santolieri (1973); IMechE (1975/44, 1977/49); Mantell (1975); Open Univ. (1975d); Patrick (1975); Roullet, Landreh and Carnes (1975); Saxton and Narkus–Kramer (1975); Stephenson et al. (1975/186); Bessellever and Schwart (1976); Boily (1976); D.R. Davies and McKay (1976); Frishbe (1976, 1978); Lazar (1976a, b); E.P. Austin (1977); Feates (1977); Hillman (1977); Keen (1977); Paulson (1977); S.W. Pearce (1977); G. Jones (1978); Morrison and Ross (1978); Ricci (1978b); Huddletone (1979); Okey, Digregorio and Kominek (1979); Pojasek (1979a, b); J. Smith et al. (1979); API (1980 WASTE MANUAL); Conway and Ross (1980); Gradlet and Short (1980); Anon. (1981a); Basta (1981b, e); Jamieson (1981); Shen (1981); ASTM (1982 STP 760, 1983 STP 805, 1984 STP 851); Bentley (1982); Farquhar (1982); Kiang and Metry (1982); R.D. Ross (1982); Skott (1982); Thibodeaux, Springer and Riley (1982); A.N. Clarke and Clarke (1983); Chivers (1983, 1984); Cope, Fuller and Willetts (1983); G.W. Davidson (1983); Dyer and Mignone (1983); Finney (1983); Jennings (1983); A. Lawrence (1983); D.A. Mills (1983); Cook (1984 LPB 55); Hawkins (1984); Hillman (1984); Kemnard (1984); Luck (1984); Mackie and Nieszen (1984); E.F. Wood (1984); Zirchky and Gilbert (1984); Anon. (1985a); Basta, Hughson and Mascone (1985); Fitt and Pitt (1985); Porteous (1985); RCEP (1985 Rep. 11); Anon. (1986a); Arthur (1986); Hollowood (1986); Payne (1986); W.F. Robinson (1986); Barclay (1987); M. Bradford (1987); CIA (1987 RC15, RC16, 1989 RC17); Colen (1987a, b); Crittenden and Kolaszkowski (1987); Crumpler and Martin (1987); EPA (1987); Loehr (1987); E.J. Martin and Johnson (1987); Stone (1987); Wiles (1987); Randell (1988a); Hammitt and Reuter (1988); Saldoco, Cross and Chrismon (1988); ACGIH (1990/42, 1992/83, 84); Barth (1990); Batchelor (1990); G.W. Jones (1990); Pekelnay (1990); Soudarajan (1990); Tedder and Pohland (1990); Veselind, Peirse and Weiner (1990); Weitzman (1990); HMIP (1991); Nemirov and Dasgupta (1991); IBC (1992/87); Paluzzi (1992); IMechE (1994/170); Petts and Eduljee (1994); Sara (1994)

Incineration
ASME (Appendix 28 Solid Waste); Frankel (1966); Monroe (1968, 1983b); Cross (1972); CONCAWE (1975/2); Dunn (1975, 1979); C.R. Lewis, Edwards and Santoro (1976); R. Harrison and Coullson (1977); Bartsch, Gilley and Steele (1978); J. Jones (1978); Dunn (1979); Fabian, Reher and Schon (1979); Hitchcock (1979); Ready and Schwab (1980 LPB 36, 1981); HSE (1981 BPPM 11); Denue (1983); Frankel, Sanders and Vogel (1983); Monroe (1983b); Anon. (1984aa); Feeley (1984); H.M. Freeman (1984); Brunner (1985, 1986, 1989, 1993); Rickman, Holder and Young (1985); Basta (1986a); Zurer (1986); Baker-Counsel (1987a); Beychock (1987b); H.M. Freeman et al. (1987); Wiley (1987); C. Butcher (1990a); IBC (1990/78, 1992/93); Vervalin (1990a); Veselind, Peirse and Weiner (1990); F.T. Williams (1990); Ondrey and Foubly (1991); Zeng and Okrent (1991); Altorfer (1992); S.E. Anderson, Dowell and Myburgh (1992); Haselton (1992); RCEP (1993 Rep. 17)

Transport
R.J. Buchanan (1982); Bromley and Finney (1985)

Ocean disposal, ocean incineration
Waste sites, site clean-up, contaminated land
Dennis (1978); Kohn (1978d); Overcash and Paul (1980); SCI (1980); IBC (1981/18, 1992/89); D.C. Wilson, Smith and Pearce (1981); Bowders, Koerner and Lord (1982); Long and Schweitzer (1982); Lord, Koerner and Freestone (1982); D.C. Wilson (1982); R.E. Edwards, Speed and Verwoert (1983); Muller, Brodd and Leo (1983); Rogoshenski, Boyson and Wagner (1983); Tyagi, Lord and Koerner (1983a–c); Block, Dragun and Kalinowski (1984); Block and Kalinowski (1984); Ehrenfelder and Bass (1984); Husak, Kissenpfennig and Gradet (1985); M.A. Smith (1985); Wagner et al. (1986); Lord and Koerner (1988); des Rosiers (1987); Areni et al. (1988); Hopper (1989); Porter (1989); Ahlert and Kosson (1990); Bleicher (1990); IP (1991 PUB 58, 1993/2); Raghavan, Coles and Dietz (1991); AGA (1992/86); N. Morgan (1992a); Vandegrift, Reed and Tasker (1992); Cairnie (1993); Pratt (1993)

**Superfund**
Ember (1984); Hoppe (1984b); Casler (1985); Sidley and Austin (1987); Redman (1989b); Bisio (1991b, 1992a)

**Love Canal**
Glaubinger, Kohn and Remirez (1979); J.L. Fox (1980a); Gage (1980); Holden (1980); Kolata (1980); Picciano (1980); M.W. Shaw (1980); M. Brown (1981); Kohn (1982); Anon. (1984hh)

**Rechem**
Anon. (1984a, i, o, aa, dd); Anon. (1985y, x); Anon. (1986d, x); Anon. (1987v); J. Cox (1988b)

Creating awareness, instilling responsibility and introducing the appropriate engineering approaches.

A11.1.4 Job descriptions
Safety and environmental issues have both grown progressively in importance for industry and government at all levels. In industry there has been an increasing tendency for job titles and descriptions to assign responsibilities which cover both safety and environment.

A11.2 Common Elements

A11.2.1 Economic factors
Both SLP and EP have a fundamental influence on the design of the plant. Each imposes constraints which may well be decisive in the economics of the design.

A poor design is more likely to require the addition of numerous protective devices and the installation of much pollution control equipment and to involve more last-minute modifications to meet legislative and other safety and environmental standards.

A11.2.2 Inherently safer/cleaner design
The concept of inherently safer design, discussed in Chapter 11, has its counterpart in that of inherently cleaner design, or, more broadly, waste minimization.

The philosophy of inherently cleaner design is to avoid the generation of noxious effluents. As with inherently safer design, this is easier said than done, but progress has been made and the pressures to operate cleaner processes continue to grow.

A11.2.3 Intermediate storage
A prime theme in inherently safer design is the elimination of intermediate storage. It transpires that the elimination of storage tanks is also a significant feature of waste minimization programmes. In the first case the motivation is to reduce the inventory of hazardous materials, while in the second it is to reduce the quantities of tank residues and wash liquids.

A11.2.4 Hazard identification
The general approach to hazard identification developed in SLP is also applicable to EP.

The hazop method, for example, is increasingly being adapted or enlarged to cover the environment.

A11.2.5 Hazard assessment
Likewise, hazard assessment is finding application in EP as well as in SLP.

Although much of the methodology of hazard assessment used in SLP is applicable to environmental problems, there are also some significant differences. The treatment of the events leading up to a release uses an essentially common methodology, but the modelling of the consequences of a release naturally differs more significantly.

Thus whereas for SLP hazard assessment involves estimating and evaluating the consequences in terms of injury to people and damage to property, for EP the consequences to be considered are the fate of chemicals in the environment, and their ultimate effects on plant and animal life.
A11.2.6 Hazard models
Many of the models used in hazard assessment for SLP are applicable also to EP, and indeed it was for the latter that some were first developed.

Thus the treatment of emission, vaporization and dispersion largely shares a common methodology, although there are some differences of emphasis. In gas dispersion, for example, heavy gas dispersion is of particular significance in SLP, while for EP passive dispersion, including dispersion over much greater distances, plays a more significant role.

A11.2.7 Fugitive emissions
A problem common to SHE and EP is that of low level, or fugitive, emissions from plant. Such emissions have an impact on the health of workers in the plant and on the population and environment outside.

In SLP the need for stricter controls on emissions within the plant was evidenced by the vinyl chloride problem in 1975, while in EP pressure for emission controls arose from studies of the causes of air pollution in cities such as Los Angeles in the later 1970s, which implicated emissions from nearby refineries.

A11.2.8 Environmental impact assessments
There has been a general trend to require that an industrial activity make an environmental impact assessment (EIA) or environmental impact statement (EIS), also referred to, respectively, as an environmental assessment (EA) and an environmental statement (ES).

Such environmental impact assessments and statements include safety issues, although mainly in respect of hazards to the public.

A11.2.9 Safety cases
Closely related is the requirement in European legislation for preparation of a safety case. The requirement to address hazards to the environment as well as humans has received increasing emphasis.

A11.2.10 Communication with public
Process plants and hazardous waste facilities are both liable to generate opposition, prior to creation or in the course of operation. The need to communicate with the public, and the approach required, are very similar in both cases.

A11.3 Some Conflicts
Another link between SLP and EP is that in some cases a degree of conflict arises. In some cases the preferred solution to a safety problem may be ruled out, or at least discouraged, on environmental grounds; in others stricter environmental controls may push the designer towards solutions which would not otherwise be adopted for safety reasons.

Accounts of such conflicts have been given by Elphick (1972), R.Y. Levine (1972b), Bodurtha (1976) and Kletz (1993c).

Some of the practices which are so affected are now considered.

A11.3.1 Reactor venting
The normal method of protection for a chemical reactor has been the provision of a bursting disc with a short, straight pipe discharging to atmosphere at a safe place.

If such discharge is not permitted but this basic method of protection is retained, it becomes necessary to pipe each bursting disc into a vent header leading to a disposal system such as a scrubber or flare. Some of the problems which this creates have been described by Levine.

It is largely for this reason that the alternative approach of using instrumented protective systems on reactors has become increasingly attractive, as described in Chapter 11.

A11.3.2 Pressure relief valve discharge
An essentially similar conflict and similar problems arise over the practice of fitting pressure relief valves which discharge directly to atmosphere.

Some of the problems of vent collection systems are described by Kletz.

Avoidance of discharge to atmosphere is one of the main arguments for the use of trip systems to protect against overpressure, as described in Chapter 13.

A11.3.3 Flaring
A flare radiates intense heat and light and may be smoky and noisy. These are all aspects of pollution which have become increasingly unacceptable.

In contrast to the oil industry, which has continuous flaring, the chemical industry often makes use of an intermittent flare. The flare may be used to burn small quantities of smelly materials. But since very small quantities are sometimes not ignited by the flare pilot burner, it is sometimes necessary to operate the flare continuously, using fuel gas which could otherwise be used more productively.

A11.3.4 Bleeding
The build-up of impurities in plants is avoided by taking off a bleed. If this practice is inhibited by environmental considerations, the impurity can accumulate and may create a hazard. Levine describes a multimillion dollar loss which occurred due to the build-up of the explosive impurity azomethane.

A11.3.5 Leaks
The degree of leakage which has been tolerated in the past is now frequently unacceptable. The problems which can then arise are illustrated by the leakage of hydrogen from mercury cell chloride plants. The hydrogen stream is one of the carriers of mercury vapour from the cells. Therefore mercury escapes in the hydrogen leakages. One possible solution is to run with the hydrogen under a slight negative pressure, but this creates the risk of air ingress leading to an explosion.

A11.3.6 Incineration
Burning in open pits has been widely used as method of disposing of waste solvents on chemical plants. Closed incinerators eliminate this pollution, but present hazards of their own.
A11.3.7 Ventilation
The hazard from flammable leaks in a compressor house can be reduced if the building is of open construction such that ventilation is much enhanced. This solution runs into the difficulty, however, that the noise of the machinery carries further.

A11.3.8 Combustion processes
The attempt to reduce the emission of nitrogen oxides from combustion processes can increase the risk of explosion. A marked decrease in nitrogen oxides formation occurs as excess air is reduced. But reduction of excess air increases the probability of an explosion due to unburned fuel in the gas leaving the combustion chamber.

A11.3.9 Pollution control equipment
Equipment for the removal of flammable dust from gases can present another hazard. Although this can be minimized by the use of wet scrubbers, these run into difficulties from water pollution controls.

A11.3.10 Halons
Halons have found a distinctive role in the process industries as fire extinguishants and explosion suppressants. The banning of chlorofluorohydrocarbons (CFCs) creates a gap which for fire extinguishants is not yet fully filled.

Pollution of the Environment
Awareness of the seriousness of environmental pollution grew rapidly in the 1960s. The publication of Silent Spring by Carson (1963) was a landmark. Other warnings have followed such as Bitter Harvest by Egginton (1980).


Also relevant are the reports of the Royal Commission on Environmental Pollution.

A11.4 Legislation
Although there are significant differences between gaseous effluents, liquid effluents and solid wastes, some of the legislation addresses more than one of these, and it is convenient therefore to take all three together.

A11.4.1 Air pollution
The Alkali etc. Works Regulation Act 1906 was for many years the principal act governing air pollution. The philosophy of enforcement of the act has been the use of best practicable means (BPM) to minimize emissions.

The HSWA 1974 states in Section 1(1)(d) that its provisions are made with a view to controlling emissions of noxious substances and it contains in Section 5 a general duty to use best practicable means to prevent such emission.

The Health and Safety (Emissions into the Atmosphere) Regulations 1983, amended 1989, create in Section 3 prescribed classes of premises for the purposes of Section 1(1)(d) of the HSWA, listed in Schedule 1, and specify under Section 4 substances prescribed as noxious. These premises and substances are listed in Schedules 1 and 2, respectively.

A11.4.2 Control of Pollution Act 1974
The Control of Pollution Act 1974 (COPA) has four main parts: Part I, Waste on Land; Part II, Pollution of Water; Part III, Noise; and Part IV, Pollution of the Atmosphere.

Part I of the act states requirements for the disposal authority to control waste disposal by a system of licensing. It prohibits the unlicensed disposal of controlled waste.

In Part II the act lays down the duties of the Water Authorities to operate a system of consents for discharges and prohibits noxious discharges.

The provisions of Part IV on atmospheric pollution are limited and deal mainly with pollution by certain fuels and with information about air pollution.

A11.4.3 Environmental Protection Act 1990
The Environmental Protection Act 1990 (EPA) has nine parts, those of principal relevance here being Part I, Integrated Pollution Control and Air Pollution Control by Local Authorities; Part II, Waste on Land; and Part III, Statutory Nuisances and Clean Air.

Part I of the act establishes a system of integrated pollution control (IPC) enforced by HM Inspectorate of Pollution (HMIP) and one of air pollution control (APC) administered by the local authorities (LAAPC).

Section 1 of Part I gives definitions of environment, pollution and harm which read as follows:

(2) The ‘environment’ consists of all, or any, of the following media, namely the air, water and land; and the medium of air includes the air within buildings and the air within other natural or man-made structures above or below ground.

(3) ‘Pollution of the environment’ means pollution of the environment due to the release (into any environmental medium) from a process of substances which are capable of causing harm to man or any other living organisms supported by the environment.

(4) ‘Harm’ means harm to the health of living organisms or other interference with the ecological systems of which they form part and, in the case of man, includes offence caused to any of his senses or harm to his property; and ‘harmless’ has a corresponding meaning.

Section 2 creates a system of prescribed processes and substances and Section 3 allows regulations to be made for their control. Subsection 2 of Section 3 allows the prescription of standard limits for the concentration, the amount or the amount in any period to be released; of standard requirements for measurement; and of standards or requirements for the process. Subsection 5 allows the making of plans for establishing limits for the total amount or total amount in any period to be released.
in any area; for quotas for operators; and for establishing or reducing limits so as progressively to reduce pollution.

Sections 6–12 create a system of authorizations to operate a prescribed process. Section 7 deals with the conditions of such an authorization. It requires that in carrying on such a process use should be made of the best available technology not entailing excessive cost (BATNEEC) to prevent release of prescribed substances or to render harmless any other potentially harmful substances.

Section 4 establishes the enforcing authorities and Sections 13–19 deal with enforcement. Section 13 gives powers to make an enforcement notice and Section 14 a prohibition notice.

Section 23 gives a list of offences and penalties. Section 27 gives powers such that where an offence causes any harm which it is possible to remedy the inspectorate may arrange for any reasonable steps to be taken to remedy the harm and may recover the cost from any person convicted.

The EPA covers discharges into all environmental media. Some processes have the potential to make significant discharges into more than one medium, in some cases as a result of transfer from one medium to another. An example is removal of substances from a gas stream which then ends up in a liquid effluent. In such situations the EPA requires the selection of the best practical environmental option (BPEO) and the operator is required to demonstrate that its process meets the BPEO criterion.

Part II of the act creates a duty of care in respect of wastes and a system of waste management licences.

Part III defines a number of statutory nuisances which are prejudicial to health or a nuisance and which include emissions such as smoke; fumes and gases; dust, steam, smell and other effluvia; accumulations or deposits; and noise. It lays on a local authority a duty to inspect its area to detect such nuisances and to act on them.

The prescribed processes and substances are given in the Environmental Protection (Prescribed Processes and Substances) Regulations 1991. Schedule 1 contains a number of chapters, each of which deals with a particular industry. The chemical industry is covered in Chapter 4 of the schedule.

A distinction is made between those processes which are subject to control by local authorities in respect of air pollution only and those which have the potential for pollution of more than one environmental medium, which require an IPC authorization from the HMIP – the Part B and Part A processes, respectively.

A11.4.4 Clean Air Act 1993
The Clean Air Act 1993 covers pollution by smoke, grit, dust and fumes from industrial processes not required to be registered under the HSWA 1974 and the Health and Safety (Emissions into the Atmosphere) Regulations 1983.

The act prohibits the emission of ‘dark’ smoke from any chimney or industrial premises.

A11.4.5 Water pollution
Until 1973 local authorities had the duty of providing sewerage and sewage treatment not only to domestic but also as far as possible to industrial users. Controls on effluents from industrial premises to the public sewerage system were established by the Public Health (Drainage of Trade Premises) Act 1937.

The Water Act 1973 transferred the responsibilities for industrial effluents to the public Water Authorities (WAs). The operation and maintenance of the sewerage system continued to be done by the local authorities on an agency basis.

The Control of Pollution Act 1974 strengthened the controls on water pollution.

The development of controls on water pollution has been influenced by the apparent deterioration of water quality in the North Sea and by a series of North Sea Conferences of the states concerned, the first being held in 1984.

Substances identified as particularly harmful to the aquatic environment by reason of their toxicity, persistence and bioaccumulation are identified in the ‘Red List’.

Control of water pollution is now governed by the Water Act 1989, described below, and the EPA 1990.

The system being developed under these acts is one of integrated pollution control based on environmental quality objectives (EQOs) and environmental quality standards (EQSs) utilizing the BATNEEC criterion.

A11.4.6 Water Act 1989
The Water Act 1989 defines the waters which are subject to control, establishes the powers of control and creates the National Rivers Authority (NRA).

Prior to privatization the Water Authorities were responsible both for the supply of water and for control of pollution of water. In other words, they were both poacher and gamekeeper. The need to separate these functions led to the creation of the NRA, which is now responsible for protecting the aquatic environment.

Section 103 of the Act defines the various waters subject to controls, which are essentially inland waters, including rivers and watercourses; groundwaters; coastal waters; and territorial waters out to a 3 mile limit.

Part III of the Act gives the NRA powers to improve water quality and to control effluent discharges.

Discharge of liquid effluent is governed by a system of discharge consents. The discharge consent procedures are given in Schedule 12 of the Act.

Public participation is allowed for by arrangements for advertising a discharge application in the local press and by a duty on the authority to consider representations made.

A11.4.7 Hazardous wastes
Control of hazardous wastes is exercised under the Deposit of Poisonous Waste Act 1972 and the Deposit of Poisonous Waste (Notification of Removal or Deposit) Regulations 1972.

Hazardous waste controls are also major elements of the Control of Pollution Act 1974, Part I and the EPA 1990, Part II, as already described. The EPA 1990 creates a system of waste management licences.

A11.4.8 Environmental impact assessment
EC Directive 85/337/EEC on the assessment of the effect of certain public and private projects on the environment creates for certain projects requirements for an environmental assessment.
In the UK implementation of these requirements is largely covered by the Town and Country Planning (Assessment of Environmental Effects) Regulations 1988 (the EA Regulations).

The regulations specify that a developer provide information on the impact of the project in the form of an environmental statement.

A11.4.9 Advisory bodies
There is a standing Royal Commission on Environmental Pollution (RCEP). The reports of the commission are listed in Appendix 28.


A11.4.10 Safety cases
EC Directive 82/501/EEC on major accident hazards creates controls on certain installations which include the submission of a safety report. There have been two subsequent modifying directives, the second 88/610/EEC containing requirements in response to the Rhine pollution incident at Schweizerhalle in 1986.

The initial directive is implemented in the UK by the CIMAH Regulations 1984 and the two later directives by amendments of these regulations. In the second set of amendments in 1990 the requirement for the safety case is contained in Regulation 7 and its contents are specified in Schedule 6.

Schedule 6 refers to information on the consequences of a major accident without specifically mentioning those to the environment, but guidance given in HS(R) 21 by the HSE (1990) states that in relation to the environment information should include the routes by which harm may be brought about and the effect on the exposed environment including persistence of the substance in the environment.

A11.5 EC Directives
There are a considerable number of EC Directives concerned with the environment. Some of the principal directives are listed in Chapter 3.

An information service on EC legislation is given in European Environment Law for Industry by Agra Europe (1994a).

Directive 76/464/EEC gives a list of substances dangerous to the environment. 80/68/EEC addresses groundwater protection. Discharge of certain substances listed in 76/464/EEC is covered by 86/280/EEC. There are directives on discharge of metals such as mercury and cadmium. Directive 84/360/EEC deals with air pollution from industrial plants and 88/609/EEC with large combustion plants. There are directives on ozone, sulphur dioxide, nitrogen dioxide and carbon dioxide. Other specific pollutants covered by directives include lead, asbestos and PCBs. Toxic and dangerous wastes are the subject of Directives 78/319/EEC and 91/689/EEC, while 84/631/EEC deals with transfrontier shipment of wastes.


A11.6 US Legislation

The account given below complements that given in Chapter 3.

A11.6.1 Air pollution
In the USA air pollution legislation includes the Air Pollution Control Act 1975, the Clean Air Act 1963 (CAA) and the Clean Air Act Amendments 1970, 1977 and 1990 (CAA).

The CAAA 1970 required the EPA to establish National Ambient Air Quality Standards (NAAQSs). The CAAA 1977 brought in requirements for the NAAQSs to be regularly up-dated and for the prevention of significant deterioration (PSD) in regions with air cleaner than the NAAQS. A system of New Source Reviews (NSRs) was instituted with New Source Performance Standards (NSPSs). Best available control technology (BACT) is required for compliance.

Title III of the CAAA 1990 gives a list of 189 air toxics and requires the EPA to publish a list of source categories emitting 1 ton/year of any one toxic or 25 ton/year of a combination and to issue for such toxics maximum achievable control technology (MACT) standards.

A11.6.2 Water pollution
Water quality in the USA is protected by legislation on effluent discharges to streams and on drinking water quality. The Federal Water Pollution Control Act 1972 envisaged a nationwide policy of zero discharge of pollutants by 1985. The EPA introduced a discharge permit system in the form of the National Pollutant Discharge Elimination System (NPDES). The Clean Water Act Amendments 1977 backed away from zero discharge and introduced a system requiring instead that in due course discharges be treated with the best conventional pollutant control technology. In addition, the EPA is now charged with setting limits for some 100 toxic substances in effluents.

Advisory standards for drinking water in the USA have long been set by the US Public Health Service (USPHS). The Safe Drinking Water Act 1974 authorizes the EPA to set minimum national drinking water standards.

A11.6.3 Hazardous wastes
Hazardous wastes in the USA, governed previously by the Solid Waste Disposal Act 1965, are now are subject to the Resource Conservation and Recovery Act 1976 (RCRA). The act seeks to ensure proper land disposal of defined hazardous wastes and to fill certain loopholes in control on air and water pollution. Under it the Office of Solid Waste (OSW) of the EPA promulgates regulations defining hazardous wastes and standards applicable to it.

In implementation of the Act, the EPA classified waste disposal sites as landfills, lagoons or landspreading operations, defined eight categories of impact which such sites might have and stated the operational and
performance standards to be met to minimize such impacts.

Hazardous wastes attract further controls. For these the EPA has set up what is in effect a 'cradle-to-grave' system covering hazardous waste generation, transport and treatment, storage and disposal facilities, imposing duties on the generator, the transporter and the facility operator and involving tracking by a system of identification numbers and control by a system of permits.

The problem of the large number of hazardous waste sites in unsatisfactory condition, or worse, is addressed by the Comprehensive Environmental Resource Conservation and Liability Act 1980 (CERCLA) or Superfund. The act creates controls on such facilities and provides for the EPA to supervise the clean-up of existing and abandoned sites. The EPA seeks to identify Potentially Responsible Persons (PRPs) and, where such parties are not found, it initiates a clean-up paid for from the Superfund.

The Superfund Amendments and Reauthorization Act 1986 (SARA) renews the Superfund. The part known as SARA Title III extends its application to accidental releases.

The numerous other items of legislation which have some bearing on hazardous waste are reviewed by Edelman (1987).

A11.6.4 Fugitive emissions

Standards governing fugitive emissions have been promulgated by the EPA under the Clean Air Act. These are the Standards of Performance of New Stationary Sources Equipment Leaks of VOC, Petroleum Refineries and Synthetic Organic Chemical Manufacturing Industry 1983, also referred to as the New Source Performance Standards (NSPSs), the NSPS Regulations or the VOC (SOCMI) Regulations. These set standards for emissions permissible from items of equipment.

In addition to these controls on VOCs, the EPA has also issued National Exposure Standards for Hazardous Air Pollutants (NESHAPs) for certain specific substances. These too give equipment emission standards.

The NSPSs apply to new equipment but also have application to reconstructed and modified equipment, and guidance has been given on determining how far they affect existing equipment. In addition, existing equipment is affected by the assimilation into EPA controls of state requirements on monitoring and maintenance (M&M).

A11.6.5 Environmental impact assessment

The National Environmental Policy Act 1969 (NEPA) contains in Section 102 the far-reaching provision that where the action of a federal agency may have significant consequences for the human environment, an environmental impact statement should be given. The practice is to prepare a draft statement, which is put out for consultation, and then to issue the final statement.

A11.7 Environmental Management

11.7.1 Environmental management systems

The environment needs to be protected by an approach to management and management systems similar to that developed for safety and loss prevention, which has been described in Chapter 6. There should be an environmental management system (EMS) which parallels the safety management system.

A11.7.2 BS 7750

Environmental management is the subject of BS 7750: 1992 Specification for Environmental Management Systems. The standard may be regarded as applying in this field the principles of quality systems given in BS 5750. An overview is given by Shillito (1991).

Requirements of BS 7750 include (1) documentation of the environmental management and management systems; (2) collation of regulatory requirements on the environment; (3) inventory of raw materials and energy usage and of wastes and releases; (4) formulation of environmental objectives; (5) an environmental management plan; (6) a system of environmental audits; (7) a system of environmental controls with verification and testing; and (8) personnel qualified and trained in environmental matters.

A11.7.3 Process environmental reviews

The EMS should require a system of process environmental reviews akin to the process safety reviews described in Chapters 6 and 8.

This review system should include formal systems for the identification and assessment of environmental hazards.

The hazop study method is now applied to identify potential problems with the environment as well as with safety and operability. Accounts are given by Isalski et al. (1992) and Ormond and Isherwood (1992).

A11.7.4 Environmental audits

Another essential feature of an EMS is a system of environmental audits. Environmental auditing stands in essentially the same relation to EP as safety auditing does to SLP.

Accounts of environmental audits are given by Baumer (1982), Keene (1982), D.L. Russell (1985) and Petts and Eduljee (1994).

A11.7.5 Environmental planning

The essential concern of planning is with the environment as broadly defined, including amenity as well as hazards and pollution.

The planning arrangements vary from country to country. Accounts of planning in the UK in relation to major hazard installations have been given by Petts (1988b, 1989, 1992).

Accounts of planning in relation to pollution are given by D.C. Wilson (1981) and Petts and Eduljee (1994), both dealing with hazardous wastes.

To a considerable extent planning centres around the environmental impact statement, discussed in Section A11.9.

A11.7.6 Environmental emergency planning

Environmental emergency planning is needed to cover both fixed installations and transport. The treatment in Chapter 24, which covers both aspects as far as safety is concerned, is in large part applicable to planning for environmental emergencies.

Further treatments relevant to the environment specifically are given in Hazardous Materials Emergency...

As stated earlier, the CIMAH safety case is required to cover environmental as well as safety aspects of emergency planning.

A11.8 Environmental Hazard Assessment

There is now an increasing activity in environmental hazard assessment. In large part this has been driven by the threat to the environment from hazardous waste sites. In the USA the pollution arising from the hazardous wastes dumped at Love Canal, described in Section A11.22, and the resultant arrangements for clearing up waste sites under Superfund have stimulated assessment of such sites to determine the extent of the risks and to set priorities for clean-up.

Hazard assessment is undertaken both for existing or proposed hazardous waste treatment, storage and disposal facilities (TSDFs) and for abandoned hazardous waste dumps.


A11.8.1 EPA guidance


The process outlined by the EPA involves the following steps: (1) hazard identification, (2) toxicity assessment, (3) exposure assessment and (4) risk characterization.

A brief description of the assessment process is given by Kolluru (1991) and a more detailed account by Asante-Duaa (1993).

These stages in the assessment are now outlined.

A11.8.2 Hazard identification

Hazard identification is the first stage and, in this context, means the identification of those chemicals which pose the greatest risks, the so-called indicator chemicals.

Since this identification involves the inventory, mobility, persistence and toxicity of the chemicals, some degree of iteration back from the subsequent stages may be necessary.

A11.8.3 Toxicity assessment

Toxicity assessment requires consideration of toxicity both for carcinogens and for non-carcinogens.

For carcinogens the assumption made by the EPA is that there is no threshold below which a dose is harmless. The probability of harm is then obtained from the slope of the dose–response curve, the so-called cancer slope factor (CSF) or potency factor. The EPA also recognizes a weight of evidence factor. Carcinogens are divided into four categories: (1) human carcinogens, (2) probable human carcinogens, (3) probable human carcinogens but with inadequate human data and (4) possible human carcinogens.

For non-carcinogens a threshold is admitted. For the dose of such a chemicals there is therefore a no observable adverse effect level (NOAEL). A reference dose (RfD) is defined which is one hundredth of the NOAEL and which thus incorporates a substantial safety factor. The reference dose is also termed the acceptable daily intake (ADI).

A11.8.4 Exposure assessment

Exposure assessment involves determining the persons exposed and their intake of toxic chemicals.

The EPA has issued standard assumptions for exposure. For adults these include the following:

- Air inhaled (m³/d) 20
- Water ingested (l/d) 2
- Soil ingested (mg/d) 100
- Fish consumption (g/d) 6.5
- Lifetime exposure (year) 70

The assessment required is for a reasonable maximum exposure (RME) under present and future land use conditions.

A11.8.5 Risk characterization

Risk characterization involves combining the toxicity and exposure estimates to obtain an assessment of risk to human health and making an assessment of the risks to the environment.

Cancer risks are expressed as the probability of contracting cancer from exposure to the chemicals over a lifetime. Non-cancer risks are expressed for a single substance in terms of a hazard quotient (HQ) or for a set of substances in terms of a hazard index (HI), the sum of the hazard quotients. The hazard quotient is the ratio of the daily intake to the reference dose RfD. If the HQ is less than unity, the chemical is not regarded as a threat to public health.

A11.8.6 Source terms and transport models

A full hazard assessment of a hazardous waste TSDF requires the modelling of source terms and of the transport and transformation of chemicals in the atmosphere and the ground. These aspects are discussed in Section A11.12.

A11.9 Environmental Impact Assessment

A11.9.1 Environmental assessments

An environmental assessment presented in an environmental statement is for some projects a regulatory requirement under the Environmental Assessment Regulations 1988.

The treatment by Petts and Eduljee is comprehensive and although concerned with hazardous waste facilities its general approach is of much wider application.

The authors describe the regulatory requirements for, the purposes of and practice in respect of an EA and they relate the EA to the requirement to select the best practicable environmental option (BPEO) with its implication that alternatives must be considered.

They outline the process of scoping. Following Elkin and Smith (1988), identification of the crucial concerns should cover (1) geographic boundaries, (2) administrative boundaries, (3) project timing and duration, (4) key stakeholders, (5) key resources and land uses, (6) key activities, (7) key policies and (8) interactions. They describe the scoping techniques and identification of impacts and their significance and indicate other techniques such as checklists, matrix and network methods, and cause–effect diagrams. They then deal specifically with the scoping of landfill and incineration.

For each feature subject to impact, Petts and Eduljee describe the feature itself, the scoping, the baseline conditions and survey, the prediction and evaluation of impacts, and the mitigation of impacts. They apply this approach to (1) flora and fauna, (2) geology and soils, (3) ground and surface water, (4) air quality and climate, (5) public health, (6) landscape and visual amenity, (7) transport, (8) social and economic features, (9) land use and heritage and (10) residuals. In addition to the usual impact factors they consider acute events, noise and vibration, and landfill gas.

As a case study, the authors consider the Seal Sands incinerator.

A US perspective is given by Veselind, Peirce and Weiner (1990). They describe an EIS as consisting of three distinct parts: (1) inventory, (2) assessment and (3) evaluation. The relevant factors are broadly similar to those just mentioned. They also outline a scoring scheme in which impacts are rated using scales of importance and magnitude.

In some instances, particularly in the early days, the EIS has constituted a major exercise. For the trans-Alaska pipeline the draft EIS, the comments and the final EIS ran to 30 volumes.

A11.9.2 Safety cases

For major hazard installations the CIMAH Regulations 1984 require the submission of a safety case which covers the consequences of a major accident not only for human but for the environment. This aspect of the safety case is discussed by Singleton (1989) and Cassidy (1990).

The safety case is concerned with acute events and it may be regarded as complementing the regulatory controls dealing with long-term pollution and environmental impact.

Cassidy advises that the safety case should give information on the land uses around the site, the environmental hazards of the substances stored or processed and the potential impact on flora and fauna and on the balance of nature. Where there is potential to contaminate water, it should give comprehensive information on the local watercourses and their uses. Particular attention should be paid to the potential for harm to targets which are rare or unique, to persistence of noxious substances in the environment and to long-term damage. The author gives decision trees for assessing land and water impacts.

He also draws attention to the need to address the environmental aspects in the emergency planning required under the regulations.

Singleton deals with the assessment of the consequences to the environment of an accident involving an ultratoxic substance. He considers the cases of copper–arsenate (CCA) wood preservatives and of pesticides.

A11.9.3 Waste facility assessments

A hazardous waste facility needs to be assessed to determine the hazard which it poses to the environment and to humans.

Petts and Eduljee (1994) describe two approaches to such assessment. One is to undertake a full environmental hazard assessment, as described in the previous section.

The other approach is the use of a structured checklist. This is the method used in the project on hazard assessment of landfill (HALO) described by Kemp and Gerard (1991).

A somewhat similar approach is taken in the Hazard Ranking Scheme (HRS) of the EPA (1982a), which utilizes a scoring system.

A11.9.4 Spill impact assessment

A more specific form of impact assessment is the assessment of the effects of a spill of hazardous material. Typically this might be a liquid spill occurring in road or rail transport or from a pipeline.

Methods of assessing the impact of a spill which has already occurred are given in the literature as one aspect of spill control, as described in Section A11.20, but assessment of the impact of potential spills in advance receives little mention.

A11.10 Environmental Economics

The costs to the process industries of environmental protection are high, but experience indicates that, as with safety, good practice is also good business.

Costs and savings may be computed at national or company level. At the national level costs in the USA have been given in Environmental Investments: The Costs of a Clean Environment by the EPA (1991) (Chementor 1991 Mar., 25). In 1972 expenditure on pollution control was some $30 billion (≈1% of GDP). By 1987 it had risen to $98 billion (≈2% GDP) and by 1990 to $115 billion (≈2.1% GDP); the projection for the year 2000 is $140–160 billion (≈3% GDP); the values are all in 1990 dollars. The 1987 figures include $28.9 billion for air and $42.9 billion for water pollution control. The process industries account for a large proportion of this expenditure.

Savings at national level are inevitably less easy to obtain.

However, as described in Section A11.13, the efforts now devoted to waste minimization are testimony to the fact that there are economic benefits.
A11.11 Environmentally Noxious Chemicals

There are a number of substances which figure particularly prominently as pollutants. Some of the principal ones are mentioned briefly in this section.

Many of these substances appear in gaseous or liquid effluent streams. To this extent, their release is controlled one. The hazard from others may arise from an accident. A pesticide is a case in point, as described below.

A11.11.1 Sulphur dioxide and acid rain

A major pollutant from combustion processes is sulphur dioxide, which is responsible for acid rain.


A11.11.2 Nitrogen oxides

Nitrogen oxides NO₃ arise from combustion processes. Both industrial combustion and cars are major contributors.

The NO₃ problem and control technologies are discussed by Marzo and Fernandez (1980), Niess (1980), Redman (1989a) and R. Smith and Petala (1991–).

A11.11.3 Pesticides

Pesticides are highly active chemicals. The exposé in Silent Spring by Carson (1963) rendered their use controversial.

The production, storage and handling of pesticides creates the potential for release in an event such as a fire, or with the fire water used.

The pesticide problem is discussed in Persistent Pesticides in the Environment by C.A. Edwards (1974) and by the SCI (1978).

A11.11.4 Polychlorinated biphenyls

For many years, until their extreme toxicity came to be appreciated, polychlorinated biphenyls (PCBs) were used as electrical transformer fluids. The main concern now is prevention of escape from such equipment and safe methods of disposal. This is discussed by Berry (1981) and Motter (1991). A guide to EPA-approved methods of disposal is given by Kokoza and Flood (1985).

A11.11.5 Toxic metals

Toxic metals which occur in trace quantities in effluents, including those from incinerators, can be very harmful to the environment.

Treatments of toxic trace metals are given in Control and Fate of Atmospheric Trace Metals by Pagna and Ottar (1989) and by Barton, Clark and Seeker (1990).

A11.11.6 Mercury

Certain processes, notably traditional processes for chloralkali production, discharge mercury, albeit in very low concentrations. Accumulation of mercury, especially in the form of methyl mercury, is very noxious to the environment.

A11.11.7 Dioxins

TCDD and other dioxins exhibit toxic effects in minute concentrations, and rank as ultratoxic substances. The toxicity of TCDD is discussed in Appendix 3 in the context of Seveso.

TCDD is produced in very low concentrations in combustion processes and can be produced in a chemical reactor.


A11.11.8 Nitrates

Nitrates are another significant pollutant, but arise mainly from the use of fertilizers, and are outside the present scope. An account is given by Nicolson (1979).

A11.11.9 Health effects

Threats to health may arise from the use, or more often abuse, of chemicals or from their release to the environment.

Health effects of chemicals in the environment are treated in Health Effects of Environmental Pollutants by Waldbott (1973), Environmental Industrial Health Hazards by Trevechak (1976), Air Pollution and Human Health by Lave and Seskin (1977a), Long-Term Hazards of Environmental Chemicals by Doll and McLean (1979) and Hazardous Waste and Human Health by the BMA (1991) and by McLean (1981) and Asante-Duah (1993), as well as in texts on environmental hazard assessment.

A11.12 Chemicals Transport, Transformation, Fate and Loading

A fundamental approach to hazard assessment in EP involves tracing the dispersion and determining the fate of chemicals in the environment.

In principle, a full treatment therefore involves study of the dispersion of gaseous effluents in the atmosphere and of the deposition of particulate matter; the transmission of chemicals through waters and soils of all types; and their passage through the food chain.

A great deal of work has been and continues to be done in all these areas. In some cases the prime concern is with potential airborne releases from nuclear power plants or leaks from nuclear waste stores into watercourses, in others it is with the effects of pesticides and other chemicals already in use.

Accounts of the transport, transformation and fate of chemicals in the environment include Environmental Pollution by Chemicals Walker (1971), Persistent Pesticides in the Environment by C.A. Edwards (1974), Pollution Criteria for Estuaries by Hellwell and Bossanyi (1975), Principles for Evaluating Chemicals in the Environment by the NAS (1975), Safety of Chemicals in the Environment by Harwell (1979), Chemical Concepts in Pollutant Behaviour by Tinsley (1979), Hydrocarbons and Halogenated Hydrocarbons in the Aquatic Environment by...

A11.12.1 Source terms
The starting point for the modelling of transport through environmental media is the definition of the source terms.

Three principal types of source terms are: (1) gaseous emissions from a hazardous waste TSDF, (2) leachate seepage from a TSDF and (3) liquid spill into a watercourse in a transport accident.

A review of gaseous emission source terms at a TSDF is given by B.P. Smith (1987). Models quoted by this author are for surface impoundments, that of Thibodeau, Parker and Heck; for aerated tanks, that of R.A. Freeman (1980); for storage tanks, the usual relations for ‘breathing’ losses; for landfill, that of W.J. Farmer, Yang and Letey (1980), as modified by Hwang (1980) and Shen (1981); and for land treatment, that of Thibodeau and Hwang (1982).

For liquid seepage the source term is highly site specific. Seepage from landfill is treated in accounts of landfill and of leachate.

A liquid spill from a transport vehicle is a relatively well defined source. Another form of transport spills is a pipeline leak, where the issues are the location and the flow rate.

A11.12.2 Transport of chemicals
Chemicals are transported through the environment by atmospheric dispersion and by movement through waters.

A review of air, surface water, groundwater, soil and multimedia transport models applicable in this context is given by McBean (1993).

For transport of gaseous emissions use is made of atmospheric dispersion models. These include the passive gas dispersion models familiar in hazard assessment, but also in some cases models for transport over much greater distances and periods and in more complex meteorological conditions.

The ISC model of the EPA is widely used, both in its short-term version ISCST and its long-term version ISCLT.

For transport through water the review by McBean may be supplemented by the exhaustive treatment of transport through soil and groundwater, based on fundamental geology and hydrology, given by Sara (1994).

Transport through water is typically modelled using compartment, or control volume, models. For movement in surface water a widely used model is EXAMS of Burns, Cline and Lassiter (1982).

The modelling of the dispersion of a chemical spilled into a stream is discussed by Kontaxis and Nusser (1982).

There is no obvious preferred model for movement through groundwater.

The TOXSCREEN model of the EPA (1984c), which assesses the potential fate of chemicals released to air, surface water or soil, may be used to screen for substances which even on conservative assumptions are unlikely to pose a threat to the environment.

In the UK, as described by Welsh (1993), the HSE is developing a risk assessment tool for pollution risk from accidental influxes into rivers and estuaries (PRAIRIE), which incorporates a family of river dispersion models DYNUT.

A11.12.3 Transformation of chemicals
Chemicals moving through the environment may undergo a number of transformations, including reactions, among which are (1) hydrolysis, (2) chemical oxidation, (3) photolysis and photo-oxidation, (4) biodegradation, (5) absorption, (6) adsorption, (7) volatilization and (8) sedimentation.

Some of these transformation processes are described by Welsh (1993).

A11.12.4 Fate of chemicals
The determination of the fate of chemicals in the environment is an extremely complex matter. In part it has to do with the transport and transformation processes just outlined and in part with the assimilative capacity of environmental media and with the effects of the take-up of chemicals into food chains. The concept of an ultimate fate appears to imply some eventual steady state, although the associated time scales may well be rather long.

A11.12.5 Capacity of the environment
To a greater or lesser degree, environmental media have the capacity to tolerate a certain chemical burden. The assumption that this is so is frequently implicit in industry practices.

In certain instances this assimilative capacity is estimated and the loading is adjusted accordingly. Two such cases are the limiting chemical load in land treatment and the oxygen demand load on watercourses.

An example of calculated loading occurs in land treatment, where the quantity of liquid waste applied to an area of land may be estimated by identifying the soil contaminant control and removal mechanisms and estimating the assimilative capacity.

A11.12.6 Loading of watercourses
Another example of loading occurs when a chemical is spilled into a watercourse, either by accidental discharge from a works or as a result of a transport accident.

The health of a watercourse such as a stream or river depends on the maintenance of sufficient dissolved oxygen (DO).

Industrial wastewater discharged into a watercourse tends to use up the oxygen in the latter, its propensity to do so being measured by its oxygen demand (OD), or more specifically its biological oxygen demand (BOD),
described below. If the wastewater is hot, it also tends to raise the temperature of the watercourse. Discharge of wastewater therefore tends to deplete the oxygen in the watercourse both by virtue of its oxygen demand and its temperature. Reaeration processes operate to make up the dissolved oxygen deficit caused by these deoxygenation processes.

There are a number of models, described by Nemerow and Dasgupta (1991), of the effect of wastewater discharge. They include the formulation of Streeter and Phelps (1925), the method of H.A. Thomas (1948) and the correlation of Churchill and Buckingham (1956). The latter found that they were able to correlate the dissolved oxygen as a function of the BOD, the temperature and the flow.

A11.12.7 Biological oxygen demand
A standard method of expressing the oxygen demand is as the biological oxygen demand (BOD) measured under specified conditions over 5 days and at 20°C.

The solubility of oxygen in water at 20°C is 9.2 mg/L. The BOD of domestic sewage is about 200 mg/L, whilst that of some industrial wastes can be as high as 30000 mg/L.

Another measure is the chemical oxygen demand (COD). The test for COD is quicker than that for BOD, but since in this case all the organics are oxidized, this test gives a higher reading.

A11.13 Waste Minimization
The development of loss prevention is paralleled by that of waste minimization. A large part of the latter is by inherently cleaner design (ICD), which stands in much the same relationship to the environment as inherently safer design does to safety. But in so far as waste minimization involves management commitment and management systems to deliver a systematic approach, the closer parallel is with loss prevention. Another term commonly used is clean technology.


In the USA the waste minimization approach is actively promoted by the EPA, relevant publications being Waste Minimization, Environmental Quality with Economic Benefits (EPA, 1987b) and Waste Minimization Opportunity Assessment Manual (EPA, 1988).

A11.13.1 Waste minimization management systems
The waste minimization philosophy has been widely adopted in the process industries. As with loss prevention, success has been achieved as management has
become convinced and committed and has developed effective strategies, put in place formal systems, allocated the necessary resources, including people, and created a self-reinforcing waste minimization culture.

An account of developments in the USA and elsewhere, is given by Redman (1989c), together with numerous examples of case studies and cost savings.

Basic approaches to waste minimization are to modify (1) the chemicals, (2) the process, (3) the equipment and (4) the effluent treatment. Chemicals which tend to be troublesome include toxic metals and halogenated hydrocarbons. Process modifications which may prove fruitful are replacement of (1) chemical by mechanical processes and (2) single pass processes, including rinse operations, with closed processes. Effluent treatment may be modified to recycle or recover materials.

Approaches to waste minimization are outlined in Figure A11.1. On an existing plant the first step is a waste audit.

The ways in which waste minimization may be effected are very varied. This comes across clearly from the examples quoted by Redman. They include minimization of plant washdowns, squeezing of sludges to remove water and reduce mass, design of drums which leave less residue, and so on.

Redman cites a case, described by Huisingh, in which installation of equipment to recover wastes from film development at a cost of $120,000 made annual savings of $2.6 million on silver and on developing, fixing and bleach solutions, a payback time of one month.

An account of a waste minimization programme in one company is given by Koenigsberger (1986).
A11.13.2 Process plant wastes
A review of the application of waste minimization in the process industries covering (1) the basic problem, (2) reactors, (3) separation and recycle systems, (4) process operations and (5) utilities is given by R. Smith and Petala (1991–).

In a reactor five main sources of waste are (1) low conversion, (2) unwanted by-products from the primary reaction, (3) unwanted by-products from the secondary reaction, (4) unwanted by-products from feed impurities and (5) degraded catalyst. There is often scope for reduction of such waste by the application of reaction engineering principles.

In separation processes there may be scope for waste minimization by (1) elimination of feed impurities, (2) elimination of extraneous materials used for separation, (3) recycling of waste streams and (4) additional separation of such streams.

As an illustration of the benefits of eliminating a feed impurity the authors instance the elimination of nitrogen by the use of oxygen rather than air in the oxychlorination stage of ethylene dichloride production. They describe a design of ethylene dichloride reactor which avoids carry-over of the ferric chloride catalyst and thus eliminates the need for washing and neutralization stages.

Under process operations they cover (1) start up and shut down, (2) product changeover, (3) equipment maintenance, (4) tank filling, (5) accidental spillages and (6) fugitive emissions. During transient operations such as start up and shut down product may be off specification, additional by-products may be made and recycles may not be possible. Product changeover and equipment cleaning give rise to cleaning wastes. Tank filling causes losses as vapours are forced out.

In the utilities wastes are associated particularly with combustion processes, steam generation and cooling water. All these wastes can be reduced by a design which promotes energy efficiency. In combustion methods are discussed of minimizing or dealing with oxides of sulphur and nitrogen. Other wastes to be minimized are boiler and cooling tower blowdowns.

A11.13.3 Refinery wastes
The application of waste minimization to refinery operations has been described by Hethcoat (1990) and Curran (1992).

Whereas originally waste minimization was applied mainly to the conservation of hydrocarbons, it is now finds much wider application. The overall strategy involves (1) source reduction and (2) recycling as well as (3) treatment.

Some principal wastes are (1) oily materials, (2) catalyst residues, (3) spent caustic and (4) wastewaters. Oil residues are oil-coated solids, mainly from oil–water separators, dissolved air filtration (DAF) units, heat exchanger cleanings and tank bottoms. Residues also arise in sewers from road dust materials carried in with runoff water. Waste catalysts arise from processes such as catalytic cracking, conversion of heavier products to lighter ones, reforming of gases to liquid products, and sulphur removal. Spent caustics occur as phenolic or sulphide caustics.

The incidence of wastes is highly variable from one refinery to another. Curran states that quantities of oil residues and usage of water can vary by almost two orders of magnitude.

Measures to reduce refinery wastes include use of mixers in crude oil tanks to keep solids suspended, elimination of intermediate storage tanks between units, elimination of blending tanks by use of in-line blending, minimization of surfactants which cause emulsions and promote sludges, preskimming of oil at the separators, use of pressurized air at the dissolved air flotation unit to give a more concentrated sludge, reprocessing of oily residues in suitable refinery units such as a coker, paving of process areas to reduce dust and sweeping of roads for the same purpose.

At the utilities measures taken include maximization of air cooling, use of a closed cooling water system and reduction of solids in the boiler blowdown water.

Segregation also has a part to play. Curran describes segregation of phenolic and sulphide spent caustics, Hethcoat provision of three separate sewer systems for non-oily liquids and one for oily ones.

Hethcoat discusses the identification of options for waste minimization, under the source reduction, recycling and treatment heads, giving as illustrations oily wastewater from separator bottoms and wastes from empty drums.

A11.13.4 Process integration
Waste minimization may be addressed in terms of process integration. The treatment by R. Smith and Petala (1991), just described, approaches the problem from this viewpoint. Another account is that of Rossiter, Spriggs and Kell (1993).

A11.13.5 Center for Waste Reduction Technology
The AIChE has set up the Center for Waste Reduction Technology (CWRT), a sister centre to the CCPS. It is described by L.L. Ross (1991).

A11.14 Gaseous Effluents
Processes tend to generate a number of gaseous effluents which include impurities entering in the feeds, notably nitrogen in process air and air dissolved in liquid feeds; unwanted gaseous products from reactions; gases from purges such as that in the flare stack; and gaseous products of combustion.

Accounts of gaseous effluents, and the technologies of dealing with them, are given in Air Pollution Handbook by Magill, Holden and Ackley (1956), Atmospheric Pollution by Meetham (1968), Air Pollution by Scorer (1968), Air Pollution Control by Strauss (1971–), Gas Purification Processes for Air Pollution Control by Nonhebel (1972), Pollution in the Air by Scorer (1973), Compilation of Air Pollutant Emission Factors by the EPA (1978a), Fundamentals of Air Pollution by Stern et al. (1973), Dust Control and Air Cleaning by Dorman (1974), Gas Cleaning for Air Quality by Marchello and Kelly (1975), Air Pollution by the Open University (1975a), Air Pollution by Seinfeld (1976), Air Pollution Control Equipment by Theodore and Buonicore (1976), Approaches to Controlling Air Pollution by Friedlander (1978), Reference Book by the National Society for Clean Air (NSCA) (1978), Industrial Air Pollution Handbook by A. Parker (1978), Air Pollution Impacts and Control by Downey and Ni Uid (1979), Air Pollution Control by

### A11.14.1 Types of gaseous effluent
A gas effluent stream may consist of a gas which is itself noxious or of a non-noxious carrier gas which contains noxious impurities. The impurities may be gases or vapours, liquid droplets or solid particles.

Some principal gaseous effluents which require to be treated are (1) hydrogen sulphide, (2) carbon dioxide, (3) sulphur-containing gases SO₂ and (4) nitrogen-containing gases NOₓ. Hydrogen sulphide and carbon dioxide are commonly referred to as acid gases.

Hydrogen sulphide figures prominently in oil handling and refining. Carbon dioxide is the main acid gas product of combustion and also arises from oil refining and chemical operations. Sulphur oxides SO₂, essentially SO₂, are generated in combustion of fuel containing sulphur and in oil refining and chemical operations. Nitrogen oxides NOₓ, essentially NO and NO₂, arise as so-called fuel-bound NOₓ and thermal NOₓ from combustion processes.

### A11.14.2 Gaseous effluent control
Waste minimization may be applied to reduce the quantities of the gaseous effluents to be treated and the concentration of noxious components in these effluents, and to facilitate any treatment necessary.

A principal application of this approach which has long been practised is desulphurization of coal prior to combustion, as described below.

### A11.14.3 Gas cleaning
The main methods of removing noxious gases or vapours from a gas stream are absorption, adsorption, reaction to a solid product and reaction with solids.

Absorption processes for removal of hydrogen sulphide and carbon dioxide are the amine family of processes, including the Girbirol process using ethanamine, and the carbonate family, including the Benfield process using potassium carbonate, and for removal of hydrogen sulphide the Stretford process using sodium carbonate.

Hydrogen sulphide is removed in the Claus process by thermal and then catalytic reaction to sulphur. Hydrogen sulphide is also removed by reaction with iron oxide, a traditional gasworks process.

Processes for removal by absorption of sulphur dioxide include the Battersea process. Prior to combustion sulphur dioxide may be removed by fuel desulphurization. In its application to coal, this approach is also known as clean coal technology. In the process sulphur dioxide may be removed by reaction with limestone.

Absorption in oil is a traditional method of removing acid gas and hydrocarbons.

Flue gas desulphurization (FGD) comprises a group of techniques. One option is desulphurization of the fuel prior to combustion. A traditional post-combustion method is the removal of sulphur dioxide by the use of lime or limestone in ‘wet scrubbers’. Advanced post-combustion methods involve contacting the gas with a sorbent such as lime either by in-stack injection or by injection into separate in-line vessels.

There are also combined processes for removal of both sulphur dioxide and nitrogen oxides, in which flue gas desulphurization is combined with a denitrification step. One method of removing nitrogen oxides is catalytic reaction with injected ammonia.

There are a large number of other gas cleaning processes. Outlines of about 80 are given by Speight (1993). Process flow diagrams are given periodically in *Hydrocarbon Processing*.

Removal of gaseous components may also be effected by the use of membrane processes.

Principal methods for the removal of particles include cyclones, fabric filters and electrostatic precipitators.


### A11.14.4 Smog reduction
A number of industrialized countries have suffered from serious air pollution in the form of smog. An account of the ‘killer smog’ in London in 1952 is given below.

In the UK considerable progress has been made in reducing this form of air pollution. Thus in the City of London between 1955 and 1974, for example, the annual average concentrations of smoke and sulphur dioxide near the ground were reduced as follows (Warner, 1976):

<table>
<thead>
<tr>
<th>Year</th>
<th>Concentration of smoke (µg/m³)</th>
<th>Concentration of SO₂ (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>≈195</td>
<td>≈230</td>
</tr>
<tr>
<td>1974</td>
<td>≈40</td>
<td>≈110</td>
</tr>
</tbody>
</table>

### A11.14.5 Tall chimneys
The use of tall chimneys for avoidance of pollution in the immediate vicinity of a plant is a traditional practice. The drawback is that noxious effluents may be spread, albeit in dilute form, further afield.

An account of the practice of the Alkali Inspectorate in relation to tall chimneys has been given by Ireland (1984).

The topic has also been discussed by Perriman (1986).

### A11.14.6 Emission bubble
An approach to air pollution control which in principle allows a company to adopt the most economic trade-offs is that of the ‘bubble’, in which all emissions from sources within the bubble are treated as if they were from a single controllable source. A formal statement of such a policy is that alternative methods of control are allowed provided it can be demonstrated that they are substantially equivalent, the criterion being the equivalence of the emissions leaving the bubble. The bubble concept was adopted by the EPA in 1979. It had a mixed reception, being welcomed in some cases by industry, but not always by the states. An account is given by Weismantel and Parkinson (1980).
A11.15 Liquid Effluents
The liquid effluents from a process plant include not just those shown as such on the flowsheet for the basic process, but a variety of other liquid flows ranging from wash water to rainwater runoff.


The modelling of the hydraulics of, and dispersion in, rivers, estuaries, etc. is described in Hydraulic Behaviour of Estuaries by McDowell and O’Connor (1977); Groundwater by Freeze and Cherry (1979); The Mathematics of Hydrology and Water Resources by Lloy, O’Donnell and Wilkinson (1979); Practical Aspects of Computation River Hydraulics by Cunge, Holly and Verwey (1980); Hydraulic Modelling by Koubis (1981); Models in Hydraulic Engineering by Noak and Cable (1981); and also in certain texts of computational fluid dynamics.

A11.15.1 Types of liquid effluent
Liquid effluents from process plants are fluids from (1) the process, (2) the cooling system, (3) the process ancillary operations, (4) the sanitary system and (5) the rainwater runoff. The process ancillary operations are those such as cleaning and washing.

A proportion of the fluids from the process are liquids which are either non-aqueous or high concentration aqueous wastes. The rest are wastewaters containing oils and chemicals at lower concentrations.

A detailed review of liquid wastes from different industries, including the oil and chemical industries, is given by Nemerow and Dasgupta (1991). They cover organic chemicals; toxic chemicals; acid and chloralkali wastes; formaldehyde wastes; pesticides wastes; and wastes from the energy, fertilizer, phosphates, plastics and rubber, soap and detergent and explosives industries.

A11.15.2 Wastewater control
Wastewater requires a degree of treatment before it is discharged to receivers such as municipal systems or watercourses. There are a number of prior measures which may be taken to minimize the extent of the treatment required. These measures include (1) volume reduction, (2) strength reduction and (3) flow equalization and proportioning.

Waste minimization may be applied to reduce the volume of wastewater either by generating less in the first place or by reusing it. It may also be applied to keep down the concentration of contaminants in the wastewater. Segregation of wastewaters also has a role to play in reducing the volume to be treated or facilitating treatment.

Flow equalization involves the control of flows discharged to smooth out plant flow fluctuations and flow proportioning the control of discharge flows to match those in the municipal system or the watercourse.

A11.15.3 Wastewater treatment
Complete treatment of wastewater is typically classified as follows: (1) wastewater pretreatment, or conditioning; (2) primary treatment; (3) secondary treatment; (4) tertiary treatment; (5) sludge treatment and (6) liquid and sludge disposal.

Wastewater pretreatment processes are screening and grit removal and neutralization.

Primary treatment of wastewater involves removal of suspended solids by (1) sedimentation and (2) flotation. Either process may be operated with chemical addition. Removal of oil droplets can be effected by gravity separation.

Solids also occur in colloidal form, and the methods of dealing with them are often termed intermediate treatment. They include (1) chemical coagulation, (2) charge neutralization coagulation and (3) adsorption. The second of these involves coagulation by neutralization of the electric charge.

Secondary treatment processes deal with dissolved organic materials and comprise a range of mainly biological treatments. These processes are (1) aerobic or (2) anaerobic.

There is a wide variety of aerobic processes including (1) lagooning, (2) activated sludge, (3) modified aeration, (4) dispersed growth aeration, (5) high rate aerobic treatment, (6) contact stabilization, (7) trickling filtration, (8) biological discs, (9) mechanical aeration, (10) wet combustion and (11) spray irrigation. Holding in lagoons is used to effect biological degradation. Activated sludge involves oxidation by flocs from suspended and colloidal solids, the sludge concentration being controlled by a recycle. Modified aeration is a modification of the activated sludge method. Dispersed growth aeration is a variant which does not involve the use of flocs. Contact stabilization, or biosorption, is another modification of the activated sludge method. High rate aerobic treatment, or total oxidation, is another sludge process but with a higher sludge return rate. Trickle filtration and biological discs involve oxidation by slimes, the substrate being in the one case a packed bed and in the other rotating discs. Mechanical aeration involves sparging air into the liquid. Wet combustion, or wet air oxidation, is described below. In spray irrigation the liquid is sprayed onto land with aerobic conditions maintained to a certain depth, and is thus both a treatment and a disposal.

Anaerobic digestion takes place in closed vessels in the absence of air. Loadings are low and residence times
long. It is most suited to small throughputs of liquids with high concentrations of readily oxidized organics and is used mainly for sludges rather than liquid wastes.

Other methods of removing organics include steam stripping and solvent extraction. Tertiary treatment processes remove dissolved inorganic materials. They involve both chemical treatments and physical separation using a variety of unit operations. Chemical methods include (1) coagulation and precipitation and (2) oxidation and reduction reactions. Unit operations utilized are (1) evaporation, (2) adsorption, (3) ion exchange, (4) reverse osmosis and (5) electrodialysis. Adsorbents used are activated carbon and polymers.

Sludge treatment methods include (1) digestion, (2) conditioning, (3) thickening, (4) dewatering and (5) drying. Digestion may be aerobic or anaerobic, utilizing some of the methods already described. Conditioning is effected using chemical and thermal methods. Thickening may be done in (1) gravity, (2) flotation or (3) centrifugal thickeners. Methods of dewatering are (1) vacuum filtration, (2) filter press dewatering, (3) belt filter dewatering and (4) centrifugal dewatering.

A11.15.4 Wet air oxidation

For water contaminated by small amounts of organic compounds a method of treatment which is often attractive is the wet air oxidation (WAO) process, also referred to as wet combustion. Accounts are given by Flynn (1979), Wilhelmi and Knopp (1979), Laughlin, Gallo and Robey (1983), Bailey, Lamparter and Barna (1985), Heimbuch and Wilhelmi (1985), E.J. Martin and Johnson (1987) and Nemerow and Dasgupta (1991).

The aqueous streams to be treated are pumped to a high pressure, passed through a heater to heat it part way to the reaction temperature, then into a reactor vessel where compressed air is blown in and where the resultant exothermic reaction raises the liquid to its reaction temperature, finally out through a cooler to a separator where the oxidized liquid is taken off the bottom and nitrogen, carbon dioxide, steam, etc., off the top. Typical reaction temperatures are in the range 275–320°C. There are numerous variations on this basic process, including the use of a catalyst.

Wet air oxidation can degrade most industrial organic compounds. The reduction, or dilution, factors obtainable are generally good, though higher in some cases than others. Wilhelmi and Knopp list factors in the range 12 to 4200.

A11.15.5 Wastewater receivers

Wastewater treated to a suitable quality may be discharged to the municipal sewage system, to watercourses such as streams or rivers, or to land. Some options available in principle are discharge of (1) raw industrial and sanitary wastes to the municipal system, (2) partially treated industrial and sanitary wastes to the municipal system, (3) completely treated industrial and sanitary wastes to the municipal system, (4) partially treated industrial wastes to a watercourse, (5) completely treated industrial wastes to a watercourse, and (6) completely treated industrial wastes to land. These options are discussed in detail by Nemerow and Dasgupta (1991).

A11.15.6 Deep well disposal

A quite different option for dealing with liquid wastes is deep well injection. Accounts are given by M.E. Smith (1979) and Nemerow and Dasgupta (1991).

This form of disposal has been used particularly in the USA, subject to strict controls and permitted only if no better method is available.

The formation selected to receive the waste is one below the levels holding potable water. The basic technology used derives from oil and gas production. The receiving formation may first be given a conditioning treatment. In order to eliminate solids, the waste is pretreated to remove suspended solids. In addition, a buffer solution such as dilute salt water may first be injected to prevent precipitation from the waste liquid.

A11.15.7 Sludge disposal

Methods of disposal of sludge from wastewater treatment include lagooning, landfill, incineration and sludge baring.

Lagoon involves digestion and is in effect a treatment process which sheds into storage or disposal. Landfill may take the form of area landfill or trench landfill. Incineration is considered below.

Sludge baring has been used but tends to involve problems of sludge rising to the surface or being washed ashore, and in many cases has been discontinued.

A11.16 Hazardous and Solid Wastes

In addition to gaseous and liquid effluents, it is also necessary to deal with hazardous and solid wastes, including sludges and residues.


A11.16.1 Types of hazardous and solid waste

Hazardous and solid wastes fall into three categories: (1) hazardous liquid wastes, (2) hazardous solid wastes and (3) non-hazardous solid wastes. The main concern here is with the first two of these.

A11.16.2 Hazardous waste control

The principles of waste minimization should be applied to minimize the quantity of hazardous waste and to ease the problems of handling it in treatment, storage and disposal facilities.

A11.16.3 Hazardous waste treatment, storage and disposal

Hazardous wastes may be stored or sent to ultimate disposal, either with or without prior treatment.

Methods of dealing with solid hazardous wastes include the use of (1) incineration, (2) landfill, (3) waste piles and (4) storage. Incineration, landfill and land treatment, which are usually treated as methods of ultimate disposal, are discussed further below.

A waste pile, or tip, may be regarded as storage or disposal, depending on the acceptability of its being permanent. Storage proper is typically in drums.

There are a number of methods of stabilization, fixation, solidification and encapsulation available for the treatment of residues and sludges, many developed originally for radioactive wastes. An account is given in E.J. Martin and Johnson (1987).

For liquid hazardous wastes methods include the use of (1) incineration, (2) surface impoundment, (3) land treatment and storage. Incineration and land treatment are both methods of ultimate disposal.

Surface impoundment (SI) or lagooning, has been discussed above. The liquid may be aerated or non-aerated. As stated, a lagoon may be regarded as a form intermediate between treatment, storage and ultimate disposal.

Storage is mainly in storage tanks, which may be open, open with external floating roof, closed with fixed roof and closed with internal floating roof. The vapour space may be inerted.

A11.16.4 Incineration

A prime method of dealing with hazardous waste is incineration. It is used for solid, liquid and sludge or residue wastes.


Incineration is a preferred method of the EPA. Incineration is commonly carried out in dedicated equipment. Types of incineration equipment are described by Novak and Pfrommer (1982) and Brunner (1989). Alternatively, in some instances items of process plant may be used as incinerators. Feeley (1984) describes the use of boilers for this purpose.

Incineration of solid wastes is done in open pits, rotary kilns and multiple hearth furnaces.

Ideally, the products of combustion from an incinerator are carbon dioxide and water vapour. In practice, the gaseous effluents may contain more noxious gases due to (1) incomplete combustion and (2) components in the waste. Some effluents which are troublesome in incinerators include sulphur and nitrogen oxides, metals and dioxins.

There are three main factors which determine the completeness of combustion: time, turbulence and temperature - the three Ts. The first two are set by the design of the system, leaving only the temperature as an operating variable. The temperature is controlled by adjusting the air/fuel ratio.

If the effluent gas falls below the concentration at which it can sustain combustion before destruction is sufficiently complete, one option may be to use an afterburn by injecting additional fuel gas. Alternatively, it may be necessary to pass the effluent gas through a scrubber. Thus an incinerator produces both gaseous effluent and ash, and may produce a liquid effluent also.

Combustion products which have proved particularly troublesome are the dioxins, notably TCDD. TCDD is a product of virtually all combustion processes, including barbecues. The production of TCDD at incinerators has been the subject of much concern. Controls are such that operators are required to keep the concentration of TCDD measured in the adjacent area vanishingly small.

Incineration has the advantages that it is an established process, can handle a wide range of wastes, can accept high throughputs and is economical in its requirement for land, especially relative to landfill. Disadvantages are the comparatively high cost and the effluents generated.

Hazardous wastes in sludge form are incinerated in rotary kilns, fluidized beds and multiple hearth furnaces.

Incineration is also practised for liquid wastes, provided they are at least partially combustible. A liquid waste may be categorized as combustible, partially combustible or non-combustible. A waste with a calorific value below about 18500 kJ/kg is regarded as only partially combustible. Where the properties allow, liquid wastes are generally injected through an atomizer.

A11.16.5 Landfill

Another principal method of disposing of hazardous waste is landfill (LF). This involves depositing the hazardous waste on land which is then covered over. Both area and trench systems are used.

The main problem with landfill is the leaching out of hazardous substances and transport of these into watercourses. Leachate management is therefore essential if landfill is used.


There are a number of options for dealing with leachates. The first should be the application of waste minimization to eliminate or reduce potential leachates. The site can be designed to minimize the generation and escape of leachates, which includes diversion of surface waters and provision of barriers such as liners and trenches. Leaching may be reduced and/or leachate treatment simplified by segregation of wastes. Stabilization methods may be used to minimize leaching. The leachates may be collected and treated.

Economic estimates generally show landfill to be appreciably cheaper than incineration but the potential for migration of leachates into watercourses can be a serious problem which may well alter the balance of advantage.

A description of an landfill project associated with the chemical industry is given by Anon. (1988k).

A11.16.6 Land treatment
Land treatment involves spraying the liquid on land, exploiting the assimilative capacity of the soil.


A11.16.7 Contract disposal
The producer of hazardous wastes often has the option of having them removed by a specialist contractor. Given the number and severity of problems often arising with such wastes, this can be an attractive option.

The main point to be made here is that regulatory controls are now such that there is a responsibility of the producer to ensure that the wastes are properly disposed of. The producer who hands over the wastes to a ‘cowboy’ contractor can expect trouble.

A11.16.8 Hazardous waste facility siting
A hazardous waste treatment, storage and disposal facility is liable to pose a more serious siting problem than the generality of process activities. In the USA more than half the applications for such developments fail. An account of the siting problem of TSDFs, with emphasis on the public consultation process, is given by Barclay (1987).

A11.16.9 Hazardous waste facility management
A hazardous waste facility needs to be managed. Incineration, landfill and storage all involve their characteristic management problems.

Active management is required of the basic activity and of the monitoring of effluents from the treatment processes, of spills and other escapes, and of the concentrations of chemicals in the immediate environment.

For landfill, leachate management assumes particular importance. An account is given by Shuckrow, Tounhill and Pajak (1987).

A11.16.10 Hazardous waste facility reclamation
In the past hazardous waste was frequently deposited in an uncontrolled manner, with the consequence that many countries have a large number of waste disposal sites which present major problems in establishing ownership and responsibility, reasserting control and effecting reclamation.


As described earlier, under CERCLA 1980, or Superfund, the EPA is charged with supervision of site clean-up and federal funds are available for this. An account is given in *Superfund Handbook* by Sidney and Austin (1987).

A11.16.11 Ocean dumping and incineration
A quite different solution to the waste disposal problem is to dump or incinerate the waste at sea.


Essential safeguards in any system of ocean dumping are that those substances which are highly toxic and persistent and do not disperse sufficiently are not dumped and that for those materials which are the assimilative capacity of the area should not be overloaded.

Vessels used for ocean incineration include *Matthias I, II* and *III, Vesta* and *Vulcanus*. Of these the MT *Vulcanus*, a cargo ship converted in 1972 into a chemical tanker with two large incinerators, is perhaps the best known and documented. These incinerator vessels are described by Finney (1982).

Both ocean dumping and ocean incineration are governed by the marine pollution conventions. The *Convention for the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972* (the London Dumping Convention (LDC)) governs ocean dumping, and provisions on ocean incineration have been added to this.

A review of the operation of this convention is given by the IMO (1991 IMO-532). The unregulated dumping which used to take place has largely stopped, the dumping of certain wastes has been eliminated altogether or is being phased out and stringent programmes are in place to assess the need for and impact of ocean disposal.
A11.16.12 Underground storage tanks
It is convenient at this point to mention briefly the problem of leaking underground storage tanks (USTs) and pipework. The use of underground storage is widespread but in recent years there has been growing concern, particularly in the USA, over leaks from such installations. Accounts are given by G. Parkinson (1987) and Stone (1987).
Underground storage tanks are considered in Chapter 22.

A11.17 Fugitive Emissions
Fugitive emissions occur on process plants from diffuse continuous sources such as valves, seals and flanges; from equipment which operates intermittently such as pressure relief valves; from the ‘breathing’ of storage tanks; and from activities such as draining and sampling and the opening up of equipment during operations or for maintenance.

Accounts of fugitive emissions are given in Fugitive Emissions of Vapour from Process Plant Equipment by the BOHS (1984 TG3) and Health Hazard Control in the Process Industries by Lipton and Lynch (1987).

The topic of fugitive emissions can be considered under the following heads: (1) emission sources, (2) emission control, (3) occupational health effects and (4) environmental effects.

Fugitive emission sources, emission control and occupational health aspects are discussed in Chapters 15, 12 and 18, respectively.

The environmental effect which initiated concern over fugitive emissions was smog, originally in Los Angeles.

The EPA has been active to reduce fugitive emissions, as instanced by Compilation of Air Pollutant Emission Factors (EPA, 1973), VOC Fugitive Emissions in Synthetic Organic Chemical Manufacturing Industry – Background Information for Promulgated Standards (EPA, 1982) and Standards of Performance for New Stationary Sources Equipment Leaks of VOC, Petroleum Refineries and Synthetic Organic Chemical Manufacturing Industry (EPA, 1984).

A11.18 Odours
Another form of pollution is noxious odours. The concentration at which a substance can cause an odour can be very low, and certainly well below the levels of the air quality standards set to prevent air pollution.


A11.18.1 Regulatory controls
Regulatory controls on odours are at present fairly rudimentary. In the UK odours are statutory nuisances under the EPA 1990 and subject to control by the local authorities.

In the USA the Clean Air Amendments 1990 provide a framework within which controls on industrial odours may develop.

In the Netherlands the authorities have taken initiatives, described below, aimed at putting odour control on a more scientific basis.

A11.18.2 Odour-generating activities
Many of the activities which give rise to noxious odours lie outside the mainstream process industries, being such as agricultural activities; animal waste rendering and leather tanning; fishmeal processing; sewage and effluent treatment and sludge disposal; brickmaking; and so on. However, petroleum refining and chemical manufacture do generate odours as do coke ovens and tar distillation; pulp and paper processing; plastics and rubber processing; soap and detergent manufacture; and fermentation processes associated with brewing or pharmaceutical manufacture.

A11.18.3 Odour measurement
A fundamental approach to odour measurement would appear to require that (1) the components responsible for the annoyance are identified, (2) their concentrations are measured and (3) their contributions, severally and possibly in combination, are quantified. This is a tall order. It is not surprising therefore that the most practical way of measuring an odour is still the human nose.

The method commonly used is to assemble an odour panel of suitably selected individuals and to use the technique of dynamic dilution. This involves diluting the original sample containing the odour with progressively larger quantities of clean air until 50% of the panel can no longer detect the odour. The results obtained are sensitive to the experimental conditions and can vary by a factor of 10 or more.

The concentration at which the odour is no longer detectable to 50% of the panel is designated as one odour unit (ou). The number D of dilutions required to get down to this concentration is a measure of the odour concentration of the original sample. Thus if dilution by a factor of 2000 is required (D=2000), the odour concentration of the sample is 2000 ou.

A11.18.4 Odour thresholds
There are available a number of compilations of odour thresholds. They include the collections in Standardised Human Olfactory Thresholds by Devis (1990) and by Leonardos, Kendall and Barnard (1969), Anoore and Hautala (1983) and Ruthe (1986).

A11.18.5 Odour sources
Odour sources may take the form of point sources, area sources, line sources or fugitive emissions. An area source is exemplified by an open tank containing liquid and a line source by a works transport route. A discussion of such sources is given by Sober and Paul (1992).

Fugitive emission sources, with typical emission rates, are listed in EPA AP-42 Compilation of Air Pollutant Emission Factors (1985).
A11.18.6 Odour dispersion
The dispersion of an odour may be modelled using passive gas dispersion models, which are described in Chapter 15.

The use of such models is discussed by Sober and Paul (1992). They refer in particular to the various EPA models such as ISC and Inpuff.

Models specific to odours, developed at Warren Spring Laboratory (WSL), have been described by Valentin and North (1980) and Valentin (1990). For short-range dispersion from a ground level source, the following simplified relation provides a rough guide:

\[ D_t = 7E/UX^2 \]  

with

\[ E = D_o F \]

where \( D_o \) is the odour concentration at the emission point (ou), \( D_t \) is the odour concentration at the receptor point (ou), \( E \) the contaminant, or odour, emission flow \((\text{m}^3/\text{s})\), \( F \) the total emission flow \((\text{m}^3/\text{s})\), \( U \) the wind speed (m/s) and \( X \) the distance between the emission and receptor points (m).

Other WSL models relate to the distance at which complaints can be expected. For ground level emissions

\[ d_{\text{max}} = (\varphi E)^{0.6} \]

with

\[ E = DF \]

where \( d_{\text{max}} \) is the maximum distance at which complaints can be expected (m), \( D \) the dilution factor (ou) and \( \varphi \) a factor. The value of \( \varphi \) is 2.2, which is the geometric mean of the uncertainty range 0.7 to 7. The equation can be used for emissions for chimneys provided that \( d_{\text{max}} \) is 40-50 times the effective chimney height.

An equation is also given for the effective chimney height for nuisance-free dispersion:

\[ H_e = (\psi E)^{0.5} \]

where \( H_e \) is the effective chimney height (m) and \( \psi \) a factor. The value of \( \psi \) is 0.1, which is close to the geometric mean of the uncertainty range 0.05 to 0.15. The actual chimney height is obtained by subtracting the plume rise from the effective chimney height.

The last two equations encompass not just dispersion but also human response. The ability to correlate the complaints distance, albeit with a wide uncertainty range, by extrapolation from panel experiments to field assessments on the basis of the dilution factor D is encouraging for the development of a generalized approach.

A11.18.8 Odour control techniques
There are a number of methods available for treating air containing air contaminated with odours. Accounts are given by Valentin (1990) and A.M. Martin et al. (1992).

Martin et al. describe a wide range of techniques, including (1) incineration, (2) adsorption, (3) absorption, (4) condensation, (5) advanced oxidation and (6) biological treatment. Incineration may be carried out in a thermal incinerator, a catalytic incinerator, a flare, a boiler or a process heater. Adsorption is commonly by carbon. Advanced oxidation involves treatment with an oxidizing agent such as ozone using UV radiation to effect photochemical stimulation of the reaction. Biological treatment may be by a biological scrubber or a biological filter. The authors give examples of the efficiencies obtained with the different methods and guidance on selection of a method.

The options available are also discussed by Valentin, who deals in particular with thermal and catalytic incineration, adsorption, absorption and biological filters.

A11.18.9 Odour impact on community
Studies of the impact of odours on the neighbouring community have been described by van Langenhove, Lootens and Schamp (1988) and Miedema and Ham (1988).

The former study involved the investigation of odour from an animal rendering plant. A questionnaire was used to assess the proportion of persons annoyed by the odour at different distances. The effective limit of the nuisance was found at about 600 m. The authors then used a passive gas dispersion model to work back to the effective strength of the source, which they assessed as \( 6.8 \times 10^5 \) ou/h.

Miedema and Ham describe field studies conducted by TNO in support of Dutch government plans for odour control. The authors emphasize the importance of the method used to assess the dilution factor D. They describe and advocate the use of the TNO ‘sniffing car’ method.

These authors too made use of a questionnaire to determine the relation between the distance and the proportion of persons annoyed by the odour. They correlate their results in terms of the \( C_{0.5} \) value, or the 1 hour average concentration which is exceeded only 2% of the year, and the probability of being annoyed, expressed as a \( Z \) score, from the normal distribution, and obtain the relation

\[ Z = 1.19 \log C_{0.5} - 2.16 \]

They suggest that a correlation of this type has potential as the basis for standards for odour control.

A11.19 Transport
A proportion of the chemicals produced are consumed on site, but a large proportion are transported from the site.

The transport of chemicals is discussed in Chapter 23 and emergency planning for such transport in Chapter 24.

Such transport, whether by vehicle or a pipeline, has the potential for an accident resulting in a spill. Spills are discussed in the following section.
A11.19.1 Transport of hazardous wastes
There is also the separate question of the transport of hazardous wastes. This has been a severe problem area due to the prevalence of illicit practices in transport and disposal, described in Laying Waste by M. Brown (1981).

The transport of hazardous wastes, and of material from spill incidents, is discussed by R.J. Buchanan (1982), Bromley and Finney (1985) and Colen (1987b).

A11.20 Spills
Another way in which pollution can occur is by a liquid spill, either at a fixed site or during transport, including by pipeline.


The variety of situations which can occur and of the responses are illustrated in the numerous case histories described in the conference series National Conference on Hazardous Materials Spills in the USA.

In the USA hazardous materials spills involve several agencies, including the DOT, the EPA and the FEMA, as reflected in the guidance published for the EPA in Manual for the Control of Hazardous Material Spills by Huebregtse et al. (1977), in Emergency Guide for Selected Hazardous Materials by the DOT (1978) and for FEMA in Planning Guide and Checklist for Hazardous Materials Contingency Planning by Gunderlo and Stone (1980).

A11.20.1 Types of spill
Some principal types of spill are those from (1) process plant or storage, (2) pipeline, (3) road tanker, (4) rail tank car, (5) barge, (6) ship and (7) drilling rig or fixed production platform.

A spill within the works occurs in a relatively controlled environment, but this is less true of one in transport.

A liquid spillage on land poses a threat to land and to watercourses. It is characterized by the facts that the release is transient and generally relatively limited in volume but often noxious.

Liquid spilled into a stream can cause a degree of pollution which kills off much of the aquatic life so that a long period elapses before recovery can occur.

A11.20.2 Response to spills onto land
If a spill occurs on land, there are a variety of measures which can be taken. A review is given by Scholz (1982), who considers the problem under the heads of (1) termination of discharge, (2) containment to prevent entry into watercourses and (3) recovery and treatment.

Chemical and physical measures are discussed by Eckemfelder (1982) who covers (1) neutralization, (2) sedimentation, (3) coagulation, (4) precipitation, (5) carbon adsorption, (6) ion exchange, (7) oxidation-reduction reactions and (8) biodegradation. A fuller account of biological measures is given by Armstrong (1982).

The EPA has developed a number of items of equipment for dealing with spills, including a portable foam diking system, a mobile physical-chemical treatment unit, a portable sedimentation tank, a mobile incineration system and a mobile soil decontamination system. The foam diking system can be used to restrict the flow of a liquid over asphalt or concrete or to plug drains to prevent liquid from entering. These and other devices are described Freestone and Brugger (1982), in an account of EPA development work on spill control technology, and also by Scholz.

Accounts of specific techniques and devices for dealing with hazardous material spills include those on physical barriers by Friis, Hiltz and Marshall (1973), sorbents by Melvold and Gibson (1988), a mobile treatment system by M.K. Gupta (1976), a mobile incineration system by Tenzer et al. (1979), groundwater protection by Huebregtse and Kastman (1981), in situ detoxification of soil by Huebregtse, LaFornara and Kastman (1978) and soil reclamation by Wentzel et al. (1981).

A11.20.3 Response to spills into streams
If a spill occurs which threatens a stream may be possible to prevent it from entering the stream, but once it does the measures which can be taken are generally limited.

Strategies for dealing with spills into streams have been described by G.W. Dawson and co-workers (Dawson, Shuckrow and Mercer, 1972; Dawson, 1975; Dawson and Parkhurst, 1976; Dawson and McNeese, 1978).

One approach is stream diversion. The EPA has developed a portable stream diversion system capable of bypassing 0.35 m³/s a distance of 300 m.


A11.20.4 Response to oil spills
Methods for the control of oil spills have been published by CONCAWE. They include a manual on inland oil spill clean-up (CONCAWE 1981 7/81), disposal techniques for spill oil (CONCAWE 1980 9/80), protection of ground-water from oil pollution (CONCAWE 1979 3/79), strategies for the assessment of biological impacts of large oil spills on European coasts (CONCAWE 1985 5/85), and field guides to inland oil clean-up (CONCAWE 1983 10/83), coastal waters clean-up (CONCAWE 1981 9/81) and oil spill dispersal (CONCAWE 1988 2/88).

A11.20.5 Ultimate disposal of spilled material
Ultimate disposal of spilled material is considered by Lindsey (1975), R.J. Buchanan (1982), Novak and Pfommer (1982) and A. Parker (1982). The options described by these authors are primarily incineration and landfill.

A11.21 Marine Pollution
Pollution of the seas occurs by discharges made following cleaning of tanks of oil tankers and as a result of accidental spillages from oil tankers and chemical carriers.

Pollution may occur as the result of illicit discharges or as the result of an accident. Most of the incidents which have hit the headlines have occurred after the ship has run aground.

Accounts of sea pollution are given in Oil Pollution of the Sea and Shore by WSL (1972), Accidental Oil

The WSL publication records experience gained as a result of the pollution mitigation activities following the Torrey Canyon disaster.

A11.22 Pollution Incidents

Incidents involving pollution occur both from fixed installations and in transport and over varying time scales.

A11.22.1 Incident databases

The SRD operates the Environmental Data Service EnvIDAS which complements its other databases MHIDAS for major hazard incidents and EIDAS for explosion incidents.

In addition, the account of an incident in a hazards database frequently includes some information on environmental effects.

A11.22.2 Air pollution

Air pollution incidents tend to take the form of (1) a sudden large release, (2) a regular lower level release which is aggravated by an unusual weather condition or (3) a regular practice of lower level release which is found to be damaging the environment.

An example of a sudden large release is that at Seveso, described in Appendix 3.

A11.22.3 Smog incidents

At the end of October 1948 a heavy smog developed in inversion conditions in the industrial town of Donora, Pennsylvania. After several days conditions became such that 17 died within one day; a further four succumbed before the smog abated.

The worst smog incident recorded was the ‘killer smog’ in London in 1952. Again a heavy smog developed in inversion conditions. The concentration of sulphur dioxide rose to some seven times its normal level. The maximum mean daily concentration of the gas in Central London reached 3500 µg/m³. Two days into the incident the death rate began to soar. The number of excess deaths was estimated at about 4000.

A11.22.4 Bonnybridge

An example of the problems attendant on incineration is provided by the travels of Rechem, a company involved in the incineration of hazardous wastes. During the 1980s the incinerators which it operated included one at Bonnybridge in Scotland and one at Pontypool in Wales. At Bonnybridge there were complaints from the public and cattle nearby suffered from an unexplained sickness. Tests did not confirm excessive levels of contamination, but the plant was closed. The company had further troubles in its relations at Pontypool, though again numerous independent surveys failed to find concentrations of contaminants above the background levels.

A11.22.5 Watercourse pollution

Watercourse pollution incidents tend to take the form of (1) a sudden large release, (2) a temporary but appreciable increase in the quantity or concentration of a regular release or (3) a regular practice of lower level release which is found to be damaging the environment.

A11.22.6 Schweizerhalle

On 1 November 1986 a fire in a agrochemical warehouse at Schweizerhalle in Basel, Switzerland, broke out and was extinguished with large quantities of fire water, which became contaminated and then found its way into the Rhine, causing serious pollution. The incident is described in Case History A113.

A11.22.7 Minimata

Discharge of mercury compounds in Minimata Bay in Japan led to severe pollution and to the Minimata mercury poisoning disaster. For some 15 years prior to 1953 the Chisso Chemical Company had been discharging mercury catalyst into the bay. People fell ill, at first in small and then in increasing numbers. In 1957 a ban was placed on fishing in the bay. Of 116 officially recorded cases in 1958 43 had died. By 1972 the official list of victims was almost 300.

A11.22.8 Hazardous waste pollution

Hazardous waste tends to give rise to developing problems at hazardous waste facilities rather than to incidents as such. However, incidents can arise such as those due to serious malpractice in transport of such wastes.


A11.22.9 Love Canal

The scale of the environmental disaster which may result from waste disposal is illustrated by the case of Love Canal. In 1953 this site was sold by the Hooker Chemical Company to the Niagara Falls education authority for a nominal sum. For over a decade the site had been used to dump chemical wastes. In 1976 local residents began to complain of odours and other nuisance. Concern escalated, leading to the relocation of 238 families and causing the President to declare the site a national environmental emergency, making it thereby eligible for federal clean-up funds.

There were numerous damage suits. In support of its suit against the company, the Justice Department commissioned a chromosome study of 36 residents; the study proved controversial.

The engineering measures taken to render the site safe are described by Glaubinger, Kohn and Remirez (1979).

A11.22.10 Land spill pollution

Incidents involving PCBs are described by AJ. Smith (1982), others involving pesticides by Frisbie (1982) and one involving phenol by A. Shepherd (1982a).

The Seveso incident, in which a large area of land was contaminated with TCDD, is described in Appendix 3.
A11.22.11 Sea pollution
Sea pollution incidents which tend to have particularly serious consequences are groundings of tankers on coasts. The three cases given below are all of this kind.

Pollution of the sea also occurs from oil production activities, as described in Appendix 18.

A11.22.12 Torrey Canyon
On 18 March 1967 the tanker Torrey Canyon, carrying 114 000 tons of crude oil, ran aground on the coast of Cornwall, releasing 30 000 tons of oil. Over the next seven days a further 20 000 tons escaped. On 26 March the ship broke its back with release of another 50 000 tons. Following this, the ship was bombed to burn the remaining 20 000 tons and the oil slick was sprayed with detergent to disperse it.

A11.22.13 Amoco Cadiz
On 16 March 1978 the oil tanker Amoco Cadiz lost its steering and ran aground at Portsall on the Britanny coast. The resulting oil spill polluted some 200 km of coastline, causing an incident which at the time was the worst to have occurred.

A11.22.14 Exxon Valdez
On 24 March 1989 the tanker Exxon Valdez ran aground near Valdez, Alaska, rupturing eight cargo tanks and releasing some 258 000 bbl of oil. The result was a major environmental disaster.

Notation
Section A11.18

- $C_{0h}$: 1-hour average concentration exceeded only 2% of the year
- $d_{\text{max}}$: maximum distance at which complaints can be expected (m)
- $D$: dilution factor (ou)
- $D_c$: odour concentration at emission point (ou)
- $D_t$: odour concentration at reception point (ou)
- $E$: contaminant, or odour, emission flow ($\text{m}^3/\text{s}$)
- $F$: total emission flow ($\text{m}^3/\text{s}$)
- $H_e$: effective chimney height (m)
- $U$: wind speed (m/s)
- $X$: distance between emission point and reception point (m)
- $Z$: score value
- $\phi$: factor
- $\psi$: factor
Appendix 12

Noise

Contents

A12.1 Regulatory Controls A12/3
A12.2 Noise Levels A12/3
A12.3 Noise Control A12/4
A12.4 Process Plant Noise A12/5
The environment may be degraded not only by pollution by chemicals but also by noise. Process plant contains a variety of noise sources. Noise from such sources may affect workers and the public, and needs to be controlled.


A long-standing code has been the Code of Practice for Reducing the Exposure of Employed Persons to Noise by the DoE (1972/1) (the DoE Noise Code). More recent guidance is that given in the HSE Noise Guides, described below.


### Table A12.1 Selected references on noise

<table>
<thead>
<tr>
<th>Reference</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>API (EA-7301, 1973 Std 615); HSE (HSW Bklt 25, 1972/3, 1975 TDN 12, 1976 TDN 43, 1977 EH 14, 1983/15, 1985 PM 56, 1987 CRR 1, 1989c, 1989/25, 1990 HS(G) 56, 1991 CRR 28, 1993 CRR 54); IOSHIC (Inf. Sht 17); WHO (EHC 12); NIOSH (1972 CD-73-11001); NPL (1955); C.M. Harris (1957); ImechE (1958/1, 1975/24); Beranek (1960, 1971); A. Wilson (1963); A. Bell (1966); Hines (1966); A. Peterson and Gross (1967); Beranek (1968); Hopkins and Congelliere (1968); Aitherley and Purnell (1969); Coates (1969); Day, Ford and Lord (1969); Parkin and Humphreys (1969); W.D. Ward and Frick (1969); Bragdon (1970); Burns and Robinson (1970); Coles and Rice (1970); Warring (1970); Broch (1971); Blake (1972); Blake and Mitchell (1972); DoE (1972/1); EPA (1971); Kinsler and Frey (1972); Anthrop (1973); Warring (1973); Noise Advis. Coun. (1975, 1978); Crocker and Price (1975); Open Univ. (1975c); Berendt and Corliss (1976); BRE (1976 CP 43/76, CP 72/76); Buggyarello et al. (1976); IChemE (1976/66); Aitherley (1977a); Sutton (1977a); Ghering (1978); J.N. Thompson (1978); J.D. Webb (1978); Yerges (1978); I.J. King (1980); Fegan (1981); Glassburn (1981); Crocker and Kessler (1982); ACGIH (1984/7, 1981/70); Sakamoto (1985); AHIA (1986/11); C. Ross (1986); C.E. Wilson (1989); Shijlrand (1990); Sounds Res. Labs (1991); Beranek and Ver (1992); R.A. Nelson and Elliott (1992); Bines (1993); Dunhavin (1993); Hodson (1993); Lester (1993); BS (Appendix 27 Noise)</td>
<td></td>
</tr>
</tbody>
</table>

**Adaptive noise cancelling**

Widrow et al. (1975); Tan and Dawson (1983)

**Process noise**

EEUMA (Publ. 142, 1980 Publ. 141, 1985 Publ. 104, 1988 Publ. 161); Jacks (1961); Proctor (1963); Anon. (1966); Caputo et al. (1967); Richings (1967); EEUMA (1968 Hudd 25); Golden (1968, 1969); Heimer (1968); P. Sutton (1968, 1975); Lacey (1969); Ranil (1969); Richards (1969); Shearer (1969); Tyler (1969); Judd (1970, 1971); Horner (1971); Judd and Spencer (1971); Caserta (1972b); Constance (1972b); D.E. Thomas, James and Sparks (1972); Arcuri (1973); Cahill (1973); Connor (1973); Lou (1973); Norman (1973); Seebold (1973, 1975a, 1982); Wershon and Bruce (1973); Winnering (1973); Dear (1974); Thumann (1974); Bruce and Wershon (1975); CONCAWE (1976 2/76, 1977 8/77, 1981 4/81, 1985 7/85); McCarty (1976); Middleton (1976); Wershon (1976); British Gas (1977 Comm. 1046, 1048 1984 BGC/PS/N1); G. Robinson (1977); BRE (1978 CP36/78); Goodwin (1978); ASME (1979/190, 1982/192, 1985 PTC 36, 1992 DSC 38); Kinsley (1979); Oil Companies Materials Ass. (1979); Pesuit (1979); Walker (1979); Stein (1980); Fader (1982); Rosenhouse, Lin and Zimmels (1982); S.D. Green (1980); Blake (1986); Cindric and Hassett (1989); Postlethwaite (1989, 1993); IGAS (1990 IGE/GE/ER/2); J. Baum (1991); Bines (1993); G. Foster (1993); IMechE (1993). **Heat exchangers** API (1981 RP 661); **Compressors, fans, pumps** Sence (1970); Cleveland and Headon (1972); Constance (1972c); Diehl (1975); Grailee (1978); S.D. Green (1980); Mather (1993); **Flares** Seebold and Hersh (1971); Seebold (1972a, 1975b, 1984); Swittenbank (1972); Shore (1973); R. Schwartz and Keller (1977); Straitz et al. (1977); S.D. Green (1980); Ohia, Tanaka and Yamaguchi (1993); **Furnaces** Seebold (1972b); Bruggink and Shadeley (1973); CONCAWE (1977 2/77); API (1980 RP 531M); S.D. Green (1980); **Motors** Nailer (1970b); **Pipework** Seebold (1982); CONCAWE (1984 85/55, 84/64, 1987 87/59); Marsh et al. (1985); Pinder et al. (1985, 1991); AJ. Green (1988); van de Loo (1988); Norton and Pruitt; **Valves** Schuder (1970); Baumann (1971); E.E. Allen (1972); Arant (1972); Seebold (1972b); Small (1972); Fagerlund (1976, 1984); S.D. Green (1980); **Pipelines** AGA (1977/4)

Earlier HSE guidance is given in Noise and the Worker (1971 HSW Bklt 25), Notes for the Guidance of Designers on the Reduction of Machinery Noise (1975 TDN 12) and Technician Level Training. Code of Practice for Reducing the Exposure of Employed Persons to Noise (1976 TDN 43) and current guidance in the HSE Noise Guides (HSE, 1989c; HSE, 1990 HS(G) 56). Noise Guides 1 and 2 deal with legal duties and Noise Guides 3–8 with the following: 3, noise surveys; 4, noise control; 5, ear protectors; 6, training for competent persons; 7, machinery noise testing; and 8, exemptions.


Noise is measured in decibels (dB) or decibels adjusted for the range of human hearing (dB(A)).

Selected references on noise are given in Table A12.1.

A12.1 Regulatory Controls

A12.1.1 EC Machinery Directive

Noise at work is governed by EC Directives. One is the Noise at Work Directive 86/188/EEC and another the Machinery Directive 89/392/EEC.

The latter lay down three action levels with the numerical values given in the following subsection.

A12.1.2 Noise at Work Regulations 1989

The main UK legislation on noise at work is the Noise at Work Regulations 1989. Guidance on these regulations is given in Noise at Work, Noise Guide No.1, Noise Guide No. 2 by the HSE (1986c) and in HS(G) 56 Noise at Work: Noise Assessment Information and Control. Noise Guides 3 to 8 (HSE 1990).

The legal duties of employers are described in Noise Guide 1 and those of designers, manufacturers, etc. in Noise Guide 2.

As regards the former, Regulation 1 defines the three action levels just mentioned. The first action level is 85 dB(A), the second action level 90 dB(A) and the peak action level 200 Pa. The latter equates to 140 dB(A). The action levels refer to the daily personal exposure of an employee. This exposure is defined in the guide as described in Section A12.2.

Regulation 4 requires that if any employee is likely to be exposed to a noise level at or above the first action level, the employer should have a noise assessment made by a competent person.

Regulation 6 requires the employer to reduce the risk of hearing damage from exposure to noise to the lowest level reasonably practicable. Regulation 8 gives requirements for the provision of equipment for ear protection. At the first action level such protection should be available on request, at the second action level it should be provided to all persons exposed.

Regulation 7 requires the employer to reduce noise so far as reasonably practicable if the noise level reaches the second action level or the peak action level. The reduction of the noise level has to be effected by means other than the use of ear protection.

Other requirements are for assessment records (Regulation 5), ear protection zones (Regulation 9), maintenance and use of equipment (Regulation 10) and provision of information to employees (Regulation 11).

A12.1.3 Control of Pollution Act 1974

Noise from process plant affecting the public is governed by the Control of Pollution Act 1974, Part III Noise.

A12.1.4 Environmental Protection Act 1990

Noise also falls within the provisions of the Environmental Protection Act 1990. One of the statutory nuisances in Section 79 of the act is 'noise emitted from premises so as to be prejudicial to health or a nuisance'.

The BATNEEC criterion of Section 25 is therefore applicable to noise.

A12.2 Noise Levels

Noise levels are defined in the NPL Noise Guide, the DoE Noise Code, the IChemE Noise Guide and the HSE Noise Guides.

A12.2.1 Noise measurement

As described in the following subsection, noise levels are measured in decibels (dB). The quantity most relevant to the effect on the human ear is the audio- or A-weighted value measured in dB(A).

Sound level meters normally measure the sound level in the frequency range of the human ear 20—20000 Hz. The most widely used meter setting is the dB(A) setting, which discriminates against low frequencies and reduces to some extent the performance of the young human ear.

A12.2.2 A-weighting correction

The method of converting the octave band sound pressure levels to the A-weighted sound levels is described in the DoE Noise Code. The corrections to be added or subtracted from each octave band sound pressure level are as follows:

<table>
<thead>
<tr>
<th>Octave band</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>centre frequency (Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-weighting correction</td>
<td>-26</td>
<td>-16</td>
<td>-9</td>
<td>-3</td>
<td>0</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
</tbody>
</table>

A12.2.3 Sound pressure level

The strength of sound sources varies over a wide range and it is convenient, therefore to measure it on a logarithmic scale. The difference from sources of power $W_0$ and $W = (W > W_0)$ is defined in terms of the number $N$ of decibels

$$N = 10 \log_{10} \left( \frac{W}{W_0} \right) \quad [A12.2.1]$$

where $N$ is the number of decibels (dB), $W$ the source power (W) and subscript 0 denotes reference level. The amplitude of the pressure disturbance caused by the sound source is

$$P \propto W^{\frac{1}{2}} \quad [A12.2.2]$$

where $P$ is the pressure disturbance (Pa). Hence from relations A12.2.1 and A12.2.2
\[ N = 20 \log_{10}(P/P_o) \]  
\[ = L \]  
where \( L \) is the sound pressure level (dB).

\[ P_o = 20 \mu \text{Pa} = 2 \times 10^{-3} \text{ Pa}; \quad W_o = 1 \times 10^{-12} \text{ W} \]

These base values are commonly stated along with the units as dB re 20 \( \mu \)Pa or dB re 10^{-2} W.

A12.2.4 Equivalent continuous sound level

The DoE Noise Code gives the following relations for the equivalent continuous sound level \( L_{eq} \). A fractional exposure \( f \) is defined

\[ f = \frac{t}{8} \text{ antilog}_{10}[0.1(L - 90)] \]  

where \( f \) is the fraction of the value, \( L \) the sound pressure level (dB(A)) and \( t \) the time (h).

Exposures below 85 dB(A) are neglected. Then

\[ L_{eq} = \frac{\log_{10} f}{0.1} + 90 \]  

where \( L_{eq} \) is the equivalent continuous sound level (dB(A)).

A12.2.5 Daily personal exposure

The daily personal exposure of an employee is defined in the schedule to the HSE Noise Guide 1 as follows:

\[ L_{EP,d} = 10 \log_{10} \left[ \frac{1}{T_o} \int_0^{T_o} \left( \frac{P_A(t)}{P_o} \right)^2 dt \right] \]  

where \( L_{EP,d} \) is the daily personal exposure (dB(A)), \( P_A \) the time-varying value of the A-weighted instantaneous sound pressure in the undisturbed field (Pa), \( P_o \) the base value of the sound pressure (Pa), \( t \) the time (h), \( T_o \) the duration of the exposure (h) and \( T_o \) a period of 8 hours (h). As before, the value of \( P_o \) is 2 \times 10^{-5} Pa.

The assessment of daily personal exposure is described in HSE Noise Guide 3. It is obtained from

\[ L_{EP,d} = \frac{\log_{10} f_{tot}}{0.1} + 90 \]  

where \( f_{tot} \) is the total fractional exposure. The fractional exposure \( f \) is obtained from Equation A12.2.5.

As an illustration consider the case given in HSE Noise Code 3 for sound level varying over a working day.

<table>
<thead>
<tr>
<th>Sound level (dB(A))</th>
<th>Duration of exposure</th>
<th>( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>114</td>
<td>10 min</td>
<td>5.2</td>
</tr>
<tr>
<td>105</td>
<td>45 min</td>
<td>3.0</td>
</tr>
<tr>
<td>92</td>
<td>10 h</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Total 10.2</td>
<td></td>
</tr>
</tbody>
</table>

Then from Equation A12.2.8

\[ L_{EP,d} = 100 \text{ dB(A)} \]

A12.2.6 Sound power level

The sound pressure level is the noise quantity measured. The sound power level is not directly measurable but is related to the sound pressure level as follows.

The IChemE Guide gives the sound power level \( H \) as

\[ H = 10 \log_{10}(W/W_o) \]  

where \( H \) is the sound power level (dB) and \( W \) is the rms power of the source (W). As before, \( W_o = 10^{-12} \text{ W} \). The relations given between the sound pressure level and the sound power level are, for spherical symmetry

\[ H = L + 20 \log_{10} r + 11 \]  

and for hemispherical symmetry

\[ H = L + 20 \log_{10} r + 8 \]  

where \( L \) is the sound pressure level at distance \( r \) (dB) and \( r \) the distance (m). The case of a noise source at ground level approximates to hemispherical symmetry.

A12.2.7 Noise exposure limits

Noise exposure limits applied in the UK for many years are those given in the DoE Noise Code. The limit for continuous exposure to reasonably steady sound over an 8 hour day is 90 dB(A). For non-continuous exposure to fluctuating sounds over an 8 hour day the equivalent continuous sound level \( L_{eq} \) is used, this limit too being 90 dB(A). The codes also gives overriding limits of 135 dB(A) and, for impulse noise, of 150 dB(A).

The current noise exposure limits are those given the Noise at Work Act 1989 described in Section A12.1.

A12.3 Noise Control

Noise control is generally considered under four heads: (1) at source, (2) in transmission, (3) on emission and (4) on receipt.

Methods of noise control are discussed in HSE Noise Guide 4 and by Hodson (1993).

Noise can be generated only if there is a vibrating source, which may take the form of a vibrating surface or of vibration in fluid flow. The topic of noise is therefore inextricably bound up with that of vibration, as attested by the titles quoted earlier.

A12.3.1 Control at source

Control of noise at source should be the first option considered. The approach is analogous to inherently safer design.

The general approach to noise control at source is to identify potential noise sources and to seek either to eliminate noise altogether or to reduce it by reducing one or more of the following features of the vibration: (1) the surface, (2) the amplitude, (3) the frequency and, in the case of a fluid, (4) the flow velocity.

HSE Noise Guide 4 outlines a number of specific methods for control of noise, such as impact reduction, clamping, damping, acoustic panels and silencers. It gives examples of machinery showing the points at which such techniques may be applied. It also discusses other aspects such as the use of low noise tools and of air supplies matched to individual tool requirements.
A12.3.2 Control in transmission
In principle, noise associated with transmission through pipes and ducts may be structure-borne or fluid-borne. For gas or vapour pipes the sound is predominantly fluid-borne as evidenced by the effectiveness of control by the example of in-line silencers. Such silencers are used, for example, on the intakes and exhausts of internal combustion engines and on the exhaust of fans.

Some other methods of noise control in transmission are discussed in Section A12.4.

A12.3.3 Control on emission
Control on emission involves modification of the route by which the noise reaches the worker. Devices used include sound absorbing materials on the workroom walls, sound-absorbing screens, total or partial enclosure of machines and cabins serving as ‘noise refuges’.

Another approach is to increase the distance between the worker and the noise source. Distance may be increased by segregation of noisy machines, use of remote controls and siting of exhausts.

A12.3.4 Control at receiver
Control at the receiver involves the use of ear protection. Types and selection of ear protectors are discussed in HSE Noise Guide 5.

Some reduction in the noise burden may be effected by limiting the time for which the person is exposed to the noise, but to be effective the proportion of time exposed has to be cut drastically. Complete removal for half a shift, for example, reduces the daily exposure by only 3 dB(A).

A12.3.5 Active noise control
A quite different approach to noise control is active noise control, or the use of anti-sound. This involves generating a sensory acoustic field which interferes destructively with the field produced by the source of unwanted sound.

Accounts are given in Active Control of Sound by P.A. Nelson and Elliott (1982) and Active Noise Control by Tokhi and Leitch (1992) and by C. Ross (1986).

Active noise control has been applied to ear protectors, in ducts and on gas turbines. Currently applications are relatively limited.

A12.4 Process Plant Noise
An account of the problem of noise in process plant and of measures for its control is given by S.D. Green (1980).

The sound pressure level of $2 \times 10^{-5}$ Pa corresponds to the threshold of audibility. For a small source, the sound pressure level decays according to the inverse square law, doubling of distance giving a reduction of 6 dB. Factors such as atmospheric absorption, ground absorption and screening can reduce the sound pressure level, whilst other factors such as reflection and wind and temperature gradients can cause anomalous effects. The effect of the combination of two sound pressure levels which are equal at a given point is to increase the level by 3 dB compared with that from one source alone.

Green refers to the DoE Noise Code and describes a design approach aiming for a sound level not exceeding 90 dB(A) which involves design for a level of 87 dB(A), thus allowing a safety margin. He also refers to the noise rating (NR) system of the ISO and states that to avoid problems of having predominant frequency bands, the criterion is usually expressed as an ISO rating of NR82, equipment with such a rating producing broad band noise of approximately 87 dB(A). He also indicates that for an area occupied less than 2 hours per day and denoted as one of limited access, the acceptable sound pressure level may be increased by 6 dB(A).

He gives a number of estimates of the sound level from various types of equipment as described below.

A12.4.1 Rotating machinery
A principal source of noise in process plant is rotating machinery. The problem of machine noise is effectively subdued in the larger one of machine vibration. The latter topic is touched on in Chapter 19.

Machinery noise and its control are discussed in the IChemE Noise Guide and by Judd and Spence (1971), Sharland (1990) and Mather (1993) as well as the various texts on vibration quoted earlier. Mather gives typical noise levels for various types of machine.

HSE Noise Guide 7 gives procedures for noise testing of machinery.

Green states that on centrifugal compressors noise levels of up to 100 dB(A) at blade passing frequency can be induced from piping and supports. The casing is usually sufficiently massive to prevent transmission of aerodynamic vibration. There are also other noise sources such as motors, turbines, gear units, lube oil pumps and control valves. His preferred solution is the use of line silencers, though this is often not practical. Full acoustic enclosure is usually unnecessary and it is more common to use a combination of acoustic insulation of and spring support for the pipework together with low noise valves.

Another source of noise on rotating machinery is electric motors. According to Green, large medium voltage motors can produce a noise level above 90 dB(A), due principally to the cooling air fan and also sometimes to magnetically induced vibration. The problem is generally soluble using smaller, more efficient cooling air fans but on occasion resort may be had to increased frame size or cooling air silencers.

A12.4.2 Fluid flow in pipes
Another main source of plant noise is the flow of fluids in pipes. Noise control of individual plant items may not be sufficient to attain the noise target and it may be necessary to address the noise in the pipework also.

Accounts of flow related noise are given in Flow-Induced Vibrations by Blevins (1977) and Mechanics of Flow-Induced Sound and Vibration by Blake (1986).


The CONCAWE model is an essentially empirical one and is somewhat similar to that in VDI 3733. The two are discussed by Pinder (1993).

With regard to noise control, Pinder outlines four methods, which relate to (1) pipewall thickness, (2) plant layout, (3) in-line silencers and (4) acoustic lagging.
The control of noise in pipework of the public gas transmission and distribution system is described by Headon (1977 IGE Comm. 1046).

Noise due to flow through valves is discussed in ISA S75.17–1989 Control Valve Aerodynamic Noise Prediction and by Seebold (1972b) and Fagerlund (1976, 1984).

According to Green, gas or flashing liquid flow in a valve can produce a noise level of 110 dB(A) through the downstream pipe wall. His preferred solution is the use of a valve with a trim giving a multi-step pressure reduction. Alternatives are liner silenters and acoustic insulation, though he describes the latter as of limited effectiveness.

A12.4.3 Combustion processes
Combustion processes are a third significant source of plant noise.

Noise generation and suppression in combustion equipment is treated by Mugridge, Hughes and Roberts (1977 IGE Comm. 1048). Measures to control furnace combustion noise are discussed by Seebold (1972b) and Bruggink and Shadley (1973).

Green states that on furnaces with induced or naturally inspired air flow the air inlet and combustion noise can reach 93 dB(A) per burner. With forced draught systems the sound levels are much less, noise in this case coming mainly from the fan intake. Noise can be transmitted by furnace wall and by duct vibration, the solution in this case being adequate stiffness.

A12.4.4 Flares
A particular type of combustion process which is liable to generate a high level of noise, including noise affecting the public, is a flare.

The problems of flare, and flare steam, noise and methods for its reduction have been discussed by Seebold and Hersh (1971), Seebold (1972a, 1975b, 1984), Shore (1973), R. Schwartz and Keller (1977) and Straitz et al. (1977).

The noise generated by a flare is a function of the energy release in the flame. Swithenbank (1972) has defined a noise generation efficiency \( \eta \) equal to the fraction of the net heat release which is given off as noise power, and has correlated it with mass velocity at the flare tip.

Fundamental studies on the noise from a turbulent diffusion flame are described by Ohiwa, Tanaka and Yamaguchi (1993).

Flares are ranked relatively low in the list of equipment causing noise problems given by Green. As he points out, proprietary flare tips are available to overcome the noise problem. One effective design is that based on the Coanda effect.

A12.4.5 Pressure relief
An alternative method of disposal which also generates noise is venting to atmosphere.

A method of estimating the noise from a high pressure relief discharging to atmosphere through a vent stack is given in API RP 521: 1990. At a distance of 30 m from the stack tip the sound level is given approximately by the relation

\[
L_{10} = L + 10 \log_{10}(0.5MC^2) \quad [A12.4.1]
\]

\[
L = f(PR) \quad [A12.4.2]
\]

where \( C \) is the velocity of sound (m/s), \( L \) the sound level (dB), \( L_{10} \) the sound level at 30 m (dB), \( M \) the mass flow (kg/s) and \( PR \) the ratio of the upstream to the downstream pressure. For \( L \) in the function A12.4.2 API RP 521 gives a correlation with linear scale for \( L \) and logarithmic scale for \( PR \). The correlation is two straight lines with a break point at \( PR = 2.8 \), \( L \approx 54 \), the two lines being defined by the additional points \( PR = 1.5 \), \( L \approx 30 \) and \( PR = 10 \), \( L \approx 57 \).

For other distances the sound level may be obtained from

\[
L_p = L_{10} - 20 \log_{10}(r/30) \quad [A12.4.3]
\]

where \( L_p \) is the sound level (dB) and \( r \) the distance from the stack tip (m).

Green states that emergency relief vents tend to be the most powerful noise sources on chemical plant. The noise from a jet is greatest in the 60° cone about the axis and hence a vertical orientation is usually to be desired. He indicates that a vent should be so located that the sound level does not exceed 125 dB in areas where operators might be, however infrequently. The jet noise is proportional to the sixth to eighth power of the exit velocity. Methods of reducing noise include velocity reduction and silencing, but reduction of velocity is in direct conflict with the need for a high velocity to promote dispersion.

A12.4.6 Equipment noise specifications
It will be apparent that an essential element of a noise control strategy is the noise specification of equipment at the time of purchase. An account of this aspect is given by Postlethwaite (1993), who discusses manufacturers' guarantees, measurement method and witnessed tests.

A12.4.7 Plant noise assessment and control
Since noise from a plant may affect the neighbouring community it is necessary to be able to assess the level of noise outside the factory fence and to control the noise. Guidance on the propagation of noise to the outside community is given by CONCAWE (1981 4/81) and on the approach to be adopted in rating such noise in BS 4142.

The IChemE Noise Guide gives a worked example of noise control in design, relating to a plant expansion project and covering a compressor, a furnace, air cooled heat exchangers and pumps. The data used are intended to be representative of those likely to be available at the design stage and are a mix of literature, manufacturers' and measured values.

An outline of the overall approach required is given by Postlethwaite (1993), who deals with noise specifications for equipment; noise attenuation, prediction, measurement and survey; and noise limit exceedances.

A case study of noise control for a plant near to a residential area and of the practical application of the BATNEEC criterion is described Bines (1993). Although the works had been on the site for 100 years, a problem had arisen because reduction of traffic flow through the town meant that noise from the factory suddenly became dominant. The author gives an account of the noise
sources in the plant and the noise values measured, the noise rating approach used, the application of the BATNEEC criterion and the negotiations with the local authority.

Following BS 4142, the method of rating is to subtract the level of the measured background noise \( L_{A00} \) from the level of the specific noise \( L_{Aeq} \). If the difference is +10 dB or more, justifiable complaints are likely, while if it is +5 dB the problem is marginal. The lower the excess below +5 dB, the less the likelihood of complaints. A difference of −10 dB is a positive indication that complaints are unlikely. A penalty of 5 dB is added to the level of the specific noise if the latter contains distinguishable, discrete continuous notes (whine, hiss, scream, hum, etc.) or distinct impulses (bangs, clicks, clatters or thumps).

**Notation**

\[ f \] fractional exposure

\[ f_{ot} \] total fractional exposure

\[ H \] sound power level (dB)

\[ L \] sound pressure level (dB(A))

\[ L_{Aeq} \] equivalent continuous sound level (dB(A))

\[ L_{EP, d} \] daily personal exposure (dB(A))

\[ L_r \] sound pressure level at distance \( r \) (dB)

\[ N \] number of decibels (dB)

\[ p_A \] time-varying value of A-weighted instantaneous sound pressure in the undisturbed field (Pa)

\[ p_o \] base value of sound pressure (Pa)

\[ P \] pressure disturbance (Pa)

\[ r \] distance (m)

\[ t \] time (h)

\[ T_e \] duration of exposure (h)

\[ T_o \] 8-hour period

\[ W \] source power (W)

**Subscript**

\[ o \] reference level
Appendix 13

Safety Factors for Simple Relief Systems

Contents

A13.1 Comments on Safety Factors to be Applied when Sizing a Simple Relief System A13/2
A13.1 Comments on Safety Factors to be Applied when Sizing a Simple Relief System

by H.A. Duxbury

It is recommended that a safety factor be applied to take account of both uncertainty in the data and inaccuracy in the calculation methods.

It is assumed in the following discussion that (1) the designer has chosen a method appropriate to the application, intended to tend towards oversizing the relief system rather than the reverse, and (2) the relief system consists at most of a safety valve or bursting disc preceded by a constant diameter pipe and followed by a constant diameter pipe to atmosphere. It is also assumed that the flow through any safety valve has been checked against the manufacturer’s data; under no circumstances should the mass flow be assumed to exceed the value so calculated.

The safe case is that which corresponds with the highest estimate of the required relief rate(s) and the lowest estimate of the actual flow(s).

The overall safety factor can be applied in one of two ways:
(1) by sizing the relief system to pass a flow equal to the required mass flow multiplied by the safety factor; or
(2) in cases where the vent capacity is determined by one particular cross-sectional area, by multiplying the calculated required vent area by the safety factor. However, it is important then to check that the capacity remains determined by this area.

The overall safety factor $F_o$ may be represented as the product of a number of sub-factors, each taking account of particular features:

$$F_o = \prod_{i=1}^{n} F_i$$  \hspace{1cm} [A13.1]

where $F_i$ is the sub-factor for feature $i$.

Some of the sub-factors which may be appropriate are

(1) A sub-factor (≥1) to reflect any features of the method, unless included in other specific sub-factors such as those suggested below, which might lead to undersizing of the relief system for the application concerned. These might be features of the methods used to calculate the required relief rate(s) or vent area, although in most cases the methods will have been chosen so as to tend to overestimate those. They may also be features of the approach to assessment of the relief system flow capacity not covered below, e.g. the method may have neglected the presence of solids in the flow. The designer must himself establish the required value for this sub-factor.

(2) A sub-factor (≥1) to take account of uncertainty in the data. The magnitude and direction of any errors arising from the data assumptions should be assessed. For reactors particular attention should be paid to any errors affecting the rate of reaction including its dependence on temperature.

(3) A sub-factor (≥1) to allow for the inaccuracy in the fluid flow calculation methods which is present even for incompressible liquid and/or ideal gas. In this discussion it is assumed that the largest realistic pipe roughness has been assumed, otherwise a larger sub-factor will be necessary.

Some recognized wide-applicability two-phase gas/vapour-liquid flow methods, when used for lines in which friction and/or static head are significant, may be accurate only to a factor of ±2 (i.e. the actual flow is in the range half to two times the calculated value), and would thus correspond to a sub-factor of 2. For poorer methods, a larger sub-factor may be needed, while for methods more targeted at the specific application a lower sub-factor may suffice; expert advice should be sought. For two-phase gas/vapour-liquid flow with negligible friction and no changes in static head, e.g. through a safety valve alone, lower sub-factor values in the range 1.2 to 1.5 may sometimes be sufficient; expert advice should be sought.

For vapour-only flow when friction is significant a reasonable value for this sub-factor will usually lie in the range 1.2 to 1.5, while if only momentum changes are significant, a lower sub-factor may be allowable; expert advice should be sought.

(4) A subfactor to allow for the effects of gas/vapour-phase nonideality if these have not been taken into account in the mass flow capacity calculation.

For critical (choke) frictionless gas/vapour-only flow (e.g. through a safety valve alone) the factor may be estimated from the work of Leung and Epstein (1988) using their Figures 2, 4, 5, 6. These figures show the ratio of real-gas critical mass flow to ideal (Z=1) critical mass flow (our sub-factor is the inverse of this ratio) as a function of the ratio (stagnation/inlet reservoir) pressure/thermodynamic critical pressure, for various values of the ideal (zero pressure) ratio of specific heats. The figures are based on the applicability of the Redlich–Kwong equation of state, but give a useful indication of the magnitude of the effects of non-ideality on critical flow. It can be seen that a sub-factor is needed for pressures exceeding about 20 times the critical pressure. At lower pressures the real critical flow is seen to be greater than the ideal critical flow, but caution should be exercised before adopting a sub-factor < 1. It should be noted that non-ideality cannot be fully compensated for by assuming a constant Z value or using an adjusted fictitious molecular weight; this is discussed below.

For gas/vapour-only flow with friction, and for non-choke flow with or without friction, the author is unaware of any treatment analogous to that of Leung and Epstein. For given inlet reservoir conditions and back pressure and assumed constant Z, the adiabatic or isothermal mass flow of a gas through a perfect nozzle, and from a reservoir via a perfect rounded inlet into and through a straight pipe, is proportional to $1/Z^{1/2}$ (Lapple, 1943). This suggests an approximate value for this sub-factor given by

$$F_o = \frac{\text{Real gas mass flow}}{\text{Ideal gas (}Z = 1\text{)} \text{ mass flow}} = Z_{\text{max}}^3$$ \hspace{1cm} [A13.2]

where $Z_{\text{max}}$ is the maximum value of $Z$ occurring in the flow. Clearly this sub-factor will be inaccurate when $Z$ varies significantly (e.g. near the thermodynamic critical point, and near choking conditions); this can be seen by comparing this sub-factor (which if $Z$ were constant would apply equally to critical frictionless flow) with the sub-factor obtained from the work of Leung and Epstein for critical frictionless flow (and also from their Figure 9). It would seem prudent to adopt a sub-factor at least
as large as the larger of these two estimated sub-factors (but again, care should be exercised before adopting any value < 1). If the non-ideality is severe and such as to reduce the flow, then ideally the relief system should be sized using a method which takes full account of non-ideality; the other sub-factors would still be required. If the non-ideality is severe but (as is more likely) is such as to increase the flow, then a sub-factor of 1 may be prudent.

It should be noted that the above sub-factors based on the work of Leung and Epstein and of Lapple are for application to the mass flow calculated on the basis of fully ideal (Z = 1) flow. If the flow has been calculated as semi-ideal with an assumed constant Z, or with an adjusted fictitious molecular weight, to give partial compensation for the departure from ideality, then this corresponds to the prior application of a sub-factor of \( Z_{\text{assumed}}^{1/2} \) or \( (MW_{\text{actual}}/MW_{\text{assumed}})^{1/2} \).

It seems likely that the effects of gas/vapour-phase non-ideality in two-phase gas/vapour-liquid flow, will be less, but the author is not aware of any studies to validate this. It is suggested that this sub-factor be taken as the same as for gas/vapour-only flow.

5. A sub-factor \( \geq 1 \) to take account of errors in the flow calculation for two-phase gas/vapour-liquid flow resulting from neglecting the variation in liquid density, liquid specific heat and latent heat along the pipe. The variation in these quantities can be judged from the calculated conditions along the pipe and thermodynamic charts. Then either a value can be assigned to this sub-factor or safe values can be assigned to those properties and the sub-factor set to 1. For calculation of mass flow capacity, safe values (giving a low mass flow) are low density, high specific heat and low latent heat. For gas-only or vapour-only flow, this sub-factor is irrelevant.

Finally the designer must check that there are no further sub-factors to be included, and decide whether to accept the calculated overall safety factor \( F_\sigma \). There is little published advice on typical factors. It would be surprising if the overall factor were to be less than 1.2 in any event, and significantly larger factors would be likely for reactors. For polymerization reactors Boyle (1967) said that the specified relief area should be two to three times the area indicated by design calculation (but note that this was before the preparation of the DIERS methods). Boyle’s recommendation is consistent with typical overall factors obtained using the approach described above for two-phase vapour/liquid venting.

Caution

It is emphasized that the above comments are offered only to assist the designer in his consideration of what might be an appropriate overall safety factor. The designer must decide whether the advice is relevant to his application (bearing in mind the restrictions defined in the second paragraph of this note) and what sub-factors and overall factor are adequate.

H.A. Duxbury

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May 1994
Appendix 14

Failure and Event Data

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A14.28 External Events A14/26 A14/26
Many of the methods described in this volume require the use of data for failure and other events. This appendix gives a brief account of such data and a selection of values which have been published in the open literature.

The data are given in summary form and primarily for illustrative purposes only. It is emphasized that there are many factors which determine the failure rate of an equipment and the range of failure rates observed can be quite wide. For industrial reliability work, therefore, it is necessary to consult the original literature and to make appropriate use of data banks and works data.

Selected references on failure and event data are given in Table A14.1.

**Table A14.1 Selected references on event and failure data**

<table>
<thead>
<tr>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Navy, Bur. of Naval Weapons (n.d.); NRC (Appendix 28 Failure Data); Dummer and Griffin (1960, 1966); Edison Elec. Inst. (1963, 1967); Timmermann (1968); R.L. Browning (1969a-c, 1970); F.R. Farmer (1971); Jacobs (1971); A.E. Green and Bourne (1972); AEC (1975); Gangadharan and Brown (1977); Cramer and Warner (1978); HSE (1978b); Ericsson and Björe (1983); Johanson and Fragola (1983); Sherwin (1983); EEE (1984); OREDA (1984, 1989); Backwitz (1984); Bendixen, Dale and O'Neill (1985); Reliability Analysis Center (1985); Rossi (1985); IAEA (1988); Boykin and Levery (1989); Hauptmans and Homke (1989); EUROSTAT (1991)</td>
</tr>
</tbody>
</table>

**Data collection and exchange**

Pollocks and Richards (1964); Boesebeck and Homke (1977); Frankel and Dapkunas (1977); Hauteur (1977); Richards (1980); B.K. Daniels (1982); Bockholtz (1983); Borkowski, Drag and Fragola (1983); Carlesso, Bastia and Borelli (1983); Himanen (1983); Melis et al. (1983); Games et al. (1985); Lamerse and Bosman (1985); Walls and Bendell (1985); Blokker and Goos (1986); Turpin and Kemath (1986); Wingender (1986, 1991); Bendell (1987)

**Data banks**

Eames (1967 UKAEA AHIB(S) R138); Naresky (1967); AEC (1975); J.H. Bowen (1977); Colliacott (1977b); B.K. Daniels (1982); Bobbio and Saraco (1983); Capobianchi (1983, 1991); K.R. Davies (1983); OREDA (1984, 1992); Bendell and Cannon (1985); Scarrone, Ficcinini and Massobrio (1989); Bendell (1991a-c); Cannon (1991b); Cannon and Bendell (1991); Cross and Stevens (1991); Mizuta et al. (1991); **SRD:** Eames (1967 UKAEA AHIB(S) R138); Ablitt (1973 UKAEA SRS/GR/14, SRD R16, 1975); Fothergill (1973 UKAEA SRS/GR/22); Eames et al. (1976); J.H. Bowen (1977); Cannon (1991a, b); **EdF:** Silberberg and Meclot (1985); Procaccia (1991); **NEI:** Avogradri, Bello and Colombari (1983); **ERDS:** Capobianchi (1991); **FACTS:** Kohorst and Bockholtz (1991); **IAEA:** Tomic and Lederman (1991); **Offshore:** Gaboraiad, Grollier-Baron and Leroy (1983); Gjestad (1983); Tveit, Ostby and Moss (1983); OREDA (1984, 1989, 1992); Bruce (1994)

**Data problems and validity**

Kletz (1973b); J.H. Bowen (1977); R.L. Browning (1977); Cannon (1977); Deverreux (1977); Lees (1977c); Parsons (1977); Rex (1977); Vesely (1977b); HSE (1978b); Apostolakis et al. (1980); Pitts et al. (1980); Apostolakis (1982, 1985a); Martz (1984); OREDA (1984, 1992); Mosleh and Apostolakis (1985); Andow (1989)

**Populations of plants, equipment, etc. at risk**

**Plants:** AgA (n.d./101); IP (Oil Data Sh 15); IPE (1967); SRI Int. (1988ac); Anon. (1985dd); HSE (1986 Major Hazards 8); **Equipment:** Hooper (1982); **Transport:** ACDS (1991)

**Mechanical equipment failure modes** (see also Table 7.1)


**Utilities**

R.L. Browning (1969c); OREDA (1984, 1992)

**Power supplies**

Dickinson (1962); R.L. Browning (1969c); AEC (1975); Jarrett (1983); B. Stevens (1983); **Diesel generators. diesel-driven equipment:** F.R. Farmer (1971); A.E. Green and Bourne (1972); AEC (1975); OREDA (1984, 1992)

**Electronic equipment**

Dummer and Griffin (1960, 1966); US Army, Dept of Defense (1965); A.E. Green and Bourne (1972)

**Electrical equipment**

F.R. Farmer (1971); A.E. Green and Bourne (1972); AEC (1975); OREDA (1984, 1992)

**Electric motors**

Dickinson (1962); Benjaminsen and van Wiechen (1968); R.L. Browning (1969c); AEC (1975); Avogradri, Bello and Colombari (1983)

**Pressure vessels**

Kellerman (1966); Kellerman and Seipel (1967); Phillips and Warwick (1968 UKAEA AHIB(S) R162); Slopianka and Mieze (1968); Butler (1974); Engel (1974); T.A. Smith and Warwick (1974); AEC (1975); Boesebeck (1975); Bush (1975); HSE (1978b); Arulanathan and Lees (1981); Hurst, Hankin et al. (1992); **Columns:** H.C.D. Phillips (1990)

**Storage tanks**


**Pipework**

S.A. Wilson (1972, 1976); AEC (1975); Boesebeck and Homke (1977); Bush (1977); HSE (1978b, d); Arulanathan and Lees (1981); Cannon (1983); R.E. Wright, Stevenson and Zuroff (1987); Blythving and Barry (1988 SRD R441); CIA, Chlorine Sector Gp (1989); Hurst, Davies et al. (1994); Strutt, Allsop and Ouchet (1994); G. Thompson (1994)

**Boilers**

Heat Exchangers  
A.E. Green and Bourne (1972); C.F. King and Rudd (1972); H.C.D. Phillips (1990); OREDA (1992)

Mills  
Notman, Gerard and de la Mare (1981)

Belt conveyors  
Notman, Gerard and de la Mare (1981)

Cranes  
F.R. Farmer (1971); OREDA (1992)

Pressure relief valves  
A.E. Green and Bourne (1972); Kletz (1972a, 1974a); Lawley and Kletz (1975); Aird (1982, 1983); Aupied, Le Coguiec and Procaccia (1983); Oberender and Bung (1984); OREDA (1984, 1992); Maher et al. (1988); Hanks (1994); D.W. Thompson (1994)

Non-return valves  
AEC (1975); Aupied, Le Coguiec and Procaccia (1983)

Bursting discs  
Lawley (1974b)

Instruments, including valves  

Process computers  
Barton et al. (1970); Hubbe (1970); E. Johnson (1988)

Rotating machinery  
Turbomachinery: R.L. Browning (1970); Sohre (1970); OREDA (1992); Compressors: Ufford (1972); Avogadri, Bello and Colomboari (1983); H.C.D. Phillips (1990); OREDA (1992); Pumps: Anon. (1972a); F.R. Farmer (1971); Emelyanov et al. (1972); A.E. Green and Bourne (1972); C.F. King and Rudd (1972); Ufford (1972); AEC (1975); R. James (1976); Sherwin and Lees (1980); Dorey (1981); Aupied le Coguiec and Procaccia (1983); Avogadri, Bello and Colomboari (1983); Sherwin (1983); Anon. (1985a); Bloch and Johnson (1985); N.M. Wallace and David (1985); Flitney (1987); H.C.D. Phillips (1990); OREDA (1992)

Fire protection, fire and gas detection, sprinkler systems  

Reactor overpressure  
Marrs and Lees (1989); Marrs et al. (1989)

Leaks and spillages  
Davenport (1977b, 1983); Kletz (1977f); HSE (1978b, d); Baldock (1980); Hawkesley (1984); A.W. Cox, Lees and Ang (1990); ACDS (1991)

Ignition of leaks  
R.L. Browning (1969c); A.W. Cox, Lees and Ang (1990); ACDS (1991)

Fire and explosions  
Pump fires: Kletz (1971); HSE (1978b); Tank fires: Kletz (1971); Furnace explosions: Kletz (1972c); Oostroot (1972); Warehouse fires: Hymes and Flynn (1992 SRD R578)

Vapour cloud explosions  
Wiekema (1983a, b, 1984); Probability of ignition: Kletz (1977f); HSE (1978b); Moussa et al. (1982); A.W. Cox, Lees and Ang (1990); ACDS (1991); Delay before ignition: Kletz (1977f); Drift before ignition: Kletz (1977f)

BLEV  
Blything (1986); Hurst, Hankin et al. (1992)

Transport  
Westbrook (1974); HSE (1978b); Appleton (1988 SRD R474); ACDS (1991); P.A. Davies and Lees (1992)

Pipelines – see Table 23.1

Ships  

LNG plants  
Welker et al. (1976); Welker and Schorr (1979); AGA (1981/33); D.W. Johnson and Welker (1981); Moussa et al. (1982)

Offshore  
Goodwin and Kemp (1980); Sofyanos (1981); Anon. (1983b); Dahl et al. (1983); OREDA (1984, 1992)

Missiles  
HSE/SRD (HSE/SRD/WP7); HSE (1978b); Holden and Reeves (1983); Holden (1988 SRD 477); ACDS (1991)

Aircraft crashes  
AEC (1975); HSE (1978b); Phillips (1981 SRD R198); Marriott (1985); Roberts (1987 SRD R388)
A14.1 Data and Data Sources

A14.1.1 Types of data
Some types of data which may be required include, for equipment:

(1) Failure frequency, probability
(2) Repair time
(3) Unavailability

and for events:

(4) Event frequency.

A14.1.2 Definition of failure
The failure rate recorded for an equipment necessarily depends on the definition of failure. The importance of this may vary. Failure of a pump to start on demand would appear relatively unambiguous, but failure of a pressure relief valve may refer either to failure of the set pressure to stay within prescribed limits when removed from the plant and tested in the workshop or to failure to relieve pressure during plant operation.

A14.1.3 Failure regimes
It is usually assumed that the failure rate, or strictly the hazard rate $\lambda$, is constant, but this may not necessarily be the case. The hazard rate may be decreasing, constant or increasing, corresponding to the regimes of early failure, constant failure or wearout failure and characterized by values of the Weibull shape parameter $\beta < 1$, 1, $> 1$, respectively. Analysis of data using the Weibull method is described in Chapter 7.

A further account of data on failure regimes is given in Section A14.26.

A14.1.4 Influencing factors
The failure rate of an equipment is influenced by a large number of factors, including specification, design, manufacture, application, operating conditions and maintenance.

Process equipment is used in a wide variety of operating conditions and environments, and it is desirable to allow for these influencing factors.

For some types of device the effect of certain influencing or environmental factors can be quite well defined. An environment factor $K$ is widely used for the effect of temperature on items of electrical equipment such as resistors. Some values of environment factors are given by A.E. Green and Bourne (1972).

It is more difficult to define the effect of such factors on mechanical equipment, but a few examples may be mentioned. An environment factor for instruments has been given by Anyakora, Engel and Lees (1971), as described in Chapter 13. Similarly, a severity index for instruments has been given by Barbin (1973).

A further account of influencing factors is given in Section A14.27.

A14.1.5 Data sources
Failure data may be obtained from external sources such as the literature and data banks. Alternatively, they may be collected within the works.

The sources available depend on the user. A company operating plant has access to data from its own works which are not available to other parties, unless supplied to an accessible database.

Failure rates depend on many factors, including the function of the equipment in the system and the definition of failure; the process environment and the maintenance practices; and the type of equipment and its manufacturer. For these reasons data obtained in the company's own works are likely to be more directly applicable than outside data. On the other hand, the effort and delay involved in collecting data are often not justifiable. Moreover, if the failures are rare events, internal collection may not be appropriate, since the confidence limits on failure data depend mainly on the numbers of failures recorded.

In most cases use is made of a judicious mixture of data from all these sources.

A14.1.6 Data collection
The collection of data from the factory is usually necessary in reliability work, but it involves a number of problems. It is essential, therefore, to design the data collection system appropriately.

In general, failure of plant equipment needs to be recorded and investigated, both in order to identify types of failure so that failure rates can be reduced by better engineering, and to obtain failure data for reliability calculations.

It is normal practice to record for production management the downtime of the plant together with its cause. Frequently the cause assigned is the failure of the particular equipment. This system may yield useful data, particularly on plant availability. Likewise, it is normal practice to record for maintenance management failures of plant equipment. Useful data on failure rates may be generated by this system.

Frequently the data yielded by the existing production and maintenance management systems are inadequate for reliability work. It is then necessary to make certain modifications to the records to be kept in order to obtain the desired data. Usually this involves some additional work by the operating and maintenance personnel.

If data collection is to be instituted for reliability work, it is necessary to define the system carefully. This includes (1) data capture, (2) data classification and (3) data utilization. The system should be appropriate in scale and in duration.

In some cases the aim is to monitor continuously features such as equipment failure and/or unit availability. In this case continuous collection is clearly necessary. On the other hand the aim is simply to obtain data for reliability engineering or hazard assessment purposes, it may be sufficient to collect certain data over a limited period on a "campaign" basis.

One pitfall is to embark upon too ambitious a scheme which is then not fully exploited and soon falls into disuse. A better policy is to start with a more modest system and to put effort at an early stage into utilizing the data and demonstrating their usefulness to those involved in collecting them.

At the other extreme, the desire to avoid this error can lead to the converse mistake of seeking so little modification to the existing system that usable data are not obtained.

It is desirable, therefore, both to design the system so that it matches the use to be made of it and, once the
system is operating, to begin as soon as possible to utilize the data which flow so that those participating can see that their efforts are not being wasted.

Particular attention should be paid to the point of generation of the data. In some cases the quality of information on documents such as job tickets is sufficiently good for the purpose. But in other cases some form of specific debriefing may be preferable in order to ensure that the data obtained are meaningful.

Further discussions of data collection are given by D.J. Smith and Babb (1973) and Wingender (1991).

A14.1.7 Status of data
In hazard assessment it good practice to indicate the status of the data. Some relevant distinctions are:

(1) Value based on historical data:
(a) value based on large number of events (narrow confidence limits);
(b) value based on small number of events (wide confidence limits);
(c) value based on number of event-free years or occasions;
(2) Value based on judgment of a number of experts.
(3) Value synthesized using fault tree methods.
(4) Value based partly on data and partly on judgment of analyst.
(5) Value entirely on judgement of analyst.

A similar classification is given in the First Canvey Report described in Appendix 7.
The status of data is discussed by Andow (1987) and Holloway (1987).

A14.2 Data Collections
There are available in the literature a number of collections of data. They include handbooks such as Standard 500 of the IEEE (1984) and OREDA (1984, 1992); hazard assessment reports such as the Rasmussen Report (AEC, 1975), the two Canvey Reports (HSE, 1978b and 1981a) and the Rijnmond Report (Rijnmond Public

<table>
<thead>
<tr>
<th>Table A14.2</th>
<th>Some data on equipment failure rates published by the UKAEA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Data from Reliability Technology by A.E. Green and J.R. Bourne, Copyright ©, 1972, reproduced with permission of John Wiley and Sons, Inc.)</td>
</tr>
<tr>
<td></td>
<td>(failures/10^6 h)</td>
</tr>
<tr>
<td>Electric motors (general)</td>
<td>10.0</td>
</tr>
<tr>
<td>Transformers (&lt;15 kV)</td>
<td>0.6</td>
</tr>
<tr>
<td>(132–400 kV)</td>
<td>7.0</td>
</tr>
<tr>
<td>Circuit breakers (general, &lt;33 kV)</td>
<td>2.0</td>
</tr>
<tr>
<td>(400 kV)</td>
<td>10.0</td>
</tr>
<tr>
<td>Pressure vessels (general)</td>
<td>3.0</td>
</tr>
<tr>
<td>(high standard)</td>
<td>0.3</td>
</tr>
<tr>
<td>Pipes</td>
<td>0.2</td>
</tr>
<tr>
<td>Pipe joints</td>
<td>0.5</td>
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<tr>
<td>Ducts</td>
<td>1.0</td>
</tr>
<tr>
<td>Gaskets</td>
<td>0.5</td>
</tr>
<tr>
<td>Bellows</td>
<td>5.0</td>
</tr>
<tr>
<td>Diaphragms (metal)</td>
<td>5.0</td>
</tr>
<tr>
<td>(rubber)</td>
<td>8.0</td>
</tr>
<tr>
<td>Unions and junctions</td>
<td>0.4</td>
</tr>
<tr>
<td>Hoses (heavily stressed)</td>
<td>40.0</td>
</tr>
<tr>
<td>(lightly stressed)</td>
<td>4.0</td>
</tr>
<tr>
<td>Ball bearings (heavy duty)</td>
<td>20.0</td>
</tr>
<tr>
<td>(light duty)</td>
<td>10.0</td>
</tr>
<tr>
<td>Roller bearings</td>
<td>5.0</td>
</tr>
<tr>
<td>Sleeve bearings</td>
<td>5.0</td>
</tr>
<tr>
<td>Shafts (heavily stressed)</td>
<td>0.2</td>
</tr>
<tr>
<td>(lightly stressed)</td>
<td>0.02</td>
</tr>
<tr>
<td>Relief valves: leakage</td>
<td>2.0</td>
</tr>
<tr>
<td>blockage</td>
<td>0.5</td>
</tr>
<tr>
<td>Hand-operated valves</td>
<td>15.0</td>
</tr>
<tr>
<td>Control valves</td>
<td>30.0</td>
</tr>
<tr>
<td>Ball valves</td>
<td>0.5</td>
</tr>
<tr>
<td>Solenoid valves</td>
<td>30.0</td>
</tr>
<tr>
<td>Rotating seals</td>
<td>7.0</td>
</tr>
<tr>
<td>Sliding seals</td>
<td>3.0</td>
</tr>
<tr>
<td>‘O’ ring seals</td>
<td>0.2</td>
</tr>
<tr>
<td>Couplings</td>
<td>5.0</td>
</tr>
<tr>
<td>Belt drives</td>
<td>40.0</td>
</tr>
<tr>
<td>Spur gears</td>
<td>10.0</td>
</tr>
<tr>
<td>Helical gears</td>
<td>1.0</td>
</tr>
<tr>
<td>Friction clutches</td>
<td>3.0</td>
</tr>
<tr>
<td>Magnetic clutches</td>
<td>6.0</td>
</tr>
<tr>
<td>Fixed orifices</td>
<td>1.0</td>
</tr>
<tr>
<td>Variable orifices</td>
<td>5.0</td>
</tr>
<tr>
<td>Nozzle and flapper</td>
<td>6.0</td>
</tr>
<tr>
<td>assemblies: blockage</td>
<td>0.2</td>
</tr>
<tr>
<td>Filters: blockage</td>
<td>1.0</td>
</tr>
<tr>
<td>leakage</td>
<td>1.0</td>
</tr>
<tr>
<td>Rack-and-pinion assemblies</td>
<td>2.0</td>
</tr>
<tr>
<td>Knife-edge fulcrum: wear</td>
<td>10.0</td>
</tr>
<tr>
<td>Springs (heavily stressed)</td>
<td>1.0</td>
</tr>
<tr>
<td>(lightly stressed)</td>
<td>0.2</td>
</tr>
<tr>
<td>Hair springs</td>
<td>1.0</td>
</tr>
<tr>
<td>Calibration springs: creep</td>
<td>2.0</td>
</tr>
<tr>
<td>breakage</td>
<td>0.2</td>
</tr>
<tr>
<td>Vibration mounts</td>
<td>9.0</td>
</tr>
<tr>
<td>Mechanical joints</td>
<td>0.2</td>
</tr>
<tr>
<td>Grub screws</td>
<td>0.5</td>
</tr>
<tr>
<td>Pins</td>
<td>15.0</td>
</tr>
<tr>
<td>Pivots</td>
<td>1.0</td>
</tr>
<tr>
<td>Nuts</td>
<td>0.02</td>
</tr>
<tr>
<td>Bolts</td>
<td>0.02</td>
</tr>
<tr>
<td>Boilers (all types)</td>
<td>1.1</td>
</tr>
<tr>
<td>Boiler feed pumps</td>
<td>1012.5</td>
</tr>
<tr>
<td>Cranes</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Sources: F.R. Farmer (1971); A.E. Green and Bourne (1972)
Note: Further failure data on electronic, mechanical, pneumatic and hydraulic components are given by A.E. Green and Bourne (1972).
Figure A14.1  Typical ranges of failure rates for parts, equipments and systems (A.E. Green and Bourne, 1972) (Reproduced with permission from Reliability Technology by A.E. Green and J.R. Bourne, Copyright ©, 1972, John Wiley and Sons, Inc.)

Table A14.3  Some failure data used in the Rasmussen Report (AEC, 1975)

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Description</th>
<th>Failure Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesels (complete plant)</td>
<td>Failure to start, ( Q^a_d )</td>
<td>( 3 \times 10^{-2}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to run, given start, in emergency conditions, ( \lambda_0 )</td>
<td>( 3 \times 10^{-3}/h )</td>
</tr>
<tr>
<td>Diesels (engine only)</td>
<td>Failure to run, given start, in emergency conditions, ( \lambda_0 )</td>
<td>( 3 \times 10^{-4}/h )</td>
</tr>
<tr>
<td>Battery power systems (wet cell)</td>
<td>Failure to provide proper output, ( \lambda_i )</td>
<td>( 3 \times 10^{-6}/h )</td>
</tr>
<tr>
<td>Electric motors</td>
<td>Failure to start, ( Q^b_d )</td>
<td>( 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to run, given start, in normal environment, ( \lambda_0 )</td>
<td>( 1 \times 10^{-5}/h )</td>
</tr>
<tr>
<td></td>
<td>Failure to run, given start, in extreme environment, ( \lambda_0 )</td>
<td>( 1 \times 10^{-3}/h )</td>
</tr>
<tr>
<td>Transformers</td>
<td>Open circuit, primary or secondary, ( \lambda_0 )</td>
<td>( 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td></td>
<td>Short, primary to secondary ( \lambda_0 )</td>
<td>( 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td>Solid state devices (low power)</td>
<td>Failure to function, ( \lambda_0 )</td>
<td>( 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td>Circuit breakers</td>
<td>Failure by short, ( \lambda_0 )</td>
<td>( 1 \times 10^{-7}/h )</td>
</tr>
<tr>
<td></td>
<td>Failure to transfer, ( Q^a_d )</td>
<td>( 1 \times 10^{-3}/d )</td>
</tr>
<tr>
<td></td>
<td>Premature transfer, ( \lambda_0 )</td>
<td>( 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td>Fuses</td>
<td>Failure to open, ( Q_d )</td>
<td>( 1 \times 10^{-3}/d )</td>
</tr>
<tr>
<td></td>
<td>Premature open, ( \lambda_0 )</td>
<td>( 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td>Relays</td>
<td>Failure to energize, ( Q^b_d )</td>
<td>( 1 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure of NO contacts to close, given energization, ( \lambda_0 )</td>
<td>( 3 \times 10^{-7}/h )</td>
</tr>
<tr>
<td></td>
<td>Failure of NC contacts by opening, given no energization, ( \lambda_0 )</td>
<td>( 1 \times 10^{-7}/h )</td>
</tr>
</tbody>
</table>
### Failure and Event Data

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Failure Mode</th>
<th>Failure Rate ( \lambda_i )</th>
<th>Probability of ( Q_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal boards</td>
<td>Failure to operate, ( Q_d )</td>
<td>( 1 \times 10^{-4}/d )</td>
<td>( 3 \times 10^{-5} - 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to remain open (plug), ( Q_d )</td>
<td>( 3 \times 10^{-4}/d )</td>
<td>( 1 \times 10^{-3} - 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to operate, ( Q_d^{(b)} )</td>
<td>( 3 \times 10^{-4}/d )</td>
<td>( 1 \times 10^{-3} - 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to remain open (plug) ( \lambda_i )</td>
<td>( 3 \times 10^{-5}/h )</td>
<td>( 3 \times 10^{-4} - 3 \times 10^{-5}/h )</td>
</tr>
<tr>
<td></td>
<td>Rupture, ( \lambda_i )</td>
<td>( 1 \times 10^{-8}/h )</td>
<td>( 1 \times 10^{-9} - 1 \times 10^{-7}/h )</td>
</tr>
<tr>
<td>Valves (motor operated, includes driver)</td>
<td>Failure to operate, ( Q_d^{(b)} )</td>
<td>( 3 \times 10^{-4}/d )</td>
<td>( 3 \times 10^{-4} - 3 \times 10^{-5}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to remain open (plug) ( \lambda_i )</td>
<td>( 3 \times 10^{-7}/h )</td>
<td>( 1 \times 10^{-7} - 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td></td>
<td>Rupture, ( \lambda_i )</td>
<td>( 1 \times 10^{-9}/h )</td>
<td>( 1 \times 10^{-9} - 1 \times 10^{-7}/h )</td>
</tr>
<tr>
<td>Valves (solenoid operated)</td>
<td>Failure to operate, ( Q_d^{(b)} )</td>
<td>( 1 \times 10^{-3}/d )</td>
<td>( 3 \times 10^{-4} - 3 \times 10^{-3}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to remain open (plug) ( \lambda_i )</td>
<td>( 1 \times 10^{-5}/d )</td>
<td>( 3 \times 10^{-5} - 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Rupture, ( \lambda_i )</td>
<td>( 1 \times 10^{-8}/h )</td>
<td>( 1 \times 10^{-9} - 1 \times 10^{-7}/h )</td>
</tr>
<tr>
<td>Relief valves</td>
<td>Failure to open, ( Q_d )</td>
<td>( 1 \times 10^{-3}/d )</td>
<td>( 3 \times 10^{-4} - 3 \times 10^{-3}/d )</td>
</tr>
<tr>
<td></td>
<td>Premature open, ( \lambda_i )</td>
<td>( 1 \times 10^{-5}/d )</td>
<td>( 3 \times 10^{-5} - 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td>Check valves</td>
<td>Failure to open, ( Q_d )</td>
<td>( 1 \times 10^{-3}/d )</td>
<td>( 3 \times 10^{-4} - 3 \times 10^{-3}/d )</td>
</tr>
<tr>
<td></td>
<td>Internal leak (severe), ( \lambda_i )</td>
<td>( 3 \times 10^{-7}/h )</td>
<td>( 1 \times 10^{-7} - 1 \times 10^{-6}/h )</td>
</tr>
<tr>
<td></td>
<td>Rupture, ( \lambda_i )</td>
<td>( 1 \times 10^{-9}/h )</td>
<td>( 1 \times 10^{-9} - 1 \times 10^{-7}/h )</td>
</tr>
<tr>
<td>Pumps (including driver)</td>
<td>Failure to start, ( Q_d )</td>
<td>( 1 \times 10^{-3}/d )</td>
<td>( 3 \times 10^{-5} - 3 \times 10^{-4}/d )</td>
</tr>
<tr>
<td></td>
<td>Failure to run, given start, in normal environment, ( \lambda_i )</td>
<td>( 1 \times 10^{-5}/h )</td>
<td>( 3 \times 10^{-6} - 3 \times 10^{-5}/h )</td>
</tr>
<tr>
<td></td>
<td>Failure to run, given start, in extreme post-accident environment inside containment, ( \lambda_i )</td>
<td>( 1 \times 10^{-3}/h )</td>
<td>( 1 \times 10^{-2} - 1 \times 10^{-4}/h )</td>
</tr>
<tr>
<td></td>
<td>Rupture/plug, ( \lambda_i ), ( \lambda_i^{(b)} )</td>
<td>( 1 \times 10^{-9}/h )</td>
<td>( 3 \times 10^{-11} - 3 \times 10^{-9}/h )</td>
</tr>
<tr>
<td></td>
<td>Rupture/plug, ( \lambda_i ), ( \lambda_i^{(b)} )</td>
<td>( 1 \times 10^{-10}/h )</td>
<td>( 3 \times 10^{-12} - 3 \times 10^{-10}/h )</td>
</tr>
<tr>
<td>Gaskets (containment quality)</td>
<td>Leak (serious) in post-accident situation, ( \lambda_i )</td>
<td>( 3 \times 10^{-6}/h )</td>
<td>( 1 \times 10^{-7} - 1 \times 10^{-4}/h )</td>
</tr>
<tr>
<td>Elbows, flanges, expansion joints (containment quality)</td>
<td>Leak (serious) in post-accident situation, ( \lambda_i )</td>
<td>( 3 \times 10^{-7}/h )</td>
<td>( 1 \times 10^{-8} - 1 \times 10^{-5}/h )</td>
</tr>
<tr>
<td>Welds (containment quality)</td>
<td>Leak (serious) in post-accident situation, ( \lambda_i )</td>
<td>( 3 \times 10^{-9}/h )</td>
<td>( 1 \times 10^{-10} - 1 \times 10^{-7}/h )</td>
</tr>
<tr>
<td>Clutches (mechanical)</td>
<td>Failure to operate, ( Q_d^{(b)} )</td>
<td>( 3 \times 10^{-4}/d )</td>
<td>( 1 \times 10^{-4} - 1 \times 10^{-3}/d )</td>
</tr>
</tbody>
</table>

\( \lambda_i = \) failure/h in operational mode
\( \lambda_i^{(b)} = \) failure/h in standby mode

(a) \( Q_d = \) failure/demand

(b) Demand probabilities are based on the presence of proper input control signals

(c) Plug probabilities are given as probabilities per demand and as rates per hour, since the plug is generally time-dependent but may only be detected upon a demand on the system.

(d) Turbine-driven pump systems may have significantly higher failure rates.

Authority, 1984); and the general literature such as A.E. Green and Bourne (1972) and D.J. Smith (1985).

A selection of data on equipment failure rates obtained by the UKAEA and given by A.E. Green and Bourne are shown in Table A14.2 and Figure A14.1. These data derive from the work of the UKAEA initially in the nuclear field but subsequently in non-nuclear applications also.
Table A14.4  Some data on equipment failure rates (D.J. Smith, 1985; reproduced by permission of Macmillan)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Failure rate(^a) (failures/10^6 h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td></td>
</tr>
<tr>
<td>Centrifugal, turbine driven</td>
<td>150</td>
</tr>
<tr>
<td>Reciprocating, turbine driven</td>
<td>500</td>
</tr>
<tr>
<td>Electric motor driven</td>
<td>100 300</td>
</tr>
<tr>
<td>Diesel generator</td>
<td>125 4000</td>
</tr>
<tr>
<td>(0.97 start)</td>
<td></td>
</tr>
<tr>
<td>Electricity supply</td>
<td>110</td>
</tr>
<tr>
<td>Gaskets</td>
<td>0.02 1</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>1 40</td>
</tr>
<tr>
<td>Pipe joint</td>
<td>0.5</td>
</tr>
<tr>
<td>Pumps</td>
<td></td>
</tr>
<tr>
<td>Centrifugal</td>
<td>10 30 80</td>
</tr>
<tr>
<td>Boiler</td>
<td>100 500</td>
</tr>
<tr>
<td>Fire(^b)</td>
<td>100 150</td>
</tr>
<tr>
<td>Fuel</td>
<td>6 50</td>
</tr>
<tr>
<td>Oil lubrication</td>
<td>10 30 100</td>
</tr>
<tr>
<td>Vacuum</td>
<td>20</td>
</tr>
<tr>
<td>Turbine, steam</td>
<td>30 80</td>
</tr>
<tr>
<td>Valves</td>
<td></td>
</tr>
<tr>
<td>Ball</td>
<td>1 3.5</td>
</tr>
<tr>
<td>Butterfly</td>
<td>1 20 30</td>
</tr>
<tr>
<td>Gate</td>
<td>1.5 15</td>
</tr>
<tr>
<td>Relief</td>
<td>4 9</td>
</tr>
<tr>
<td>Non-return</td>
<td>2 5</td>
</tr>
<tr>
<td>Slam shut</td>
<td>10 30</td>
</tr>
<tr>
<td>Solenoid</td>
<td>1.5 10 30</td>
</tr>
<tr>
<td>Valve actuators(^c)</td>
<td></td>
</tr>
<tr>
<td>Fail open</td>
<td>0.1 4</td>
</tr>
<tr>
<td>Spurious close</td>
<td>5 40</td>
</tr>
</tbody>
</table>

\(^a\) Entries are given in three formats: a single value, where the various references are in good agreement; two values, indicating a range; and three values with one in bold, indicating a range with the value in bold predominating. Bold is also used for one end of a range, where that value predominates.

\(^b\) Approximately 800 for a complete fire pump and primer system.

\(^c\) Depends on the complexity of the pneumatic circuit; requires FMEA.

Failure rate data for offshore have been given in the collections by OREDA (1984, 1992). These data include not only overall failure rate but also failure rate in some failure modes. The number of failures, which determines the confidence bounds on the values, is also given.

### A14.3 Databases

An account of data banks and databases is given in *Reliability Data Banks* by Cannon and Bendell (1991).

The two main kinds of database are the incident database and the reliability database. An incident database does not have an inventory of items at risk and concentrates on the attributes and development of the incidents. A reliability database may well record incidents, but treats them primarily as events from which statistical information on reliability, availability and maintainability are to be derived.

Reliability databases are created by different users for somewhat different purposes. They range from the database created by a single individual through those at company level to those operated by specialist organizations.

The investment of effort in creating and operating a reliability database is appreciable and the exercise is not one to be undertaken lightly. It is essential to define clearly the data to be held, the uses to which they will be put and the means by which they will be acquired.

Most serious reliability databases are part of the activities of an organization which is involved in other aspects of reliability work also. The organization thus has an interest in the database as a user, which is likely to make it more friendly to other users.

In the following, brief descriptions are given of three principal databases: the NCSR, ERDS and FACTS databases. Other databases include the EDF database (Procaccia, 1991); the IAEA database (Tomic and Lederman, 1991); the CREDO database at ORNL (Knee, 1991); and the Dane database (Mizuta et al., 1991).

#### A14.3.1 Database design

The construction of a database involves the translation of the logical data model, giving the relationships between the data field into the physical database embodied in the computer. This is effected by the database management system (DMBS).

Three main types of database are the hierarchical, network and relational databases. The merits of these different approaches for reliability databases are discussed by Cross and Stevens (1991).

Information about components held in the database comes under two main heads: the component inventory and the component history. The component inventory contains a description of each component on which information is held. The component history gives the detailed failure and maintenance history of each component.

Both for component inventory and component history the design of the data set to be held is not a trivial question. For inventory it is first necessary to define the component boundary. A valve actuator, for example, may not remain permanently on the same valve.

It is then necessary to specify the attributes of the components. This involves deciding the degree of

Further selected failure rate data given in the *Rasmussen Report* are shown in Table A14.3. The failure data in this table include both failure rate per unit time and failure probability on demand and are quoted as a median value together with a range. These data were obtained from both nuclear and non-nuclear sources, but were collected for use in nuclear hazard assessment, in particular on the critical loss of coolant accident (LOCA).

The report, which is described more fully in Appendix 23, gives extensive documentation qualifying the data presented.

Another set of failure rate data are those given by D.J. Smith (1985) and a selection is shown in Table A14.4. In this case the failure rate is given as a single value, a range or a single value and a range.
subdivision or, alternatively, the level of aggregation. Excessive subdivision results in samples which are too small, while excessive aggregation lumps together items which differ significantly.

For component history, information is typically recorded on failure mode and failure cause. Here the problem is the tendency toward excessive subdivision by creation of additional failure mode and cause categories. This problem is aggravated if numbers of persons are authorized to extend these categories.

It is also desirable to have a plain language fault descriptor. Experience suggests that a set of pre-specified descriptors is on some occasions too detailed and on others not detailed enough, and that there is value in a facility to use free text.

In general, it is desirable to store the data in their ‘original’ form rather than in an abstracted form which involves loss of information. For this reason, the data in a reliability data bank may be stored as a set of events from which statistical data may then be obtained.

A14.3.2 Database operation
The operator of a reliability database has to maintain a sufficient flow of data from the data suppliers and satisfy the needs of the data users in a manner which is cost effective. This is no easy task.

Fresh data are the lifeblood of a reliability data bank. There must be a sufficient incentive for an organization to supply them, either by collecting them itself or by allowing access for their collection. Typically it will be one which is also a user of the data.

The data user will have a set of requirements which often can be met only in part. Ideally the user would like data from which to obtain failure and repair time distributions, and so on. Often these will simply not be available, the best on offer being perhaps failure or repair rates based on a constant rate assumption. There may also be problems of sample size.

The data bank operator has to balance the often conflicting requirements of user demand, data supply and economy in handling.

A14.3.3 Data acquisition
Information on equipment for the component inventory is obtained from the plant documentation, which includes equipment records and equipment and plant drawings. Acquisition of the inventory data for a plant may not be straightforward. Records and drawings may be incomplete from the outset, and it is even more common that modifications made are not entered. There can be confusing identifications, with the same item allocated several quite different code numbers. There can be a corruption of the component design parameters, with differences between the item as designed and as purchased and installed being quite common. As Cross and Stevens comment: ‘It is incredible how poor the average plant inventory records are’.

For information on equipment failure and repair a basic source of information is the job card or ticket. Typically this gives as a minimum the identity of the equipment, the failure notified or diagnosed and the repair work done. Other documentation such as logbooks, permits-to-work and stores requisitions are generally useful as cross-checks rather than prime sources.

To the extent practical, the failure data should be such as to permit analysis to obtain failure distributions as well as average values. This implies that the data should give the times to failure for individual equipments rather than just the total number of failures. This greatly enhances the value of the data to the data analyst.

Some data require a degree of reinterpretation or filtering. One common problem is the failure which presents as a cluster of events arising over a short time interval. This may take several forms, each of which involves events which are in some sense dependent. One is the repair which is unsatisfactory so that failure recurs almost immediately and the work has to be done again. Somewhat similar is the repair which is made in several passes such as a leaking valve which is first tightened, then repacked and finally replaced. A third situation is the nearly simultaneous failure of a number of items due to a common cause.

A14.3.4 NCSR database
The NCSR Reliability Data Bank is a major database system which has been in operation for over twenty years serving the nuclear, aerospace, electronics, oil, chemical and other industries.

Accounts of the early database and SYREL data bank have been given by Eames (1967 UKAEA AHSB(S) R138), Ablitt (1973 SRS/GR/14) and Fothergill (1973 SS/GR/22). The mature database has been described by Cannon (1991a, b). An account of further developments in the database is given by Cross and Stevens (1991).

As described by Cannon (1991a) the data bank about the mid-1980s consisted of data stores for (1) generic reliability, (2) events, (3) accidents, (4) human reliability and (5) maloperation. Much of the data collection was carried out by placement of students in co-operating companies. Cannon gives examples of the use of the data bank, including cases where application of the data resulted in reductions in the observed failure rates.

Cross and Stevens (1991), writing from the perspective of the user as well as the operator of a data bank, describe the transition of the NCSR system from a system which was based originally on 1960s technology, using mainframe computers, large in size and not readily modified, to one utilizing modern database methods and implemented on PCs.

Of the two basic formats for storage of information, summary and complete record, the NCSR system utilizes the latter, so that complete details of each event are held. From these complete records statistical data can then be abstracted as required.

A14.3.5 ERDS database
The European Reliability Data System (ERDS) is an EC database operated by the JRC at Ispra. It is described by Capobianchi (1991).

ERDS acquires its data from European and other databases, and is therefore in effect a database of databases. It is oriented particularly to serve the nuclear industry.

The data are rendered homogeneous by conversion to a uniform format. This format is specified in a detailed system of classification which is thus by way of being a European standard.

ERDS has four main data subsystems: (1) the Component Event Data Bank (CEDB), (2) the
Abnormal Occurrences Reporting System, (3) the Operating Unit Status Report and (4) the Reliability Parameter Data Bank.

A14.3.6 FACTS database
The Failure and Accident Technical Information System (FACTS) is an incident data bank operated by TNO in the Netherlands. It is described by Koehorst and Bockholt (1991).

The information is derived from the literature; from companies; from inspectorates, fire services, etc.; and from FACTS agencies in other countries, respecting anonymity. Press reports serve as triggers to acquire information.

Features of the database are a schedule of accident attributes and values and a hierarchical keyword structure. Another structure is the cause classification in which the course of the accident is translated into a sequence of occurrences. This makes it possible to trace back from an event down the causal chain. The original plain text accounts are held on microfiche.

Applications of the system described by the authors include (1) analysis of the role of instrumentation in accidents; (2) analysis of incorrect human response; and (3) compilation of a reference book to trace incident causes (the Cause Book), giving a survey of incident causes which can occur in a large number of systems and operations.

Further analysis is given in An Analysis of Accidents with Casualties in the Chemical Industry Based on Historical Facts by Koehorst (1989).

Developments of the system include an expert system front end.

A14.3.7 OREDA database
The Offshore Reliability Data (OREDA) project is an offshore reliability database described in the handbook by OREDA (1984, 1992). It gives failure and repair data for offshore installations, mainly in the UK and Norwegian sectors of the North Sea.

A substantial effort was devoted to the design of the system to ensure as far as possible that the components, their boundaries and environment, are well defined and that the data obtained are high quality and statistically meaningful. The database is fully explained in the OREDA handbook, which describes the system, gives the data and outlines the statistical treatment.

The project therefore serves as a good illustration of a reliability database.

The data cover (1) process systems, (2) safety systems, (3) electrical systems, (4) utility systems, (5) crane systems and (6) drilling systems. The component inventory gives the following information: (1) brief description, (2) application, (3) operational mode (continuous, standby, protective, etc.), (4) internal environment (fluids handled), (5) external environment and (6) boundary specification, including a sketch.

The operating data include (1) population at risk, (2) number of installations supplying data, (3) total calendar and operational times and (4) number of demands (where applicable). The failures are broken down into three broad categories of mode: (1) critical, (2) degraded and (3) incipient; there may be a number of modes in each category. The failure and repair data comprise (1) number of failures, (2) failure rate, (3) active repair time and (4) repair time. Mean and lower and upper bound values are given for the failure rates and mean, minimum and maximum values for the repair times. The active repair time is the average time required to analyse and repair the item and return it to service, excluding time to detect the fault and isolate the equipment and any delay due to tools or spares. The repair time is the number of manhours required for the repair. The failure and repair data are given for each mode and for the equipment overall.

Some of the events recorded in the OREDA as failures are those such as failure to start and spurious trip.

The number of installations participating, the number of components at risk and the number of failures experienced are very variable. In many cases the population at risk is 10 or less.

The handbook states that data in the form of times between failures are collected, but that confidence in the statistical data varies between the different generic groups and that for most purposes time-independent failure rates are a relevant approximation. It does not give data on times between failures.

A14.3.8 User viewpoint
Accounts of the viewpoint of the user of such databases are given by J.H. Bowen (1977) and Cross and Stevens (1991).

A14.4 Inventory of Plants
Information is sometimes required on the number of plants at risk, either nationally or world-wide. This is needed, for example, in order to convert data on the number of a particular type of event, for example vapour cloud explosions, into a frequency per plant.

A14.4.1 Process plants
Data on the number and capacity of chemical and petrochemical plants in various countries are given in the publications by SRI International which include Directory of Chemical Producers – United States 1988 and Directory of Chemical Producers – Western Europe 1988 (SRI Int., 1988b, c).

From the SRI data for the United States (US) and Western Europe (WE):

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>WE</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of chemical/petrochemical plants</td>
<td>1420</td>
<td>1455</td>
<td>185</td>
</tr>
</tbody>
</table>

The following ratios apply for the number of plants and for the plant capacity:

<table>
<thead>
<tr>
<th></th>
<th>US/WE</th>
<th>UK/WE</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of plants</td>
<td>0.92</td>
<td>0.12</td>
</tr>
<tr>
<td>Plant capacity</td>
<td>1.08</td>
<td>0.12</td>
</tr>
</tbody>
</table>

For petroleum refineries similar data are given in the International Petroleum Encyclopaedia (IPE, 1988).
From the IPE data

<table>
<thead>
<tr>
<th>Non-Communist world, excluding US</th>
<th>US</th>
<th>WE</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of refineries</td>
<td>412</td>
<td>182</td>
<td>120? 15</td>
</tr>
</tbody>
</table>

A refinery contains a major number of units and this number varies. Information given in periodic surveys (e.g. Anon., 1985dd) suggests an average value of about five such units per refinery.

Information is also available on the number of installations which attract certain regulatory controls. In the UK the number of installations notifiable under the NIHHS Regulations 1982 has been given by Pape and Nussey (1985) and by Pape (1989) as

<table>
<thead>
<tr>
<th>LPG</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>400</td>
</tr>
<tr>
<td>Chlorine</td>
<td>120</td>
</tr>
<tr>
<td>Total</td>
<td>1600</td>
</tr>
</tbody>
</table>

Of the LPG installations 450 are storage installations and 130 gas cylinder storages.

In a discussion of the CIMAH Regulations 1984 Welsh (1993) states that over 400 safety reports have been submitted. In interpreting this figure, it should be borne in mind that the number of reports cannot necessarily be equated to the number of CIMAH installations.

A14.4.2 Ammonia plants

Estimates of the number of ammonia installations and carriers have been given by Baldock (1980) and are shown in Table A14.5.

<table>
<thead>
<tr>
<th>Plants</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage areas</td>
<td>1000</td>
</tr>
<tr>
<td>Vessels</td>
<td>10000</td>
</tr>
<tr>
<td>Refrigeration plants</td>
<td>100000</td>
</tr>
<tr>
<td>Transfer points</td>
<td>1000</td>
</tr>
<tr>
<td>Road tankers</td>
<td>1000</td>
</tr>
<tr>
<td>Rail tankers</td>
<td>5000</td>
</tr>
<tr>
<td>Ammonia ships</td>
<td>20</td>
</tr>
<tr>
<td>Pipeline miles</td>
<td>2000</td>
</tr>
</tbody>
</table>

Source: Baldock (1980), Table 2

### Table A14.6 Pipework fittings and valves

<table>
<thead>
<tr>
<th>Nominal pipe diameter (in.)</th>
<th>Total length of pipe (ft)</th>
<th>Flanges</th>
<th>Valves</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>33990</td>
<td>1818</td>
<td>11589</td>
</tr>
<tr>
<td>1/2</td>
<td>33123</td>
<td>2973</td>
<td>7551</td>
</tr>
<tr>
<td>1</td>
<td>124513</td>
<td>12552</td>
<td>10363</td>
</tr>
<tr>
<td>1 1/2</td>
<td>121212</td>
<td>7299</td>
<td>3313</td>
</tr>
<tr>
<td>2</td>
<td>142891</td>
<td>11727</td>
<td>4199</td>
</tr>
<tr>
<td>3</td>
<td>125550</td>
<td>10427</td>
<td>2441</td>
</tr>
<tr>
<td>4</td>
<td>84705</td>
<td>6608</td>
<td>1346</td>
</tr>
<tr>
<td>6</td>
<td>7717</td>
<td>4578</td>
<td>898</td>
</tr>
<tr>
<td>8</td>
<td>67667</td>
<td>3592</td>
<td>466</td>
</tr>
<tr>
<td>10</td>
<td>39225</td>
<td>1613</td>
<td>301</td>
</tr>
<tr>
<td>12</td>
<td>16445</td>
<td>762</td>
<td>162</td>
</tr>
<tr>
<td>14</td>
<td>3997</td>
<td>342</td>
<td>72</td>
</tr>
<tr>
<td>16</td>
<td>10292</td>
<td>506</td>
<td>90</td>
</tr>
<tr>
<td>18</td>
<td>3530</td>
<td>362</td>
<td>41</td>
</tr>
<tr>
<td>20</td>
<td>5698</td>
<td>804</td>
<td>34</td>
</tr>
<tr>
<td>24</td>
<td>5983</td>
<td>357</td>
<td>40</td>
</tr>
<tr>
<td>30</td>
<td>3121</td>
<td>255</td>
<td>13</td>
</tr>
<tr>
<td>36</td>
<td>1608</td>
<td>66</td>
<td>12</td>
</tr>
</tbody>
</table>

Source: Hooper (1982), table on p.128

### Table A14.7 Inventory of potential leak sources: number of sources on four petrochemical plants

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of items</th>
<th>Monochlorobenzene plant</th>
<th>Butadiene plant</th>
<th>Ethylene oxide/glycol plant</th>
<th>Dimethyl terephthalate plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flanges</td>
<td>1500</td>
<td>26000</td>
<td>NA*</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Valves</td>
<td>640</td>
<td>6700</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Pumps</td>
<td>25</td>
<td>174</td>
<td>69</td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>

Source: T.W. Hughes, Tierney and Khan (1979), Table 3
* NA, not available.

### Table A14.8 Inventory of potential leak sources: estimates of number of leak sources on a medium sized plant

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of sources</th>
<th>No. of items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flanges</td>
<td>2410</td>
<td></td>
</tr>
<tr>
<td>Valves</td>
<td></td>
<td>In-line, gas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In-line, liquid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open-ended</td>
</tr>
<tr>
<td>Pump seals</td>
<td></td>
<td>Packed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical, single</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical, double</td>
</tr>
<tr>
<td>Compressor seals</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Safety relief valves</td>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>

Source: D.P. Wallace (1979), p.92
Table A14.9 Inventory of potential leak sources: estimated number of sources in a large refinery

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flanges</td>
<td>46500</td>
</tr>
<tr>
<td>Valves</td>
<td>11500</td>
</tr>
<tr>
<td>Pump seals</td>
<td>350</td>
</tr>
<tr>
<td>Compressors</td>
<td>70</td>
</tr>
<tr>
<td>Relief valves</td>
<td>100</td>
</tr>
<tr>
<td>Drains</td>
<td>650</td>
</tr>
</tbody>
</table>

Source: Lipton and Lynch (1987), Table 7.2

Table A14.10 Inventory of potential leak sources: number of valves in a refinery and two other plants

<table>
<thead>
<tr>
<th>A</th>
<th>No. of valves in three plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of valves</td>
<td></td>
</tr>
<tr>
<td>Large integrated refinery</td>
<td>21 800</td>
</tr>
<tr>
<td>Large olefins plant</td>
<td>15 000</td>
</tr>
<tr>
<td>Cumene process unit</td>
<td>1179</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>No. of valves on different duties in large refinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of valves</td>
<td></td>
</tr>
<tr>
<td>Valves</td>
<td></td>
</tr>
<tr>
<td>Gas and light liquid only</td>
<td>13 334</td>
</tr>
<tr>
<td>All</td>
<td>21 776</td>
</tr>
</tbody>
</table>


Numbers of potential leak sources on various types of plant have been given, mainly in the context of fugitive emissions. Table A14.7 shows the numbers given by T.W. Hughes, Tierney and Khan (1979) for some potential leak sources in four petrochemical plants and Table A14.8 those given by D.P. Wallace (1979) for some sources in a single medium sized plant. Table A14.9 shows data given by Lipton and Lynch (1987) on the number of some sources in a large refinery. Table A14.10 after Wetherold (1983) gives the number of valves in a refinery and in two other plants.

Using such data it is possible to construct a profile of the potential leak sources on a typical plant.

A14.6 Vessels and Tanks

A14.6.1 Pressure vessels

The failure rates of pressure vessels are discussed in Chapter 12.

A14.6.2 Storage tanks

Estimated failure rates of storage tanks quoted by Batstone and Tomi (1980) are shown in Table A14.11.

Table A14.11 Estimated failure rates of storage tanks

<table>
<thead>
<tr>
<th>Failure rate (failures/10^6 year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric tank</td>
</tr>
<tr>
<td>Refrigerated tank:</td>
</tr>
<tr>
<td>Single wall</td>
</tr>
<tr>
<td>Double wall</td>
</tr>
</tbody>
</table>

Source: Batstone and Tomi (1980), Table A1

Data on the failure rates of storage tanks in ammonia and LNG are given in Sections A14.18 and A14.19, respectively.

Data on storage tank fires are given in Section A14.23.

A14.7 Pipework

A14.7.1 Pipes

The failure rates of pipes are discussed in Chapter 12.

A14.7.2 Flanges and gaskets

Data on the failure rates of gaskets are given in Tables A14.2–14.4 and by Pape and Nussey (1985).

Comparison of these values gives for the failure frequency of gaskets:

<table>
<thead>
<tr>
<th>Failure frequency (failures/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith: lower limit</td>
</tr>
<tr>
<td>upper limit</td>
</tr>
<tr>
<td>UKAEA</td>
</tr>
<tr>
<td>Rasmussen Report</td>
</tr>
<tr>
<td>Pape and Nussey</td>
</tr>
</tbody>
</table>

A14.7.3 Bellows

There is a potential ambiguity in the term bellows, which may refer to bellows used in instrumentation or to those used in pipework.

The UKAEA data on the failure rate of bellows in Table A14.2 gives a failure frequency of 5 × 10^-6 failures/year. D.J. Smith (1985) gives a failure rate of 4 × 10^-6 failures/year.

A14.8 Heat Exchangers

Data on the failure rates of heat exchangers are given in Table A14.4.

Some information on the failure rate of heat exchangers has been given by C.F. King and Rudd (1972) in a reliability study of a heavy water plant. With some 21 heat exchangers the MTTF ranged from 677 to 7865 h.

For offshore heat exchangers the data given by OREDA (1992) include the following:
### Table A14.12 Failure modes of ethylene plant pumps

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>No. of failures</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seals/glands</td>
<td>119</td>
<td>49.0</td>
</tr>
<tr>
<td>Overhauls(^a)</td>
<td>62</td>
<td>25.5</td>
</tr>
<tr>
<td>Cleaning</td>
<td>14</td>
<td>5.8</td>
</tr>
<tr>
<td>Repeat overhauls</td>
<td>7</td>
<td>2.9</td>
</tr>
<tr>
<td>Leaks(^b)</td>
<td>7</td>
<td>2.9</td>
</tr>
<tr>
<td>Motor failures</td>
<td>5</td>
<td>2.0</td>
</tr>
<tr>
<td>Couplings</td>
<td>5</td>
<td>2.0</td>
</tr>
<tr>
<td>Bearings</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>Other</td>
<td>22</td>
<td>9.1</td>
</tr>
<tr>
<td>Total</td>
<td>243</td>
<td>100.0</td>
</tr>
</tbody>
</table>

\(^a\) Overhauls were not at regular intervals but as a result of conditions found on opening up following a failure.
\(^b\) Leaks other than those due to seals/glands.

### Table A14.13 Failure modes of feedwater pumps in some French nuclear power stations

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body, shaft</td>
<td>5</td>
</tr>
<tr>
<td>Packing</td>
<td>29</td>
</tr>
<tr>
<td>Overspeed</td>
<td>10</td>
</tr>
<tr>
<td>Contactors</td>
<td>13</td>
</tr>
<tr>
<td>Control</td>
<td>16</td>
</tr>
<tr>
<td>Lubrication</td>
<td>12</td>
</tr>
<tr>
<td>Human error</td>
<td>6</td>
</tr>
</tbody>
</table>

Source: Aupied, Le Coguiec and Procaccia (1983), Figure, p.149

### A14.9 Rotating Machinery

#### A14.9.1 Compressors

Data on the failure rates of compressors are given in Table A14.4. For offshore compressors the data given by OREDA (1992) include the following:

<table>
<thead>
<tr>
<th>Population</th>
<th>No. of failures</th>
<th>Failure rate (failures/10(^6) h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifugal, motor driven (1600–3600 kW)</td>
<td>3</td>
<td>104</td>
</tr>
<tr>
<td>Centrifugal, motor driven (4800–7100 kW)</td>
<td>9</td>
<td>218</td>
</tr>
<tr>
<td>Centrifugal, turbine driven (3800–8900 kW)</td>
<td>12</td>
<td>164</td>
</tr>
<tr>
<td>Centrifugal, turbine driven (20000–28000 kW)</td>
<td>9</td>
<td>172</td>
</tr>
<tr>
<td>Reciprocating, motor driven (500–3200 kW)</td>
<td>14</td>
<td>664</td>
</tr>
<tr>
<td>Reciprocating, motor driven (4100–9300 kW)</td>
<td>8</td>
<td>272</td>
</tr>
</tbody>
</table>

#### A14.9.2 Fans

Data on the failure rates of fans are given in Table A14.24.

#### A14.9.3 Pumps

There are wide variations in the type, duty and environment, and hence in the failure rate, of pumps. However, many pumps have a failure rate of some 1–5 failures/y.

Data on the failure rates of pumps are given in Tables A14.2–A14.4. D.J. Smith (1985) gives the failure modes of pumps as about 50% leakage and 50% no transmission.

Some information on the failure rate of pumps has been given by C.F. King and Rudd (1972) in a reliability study of a heavy water plant. MTTFs for four auxiliary pumps ranged from 51 to 398 days according to maintenance data, but from 12.5 to 439 days according to production data.

An account has been given by R. James (1976) of a pump maintenance programme on 880 major process pumps, mainly centrifugal pumps, aimed at eliminating premature wearout failures, in which the MTBF of the pumps was raised from 8.7 months to 12.2 months.

In accounts of pump reliability improvements by a particular manufacturer (Anon., 1985x; Bloch and Johnson, 1985) it is stated that for pumps the industry average MTBF is some 6 months, corresponding to a failure rate of 2 failures/year. Bloch and Johnson state that ANSI standard pumps have an MTBF of 13 months, or failure rate of 0.9 failures/year. It is claimed, however, by Anon. (1985x) that specified improvements have resulted in the achievement of an MTBF of some 25 months, or failure rate of 0.48 failures/year. For individual features improvements are said to have
extended the lives of the ball bearings, the mechanical seal system, the shaft and the coupling to 5, 2.5, 15 and 7 years, respectively.

A study of 85 ethylene plant pumps has been reported by Sherwin (1983). There were 243 failures and the failure rate was 1.8 failures/year. The failure modes are shown in Table A14.12.

Data on the failure rates of pumps in LNG plants are given in Table A14.25.

A study of feedwater pumps in French nuclear power stations has been made by Aupied, Le Coguic and Procaccia (1983). The overall failure rate was

Failure rate of feedwater pumps = 5.6 \times 10^{-4} \text{ failures/h}

= 4.9 \text{ failures/year}

The failure modes of the pumps are shown in Table A14.13.

A survey of pump mechanical seals by BHRA has been reported by Fitney (1987) in which pumps were surveyed in three refineries and five chemical plants, a sample of some 200–300 pumps being taken at each site. The two principal reasons for seal removal were

<table>
<thead>
<tr>
<th>Leakage</th>
<th>66%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing replacement</td>
<td>12%</td>
</tr>
</tbody>
</table>

Mechanical seals are also the subject of a study at Esso reported by N.M. Wallace and David (1985). They give a table of seal lives for some 17 cases, the lives varying from 2–12 months.

For catastrophic failure of a pump the Rijnmond Report uses a value of 1 \times 10^{-4} \text{ failures/year}.

For offshore pumps failure data are given by OREDA (1992), covering motor and turbine driven oil pumps and motor and diesel driven fire pumps.

A14.9.4 Turbines

Data on the failure rates of turbines are given in Table A14.4.

A study of steam turbine failure with particular reference to catastrophic failure and the generation of missiles has been described by Bush (1973). He quotes data from six major suppliers of steam turbines. The accumulated operating experience is 12,330 years prior to 1950 and 57,950 years in the period 1950–72. There were no failures in the earlier period and 10 in the later period. All four failures after 1950 were due to over-speed. Of the ten incidents seven generated missiles. His analysis indicates that the failure frequency was slowly decreasing. His estimates of the then current failure frequencies are

Frequency of failure = 9 \times 10^{-5} \text{/year}

Frequency failure resulting in missile generation = 8 \times 10^{-5} \text{/year}

For offshore gas turbines failure data are given by OREDA (1992).

A14.10 Valves

A14.10.1 General

A study of valves in French nuclear power stations has been carried out by Aupied, Le Coguic and Procaccia (1983). Some of the more critical valves are classified as primary valves and the others as secondary valves. Some of the failure rates obtained in this work are shown in Table A14.14, while failure modes are given in Table A14.15.

A survey designed to identify significant and common valve problems such as leakage and jamming and to relate them to valve type, service and manufacturer has been described by Vivian (1985). The survey was conducted in a major oil company and covered 10 businesses involving 17 facilities, of which a significant proportion are in the North Sea. Some quarter of a million valves were covered, of which almost 10% were reported as giving significant problems. The numbers of each type of valve are shown in Figure A14.2(a) and the associated problems in Figure A14.2(b).

The UKAEA data in Table 14.2 gives for control valves a failure rate of 0.25 failures/year and for manual valves 0.13 failures/year. The values used in the Rijnmond Report are 0.3 and 0.1 failures/year for control and manual valves, respectively.

| Table A14.14 Failure rates of valves in some French nuclear power stations |
|--------------------------|------------------|-----------------|------------------|------------------|
|                         | No. of valves | Total operating time | Total no. of demands | No. of failures in operation | No. of failures demand | Failure rate |
|                         |               |                  |                   |                         |                       |             |
|                         |               |                  |                   |                         |                       | In operation (failures/year) | On demand (failures/year) |
| Primary valves | Pressurizer safety relief valve | 18 | 175 500 | 382 | 9\textsuperscript{a} | 4 | 51 | 0.01 |
|                         | Heat removal loop safety relief valve | 12 | 105 000 | 12 | 3 | 2 | 29 | 0.17\textsuperscript{b} |
| Secondary valves | Condensate and drain pumps non-return valves | 12 | 88 700 | 1375 | 2 | 0 | 23 | —\textsuperscript{c} |

Source: Aupied, Le Coguic and Procaccia (1983), Tables 4 and 5

\textsuperscript{a} Failures mainly detected during annual tests.

\textsuperscript{b} Original table leaves this space blank.

\textsuperscript{c} Original table gives value of 0.0034.
Table A14.15  Failure modes of valves in some French nuclear power stations

<table>
<thead>
<tr>
<th>Type of valve</th>
<th>Outlet leakage</th>
<th>Corrosion</th>
<th>Untightness</th>
<th>Mechanical</th>
<th>Non-operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate valve</td>
<td>23</td>
<td>11</td>
<td>9</td>
<td>26</td>
<td>31</td>
</tr>
<tr>
<td>Globe valve</td>
<td>22</td>
<td>20</td>
<td>25</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Plug valve</td>
<td>55</td>
<td>17</td>
<td>22</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Safety relief valve</td>
<td>30</td>
<td>17</td>
<td>28</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Non-return valve</td>
<td>42</td>
<td>21</td>
<td>13</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Overall value</td>
<td>30</td>
<td>15</td>
<td>20</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

Source: Aupied, Le Coguie and Procaccia (1983), Figure, p.139

Further values for valve failure rates obtained by Moss (1977 NCSR R11) are discussed in Section A14.25. These values are 0.1 and 0.01 failures/year for valves on steam and water service, respectively. The latter value in particular is a lower than the others quoted here.

For valve rupture the Rasmussen Report gives a failure frequency of $1 \times 10^{-8}$/h ($0.9 \times 10^{-5}$/year).

A14.10.2 Control valves

Data on the failure rates of control valves are given in Tables A14.2–A14.4. Further data are given in various parts of this appendix.

A14.10.3 Pressure relief valves

For pressure relief valves (PRVs) the definition of failure is particularly important. Definitions of failure which may be used include failure of any kind, failure to lift within a certain proportion of the set pressure and failure to open on demand. The failure rates for these different types of failure are quite different.

Data on the failure rates of pressure relief valves are given in Tables A14.2–A14.4, A14.14 and A14.15.

The following data are for the failure rates of PRVs are given by Kletz (1972a, 1974a) and by Lawley and Kletz (1975):
### Failure rate

<table>
<thead>
<tr>
<th>Failure</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve fails shut</td>
<td>0.001</td>
</tr>
<tr>
<td>Valve lifts heavy</td>
<td>0.004</td>
</tr>
<tr>
<td>Total fail danger</td>
<td>0.005</td>
</tr>
<tr>
<td>Valve lifts open or light</td>
<td>0.02</td>
</tr>
<tr>
<td>Total fail safe</td>
<td>0.02</td>
</tr>
</tbody>
</table>

A survey of PRV inspections in a large chemical company has been reported by Aird (1983). Failure was defined as lifting 10% outside the set pressure when put under test. The number of useful tests was 866. The proportion of failures was 44.5%.

The failure rate showed no discernible trend with operating time and it was concluded that PRVs may be subject to changes which occur relatively rapidly. One cause often quoted is spring relaxation.

A study of controlled safety valves in power stations has been made by Oberender and Bung (1984). The valves were either intrinsically controlled by the vented fluid or externally controlled by a control fluid (pneumatic or hydraulic). Two basic events were considered: faultless functioning and failure to open on demand. Some 1378 tests were conducted. The proportion of valves giving faultless functioning was approximately:

<table>
<thead>
<tr>
<th>Type</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic control</td>
<td>40%</td>
</tr>
<tr>
<td>External control</td>
<td>80%</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>85%</td>
</tr>
</tbody>
</table>

The proportion giving failure on demand was approximately:

<table>
<thead>
<tr>
<th>Type</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic control</td>
<td>2%</td>
</tr>
<tr>
<td>Load principle</td>
<td>4.5%</td>
</tr>
<tr>
<td>Relief principle</td>
<td>0.3%</td>
</tr>
<tr>
<td>External control</td>
<td>0.8%</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>0.3%</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

For the intrinsically controlled valves, however, there was an improvement over time, the failure rate falling from some 10% in the initial period to < 1% in the final period.

Estimates of the success rate of PRVs in particular applications have been given by Prugh (1981) as follows:

<table>
<thead>
<tr>
<th>Event</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venting of vapour/air explosion</td>
<td>1%</td>
</tr>
<tr>
<td>Venting of runaway reaction</td>
<td>95%</td>
</tr>
<tr>
<td>Venting of excessive nitrogen purge</td>
<td>99%</td>
</tr>
</tbody>
</table>

#### A14.10.4 Non-return valves

Data on the failure rates of non-return, or check, valves are given in Tables A14.3–A14.4, A14.14 and A14.15.

#### A14.10.5 Emergency isolation valves

Data on the failure rates of emergency isolation valves, also called slam shut or shut-off valves, are given in Table A14.4.

#### A14.10.6 Manual valves

Data on the failure rates of manual isolation valves are given in Tables A14.2 and A14.3.

### A14.11 Instruments

For instruments the definition of failure is particularly important. This was discussed in detail in Chapter 13.

The importance of the definition of failure has been studied by Kortland (1983) for differential pressure transmitters. For transmitters required to maintain their calibration within 2% the failure rate observed was 0.1 failures/year. For transmitters with a required calibration within 5%, a less severe specification, the observed failure rate was a function of the calibration interval, being about 0.01 failures/year with a calibration interval of 1 year, but increasing for longer calibration intervals.

Some data on the failure rates of instruments are given in Chapter 13. The data given there refer mainly to instrumentation in the early and mid-1970s. The data given in this section supplement those given in Chapter 13 and include more recent data.

Data on the failure rates of instruments are given in Tables A14.2 and A14.3.

A study of control system failure sequences in ammonia plants has been described by Prijatel (1984). A comparison is given between predicted and actual failure sequences. Information on actual failure sequences was obtained from the work of G.P. Williams and Hoehing (1983). Some 95% of the actual failure sequences were single event failures.

Data on instrument failure were obtained from plant records and from the literature. Some of the data used in the study are given in Table A14.16.

For control failure sequences the actual shut down frequencies of particular units such as compressors were some 2–4 times as high as the predicted frequencies. The ranking of the instruments as a cause of shut down was in descending order of importance controllers, switches, solenoid valves, control valves and uninterruptible power supply (UPS) system, the contribution of

#### Table A14.16 Failure of instruments in ammonia plants (after Prijatel, 1984)

<table>
<thead>
<tr>
<th>Instrument Type</th>
<th>Failure rate (failures/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control valves</td>
<td>0.028</td>
</tr>
<tr>
<td>Controllers a</td>
<td>0.25</td>
</tr>
<tr>
<td>Switches b</td>
<td>0.22</td>
</tr>
<tr>
<td>Redundant switch systems c</td>
<td>$1.68 \times 10^{-4}$</td>
</tr>
<tr>
<td>Solenoid valves</td>
<td>0.046</td>
</tr>
<tr>
<td>UPS system</td>
<td>0.026</td>
</tr>
</tbody>
</table>

a For flow, pressure, level.
b For flow, pressure, temperature, level.
c An alternative figure of $2.9 \times 10^{-3}$ failures/year is also given.
these items to shutdowns being 41.2, 36.7, 7.5, 4.6 and 4.3%, respectively. Thus two items, controllers and switches, accounted for 78% of shutdowns.

Data on the failure rates of process chromatographs and other analytical instruments have been given by Huyten (1979). Some 870 instruments are considered in the survey. He gives the following availabilities:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysers</td>
<td>93.8%</td>
</tr>
<tr>
<td>Gas chromatographs</td>
<td>91.0%</td>
</tr>
</tbody>
</table>

He also gives for analysers failure modes which include the following:

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling system</td>
<td>39%</td>
</tr>
<tr>
<td>Analyser</td>
<td>18%</td>
</tr>
<tr>
<td>Nonavailability of spares</td>
<td>16%</td>
</tr>
<tr>
<td>Plant upsets, start up</td>
<td>11%</td>
</tr>
<tr>
<td>and shut down</td>
<td></td>
</tr>
</tbody>
</table>

A comparative study of the MTBF and maintenance time for controllers from five manufacturers has been described by H.S. Wilson (1978). He gives the following data:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>MTBF (year)</th>
<th>Maintenance time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Electronic</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>Electronic</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>Pneumatic</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>Electronic</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>Pneumatic</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>

He comments that the controller from manufacturer E failed so rarely that the maintenance time was greater due to unfamiliarity. From this comment the maintenance times are evidently times per failure.

A good deal of the literature data for instrument failure is now quite old. In general, it is to be expected that the failure rates have fallen. The following is a comparison of the failures rates given for certain measuring instruments by Anyakora, Engel and Lees (1971) and for sensors in process alarm systems by OREDA (1992):

<table>
<thead>
<tr>
<th>Failure rate (failures/year)</th>
<th>Anyakora, Engel and Lees</th>
<th>OREDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (p) (&lt; 1500 psig)</td>
<td>1.41</td>
<td>0.019</td>
</tr>
<tr>
<td>(e)</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>Flow (p) (gas)</td>
<td>1.73</td>
<td>0.25</td>
</tr>
<tr>
<td>(e) (gas)</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>Level (e)</td>
<td>1.71</td>
<td>0.096</td>
</tr>
<tr>
<td>Temperature (e)</td>
<td>0.88</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The first authors refer for pressure to 'pressure measurement', for flow and level to differential pressure transducers and for temperature to temperature transducers, but do not distinguish between transducers with pneumatic (p) or electronic (e) output. The instruments selected from the OREDA collection are all transducers with specified type of output. In comparing the figures, allowance needs to be made for the effects on failure rate of environment and calibration requirements. Nevertheless, the data do suggest an improvement in reliability.

### A14.12 Process Computers

The reliability of process computer systems is discussed in Chapter 13.

Data on the failure rates of twelve process computer systems in the paper industry given by Hubbe (1970) are shown in Table A14.17.

Data by E. Johnson (1983) on the failure rates of several different process computer configurations are summarized in Table A14.18. The data refer to total system failure, rather than failure of individual items such as printers. Johnson gives full details of the fault and downtime incidents. He states that for the total system an MTBF of 5000 h with a combined availability of about 99.9%, corresponding to no more than 8 h downtime per year, is about the level which may be found acceptable.

### A14.13 Relief Systems

Some information is available on the failure rates of the individual elements of a pressure relief system, such as pressure relief valves, bursting discs and vent systems. Data on the failure of these items is given in this section.

For chemical reactors information on the failure rate of pressure relief systems has been given by Marrs and Lees (1989) as described in Chapter 11.

#### A14.13.1 Pressure relief valves

Data on the failure rate of pressure relief valves are given in Section A14.10.

#### A14.13.2 Bursting discs

Data for the failure rate of bursting discs are given by Lawley (1974b) as follows:

| Table A14.17 Failure data for 12 process computer systems in the paper industry (Hubbe, 1970) |
|-----------------------------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| MTBF                                          | Availability        | Hardware faults (h) | Software faults (h) | Hardware faults (%) | Software faults (%) |
| Composite average                             | 550                 | 1365                | 99.1                | 99.80               |                      |
| Best case                                     | 1633                | 8163                | 99.94               | 99.97               |                      |
Appendix 14/18  Failure and Event Data

Table A14.18  Failure data for some process computer systems in the chemical industry (after E. Johnson, 1983; reproduced by permission of Elsevier Science Publishers)

<table>
<thead>
<tr>
<th>System</th>
<th>Operating time (h)</th>
<th>No. of failures</th>
<th>Downtime Failure (h)</th>
<th>Planned (h)</th>
<th>Availability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single computer system</td>
<td>66.528</td>
<td>13</td>
<td>65</td>
<td>300</td>
<td>99.9</td>
</tr>
<tr>
<td>with analogue standby</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin computer system</td>
<td>35.040</td>
<td>8</td>
<td>30.5</td>
<td>38</td>
<td>99.91</td>
</tr>
<tr>
<td>with analogue standby</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin computer system</td>
<td>78.888</td>
<td>21</td>
<td>172</td>
<td>48</td>
<td>99.78</td>
</tr>
<tr>
<td>with shared critical loops – 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin computer system</td>
<td>78.888</td>
<td>37</td>
<td>388</td>
<td>73</td>
<td>99.5</td>
</tr>
<tr>
<td>with shared critical loops – 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin computer system</td>
<td>13.848</td>
<td>6</td>
<td>54</td>
<td>17</td>
<td>99.61</td>
</tr>
<tr>
<td>with analogue standby</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Different configurations

Frequency of disc rupture at normal pressure = 0.2 failures/year.

For chemical reactors the failure rate of bursting discs in a single company has been investigated by Marrs and Lees (1989). The estimates obtained refer to the bursting disc itself, including blockage before the disc, but not to the vent pipework after the disc. There were during the period of investigation 11 successful ventings and no failures. The estimated probability of failure from these data is 0.083 failures/demand. An alternative, and less pessimistic, estimate was obtained from the fact that there were four unrevealed fail-to-danger failures in 164 reactor-years with an inspection interval of one year, giving an estimated probability of failure of 0.012. The authors' best estimate of the probability of failure is 0.01 failures/demand, but the confidence bounds are relatively wide.

A14.13.3 Vent systems

For chemical reactors and vented vessels the failure rate of vent systems, excluding bursting discs, in a single company has been investigated by Marrs and Lees (1989). There were during the period of investigation 28 successful ventings and no failures.

The estimated probability of failure from these data is 0.034 failures/demand. An alternative, and less pessimistic, estimate was obtained from the fact that there was one unrevealed fail-to-danger failure in 262 vessel-years with an inspection interval of one year, giving an estimated probability of failure of 0.0019. The authors' best estimate of the probability of failure is 0.002 failures/demand, but the confidence bounds are relatively wide.

A14.14 Fire and Gas Detection Systems

A study of fire detection systems with particular reference to false alarms has been described by Peacock, Kamath and Keller (1982). Some data from this study are shown in Table A14.19. Section A of the table shows the event rates for fire detection systems as assessed for chemical plant by safety officers from a single company. Section B gives the event rates for each type of detector.

Hanks (1983) has described a study of the fire and gas detection system at the gas terminal at St Fergus. The results reported for failure rates are confined to those for the gas detectors, which were mainly in compressor cabs and emergency generator rooms.

Hanks gives the following failure rates:

<p>| Failure rate (failures/10^5 h) |</p>
<table>
<thead>
<tr>
<th>Compressor cab</th>
<th>Other installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas detector</td>
<td>48</td>
</tr>
<tr>
<td>Gas detector and module</td>
<td>75</td>
</tr>
</tbody>
</table>

The failure rates for the gas detectors with modules include an allowance for power supplies, cables and connectors.

Y.P. Gupta (1985) describes a survey of automatic fire detection systems at six sites. His account includes estimates of the failure rates of ionization-type smoke detectors synthesized from data on the reliability of electronic components. For detectors in a first class, or non-adverse, environment, the overall failure rate was assessed as 0.057 faults/year, of which 0.04 faults/year were class as fail-safe and 0.017 faults/year as dangerous. Most adverse environments result in a much higher failure rate. For such environments the failure rate was assessed as 0.46 faults/year. For control units the failure rate was assessed for false alarms as 0.044 faults/year and for unrevealed dangerous faults as 0.06 faults/year.

For offshore fire and gas detection systems failure data are given by OREDA (1992).
Table A14.19  Some event rates in fire detection systems (after Peacock, Kamath and Keller, 1982; reproduced by the permission of the American Institute of Chemical Engineers)

A  Events by location

<table>
<thead>
<tr>
<th></th>
<th>Event rate (events/10^3 detector-year)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real alarms</td>
<td>False alarms</td>
</tr>
<tr>
<td>Plant in buildings</td>
<td>4.7</td>
<td>3.4</td>
</tr>
<tr>
<td>Plant in open</td>
<td>60</td>
<td>273</td>
</tr>
<tr>
<td>All locations</td>
<td>2.1</td>
<td>7.2</td>
</tr>
</tbody>
</table>

B  Events by type of detector

<table>
<thead>
<tr>
<th></th>
<th>Event rate (events/10^3 detector-year)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real alarms</td>
<td>False alarms</td>
</tr>
<tr>
<td>Smoke</td>
<td>5.9</td>
<td>40</td>
</tr>
<tr>
<td>Heat</td>
<td>1.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Smoke and heat</td>
<td>16</td>
<td>38</td>
</tr>
<tr>
<td>Flame (UV, IR)</td>
<td>108</td>
<td>622</td>
</tr>
</tbody>
</table>

A14.15 Fire Protection Systems

Data on the failure rates of sprinkler systems are available from sources such as the Factory Mutual Research Corporation and the NFPA.

A review of failure rates of sprinkler systems which draws on these sources has been given by Rasbash (1975a). For fires in buildings in the UK in the period 1966–71, the breakdown of incidents given is

<table>
<thead>
<tr>
<th>Type of incident</th>
<th>No. of incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small fire, extinguished by other means</td>
<td>5229</td>
</tr>
<tr>
<td>Sprinkler system installed and operated</td>
<td></td>
</tr>
<tr>
<td>Fire controlled by other means</td>
<td>275</td>
</tr>
<tr>
<td>Fire controlled by sprinkler</td>
<td>3180</td>
</tr>
<tr>
<td>Fire extinguished by sprinkler</td>
<td>651</td>
</tr>
<tr>
<td>Effect of sprinkler unknown</td>
<td>73</td>
</tr>
<tr>
<td>Sprinkler system installed but did not operate</td>
<td>676</td>
</tr>
<tr>
<td>Total</td>
<td>10084</td>
</tr>
</tbody>
</table>

Thus, excluding the small fires, sprinkler performance was unsatisfactory in some 14% of cases.

NPFA statistics for the period 1925–64 quoted by Rasbash indicate that in some 75290 fires sprinkler performance was unsatisfactory in some 3.8% of cases.

Rasbash also quotes statistics from the Australian Fire Protection Association (AFPA). For some 5734 fires in the period 1886–1968 the proportion of sprinklers which gave unsatisfactory performance was 0.2%. For some 1250 fires in the period 1968–73 the proportion was 0.64%. These very low AFPA values are discussed by Rasbash, who refers to differences in the criteria for satisfactory operation.

For the UK fires the two principal causes of unsatisfactory performance were that the sprinkler heads were inaccessible to the fire and that the water was shut off, these occurring in 9.6% and 4.3% of the incidents, respectively.

The figures for unsatisfactory performance of sprinklers given by P. Nash and Young (1976) for the NFPA and Australian data are similar, but they give for the UK for the period 1965–69 a figure of 8.3% and quotes a figure of 15% given by the Factory Mutual Corporation for the period 1970–72.

From the UK data the causes of unsatisfactory performance are given as system shut off, defective system, system frozen and unknown, these occurring in 4.6%, 0.60%, 0.07% and 3.0% of the incidents, respectively.

From the NFPA data some principal causes of unsatisfactory performance were valve shut, inadequate water supply and obstruction to distribution, these occurring in 36.0%, 9.6% and 8.4% of the incidents, respectively. The causes for the valve being closed were closed for no known reason, closed too early in the fire, closed for system repair or modification and closed to prevent freezing, these occurring in 22%, 22%, 21% and 20% of cases with a closed valve.

Nash and Young also give failure rates for the components of sprinkler systems as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure rate (failures/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Safe</td>
</tr>
<tr>
<td>Wet alarm valve</td>
<td>$15 \times 10^{-2}$</td>
</tr>
<tr>
<td>Alternate alarm valve</td>
<td>$15 \times 10^{-2}$</td>
</tr>
<tr>
<td>Alarm motor and gong</td>
<td>$6 \times 10^{-2}$</td>
</tr>
<tr>
<td>Accelerator</td>
<td>$13 \times 10^{-2}$</td>
</tr>
<tr>
<td>Main sprinkler stop valve</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Non-return valves</td>
<td>$10 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Further data on the effectiveness of fire protection systems have been given by M.J. Miller (1977), based on Factory Mutual experience in the period 1970–75. In
presenting data, the author warns that an unknown number of system operations are not reported. He also points out that there is no standard definition of effectiveness so that there is an element of subjectivity. He states as rough guidance that the performance would be considered acceptable if the system is designed to FM/ NFPA standards and is operated within the design conditions and if any loss does not exceed the estimated Normal Loss Expectancy. For sprinkler systems, the number of reported events by type of system, with the proportion effective in brackets, was as follows: wet 2102 (91%); dry 650 (86%); deluge 62 (76%) and non-freeze 16 (88%).

For special protection systems, the number of events with the proportion of successes, was as follows: water spray 49 (53%); dry chemical 22 (27%); carbon dioxide 100 (51%) and steam 30 (63%).

Information on failure rates of special protection systems is limited. For carbon dioxide systems in Germany Miller quotes a success rate of some 76–78% over a 14-year period.

For Halon systems he states that data are even scantier, but refers to a series of 300 tests of such systems by Dupont in which in some 23% of installations significant problems were identified and corrected.

Miller also gives data on the effectiveness of other active protection systems, namely: gas analyser; smoke detector; rate-of-rise detector; spray nozzles; foam water sprinkler; high expansion foam; low expansion foam; explosion suppression; halon (fire protection); halon (explosion suppression); vaporizing liquid; inert gas; in-rack sprinklers; standpipes. For only three of these is the number of reported events 10 or more, the numbers, with the number of successes, being as follows: gas analyser 13 (2), high expansion foam 10 (3) and low expansion foam 12 (5).

### A14.16 Emergency Shutdown Systems

Data on emergency isolation valves are given in Section A14.10.

For offshore emergency shutdown systems failure data are given by OREDA (1992). They deal mainly with well head shutdown, but also include emergency isolation valves as follows:

<table>
<thead>
<tr>
<th>Population</th>
<th>No. of failures</th>
<th>Failure rate (failures/10⁶ h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas (2–3 in.)</td>
<td>254</td>
<td>65 (41) 12.9</td>
</tr>
<tr>
<td>Gas (8–12 in.)</td>
<td>34</td>
<td>25 (8) 35</td>
</tr>
<tr>
<td>Gas (22–26 in.)</td>
<td>12</td>
<td>40 (10) 104</td>
</tr>
<tr>
<td>Oil</td>
<td>18</td>
<td>21 (10) 70</td>
</tr>
</tbody>
</table>

The values for number of failures in brackets refer to failure to close or to failure involving some degree of internal leakage.

For offshore platforms in the Gulf of Mexico Forsth (1983) has reported that in 12 cases where the emergency shutdown system was mentioned in the fire or explosion incident report, the system operated properly in 11 but failed in one.

### Table A14.20 Outage times of electrical power supply following a transmission line failure (after Atomic Energy Commission, 1975)

<table>
<thead>
<tr>
<th>Outage time (%)</th>
<th>Proportion of outages (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.01</td>
<td>1.1</td>
</tr>
<tr>
<td>0.01–0.032</td>
<td>6.1</td>
</tr>
<tr>
<td>0.032–0.1</td>
<td>18.7</td>
</tr>
<tr>
<td>0.1–0.32</td>
<td>37.9</td>
</tr>
<tr>
<td>0.32–1.0</td>
<td>12.6</td>
</tr>
<tr>
<td>1.0–3.2</td>
<td>11.7</td>
</tr>
<tr>
<td>3.2–10</td>
<td>8.4</td>
</tr>
</tbody>
</table>

### Table A14.22 Failure rates of electrical power supply equipment (after Ketron, 1980; reproduced by permission of the American Institute of Chemical Engineers)

<table>
<thead>
<tr>
<th>Failure rate <em>a</em> (failures/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel engine</td>
</tr>
<tr>
<td>Electric generator</td>
</tr>
<tr>
<td>Electric motor</td>
</tr>
<tr>
<td>Steam turbine</td>
</tr>
<tr>
<td>Solenoid valves</td>
</tr>
<tr>
<td>Pneumatic valve</td>
</tr>
<tr>
<td>Globe valve</td>
</tr>
</tbody>
</table>

*a* Literature values

### A14.17 Utility Systems

#### A14.17.1 Electrical power

The failure rate of the outside power supply varies with the country concerned. In the UK the National Grid system gives a high reliability supply and the failure rate is relatively low. In addition, chemical works often have their own power station. The failure rate of the power supply to a plant should normally be determined for the particular works.

For the USA the Rasmussen Report (Figure III 6–5) gives data for outage times following a transmission line failure, as shown in Table A14.20.
Table A14.23  Failure modes of emergency engines/generators (after B. Stevens, 1983; reproduced by permission of the American Institute of Chemical Engineers)

<table>
<thead>
<tr>
<th>Mode</th>
<th>No. of cases</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking/overheating</td>
<td>36</td>
<td>26.1</td>
</tr>
<tr>
<td>Cracking/freezing</td>
<td>13</td>
<td>9.4</td>
</tr>
<tr>
<td>Mechanical breakage</td>
<td>6</td>
<td>4.4</td>
</tr>
<tr>
<td>Bearings and journals/scoring</td>
<td>18</td>
<td>13.0</td>
</tr>
<tr>
<td>Engine block/breakage</td>
<td>14</td>
<td>10.1</td>
</tr>
<tr>
<td>Pistons/breakage</td>
<td>9</td>
<td>6.5</td>
</tr>
<tr>
<td>Valves/breakage</td>
<td>7</td>
<td>5.1</td>
</tr>
<tr>
<td>General mechanical</td>
<td>20</td>
<td>14.5</td>
</tr>
<tr>
<td>Piston rings/breakage</td>
<td>7</td>
<td>5.1</td>
</tr>
<tr>
<td>Crankshaft/cracking/breaking</td>
<td>8</td>
<td>5.8</td>
</tr>
<tr>
<td>Total</td>
<td>138</td>
<td>100.0</td>
</tr>
</tbody>
</table>

A detailed study of the power supply to a plant making RDX explosive, on which it is critical that agitation should not stop, has been described by Ketron (1980). His analysis of the distribution of power failures by duration may be summarized as shown in Table A14.21. The dates quoted in the table run from December 1968 to January 1974.

Literature failure rates of equipment used in power supply systems given by Ketron are shown in Table A14.22.

Weather-related features of power supplies have been considered by Jarrett (1983).

A14.17.2 Diesel generators

Information on the reliability of diesel generators is given in the Rasmussen Report (AEC, 1975). The study gives a probability of failing to start on demand of $3 \times 10^{-2}$.

Thus if there are two diesel generators, but only one is required to provide the full emergency load, it might be calculated that the probability of both generators failing to start on demand is $9 \times 10^{-4}$. In fact, however, startup is treated in the study (p. III-72) as a single event which may trip both units. The probability of both generators failing to start on demand is assessed as $10^{-2}$.

The repair time for a diesel generator is given in the study (p. III-55/56) as a mean time of 21 h with a range of times of 2–300 h.

A survey of emergency generating equipment over the period 1977–82 has been reported by R. Stevens (1983). Much of the equipment was found to be in appalling condition. The failure modes are shown in Table A14.23.

For offshore diesel-driven pumps and emergency power generators failure data are given by OREDA (1992).

A14.17.3 Instrument air

An estimate of the failure rate of the instrument air supply has been given Lawley and Kletz (1975). They give: failure frequency of instrument air supply = 0.05 failures/year.

This evidently refers to the instrument air supply rather than to the connections from the air supply to the instrument, for which separate failure rates are quoted.

Table A14.24  Failure rates of some components of a steam supply system (after Coltharp et al., 1979; reproduced by permission of the American Institute of Chemical Engineers)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Failure rate* (failures/10^6 h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drives for spreader stoker:</td>
<td></td>
</tr>
<tr>
<td>Electric drive</td>
<td>0.3</td>
</tr>
<tr>
<td>Steam drive</td>
<td>50</td>
</tr>
<tr>
<td>Boiler feedwater pump</td>
<td>0.9</td>
</tr>
<tr>
<td>Condensate collection and return</td>
<td>10</td>
</tr>
<tr>
<td>Waterwall tubes</td>
<td>57</td>
</tr>
<tr>
<td>Steam generating tubes</td>
<td>0.3</td>
</tr>
<tr>
<td>Superheater</td>
<td>0.4</td>
</tr>
<tr>
<td>Air preheater</td>
<td>1.1</td>
</tr>
<tr>
<td>Fans</td>
<td>57</td>
</tr>
<tr>
<td>Overfire air</td>
<td>Induced draft</td>
</tr>
<tr>
<td>Drives for fans (forced draft, overfire air, induced draft)</td>
<td>1.1</td>
</tr>
<tr>
<td>Electric drive</td>
<td>2</td>
</tr>
<tr>
<td>Steam drive</td>
<td>3</td>
</tr>
<tr>
<td>Ash conveyor</td>
<td>10</td>
</tr>
</tbody>
</table>

* Sources of data are Edison Electric Institute (EEI), Hartford Steam Boiler (HSB) and automobile company.

A14.17.4 Cooling water

The arrangements for the supply of cooling water in a works vary somewhat. Generally there is a works cooling water supply system, but use may also be made of other sources of supply, such as wells.

A typical estimate of the failure rate of the cooling water supply of about 0.1 failures/year. This is for the supply of equipment does not include failure of such as cooling water pumps serving a particular plant.

A14.17.5 Steam

Information on the failure rates of components of steam supply systems has been given by Coltharp et al. (1978), who carried out a study on the steam system of an automobile factory. Some of the data given by these authors is shown in Table A14.24.

A14.18 Ammonia Plants

Estimates of the inventory of ammonia installations and carriers, of the number of leak sources and of the frequency of releases have been made by Baldock (1980). These three sets of estimates are given in Sections A14.4 and A14.20, Subsections A14.20.1 and A14.20.2, respectively.

A14.19 LNG Plants

A survey of events on LNG plants has been reported by Welker and Schorr (1979). The data were obtained on 25 LNG peak-shaving plants in the US ranging in age from 10 years to a few months. The survey covered nearly 35,000 hours of vaporization experience, more than 400,000 hours of liquefaction experience and more than 1.5 million hours of tank storage, as well as nearly 1.5
### Table A14.25  Failure and event rates on LNG plants (after Welker and Schorr, 1979; reproduced by permission of the American Gas Association)

<table>
<thead>
<tr>
<th>Plant section or equipment</th>
<th>MTBF (h)</th>
<th>Major failure</th>
<th>Minor failure</th>
<th>Safety-related failure</th>
<th>Total failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas pretreatment</td>
<td></td>
<td>20000</td>
<td>3000</td>
<td>&gt;350000(^a)</td>
<td>3000</td>
</tr>
<tr>
<td>Liquefaction</td>
<td></td>
<td>6500</td>
<td>2500</td>
<td>&gt;420000(^a)</td>
<td>1800</td>
</tr>
<tr>
<td>LNG vaporizers</td>
<td></td>
<td>8000</td>
<td>700</td>
<td>15000</td>
<td>700</td>
</tr>
<tr>
<td>Compressors</td>
<td></td>
<td>3000</td>
<td>900</td>
<td>&gt;2 \times 10^6(^a)</td>
<td>700</td>
</tr>
<tr>
<td>LNG pumps</td>
<td></td>
<td>&gt;35000</td>
<td>3500</td>
<td>&gt;35000</td>
<td>3500</td>
</tr>
<tr>
<td>Cryogenic valves</td>
<td></td>
<td>&gt;4 \times 10^7(^a)</td>
<td>2 \times 10^7</td>
<td>&gt;4 \times 10^7(^a)</td>
<td>2 \times 10^7</td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td>15 \times 10^6</td>
<td>700000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**MTBF (h)**

**B  Other events**

**MTBF (h)**

**LNG tanks:**
- Gas leaks: >1.5 \times 10^6 (no leaks)
- Liquid leaks: >1.5 \times 10^6 (no leaks)
- Cold spots: 100000

**Pipelines (per ft):**
- LNG pipelines: >1.5 \times 10^6 (no failures)\(^b\)
- Pipe insulation: >1.5 \times 10^6 (no failures)
- Fire water mains: >1.6 \times 10^6

**Hazard detection sensors:**
- Gas: 100000\(^c\)
- Radiation: 350000\(^c\)
- High temperature: >4 \times 10^6 (no failures)
- Smoke: 1.4 \times 10^6

**Emergency systems:**
- Water hydrants, monitors: 4 \times 10^6
- Halon systems: 100000
- Dry chemical systems: 3 \times 10^6

**Human errors, leaks and fires:**
- Human error incidents: 50000
- Major gas leaks: 300000
- Major liquid leaks: 150000
- Major fires: 200000\(^d\)

---

\(a\) No failures  
\(b\) Small leaks from gaskets not included  
\(c\) Excluding false alarms  
\(d\) Leaks only

*Some failure and event rates given in this survey are shown in Table A14.25.*

**A14.20 Leaks**

**A14.20.1 Leak sources**

Information on the distribution of leak sources is available in several different classifications.

The distribution of the place of origin for large fires in Great Britain 1971–73 has been given in Table 2.11.

The distribution of leak sources for process industry accidents reported to the HSE in the year 1987–88 has been analysed by A.W. Cox, Ang and Lees (1990). Separate analyses are given for normal, closed process plant and for plant and activities with open surfaces, etc., as shown in Tables A14.26 and A14.27, respectively.
### Table A14.26  Leak sources on closed process plant (after A.W. Cox, Ang and Lees, 1990; reproduced by permission of the Institution of Chemical Engineers)

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of incidents</th>
<th>Proportion of incidents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>19</td>
<td>22.1</td>
</tr>
<tr>
<td>Reactor</td>
<td>8</td>
<td>9.3</td>
</tr>
<tr>
<td>Vessel</td>
<td>10</td>
<td>11.6</td>
</tr>
<tr>
<td>Tank</td>
<td>7</td>
<td>8.1</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>4</td>
<td>4.7</td>
</tr>
<tr>
<td>Vaporizer</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>Pump</td>
<td>13</td>
<td>15.1</td>
</tr>
<tr>
<td>Pipework</td>
<td>17</td>
<td>19.8</td>
</tr>
<tr>
<td>Hose</td>
<td>6</td>
<td>7.0</td>
</tr>
<tr>
<td>Total</td>
<td>86</td>
<td>100.0</td>
</tr>
</tbody>
</table>

### Table A14.27  Leak sources for plants and activities with open surfaces, etc. (after A.W. Cox, Ang and Lees, 1990; reproduced by permission of the Institution of Chemical Engineers)

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of incidents</th>
<th>Proportion of incidents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent evaporating oven</td>
<td>4</td>
<td>2.9</td>
</tr>
<tr>
<td>Spray booth</td>
<td>15</td>
<td>10.8</td>
</tr>
<tr>
<td>Small container</td>
<td>31</td>
<td>22.3</td>
</tr>
<tr>
<td>Cleaning/degreasing process</td>
<td>15</td>
<td>10.8</td>
</tr>
<tr>
<td>Tanker/mobile plant</td>
<td>33</td>
<td>23.7</td>
</tr>
<tr>
<td>Other</td>
<td>41</td>
<td>29.5</td>
</tr>
<tr>
<td>Total</td>
<td>139</td>
<td>100.0</td>
</tr>
</tbody>
</table>

### Table A14.28  Leak sources in vapour cloud explosion incidents for 1962–1982 (after A.W. Cox, Ang and Lees, 1990; reproduced by permission of the Institution of Chemical Engineers)

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No.</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor – reaction</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Vessels – explosion</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Vessels – rupture</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Tanks – reaction</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Tanks – overfilling, frother</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Tanks – refrigerated storage</td>
<td>2</td>
<td>5.7</td>
</tr>
<tr>
<td>Pipe</td>
<td>9</td>
<td>25.8</td>
</tr>
<tr>
<td>Flange</td>
<td>2</td>
<td>5.7</td>
</tr>
<tr>
<td>Other fittings</td>
<td>7</td>
<td>20.0</td>
</tr>
<tr>
<td>Hose</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Valves</td>
<td>3</td>
<td>8.6</td>
</tr>
<tr>
<td>Sight glass</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Pumps</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Flare</td>
<td>2</td>
<td>5.7</td>
</tr>
<tr>
<td>Valve opened</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Venting</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>100.0</td>
</tr>
</tbody>
</table>

### Table A14.29  Leak sources for fires and explosions in the Gulf of Mexico (after Forst, 1981b; reproduced by permission of Det Norske Veritas)

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of incidents</th>
<th>Proportion of incidents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanks, vessels, sumps, pans, pits</td>
<td>18</td>
<td>13.7</td>
</tr>
<tr>
<td>Holes, cracks</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>Flanges, unions</td>
<td>26</td>
<td>19.8</td>
</tr>
<tr>
<td>Hoses</td>
<td>4</td>
<td>3.1</td>
</tr>
<tr>
<td>Nipples</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>Valves</td>
<td>16</td>
<td>12.2</td>
</tr>
<tr>
<td>Exhaust</td>
<td>8</td>
<td>6.1</td>
</tr>
<tr>
<td>Other</td>
<td>47</td>
<td>35.9</td>
</tr>
<tr>
<td>Unknown</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>Total</td>
<td>131</td>
<td>100.0</td>
</tr>
</tbody>
</table>

### Table A14.30  Leak sources for fires and explosions in the Norwegian North Sea (after Forst, 1981a; reproduced by permission of Det Norske Veritas)

<table>
<thead>
<tr>
<th>Leak source</th>
<th>No. of incidents</th>
<th>Proportion of incidents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanks, vessels, drains, sumps, pans, etc.</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Ruptures, holes, cracks</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Flanges, unions</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Valves, vents</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Other</td>
<td>30</td>
<td>21</td>
</tr>
<tr>
<td>Unknown</td>
<td>48</td>
<td>36</td>
</tr>
</tbody>
</table>

### Table A14.31  Estimated frequency of releases on ammonia installations and carriers (after Baldock, 1980; reproduced by permission of the American Institute of Chemical Engineers)

<table>
<thead>
<tr>
<th>Incident</th>
<th>No. of incidents</th>
<th>Estimated frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major failure of storage vessel</td>
<td>2</td>
<td>1 in 6×10⁴ vessel-year</td>
</tr>
<tr>
<td>Major release from storage vessel</td>
<td>1</td>
<td>1 in 10⁴ storage area-year</td>
</tr>
<tr>
<td>Serious release on plant</td>
<td>12</td>
<td>1 in 2000 plant-year</td>
</tr>
<tr>
<td>Release on refrigeration plant</td>
<td>15</td>
<td>1 in 10⁵ plant-year</td>
</tr>
<tr>
<td>Release at transfer point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible hose failure</td>
<td>11</td>
<td>1 in 1000 transfer point-year</td>
</tr>
<tr>
<td>Movement while still connected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major release</td>
<td>3</td>
<td>1 in 4000 transfer point-year</td>
</tr>
<tr>
<td>Other release</td>
<td>8</td>
<td>1 in 1500 transfer point-year</td>
</tr>
<tr>
<td>Major releases in transport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road</td>
<td>6</td>
<td>1 in 2000 tanker-year</td>
</tr>
<tr>
<td>Rail</td>
<td>18</td>
<td>1 in 3000 tanker-year</td>
</tr>
<tr>
<td>Pipeline</td>
<td>8</td>
<td>1 in 3000 mile-year</td>
</tr>
<tr>
<td>Sea</td>
<td>1</td>
<td>1 in 200 ship-year</td>
</tr>
<tr>
<td>Total</td>
<td>79</td>
<td></td>
</tr>
</tbody>
</table>

Author gives various qualifying notes
For vapour cloud explosions the distribution of leak sources has been obtained by A.W. Cox, Ang and Lees (1990) from the case histories listed by Davenport (1977, 1983) as shown in Table A14.28.

For fires and explosions on offshore installations in the Gulf of Mexico and in the Norwegian North Sea the distribution of leak sources has been obtained by A.W. Cox, Ang and Lees (1990) from data given by Forsth (1981a, b) as shown in Tables A14.29 and A14.30.

A14.20.2 Leak frequency
Estimates of the frequency of leaks on ammonia installations and carriers have been made by Baldock (1980) and are given in Table A14.31.

Table A14.32 Ignition sources for plants and activities with open surfaces, etc. (after A.W. Cox, Ang and Lees, 1990; reproduced by permission of the Institution of Chemical Engineers)

<table>
<thead>
<tr>
<th>Source</th>
<th>No. of incidents</th>
<th>Proportion of incidents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flames: general</td>
<td>27</td>
<td>19.4</td>
</tr>
<tr>
<td>LPG fired equipment</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>Hot surfaces</td>
<td>20</td>
<td>14.4</td>
</tr>
<tr>
<td>Friction</td>
<td>11</td>
<td>7.9</td>
</tr>
<tr>
<td>Electrical</td>
<td>29</td>
<td>21.0</td>
</tr>
<tr>
<td>Hot particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static electricity</td>
<td>10</td>
<td>7.2</td>
</tr>
<tr>
<td>Smoking</td>
<td>17</td>
<td>12.2</td>
</tr>
<tr>
<td>Auto-ignition</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>Unknown</td>
<td>21</td>
<td>15.1</td>
</tr>
<tr>
<td>Total</td>
<td>139</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table A14.33 Ignition of blowouts in the Norwegian North Sea (after Dahl et al., 1983; reproduced by permission of Det Norske Veritas)

<table>
<thead>
<tr>
<th>Source</th>
<th>No. of incidents</th>
<th>Proportion of incidents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No ignition</td>
<td>81</td>
<td>70</td>
</tr>
<tr>
<td>Fire</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>Explosion</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Subtotal</td>
<td>116</td>
<td>100</td>
</tr>
<tr>
<td>Oil:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No ignition</td>
<td>11</td>
<td>92</td>
</tr>
<tr>
<td>Fire</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Explosion</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subtotal</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>Oil and gas:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No ignition</td>
<td>13</td>
<td>57</td>
</tr>
<tr>
<td>Fire</td>
<td>10</td>
<td>43</td>
</tr>
<tr>
<td>Explosion</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subtotal</td>
<td>23</td>
<td>100</td>
</tr>
<tr>
<td>Fire</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Explosion</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>171</td>
<td></td>
</tr>
</tbody>
</table>

A14.21 Ignition

A14.21.1 Ignition sources
There is a small amount of information on the distribution of ignition sources, much of it for offshore installations.

A study by the Fire Protection Association (1974) of ignition sources for large fires in the chemical and petroleum industries in Great Britain in 1971–73 gave the data shown in Table 2.11. There were 79 fires of which 23 were solid and 10 unknown, the other 46 being gas, vapour or liquid.

Ignition sources for process industry fire and explosions reported to the HSE in the year 1987–88 have been analysed by A.W. Cox, Ang and Lees (1990). Separate analyses are given for normal, closed process plants and for plants and activities with open surfaces, etc. The former set have been given in Table 16.46 and the latter are shown in Table A14.32.

For offshore ignition sources have been given for fires and explosions in the Gulf of Mexico (GoM) and in the Norwegian North Sea (NNS) in reports by workers at Det Norske Veritas (Sofyanos, 1981; Forsth, 1981a, b, 1983).

Forsth (1983) has given the data shown in Table 16.47 for ignition sources in these two locations. The number of accidents considered was for the GoM was 326 over the period 1956–81 and for the NNS 133 over an unspecified period.

A14.21.2 Ignition probability
A discussion of the probability of ignition of gas and liquid releases is given in Chapter 16.

The account there utilizes data on blowouts on offshore installations given by Dahl et al. (1983). A fuller tabulation of these data is shown in Table A14.33.

A14.22 Explosion Following Ignition

A14.22.1 Explosion probability
The discussion of ignition in Chapter 16 also covers the probability of explosion, given ignition.

A14.23 Fires

A14.23.1 Process plant fires
A survey of the frequency of fires in industry in Britain has been reported by Rutstein and Clarke (1979). For the chemical and allied industries (Standard Industrial Classification 5) they correlate the probability of fires per year with the floor space of the building using a function of the form

\[ P = aB^c \]  

where \( B \) is the floor space (m\(^2\)), \( P \) the probability of fire over one year, \( a \) is constant and \( c \) an index. They give the following data:
### Probability of fire over one year

<table>
<thead>
<tr>
<th></th>
<th>All buildings</th>
<th>Process buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability function</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = 0.017B^{0.27}$</td>
<td>$P = 0.0069B^{0.46}$</td>
</tr>
<tr>
<td>Probability for 1500 m$^2$ building</td>
<td>0.12</td>
<td>0.21</td>
</tr>
</tbody>
</table>

**Table A14.34** Number of fires in US petroleum industry 1982–85 (API, 1983, 1984 and 1985)

<table>
<thead>
<tr>
<th>Installations</th>
<th>No. of fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration, production, drilling</td>
<td>68</td>
</tr>
<tr>
<td>Gas processing</td>
<td>28</td>
</tr>
<tr>
<td>Exploration, production, drilling and gas processing, not separated</td>
<td>25</td>
</tr>
<tr>
<td>Total of above</td>
<td>163</td>
</tr>
<tr>
<td>Offshore portion only</td>
<td>13</td>
</tr>
<tr>
<td>Refining</td>
<td>201</td>
</tr>
<tr>
<td>Chemical operations</td>
<td>61</td>
</tr>
<tr>
<td>Petrochemicals</td>
<td>33</td>
</tr>
</tbody>
</table>

A14.23.2 Petroleum industry fires

Information on the frequency of fires in the petroleum industry in the US is given in the annual series *Reported Fire Losses in the Petroleum Industry* by the API. The fires reported are those involving losses greater than $2500. The fire losses for the period 1982–85 are shown in Table A14.34.

A14.23.3 Refinery fires

Data on the frequency of refinery fires are given in Table A14.34. The API fire loss reports also give a breakdown of the fire losses. For 1985 the sizes of fire by loss were

<table>
<thead>
<tr>
<th>Size of loss (1000$)$</th>
<th>No. of fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5–100</td>
<td>65</td>
</tr>
<tr>
<td>100–1000</td>
<td>37</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>7</td>
</tr>
</tbody>
</table>

The frequency of refinery fires may be estimated from these data and from the number of refineries given in Section A14.4.

The First Canvey Report gives

Frequency of fire in a refinery = 0.1 fires/year

A14.23.4 Pump fires

Estimates of the frequency of pump fires have been given by Kletz (1971) and are shown in Table A16.55. N.M. Wallace and David (1985) have described a study in Esso on mechanical seals, in which losses due to fires from pump failures were apportioned as follows:

- Seal failure: 54%
- Bearing or shaft failure: 36%
- Unknown: 10%

A14.23.5 Storage tank fires

Information on the frequency of fires on storage tanks in the petroleum industry in the US is given in the annual series *Reported Fire Losses in the Petroleum Industry* by the API. The fires reported are those involving losses greater than $2500. The storage tank fire losses for the period 1982–85 are shown in Table A14.35.

**Table A14.35** Number of fires in US refineries 1982–85 (API, 1983, 1984 and 1985)

<table>
<thead>
<tr>
<th>Type of tank</th>
<th>No. of fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating roof</td>
<td>6</td>
</tr>
<tr>
<td>Cone roof</td>
<td>9</td>
</tr>
<tr>
<td>Dome roof</td>
<td>0</td>
</tr>
</tbody>
</table>

For fires in fixed roof storage tanks for hydrocarbons Kletz (1971) states that based on data from more than over 500 tanks over a period of 20 years the frequency of a tank fire or explosion is once in 883 tank-year.

His estimate of the factor by which the frequency of fire or explosion may be reduced by the use of inerting is 10.

A14.24 Explosions

A14.24.1 Furnace explosions

Data on the distribution of causes of furnace explosions has been given by Ostroot (1972). The number of incidents listed are

<table>
<thead>
<tr>
<th>Cause of explosion</th>
<th>Furnace firing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas</td>
</tr>
<tr>
<td>Inadequate purge</td>
<td>55</td>
</tr>
<tr>
<td>Delayed ignition</td>
<td>42</td>
</tr>
<tr>
<td>Incorrect fuel-air ratio</td>
<td>19</td>
</tr>
</tbody>
</table>

In the discussion to the paper Kletz (1972) said that his company reckoned on a frequency of explosion of 1 in 25 furnace-year. Ostroot quoted for his company a figure of about 1 in 100, or even 1 in 1000 furnace-year.

A14.24.2 Vapour cloud explosions

Data on vapour cloud explosions have been given by Davenport (1977, 1983).

For vapour cloud explosions at fixed installations Davenport (1983) records some 35 cases over the period 1962–1982 inclusive. The location of these explosions is

<table>
<thead>
<tr>
<th>Location</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>19</td>
</tr>
<tr>
<td>Western Europe</td>
<td>10</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
</tr>
</tbody>
</table>
If it is assumed that there were at risk in the US and Western Europe over this period some 10000 chemical/ petrochemical plants, major refinery units, LPG storages and natural gas plants, then

Frequency of vapour cloud explosion
\[ = \frac{29}{(21 \times 10^4)} \]
\[ = 1.4 \times 10^{-4} \text{ explosions/year} \]

Information on the distribution of leak sources in vapour cloud explosions is given in Table A14.28.

Further data on vapour cloud explosions are given in Chapter 17.

**A14.25 Transport**

Failure data for transport are given in Chapter 23 and Appendix 17.

**A14.26 Failure Regimes**

The failure regime of an equipment may be determined by analysis of times-to-failure using the Weibull method. Using this method, a number of workers have found an early failure regime, corresponding to 1 < \( \beta \). Some typical results are

<table>
<thead>
<tr>
<th>Equipment</th>
<th>( \beta )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps, type A</td>
<td>0.74–1.07</td>
<td>de la Mare (1976), Berg (1977)</td>
</tr>
<tr>
<td>type B</td>
<td>0.69–0.87</td>
<td>de la Mare (1976)</td>
</tr>
<tr>
<td>Valves</td>
<td>0.70–1.02</td>
<td>de la Mare (1976)</td>
</tr>
<tr>
<td>Pumps</td>
<td>as low as 0.5</td>
<td>Aird (1977b)</td>
</tr>
</tbody>
</table>

Sherwin and Lees (1980) found values of \( \beta \) < 1 for equipment in process plants and also for hospital autoclaves. In most cases the equipment was by no means new.

Work on failure regimes is also described in Chapter 7.

**A14.27 Influencing Factors**

Several authors have given correlations for the effect of particular influencing factors on equipment. Moss (1977 NCSR R11) has given data on the failure rates of mechanical valves in two nuclear power stations. The overall failure rates \( \lambda \) of the valves were

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam valves</td>
<td>0.1 faults/year</td>
</tr>
<tr>
<td>Water valves</td>
<td>0.01 faults/year</td>
</tr>
</tbody>
</table>

The variation of the failure rate with the severity of the operating conditions pressure and temperature was correlated by an equation of the form

\[ \lambda = \lambda_o \exp \left( \frac{D - D_o}{D_o} \right) \]

with

\[ D = p + t \]

where \( D \) is a severity parameter, \( p \) pressure (psi), \( t \) temperature (°C) and subscript \( o \) base case.

C.F. King and Radd (1972) have expressed the hazard rate \( z \) for pumps as function of the form

\[ z = A t^{-1/2} + B + Ct^3 \]

where \( t \) is time and \( A, B, C \) are functions of pressure, temperature, motor power and pump utilization.

**A14.28 External Events**

A14.28.1 Aircraft crash

Information on the probability of a potentially damaging accident due to an aircraft crash at various reactor sites is given in the *Rasmussen Report* (Table III 6–4). The highest probability quoted is \( 1 \times 10^{-8} \)/year for a crash at a site located 3 mile from an airport with 40000 air carrier and 40000 naval flight movements per year. The assumed target area is 0.01 mile\(^2\) for larger aircraft and 0.005 mile\(^2\) for smaller ones.

The impact of the aircraft would not necessarily cause damage within the containment. In fact the estimated probability that such damage would occur given impact is less than 1 in 100.

Other accounts of the risk of aircraft crash are those of D.W. Phillips (1981 SRD R198) and Marriott (1987).

**Notation**

Section A14.23

- \( a \) constant
- \( B \) floor space (m\(^2\))
- \( c \) index
- \( P \) probability of fire in one year

Section A14.27

- \( A, B, C \) constants
- \( D \) severity parameter
- \( p \) pressure (psi)
- \( t \) temperature (°C)
- \( z \) hazard rate
- \( \lambda \) failure rate

Subscript

- \( o \) base case
# Appendix 15

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<th>Page</th>
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<td>A15.2 Earthquake Characterization</td>
<td>A15/5</td>
</tr>
<tr>
<td>A15.3 Earthquake Effects</td>
<td>A15/6</td>
</tr>
<tr>
<td>A15.4 Earthquake Incidents</td>
<td>A15/7</td>
</tr>
<tr>
<td>A15.5 Earthquake Damage</td>
<td>A15/9</td>
</tr>
<tr>
<td>A15.6 Ground Motion Characterization</td>
<td>A15/10</td>
</tr>
<tr>
<td>A15.7 Ground, Soils and Foundations</td>
<td>A15/11</td>
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<td>A15.8 Earthquake-Resistant Design</td>
<td>A15/13</td>
</tr>
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<td>A15.9 Earthquake Design Codes</td>
<td>A15/14</td>
</tr>
<tr>
<td>A15.10 Dynamic Analysis of Structures</td>
<td>A15/15</td>
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<td>A15/16</td>
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<td>A15/17</td>
</tr>
<tr>
<td>A15.13 Nuclear Installations</td>
<td>A15/18</td>
</tr>
<tr>
<td>A15.14 Process Installations</td>
<td>A15/19</td>
</tr>
</tbody>
</table>
An earthquake is one of the principal natural hazards from which processes plants work-wide are at risk. Some account is therefore necessary of the seismic design of plants and the assessment of seismic hazard to plants. Accounts of earthquakes are given in Seismic Design of Steel Structures by Greve (1968); Ground Motion and Seismological Engineering by Bakun (1969); Earthquake Engineering by Wiener (1970); Fundamentals of Earthquake Engineering by Newmark and Rosenblueth (1970), Earthquake-Resistant Design by Dowrick (1977, 1987), Ground Motion and Seismological Engineering by Bakun (1969) and Manual of Seismic Design by Stratta (1987). UK conditions are dealt with in Earthquake Engineering in Britain by the Institution of Civil Engineers (1985) and by Litwall (1976) and Alderson (1982 SRD R246, 1985).

It is proper to recognize also the large amount of work done on seismicity and seismic engineering in Japan. Earthquake engineering is a specialist discipline. The account given here is limited to an elementary introduction.

Selected references on earthquakes, earthquake-resistant design and earthquake hazard assessment are given in Table A15.1.

### Table A15.1 Selected references on earthquakes, earthquake-resistant design and earthquake hazard assessment

See also Tables 9.1 and 10.2

California Inst. Technol. (n.d.); NRC (Appendix 28 Seismic Events); Mercalli (1902); Winch and Jeffrey (1923); Mih (1939); Nordquist (1945); Housner (1947); Bienstock (1952); EERI (1952); Gutenberg and Richter (1954, 1956, 1965); Neumann and Oakshott (1956); Gutenberg (1956); Richter (1958); Bullen (1969); Evison (1963); Esteva and Rosenbuhl (1964); Matuzawa (1964); C.R. Allen (1967); Esteva (1967, 1974); Jennings, Housner and Tsai (1968); Karkin (1968, 1991); Rothe (1969); Stacey (1969); P.D. Marshall (1970); NEC (1970); Tucker, Cook et al. (1970); Anon. (1971e); Greensfelder (1971); Nat. Ocean Atmos. Admin (1972); Bath (1973, 1979); Donovan (1973); Tank (1973); Barbreau, Ferriex and Mohammadioun (1974); Lomnitz (1974); Hsieh, Okrent and Apostolakis (1975a, b); Okrent (1975); US Geol. Survey (1975); H.D. Foster (1976); H.D. Foster and Carey (1976); H.D. Foster and Carey (1976); H.D. Foster (1976); Lomnitz and Rosenblueth (1976); McGuire (1976); Bolt (1978, 1980, 1982, 1988); Lee, Okrent and Apostolakis (1979); Verney (1979); Berlin (1980); Eby (1980); BRE (1983 RB31); Veneziano, Cornell and O’Hara (1984); Bulen and Bolt (1985); Muir Wood (1985); EPRI (1986); Mosheh and Apostolakis (1986); ASCE (1987/33, 1988/36); Bernreuter, Savv and Mensing (1987); Cassaro and Martinez-Romero (1987); Cermak (1987); J. Evans et al. (1987); Grandori, Perotti and Tagliani (1987); Kropp (1987); Nutti and Herrman (1987); Savv, Bernreuter and Chen (1987); Stratta (1987); Van Gils (1988); EEFF (1991).

**Earthquakes in Britain**

Davison (1924); Lilwall (1976); Alderson (1982 SRD R246, 1985); Instr Civil Engrs (1985); Irving (1985); Liam Finn and Atkinson (1985)

**Earthquake-resistant design, earthquake hazard assessment**


**Structures**

Tinoshenko (1936); Flugge (1960); Warburton (1976); Pilkey and Chang (1978)

**Storage tanks, vessels**

Veletsos and Yang (1976); Eberhart (1979); R.P. Kennedy (1979, 1982a); Haroun and Housner (1981); R. Davies (1982); D.W. Phillips (1982); Veletsos (1984); Priestley et al. (1986); Veletsos and Yu Tang (1986a, b)

**Fluid-structure interactions, liquid sloshing**

ASME (PVP 128, 1988 PVP 145, 1989 PVP 157); ASCE (1984/18)

### A15.1 Earthquake Geophysics

#### A15.1.1 Earth structure

The structure of the earth is illustrated in Figure A15.1 and is approximately as follows: a crust 30 km thick, a mantle 2900 km thick and a core of 3470 km radius, giving a total radius of 6370 km. The core has an inner core of 1400 km radius. The crust exhibits two layers. In the lower of these layers the velocity of seismic waves is rather higher. The interface between the two is known as the Conrad discontinuity. Likewise, the mantle is divided into the upper and lower mantle. The crust and the upper mantle are termed the lithosphere. Other discontinuities are the Mohorovicic discontinuity at the boundary of the crust.
and the mantle, and the Gutenberg discontinuity at the boundary of the mantle and the core.

A15.1.2 Crustal strain and elastic rebound
The earth's crust has a degree of elasticity and when subject to stress due to the earth's forces it undergoes crustal strain. This property is the basis of the elastic rebound theory of Reid, which provides one explanation of the way in which earthquakes occur. Reid suggests that the crust, in many parts of the earth, is being slowly displaced, and the difference between displacements in neighbouring regions sets up elastic strains, which may become greater than the rock can endure. A rupture then takes place, and the strained rock rebounds under its own elastic stresses, until the strain is largely or wholly relieved.

A15.1.3 Plate tectonics, faults and fault creep
In some regions earthquakes are associated with faulting of the earth, while in others there appears to be little apparent correlation between earthquakes and structural features.

Earthquakes are frequently associated with faulting of the earth. There has been debate, however, as to whether the faults have caused the earthquakes or the earthquakes the faults. The latter viewpoint has been argued by Evison (1963).

A fault in the crust may be caused by tension, compression or shear. A normal fault, in which slip occurs between one block and another, is usually considered to be the result of tension and a reverse fault, in which one block is thrust below another, the result of compression, or thrust. These two types of fault are also termed dip-slip faults. The slip plane is characterized by the angle of dip, or angle of the plane to the horizontal; an angle of dip close to 90° corresponds to a nearly vertical slip plane. In a shear fault the relative movement of the two blocks is predominantly horizontal. This type is also termed a strike-slip, or transcurrent, fault. There are also oblique slip faults in which there is a combination of vertical and horizontal movement.

As a result of displacement, the ground in a zone extending out from a fault can become permanently deformed. The disturbed zone, or shatter zone, can be up to 1 km wide. The magnitude of displacements is discussed by Berlin, who mentions cases of a 14.4 m vertical displacement, or uplift, in Alaska and of a 4.9 m horizontal displacement in California; there is a 6.1 m horizontal displacement reported for the 1906 San Francisco earthquake but this is subject to some doubt.

The build-up of strain in the crust may be relaxed by a much more gradual movement of the crust, or fault creep. This process, which may be continuous or episodic, does not generate earthquake waves. An account is given by Berlin.

In some regions there are faults which are associated with recent seismic activity, or active faults. Perhaps the

Figure A15.1 The structure of the earth and passage of seismic waves through it (US Geological Survey, 1975)
best known is the San Andreas fault in California. This fault is a strike-slip fault, or, viewed on a finer scale, a system of strike-slip faults. There are often lesser faults associated with the main fault as branch faults or as subsidiary faults, joining the main fault at oblique angles and sometimes in echelon along it.

There are some regions which are very much more prone to earthquakes than others. One explanation for this is given by the theory of continental drift, and of plate tectonics, according to which the earth’s lithosphere is divided into a number of rigid plates which move relative to each other. Earthquakes are much more frequent at these interfaces. The Pacific rim is the most striking example, but there are a number of others.

There are a number of definitions of what constitutes an active fault. For the siting of nuclear power plants in the USA, the NRC considers a fault to be active if there has been movement at least once in last 35,000 years. Other definitions are discussed by Berlin (1980).

As stated earlier, however, earthquakes do also occur in regions where there is no apparent correlation with active fault structures.

A15.1.4 Focus and epicentre
The origin of an earthquake is termed the focus, or hypocentre, and the point on the earth’s surface directly above the focus the epicentre.

Earthquakes are classified as shallow focus (focus depth < 70 km), intermediate focus (depth 70–300 km) and deep focus (depth > 300 km).

A15.1.5 Seismic waves
During an earthquake waves pass through the earth and impart motion to the ground. These waves are elastic in that the rocks through which they pass then return to their original shapes and positions.

There are two broad types of wave: body waves and surface waves. Body waves are classified as primary, or P, waves and secondary, or S, waves. A P wave is a longitudinal or compression wave, is analogous to a sound wave and has a velocity of some 8 km/s. An S wave is a transverse or shear wave, is analogous to electromagnetic waves and has a velocity of some 4.5 km/s. The passage of P and S waves is illustrated in Figure A15.1. Both P and S waves can undergo reflection. Reflection can occur at the earth’s surface or at a boundary such as that between the mantle and the core. Refraction can occur through the core. On reflection both types of wave can be transformed to the other type, i.e. a P wave to an S wave, or vice versa.

The notation used for P and S waves is illustrated in Figure A15.1. A P wave travelling directly from the focus to the point of measurement without reflection is denoted P, one undergoing one reflection at the surface PP and one undergoing two reflections at the surface PPP. A P wave undergoing one reflection at the core is denoted PcP. The corresponding notation for S waves is S, SS and SSS for a wave with zero, one and two surface reflections and ScS for one with one core reflection. There are also hybrid waves such as PS, PSS, PPS, PSP, SP, SPP, SSP, SPS, PcS and ScP.

Both P and S waves can undergo refraction through the earth’s core. In the core itself there is a difference between P and S waves: an S wave cannot pass through the core. However, the wave leaving the core can be either a P wave or an S wave; in the latter case this is due to transformation at the core boundary. Hence an S wave can enter the core, undergoing transformation to a P wave on entry and further transformation to an S wave on exit, and then travel on as an S wave again. The principal refractions through the core are denoted PKP, PKS, SKP and SKS (K for Kern in German). There are also more complex waves such as PKKP (refraction – reflection – refraction in the core) and PKPPP (refraction in core – reflection at surface – refraction in core).

The distance between the focus and the point of measurement is generally expressed in degrees rather than kilometres. A degree corresponds to about 111 km.

There is a limiting angle of about 103° at which a P wave is reflected from the core. At any angle greater than this the wave is refracted through the core. The effect is to create between an angle of about 103° and one of about 142° a ‘shadow zone’ to which waves do not penetrate.

The other main type of wave is surface waves. Surface waves, long waves, or L waves, travel round the surface of the earth rather than through the interior. They are classified as Love, or L0, waves and Rayleigh, or Ls, waves. Love waves have a horizontal but no vertical component, Rayleigh waves have both horizontal and vertical components. A Rayleigh wave is generally described as having a retrograde elliptical motion. Both types of wave travel more slowly than S waves, with the Rayleigh wave slower than the Love wave.

L waves may travel round the earth several times and generate ground movement with amplitudes of about 1 mm. They have a typical period of 10–20 seconds. They contain large amounts of energy but do relatively little damage on account of the long period. Often an earthquake is ‘heard before felt’. Sounds like a low rumble can be generated by the faster P waves, while the ground shaking is due to the larger amplitude but slower S waves.

![Figure A15.2](image)

Figure A15.2 A seismogram showing P, S and L waves (National Oceanic and Atmospheric Administration, 1972)
A15.1.6 Seismic measurements
An instrument for the recording of the ground motion caused by an earthquake is known as a seismometer and the record which it produces as a seismogram. Measurements may be made of any of the three main time-domain parameters: displacement, velocity and acceleration.

The measurement of ground motion is well developed and records have been obtained for the amplitude and for the acceleration of a large number of earthquakes.

Figure A15.2 gives a seismogram showing the arrival of the P, S and L waves.

There are a number of seismographic networks. A region of high seismic activity may have a number of such networks. Thus in California, Berlin describes networks operated by the US Geological Survey, the Nuclear Regulatory Commission, the University of California and several other bodies. At the international level there is the World-wide Standard Seismographic Network (WSSN).

A15.2 Earthquake Characterization
The quantitative characterization of earthquakes is largely in terms of magnitude and intensity scales and of empirical correlations. Earthquakes are a geographical phenomenon and hence in many cases the original correlations have been derived for a specific region, often California. This should be borne in mind in respect of the relationships quoted below.

A15.2.1 Focus and epicentre
For a particular location the distance r to the epicentre is the epicentral distance and the distance to the focus is the focal distance so that

\[ R^2 = h^2 + r^2 \]  \[ \text{[A15.2.1]} \]

where \( R \) is the focal distance, or slant distance (km), \( h \) the distance between the focus and the epicentre, or focal depth (km) and \( r \) the epicentral distance (km). Use is often made of a modified focal distance defined as

\[ R^2 = h^2 + r^2 + k^2 \]  \[ \text{[A15.2.2]} \]

where \( k \) is a modifying factor (km). Esteva (1967) has given an estimate of \( k = 20 \).

A15.2.2 Magnitude and magnitude scales
The severity of an earthquake is defined in terms of its magnitude and intensity. The more objective is the magnitude, which is a measure of the total energy in the seismic waves.

A scale for the representation of the magnitude of an earthquake was devised by Richter and magnitude is commonly quoted in terms of the value on the Richter scale. The value is a measure of the ratio of the maximum amplitude recorded for the earthquake in question to the maximum amplitude for a standard earthquake, with both measurements made on a standard seismograph located at a standard distance from the earthquake, the instrument being a Wood-Anderson seismograph of defined characteristics.

The magnitude \( M \) of an earthquake may be measured locally, in which case it is denoted \( M_L \), or at a distant point through surface waves, when it is denoted \( M_S \). The two differ and in order to overcome this difficulty Gutenberg introduced the concept of unified magnitude \( m \), or \( m_{ub} \) which depends on the body waves. The magnitudes quoted in the literature are frequently not fully defined.

The relation of Richter for the magnitude of a local earthquake is

\[ M_L = \log_{10}(A/A_0) \]  \[ \text{[A15.2.3]} \]

where \( A \) is the maximum amplitude (mm), \( A_0 \) the maximum amplitude of the standard earthquake (mm) and \( M_L \) is the local magnitude, under the standard conditions described. The value of \( A_0 \) assigned to the standard earthquake is \( A_0 = 0.001 \) mm.

The Richter scale is thus a logarithmic one and an earthquake which is one unit higher on the scale has an amplitude ten times as great as that below it.

The Richter magnitude scale is open-ended with no lower or upper limit. The scale point 0 is an arbitrary one.

A number of equations have been developed for the surface wave magnitude \( M_S \) and the body magnitude \( m_{ub} \), relating these quantities to the characteristics of the seismographic record.

It is often necessary to convert one type of magnitude to another. Two widely used approximate relations are those given by Richter (1958)

\[ M_S = 1.59m_{ub} - 3.97 \]  \[ \text{[A15.2.4]} \]

and

\[ m_{ub} = 2.5 + 0.63M_S \]  \[ \text{[A15.2.5]} \]

These two magnitudes agree at a value of about 6.8; below this \( m_{ub} \) is larger and above it \( M_S \) is larger. There is also the empirical equation of Gutenberg (1956)

\[ m_{ub} = 1.7 + 0.8M_L - 0.01M^2_L \]  \[ \text{[A15.2.6]} \]

A15.2.3 Energy
The relationship between the total seismic wave energy and the surface wave magnitude was the subject of a series of studies by Gutenberg and Richter, who produced between 1936 and 1956 a number of correlations. The 1956 Gutenberg–Richter equation for energy, quoted by Gutenberg (1956), is

\[ \log_{10}E = 11.8 + 1.5M_S \]  \[ \text{[A15.2.7]} \]

where \( E \) is the total energy (erg).

Gutenberg has also given the following relations between the total energy and the other magnitudes:

\[ \log_{10}E = 9.9 + 1.9M_L - 0.024M^2_L \]  \[ \text{[A15.2.8]} \]

\[ \log_{10}E = 5.8 + 2.4m_{ub} \]  \[ \text{[A15.2.9]} \]

An earthquake which is one unit higher on the Richter magnitude scale has an energy some 27 times as great as that below it.

A15.2.4 Frequency and return period
A correlation between the frequency and magnitude of earthquakes was obtained by Gutenberg and Richter. Their equation is given by Richter (1958) as
\[
\log_{10} N = a - bM \tag{A15.2.10}
\]

where \( N \) is the frequency of earthquakes exceeding that magnitude (per year), and \( a \) and \( b \) are constants. This equation is generally referred to as the Gutenberg-Richter equation for frequency.

Various workers have used the Gutenberg-Richter equation to correlate the frequency of earthquakes for different regions and periods.

Estimates for the relationship between the magnitude and the frequency of earthquakes world-wide by Gutenberg and Richter (1940) are given below together with later estimates by the National Earthquake Information Center (NEIC) (1970).

<table>
<thead>
<tr>
<th>( M_L )</th>
<th>Description</th>
<th>Annual frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 8.0 )</td>
<td>Great earthquakes</td>
<td>1</td>
</tr>
<tr>
<td>7.0-7.9</td>
<td>Major earthquakes</td>
<td>10</td>
</tr>
<tr>
<td>6.0-6.9</td>
<td>Destructive shocks</td>
<td>100</td>
</tr>
<tr>
<td>5.0-5.9</td>
<td>Damaging shocks</td>
<td>1000</td>
</tr>
<tr>
<td>4.0-4.9</td>
<td>Minor strong shocks</td>
<td>10000</td>
</tr>
<tr>
<td>3.0-3.9</td>
<td>Generally felt</td>
<td>100000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Annual frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Great</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Major</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Large (destructive)</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Moderate (damaging)</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Minor (damage slight)</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>Generally felt</td>
<td>49000</td>
</tr>
</tbody>
</table>

**A15.3 Earthquake Effects**

The effects of an earthquake may be classified as direct or indirect. The direct effects include

(1) ground shaking;
(2) ground lateral displacement;
(3) ground up-lift and subsidence;

and the indirect effects

(4) ground settlement;
(5) soil liquefaction;
(6) slope failure:
   (a) avalanches, landslides
   (b) mud slides;
(7) floods;
(8) tsunamis and seiches;
(9) fires.

Of the direct effects, ground shaking usually occurs over a wide area. At faults, fault displacement results in lateral movement of the ground and surface breaks. The distance over which the surface breaks occur is variable. There may be tectonic up-lift and subsidence.

Of the indirect effects, ground settlement may occur due to compaction of unconsolidated deposits. There may be soil liquefaction, giving a `quick condition' failure. Slope failures may occur in the form of avalanches, landslides and mud slides.

The earthquake may cause floods due to the failure of dams or levees. In certain regions there may occur tsunamis. A tsunami is a wave occurring in relatively shallow water and is caused by vertical displacement of the earth beneath the water. Seiches may also occur. A seich is a standing wave on the surface of water such as a lake.

The destruction of buildings and the rupture of gas mains tends to give rise to widespread fires.
Table A15.2  The Modified Mercalli intensity scale

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Not felt. Marginal and long-period effects of large earthquakes</td>
</tr>
<tr>
<td>II</td>
<td>Felt by persons at rest, on upper floors, or favourably placed</td>
</tr>
<tr>
<td>III</td>
<td>Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake</td>
</tr>
<tr>
<td>IV</td>
<td>Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak</td>
</tr>
<tr>
<td>V</td>
<td>Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate</td>
</tr>
<tr>
<td>VII</td>
<td>Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments – CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged</td>
</tr>
<tr>
<td>VIII</td>
<td>Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes</td>
</tr>
<tr>
<td>IX</td>
<td>General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations – CFR). Frame structures, if not bolted, shifted off foundations. Frames cracked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters</td>
</tr>
<tr>
<td>X</td>
<td>Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly</td>
</tr>
<tr>
<td>XI</td>
<td>Rails bent greatly. Underground pipelines completely out of service</td>
</tr>
<tr>
<td>XII</td>
<td>Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air</td>
</tr>
</tbody>
</table>

CFR. Charles F. Richter additions to the 1931 scale. Masonry A, good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces; masonry B, good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces; masonry C, ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces; masonry D, weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.


A15.4 Earthquake Incidents

Tabulations of earthquakes are given in a number of texts. Eiby (1980) gives a chronological list; this includes the values of the magnitudes. Berlin gives tables showing earthquakes which have caused major fatalities worldwide, major fatalities in the USA, and major property damage in the USA. Bolt (1988) gives tables of earthquakes worldwide, in the USA and Canada, and in Central and South America; the North American list gives MM intensities. Berlin (1980) also gives lists of earthquakes with special features such as shattered earth, vertical displacement, and bad ground and soil liquefaction effects.

Table A15.3 gives some earthquakes in this century which have caused major loss of life worldwide or property damage in the USA. Table A15.4 lists some earthquakes which are frequently discussed in texts on earthquakes or earthquake-resistant design as having features of particular interest; accounts of these earthquakes are given in the references shown in the table.

Table A15.3 gives only earthquakes which have occurred since 1920. It nevertheless includes some which have caused very large loss of life, in particular
# APPENDIX 15/8 EARTHQUAKES

## Table A15.3 Some earthquakes causing major loss of life or property damage

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Number of deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920</td>
<td>Kansu, China</td>
<td>180,000</td>
</tr>
<tr>
<td>1923</td>
<td>Tokyo-Yokohama, Japan</td>
<td>143,000</td>
</tr>
<tr>
<td>1932</td>
<td>Kansu, China</td>
<td>70,000</td>
</tr>
<tr>
<td>1935</td>
<td>Quetta, India</td>
<td>60,000</td>
</tr>
<tr>
<td>1939</td>
<td>Chillan, Chile</td>
<td>30,000</td>
</tr>
<tr>
<td>1939</td>
<td>Erzincan, Turkey</td>
<td>23,000</td>
</tr>
<tr>
<td>1960</td>
<td>Agadir, Morocco</td>
<td>14,000</td>
</tr>
<tr>
<td>1962</td>
<td>North-western Iran</td>
<td>14,000</td>
</tr>
<tr>
<td>1968</td>
<td>North-eastern Iran</td>
<td>11,600</td>
</tr>
<tr>
<td>1970</td>
<td>Peru</td>
<td>66,000</td>
</tr>
<tr>
<td>1972</td>
<td>Managua, Nicaragua</td>
<td>12,000(^b)</td>
</tr>
<tr>
<td>1976</td>
<td>Guatemala</td>
<td>22,000</td>
</tr>
<tr>
<td>1976</td>
<td>Tangshan, China</td>
<td>(\approx 250,000)(^c)</td>
</tr>
<tr>
<td>1976</td>
<td>Hopei, China</td>
<td>655,000</td>
</tr>
</tbody>
</table>

### B Earthquakes causing major property damage in USA\(^d\)

<table>
<thead>
<tr>
<th>Year</th>
<th>Property damage ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1906</td>
<td>San Francisco, CA</td>
</tr>
<tr>
<td>1933</td>
<td>Fire loss</td>
</tr>
<tr>
<td>1952</td>
<td>Kern County, CA</td>
</tr>
<tr>
<td>1964</td>
<td>Alaska and US West Coast</td>
</tr>
<tr>
<td>1971</td>
<td>San Fernando, CA</td>
</tr>
</tbody>
</table>

Sources: Berlin (1980); Bolt (1985)

\(^a\) Earthquakes since 1920 causing 10,000 or more deaths.

\(^b\) This is Berlin’s figure; Bolt gives 500.

\(^c\) For China in 1976 this is Bolt’s entry; Berlin gives Hopei with 655,000 deaths.

\(^d\) Earthquakes since 1900 causing $40 million or more property damage.

## Table A15.4 Some earthquakes of particular interest

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitude</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1906 April 18</td>
<td>8.3</td>
<td>Dowrick (1977)</td>
</tr>
<tr>
<td>1923 Sept. 1</td>
<td>8.3</td>
<td>Alderson (1982)</td>
</tr>
<tr>
<td>1940 May 18</td>
<td>6.9</td>
<td>Berlin (1980); Alderson (1982)(^a)</td>
</tr>
<tr>
<td>1952 July 21</td>
<td>7.7</td>
<td>Berlin (1980); Alderson (1982)</td>
</tr>
<tr>
<td>1957 March 22</td>
<td>5.3</td>
<td>Alderson (1982)</td>
</tr>
<tr>
<td>1957 July 28</td>
<td>7.5</td>
<td>Berlin (1980)</td>
</tr>
<tr>
<td>1960 Feb. 29</td>
<td>5.8</td>
<td>Eiby (1980)</td>
</tr>
<tr>
<td>1960 May 22</td>
<td>8.4</td>
<td>Eiby (1980)</td>
</tr>
<tr>
<td>1964 March 27</td>
<td>8.4</td>
<td>Berlin (1980); Alderson (1982)</td>
</tr>
<tr>
<td>1964 June 16</td>
<td>7.5</td>
<td>Dowrick (1977); Berlin (1980);</td>
</tr>
<tr>
<td>1966 June 27</td>
<td>5.6</td>
<td>Dowrick (1977); V.W. Lee and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trifunac (1987); Bolt (1988)</td>
</tr>
<tr>
<td>1975 Feb. 4</td>
<td>7.4</td>
<td>Bolt (1988)</td>
</tr>
<tr>
<td>1975 Sept. 6</td>
<td>6.7</td>
<td>Berlin (1980)</td>
</tr>
<tr>
<td>1976 May 6</td>
<td>6.5</td>
<td>Alderson (1982)</td>
</tr>
<tr>
<td>1983 May 2</td>
<td>6.7 (M&lt;sub&gt;L&lt;/sub&gt;)</td>
<td>Bolt (1988)</td>
</tr>
<tr>
<td>1985 March 3</td>
<td>7.8</td>
<td>Bolt (1988)</td>
</tr>
</tbody>
</table>


\(^b\) This earthquake is described by Bolt (1988) as ‘similar’ to that in Imperial Valley in 1940
those at Kwanto in Japan in 1923 and Tangshan in China in 1976, where the death tolls were 143,000 and 250,000, respectively.

The San Francisco earthquake in 1906 was one of large magnitude (8.3) and high intensity (XI). The ground shook for some 40–60 seconds. Notable features were the difference in damage between buildings on good ground and those on bad ground and the outbreak of large numbers of fires. Some 700 people were killed.

The Tokyo-Yokohama earthquake in Japan in 1923, also known as the Kwanto Earthquake after the province most affected, was another with large magnitude (8.3). Tokyo and Yokohama, both very densely populated, were almost completely destroyed. Fire broke out on a large scale and it was this rather than building collapse which was responsible for the high death toll of some 143,000.

These two disasters gave impetus to the development of seismological studies and seismic engineering in the USA and Japan.

The earthquake in Imperial Valley, California, in 1940, also known as El Centro, which had a magnitude of 6.9, is of particular interest to seismologists. A seismograph in El Centro recorded a peak ground acceleration of some one third that of gravity. For many years this was the only record available to engineers showing clearly the ground shaking caused by a large earthquake close to its source.

Another earthquake which has been of particular interest to seismological engineers is that at Parkfield in 1966 with a magnitude of 5.6. The Parkfield earthquake was less destructive than that at El Centro in 1940, but it gave a peak ground acceleration of 0.5 g compared with that of 0.33 g for El Centro.

The destructiveness of two earthquakes has been enhanced by a further earthquake at Imperial Valley in 1979, which was of similar size to the 1940 event, and by the fact that Parkfield has been the subject of one of the principal examples of the prediction of future earthquakes.

In 1954 the oil fields of Kern County, California, were subject to an earthquake. The damage caused by this event to process installations is described in Section A15.5.

Several earthquakes have occurred in areas which were not regarded as major seismic risk zones. One of these happened at Agadir in 1960. The epicentre of the earthquake was close to the town and although of relatively low magnitude (5.8) it was very destructive. Much of the town consisted of old buildings and this was a further major contributor to the destruction. The death toll is quoted as 14,000.

The earthquake at Skopje in 1963 had similar features. The area was not regarded as one of particular seismic activity. Its epicentre was close and it was highly destructive despite being of relatively low magnitude (6.0). About 1200 people were killed.

Both the Agadir and Skopje earthquakes were practically a single shock.

The earthquake at Mexico City in 1957, which had a magnitude of 7.5, was notable for the damage to buildings standing on bad ground. In locations where the soil was alluvium, there was widespread soil liquefaction. The old lake bed area of the city experienced intensities of VII, whereas at other locations the intensities were V or less.

Another earthquake in which there was extensive damage due to soil liquefaction was that at Niigata in 1964, which had a magnitude of 7.5. The Niigata earthquake gave impetus to the study of soil effects, and particularly soil liquefaction.

A large earthquake, of magnitude 8.4, occurred in Alaska in 1964. This event was notable for its long duration and wide reach, and for its destructiveness. The earth shook for about 3 minutes. Ground fissures occurred 725 km from the epicentre. Quite large areas suffered up-lift or subsidence. The docks at the port of Anchorage suffered large displacements. The damage caused to process installations by this event is described in Section A15.5.

The San Fernando earthquake of 1971 has several features of interest. It is a prime instance of the shattered earth effect described in Section A15.7. In localized areas the intensity was assessed as high as XII. Ground accelerations were the highest recorded at 1.25 g and 0.7 g for horizontal and vertical accelerations, respectively. Some of the damage effects, particularly to lifelines, are described in Section A15.5.

As far as concerns the UK, mention should be made of the Great British Earthquake of April 22, 1884, near Colchester, to which a magnitude of 5.3 has been assigned. The peak ground acceleration has been estimated as between 0.07 and 0.2 g.

A15.5 Earthquake Damage

There are available numerous accounts of earthquake damage. Most texts on seismology contain descriptions and illustrations of the damage caused by particular earthquakes. These accounts deal largely, often exclusively, with damage to buildings, which is not the prime concern here. There is rather less information available on damage to plant.

A review of seismic damage to process plant and utilities has been given by Alderson (1982 SRD R246). Information is also given by Berlin (1980).

The earthquake in Kern County near Bakersfield in 1952 (Case History A20) occurred in an oil production area. The production rate of several oilfields was affected. Many storage tanks skidded but only a few collapsed.

The most spectacular effect occurred at the Paloma Cycling Plant, where the earthquake caused two of the five large butane spheres to collapse, rupturing pipework and giving a major release. A large vapour cloud formed and was ignited at electrical transformers almost three blocks away. There was a large vapour cloud explosion, followed by a major fire.

On vessels, columns and tall heat exchangers steel foundation bolts were stretched. The top of one vessel standing 60 ft high and weighing some 100 t was estimated from the 1 inch stretch of the bolts at its base to have moved over an arc of 3 ft. There were no major failures, however, of horizontal vessels or pressure storage tanks. High pressure pipework withstood the earthquake well, although there were thermal failures in the subsequent fire; only one cold failure was reported.

At other installations damage was minimal. At one plant oil sloshing in storage tanks broke through the roof. At one pipeline station pipe displacements of 5 in. were found. Elevated water tanks with no lateral support
suffered badly. Of the twelve in the area, two collapsed and seven had suffered damage to their supports.

There was damage to a number of electrical power plants and electrical distribution systems. Overall plant management in this area were earthquake-conscious. Generally, tall vesseles were well anchored and pipework provided with flexibility.

Another instructive case is the earthquake at San Fernando in 1971. This was the first occasion on which a major effort was made to investigate the effects on lifeline systems.

The earthquake was particularly severe over an area of some 30 km² at San Fernando and Sylmar. Violent ground movement in this area broke gas mains and valves, but this was the only area where the gas distribution system suffered serious damage. The water supply system to San Fernando was devastated.

The earthquake disrupted power supplies to large parts of Los Angeles. There was damage to Sylmar Converter Station (40% equipment loss), Olive Switching Station (80% loss) and Sylmar Switching Station (90% loss). The restoration time for the first of these was estimated at 1½–2 years.

At the Sylmar Central Office of the local telephone company 91 tele automatic switching equipment were destroyed, putting the telephone service out of action.

The transport system was also severely affected. Some 62 bridges were damaged, of which 25% collapsed or were severely damaged.

Other earthquakes for which Alderson gives some information on damage to plant include Eureka in 1954, San Francisco in 1957, Alaska in 1964 and Santa Barbara in 1978. It is not uncommon for there to be some rupture of water mains, often due to a combination of corrosion and pressure surge. Some rupture of gas pipes also occurs.

In the 1964 Alaska earthquake there were many failures of tanks and pipework. Tanks of all kinds moved and, if not well anchored, toppled over. Pipes failed at screwed joints and poorly guided thermal loops, as did long unsupported cast iron pipe runs.

A15.6 Ground Motion Characterization

The ground motion caused by an earthquake may be characterized in terms of the peak values of the acceleration, velocity and displacement; of the full time-domain responses of these quantities, particularly the accelerogram; or of the response spectrum. The latter is described below.

The information required for design depends on the method used. Some methods utilize the peak acceleration. The trend is, however, to use the full response or the form of an accelerogram or a response spectrum.

For a single parameter, such as the peak ground acceleration, methods of prediction are available. For a full response, such as an accelerogram or response spectrum, it is necessary to select one which is judged appropriate for the site.

A15.6.1 Strong ground motion

The typical pattern of ground motion is a sudden transition from zero to maximum shaking, followed first by a period of more or less uniform intense vibration and then by a rather gradual attenuation of this vibration.

There are, however, appreciable differences in the ground motion from different earthquakes. Newmark and Rosenblueth (1971) distinguish four types of strong ground motion: (1) practically a single shock; (2) a moderately long, extremely irregular motion; (3) a long ground motion exhibiting pronounced prevailing periods of vibration; and (4) a ground motion involving large-scale, permanent deformations of the ground.

They give the earthquakes at Agadir in 1960 and Skopje in 1963 in the first category; that at El Centro in 1940 in the second; that at Mexico City in 1964 in the third; and those in Alaska and at Niigata both in 1964 in the fourth.

A15.6.2 Peak ground motion

Methods are available for the estimation of the peak ground motion parameters. For ground acceleration one widely quoted relation is that given by Donovan (1973), derived from data for several seismic regions:

\[ a = \frac{1080 \exp(0.5M)}{(R + 25)^{1.32}} \]  \[ \text{[A15.6.1]} \]

where \( a \) is the peak ground acceleration (cm/s²).

Esteva (1974) has used data for earthquakes in California to obtain equations for both peak ground acceleration and peak ground velocity:

\[ a = \frac{5600 \exp(0.8M)}{(R + 40)^2} \quad R > 15 \]  \[ \text{[A15.6.2]} \]

\[ v = \frac{32 \exp M}{(R + 25)^{1.7}} \quad R > 15 \]  \[ \text{[A15.6.3]} \]

where \( v \) is peak ground velocity (cm/s).

For peak ground displacement Newmark and Rosenblueth (1971) give the following approximate empirical relation

\[ 5 \leq \frac{ad}{v^3} \leq 15 \]  \[ \text{[A15.6.4]} \]

where \( d \) is peak ground displacement (cm). The lower limit of 5 and the upper limit of 15 apply to large epicentral distances, say 100 km, and to small ones, respectively.

A15.6.3 Vibration parameters

The vibration characteristics of the earthquake are also important. Correlations are available for the fundamental frequency, or period, of earthquakes. These are described by Dowrick (1977).

A15.6.4 Accelerograms

The basic seismographic measurement is the accelerogram. Profiles of velocity and displacement may be obtained from this by integration. A set of such profiles is illustrated in Figure A15.3.

There are now available accelerograms for quite a large number of real earthquakes. Collections are maintained by major seismographic institutions such as the California Institute of Technology.

Accelerograms are also available for simulated earthquakes. A set of eight such accelerograms has been described by Jennings, Housner and Tsai (1968). There
Figure A15.3  Time histories of acceleration, velocity and displacement of the earthquake at Mexico City 6 July 1964 (after Rosenblueth, 1966)

exist computer codes for the generation of simulated earthquakes.

The design of earthquake-resistant structures is increasingly based on dynamic analysis. The structure is modelled using the appropriate equations of motion and this model is then perturbed by a suitable forcing function. The natural forcing function to use is an accelerogram.

A15.6.5 Response spectra

The main interest in design, however, is in the maximum values of certain responses of the structure. Many of these depend only on the natural period and the degree of damping. A plot which shows the response of one of the parameters acceleration, velocity or displacement for a given degree of damping is known as a response spectrum and that for a set of values of the damping as the response spectra.

Response spectra may be obtained from accelerograms by Fourier analysis and there are computer codes to do this.

There are response spectra available for both real and simulated earthquakes. A regulatory body may specify a standard set of response spectra for use in design.

Figure A15.4 shows a set of response spectra issued by the NRC.

A15.7 Ground, Soils and Foundations

The characteristics of the ground have profound effects on virtually all aspects of earthquake assessment and earthquake-resistant design.

A15.7.1 Ground effects

Experience of earthquakes shows that differences in the ground can result in large differences in the damage done. According to Elby (1980), in extreme cases this can amount to up to four degrees of intensity on the MM scale. It is therefore important to avoid siting structures on bad ground.

Bedrock is generally regarded as a sound foundation and alluvium as less satisfactory. Alluvium tends to absorb the effects of small earthquakes but to amplify those of large ones, giving rise to the effect of soil amplification.

A particular effect of bad ground is soil liquefaction, which can result in very severe damage. This is considered below.
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Figure A15.4 Seismic design response spectra given in Regulatory Guide 1.60 of the Nuclear Regulatory Commission (Nuclear Regulatory Commission, 1973). The four damping levels shown are for viscous damping of 0.5, 2, 5 and 10% of critical damping.

An important class of locations where alluvium is present is old river terraces, which are often the site of ports.

As just stated, structures on the same site may suffer quite different degrees of damage due to differences in the quality of the ground. In the earthquake in 1957 in Mexico MM intensities of VII were determined for the old lake bed area of Mexico City, while other parts had intensities of V or less. The earthquake at Varto, Turkey, in 1966 destroyed some buildings in a school complex but not others, the large difference in damage being attributed to the effect of very localized differences in the ground.

Where a structure straddles two types of soil, damage tends to be enhanced, and this is to be avoided.

It is not universally the case that ground motion is worse in bad ground than in bedrock. Where the rock is on a ridge there can occur a phenomenon variously known as shattered earth, exploded outcrop or churned ground. The 1971 San Fernando earthquake produced numerous instances.

The susceptibility of steep slopes to avalanches is affected by the nature of the soil. A major slope failure occurred in the earthquake at Chimbote in Northern Peru in 1970 when an avalanche with an estimated velocity of 200-400 km/h travelled 18 km, buried whole towns and killed some 20,000. However, slope failures can also occur on relatively gentle slopes. In the Alaska earthquake in 1964 slope failures occurred due to liquefaction of lenses of sand contained in clay deposits.

A15.7.2 Soil settlement and liquefaction

Some of the worst earthquake damage has been due to a quick condition failure in which liquefaction of the soil has occurred. It is important, therefore, to be able to assess susceptibility to soil liquefaction. Damage may also occur due to soil compaction and settlement short of liquefaction.

The behaviour of a soil under earthquake loading is a function of the strain magnitude, strain rate and number of cycles of loading. Some soils increase in strength under rapid cyclic loading, while others, such as saturated sands, tend to lose strength.

Broadly, gravel and clay soils are not susceptible to liquefaction and dense sands are less likely to liquefy than loose ones.

Two important characteristics of a soil bearing on liquefaction are its cohesion and its water content. Saturated cohesionless soils are prone to liquefaction. A full discussion of the effect of cohesion and saturation on soil liquefaction is given by Newmark and Rosenblueth (1971).

The susceptibility of a cohesionless soil to liquefaction depends on its water content. For a dry cohesionless soil grain size is another important factor. For a medium grain size soil experiencing vibration a critical void ratio exists below which it tends to dilate and above which it tends to reduce in volume. This effect has been modelled by Barkan (1962). Other effects which can occur are breakage in large grain soils and air entrapment and soil liquefaction in fine grain soils.

A saturated cohesionless soil is most prone to liquefaction. The effect is not well understood, although it is known that relative density, confining pressure and drainage conditions are three important variables. Loose sands often liquefy after only a few loading cycles, whereas dense ones may require several hundred cycles. Conditions which prevent water from escaping promote liquefaction.

Extensive soil liquefaction occurred in the earthquake at Niigata in 1964. There was loose sand and water was not able to escape, partly due to the extent of the foundations.

With a saturated cohesive soil the strength tends to increase due to strain rate but to decrease due to cyclic loading. The net effect may be to increase or decrease the strength, depending on the nature of the soil. In a very sensitive soil a decrease in strength may set in after only a few cycles, whereas with a relatively insensitive one the strength may still be increasing after some 50 cycles.

A15.7.3 Site investigation

It is practice to carry out a site investigation to determine the characteristics of the ground. An account of the laboratory and field tests and of the information which they yield is given by Dowrick (1977). Laboratory tests on relative density and particle size distribution and field tests on groundwater conditions and penetration resistance bear on the problems of soil liquefaction and settlement, while field tests on soil distribution, layer depth and depth to bedrock, on groundwater conditions and the natural period of the soil provide data for response calculations. Other tests may be performed to obtain the shear modulus and damping characteristics.

In addition to the use of drill holes to make the field tests just described, use may also be made of other techniques such as inducing and measuring vibrations.
A15.7.4 Design basis earthquake
Where dynamic analysis is to be performed, it may be necessary to modify the accelerogram to take account of the nature of the ground. The case of bedrock would seem at first sight to be the most straightforward, but this is not necessarily so, since most accelerograms are for softer soils, and there are very few for bedrock. The modification of accelerograms to take account of ground conditions is a specialist matter. An account is given by Dowrick (1977).

The ground motion is also affected by any structure placed on it. The accelerogram relevant to the site as a whole is therefore the free field accelerogram.

A15.7.5 Soil-structure interaction
It has been found by experience that there is an appreciable interaction between the soil and the structure and that it is necessary to take this into account.

The effects of bad ground have already been described. One such effect is soil amplification of the earthquake vibrations.

The effects of soil-structure interaction (SSI) are to modify the dynamics of the structure and to dissipate its vibrational energy.

In general, damage is greater if the natural period of a structure is similar to that of the soil on which it is built, e.g. a low, short-period building on a short-period soil deposit or a tall, long-period building on a long-period deposit. In the earthquake in 1957 at Mexico City extensive damage was done to long-period structures standing on deep (>100 m) alluvium. Another case where the natural periods of structures suffering damage appeared closely correlated with the depth of subsoil was the earthquake at Caracas, Venezuela, in 1967.

The Uniform Building Code (UBC) in the USA, described below, originally contained a soil amplification factor which was then removed due to lack of knowledge as to what the factor should be. The 1976 version contains a site-structure resonance factor S. This factor is a function of the ratio \(T/T_s\) where \(T\) and \(T_s\) are the natural periods of the structure and soil, respectively.

A soil deposit may be characterized by the width and depth of soil overlying the bedrock. The natural period increases with the depth of the deposit. Relations are available for the determination of the natural period of horizontal vibration of a soil deposit. Dowrick (1977) gives the equation

\[
T = \frac{4H}{v_s} \quad [A15.7.1]
\]

where \(H\) is the depth of the soil layer (m), \(T\) the natural period of the soil layer (s) and \(v_s\) the velocity of the shear wave (m/s).

In determining soil-structure interaction use is made of soil-structure models. In the simpler models the soil layer is represented using models of the lumped mass with spring and damping forces type not dissimilar to those used for the structure itself.

A full dynamic analysis of soil-structure interaction is perhaps the most difficult task in earthquake engineering.

A15.8 Earthquake-Resistant Design
The design of an earthquake-resistant structure includes the following principal steps:

1. seismic assessment;
2. ground assessment;
3. selection of structural form;
4. selection of the materials;
5. overall design of the structure.

The first and second of these are considered in Sections A15.11 and A15.7, respectively.

A15.8.1 Structural form
It has been found by experience that certain structural forms resist earthquakes well while others do not. An account of the features of structural form which give earthquake resistance is given by Dowrick (1977). In broad terms the structure should be simple and symmetrical and not excessively elongated in plan or elevation. It should have a uniform and continuous distribution of strength. It should be designed so that horizontal members fail before vertical members.

The desirable degree of stiffness has been a matter of debate. The point is discussed by Dowrick, who states that either a stiff or a flexible structure can be made to work.

A15.8.2 Materials
The properties of materials of construction which confer good resistance to earthquakes include homogeneity, ductility and high strength/weight ratio.

Materials generally quoted as being suitable for earthquake-resistant structures include steel, in situ reinforced concrete and prestressed concrete.

A15.8.3 Static analysis
The traditional method of earthquake-resistant design is static force analysis, also referred to as the static, or equivalent static design method.

The static method is based on the following relation for the effective horizontal force, or base shear, on the structure:

\[
V = ma \quad [A15.8.1]
\]

where \(a\) is the acceleration (m/s²), \(m\) mass (kg) and \(V\) horizontal force (N).

The value of the acceleration \(a\) used in static design is typically in the range 0.05 to 0.20 g.

Methods for the design of structures to withstand a horizontal force in the form of a wind load are well established in civil engineering, and the approach required for the static method for earthquake resistance is not dissimilar.

Equation A15.8.1 is the basic relation traditionally used in earthquake design codes. These codes are described in Section A15.9.

A15.8.4 Dynamic analysis
It has long been recognized that the static design method is oversimplified, and a variety of dynamic design methods have been developed.

In dynamic analysis an unsteady-state model of the structure is produced and the forcing function of the design earthquake is defined. The model is then excited using this forcing function. Methods of dynamic analysis differ in the type of model used, the use of model decomposition and the domain (time, frequency) in which the forcing is applied.
The forces estimated using the more rigorous methods of dynamic analysis can be an order of magnitude greater than those obtained from the static method.

An account of dynamic analysis is given in Section A15.10.

A15.8.5 Detailed structural design
The design methods described give information on the forces to be expected at different points in the structure. The detailed design of the various elements of the structure can then be performed.

Discussions of the behaviour of structural elements and of detailed design using different materials are given by Newmark and Rosenblueth (1971) and Dowrick (1977).

A15.8.6 Detailed non-structural design
It is also necessary to design the non-structural features for seismic resistance. Much of the damage done by earthquakes is non-structural.

These features include in-fill panels and partitions; cladding; and doors and windows. An account of their design is given by Dowrick (1977).

A15.8.7 Services
The seismic resistance of services is also relevant. Guidance on this aspect is given by Dowrick (1977).

For services, the specification of the seismic resistance required is of particular importance. There may be some key services whose survival in full working order is regarded as vital.

For such essential services Dowrick suggests the use of earthquake accelerations higher than those utilized in building design; the use of dynamic rather than static design methods and of the response spectrum technique; and design for elastic rather than plastic deformation. He states that a high degree of seismic resistance can usually be obtained at relatively little extra cost.

Some services which he considers are electrical equipment, such as transformers; mechanical equipment, such as boilers; and pipework.

A15.8.8 Specific structures
The bulk of guidance on earthquake-resistant design relates to buildings and similar structures, but some is available for other types of structure. The types of structure relevant to process plant include columns, storage tanks and pipes.

Newmark and Rosenblueth (1971) discuss the seismic design of towers, stacks and stack-like structures; tanks and hydraulic structures; and pipes. Columns are also considered by Dowrick (1977).

Accounts of particular earthquakes frequently give information on the extent of survival of, or damage to, process plant items.

A15.9 Earthquake Design Codes
Guidance on the design of earthquake-resistant structures is available in earthquake design codes. These codes have been developed particularly in the USA and Japan, and many countries have adopted or adapted the US codes.

Some earthquake design codes which have been developed in the USA include the Uniform Building Code (UBC) of the International Conference of Building Officials (ICBO); the Basic Building Code of the Building Official and Code Administration (BOCA); the Standard Building Code (SBC) of the Southern Building Code Congress International; the recommendations of the Structural Engineers Association of California (SEAOC); and the ANSI code.

The UBC appears the most widely quoted and influential. An account of the development of the code is given by Berlin (1980).

The method of design used in the code is the equivalent static method, also known as the seismic coefficient method. The account given here is based on the 1976 version of the code.

In its simplest form the basic equation of the code is

\[ V = CW \]  

where \( V \) is the lateral or shear force (N), \( W \) the load (N) and \( C \) a coefficient. The lateral shear force \( V \) is commonly known as the base shear coefficient.

The working equation of the code has passed through various versions. That given in the 1976 code is

\[ V = ZIKSW \]  

where \( C \) is the flexibility factor; \( I \) the occupancy importance factor; \( K \) the framing factor; \( S \) the site factor; and \( Z \) the seismic risk zone factor.

The values to be used for the various factors are treated in the code. A discussion of these factors are given by Berlin (1980).

The flexibility factor \( C \) is a function of the natural period of the structure. There are a number of equations for the estimation of \( C \). One principal equation is

\[ C = 1/15T^2 \]  

where \( T \) is the fundamental period of vibration of the structure in the direction under consideration (s).

The occupancy importance factor \( I \) is 1.5 for essential facilities, 1.25 for a building where the primary occupancy is more than 300 people, and 1.0 for other buildings.

The framing factor \( K \) allows for the types of structure. It has values ranging from 0.67 to 1.33. The lower value is for a structure with ductile, moment resisting frame and the higher for a structure with a box system, in which lateral forces are resisted by shear walls or braced frames. A tabulation of values is given for different types of structure.

For the seismic zone risk factor \( Z \) the USA is divided into five zones, which are defined in the code and may be characterized as follows:

- **Zone 0** No damage
- **Zone 1** Minor damage (MM intensity V and VI)
- **Zone 2** Moderate damage (intensity VII)
- **Zone 3** Major damage (intensity VIII)
- **Zone 4** Areas within Zone 3 close to certain major fault systems

The values of \( Z \) for use in these zones are 3/16, 3/8, 3/4 and 1 for Zones 1, 2, 3 and 4, respectively.

An account of codes in various countries is given by Alderson (1982 SRD R246).
A15.10 Dynamic Analysis of Structures

There are a variety of methods of dynamic analysis. Features of these methods are the unsteady-state model of the structure, the use of decomposition techniques, the forcing function and the domain in which the analysis is conducted.

In the following account, dynamic analysis is described mainly in terms of a single design earthquake. It is generally recommended that the analysis be repeated for further earthquakes.

A15.10.1 Unsteady-state models of structures

Unsteady-state models of the structure are distinguished by the number of degrees of freedom (DoF). Both single degree-of-freedom (SDF) and multiple degree-of-freedom (MDF) models are used. Basic SDF and MDF models are described by Dowrick (1977).

The basic SDF model is the standard second-order system. This may be written as

\[ F_I + F_D + F_S = F(t) \]  \hspace{1cm} [A15.10.1]

where \( F \) is the applied force, or forcing function (N), \( F_D \) the damping force (N), \( F_I \) the inertia force (N) and \( F_S \) the elastic force (N).

Substituting for the various force terms, Equation [A15.10.1] may be written

\[ m\ddot{x} + c\dot{x} + kx = F(t) \]  \hspace{1cm} [A15.10.2]

where \( c \) is the damping coefficient (kg/s), \( k \) the resistance (kg/s²), \( m \) the mass of the system (kg), \( t \) time (s) and \( x \) the displacement (m). In standard form the equation becomes

\[ \frac{1}{\omega_n^2} \ddot{x} + \frac{2\zeta}{\omega_n} \dot{x} + x = \frac{1}{k} F(t) \]  \hspace{1cm} [A15.10.3]

with \( \zeta = (c^2/4mk) \) \hspace{1cm} [A15.10.4]

\[ \omega_n = (k/m)^{1/2} \]  \hspace{1cm} [A15.10.5]

where \( \zeta \) is the damping factor and \( \omega_n \) the natural frequency (s⁻¹). The damped frequency is

\[ \omega = \omega_n \sqrt{1 - \zeta^2} \]  \hspace{1cm} [A15.10.6]

where \( \omega \) is the frequency of damped oscillation (s⁻¹).

The single-degree-of-freedom model is a lumped mass model. The distribution of mass may be taken into account by the use of a multiple-degree-of-freedom model. Thus a n-storey structure might be represented by a MDF model in which the mass of each storey is assumed to be located at the floor of that storey. The model obtained then consists of a set of \( n \) equations similar to Equation A15.10.2.

In the simpler case, the model is formulated as a linear one. For some systems a linear model represents an unacceptable oversimplification and a nonlinear model is required.

A15.10.2 Time-domain solution

The dynamic model is then subjected to the forcing function of the design basis earthquake. In time-domain analysis, the unsteady-state model is excited by the time forcing function, which is the accelerogram. The equations are integrated numerically and the time response of the structure is obtained. These responses include the forces, or stresses, on, and displacements of, the structural elements.

A15.10.3 Normal modal analysis

In some cases it is permissible to simplify the solution of a multiple degree-of-freedom model by a method known as normal modal, or simply modal, analysis. In this technique the vibrations in mutually perpendicular directions are treated as uncoupled and the responses are obtained for the separate modes and are then combined by superposition to give the overall responses. The method is applicable only to linear systems.

A15.10.4 Response spectra

Another approach is the response spectrum method. As described above, a response spectrum represents for a series of single degree-of-freedom systems with a given degree of damping the peak acceleration, velocity or displacement obtained when forced by the acceleration-time profile, or accelero gram, of the design earthquake. The family of curves for different degrees of damping constitutes the response spectra. The response spectra most commonly given are those for acceleration.

The determination of the response spectra from the forcing function \( F(t) \) of the design earthquake is described by Dowrick. The displacement \( x(t) \) is given by

\[ x(t) = \int_0^t \frac{F(\tau)}{m\omega} \exp[-\zeta\omega(t - \tau)] \sin[\omega(t - \tau)] \, d\tau \]  \hspace{1cm} [A15.10.7]

Then taking \( \omega \approx \omega_n \), a response function is defined as

\[ V(t) = \omega_n x(t) \]  \hspace{1cm} [A15.10.8]

where \( V(t) \) is the response function (m/s).

It is the maximum values of the responses which are of interest. The maximum value of the response function is termed the spectral velocity, or strictly the pseudo-spectral velocity:

\[ S_v = V_{\text{max}} \]  \hspace{1cm} [A15.10.9]

where \( S_v \) is the spectral velocity (m/s) and \( V_{\text{max}} \) the maximum value of the response function (m/s). Further

\[ S_a = S_v / \omega_n \]  \hspace{1cm} [A15.10.10]

\[ S_d = \omega_n S_v \]  \hspace{1cm} [A15.10.11]

where \( S_a \) is the spectral acceleration (m/s²) and \( S_d \) the spectral displacement (m).

The application of the response spectra is as follows.

The natural frequency and damping of the structure is determined. The response spectra are then used to obtain the peak acceleration. This peak acceleration is then applied to find the forces on, and displacements of, the structural elements.

The basic response spectra technique is described by Dowrick as essentially a special case of modal analysis, in that the method treats the system as a linear one and uses the principle of superposition. He also describes, however, adaptations of the method to nonlinear analysis.

A15.10.5 Frequency domain solution

Alternatively, the analysis may be performed in the frequency domain. The method is described by Dowrick. The acceleration-time profile is converted by Fourier transform methods into an acceleration-frequency
profile. This is then used to excite the model of the system. The response in the frequency domain is then converted back using the inverse transform to give the response–time profile.

R. Davies (1982) describes the use of a version of this approach. The acceleration–time profile of the design earthquake, the accelerogram, is converted by Fourier analysis into an acceleration–frequency profile. The analysis then proceeds in two stages. In the first stage, using a series of frequencies from the acceleration–frequency profile, the unsteady-state model is excited at each frequency by a sinusoidal force of that frequency and with an acceleration amplitude set at an arbitrary value. The outputs are the forces on, and displacements of, the structural elements as a function of frequency. In the second stage these outputs are converted back to time profiles of forces and displacements.

A15.10.6 Selection of method
The selection of a method of dynamic analysis is discussed by Dowrick (1977). The structures to be analysed range from small, simple structures to large, complex ones. Broadly, more complex structures demand more sophisticated methods. He gives in ascending order of complexity the methods of static analysis, response spectra, modal analysis and nonlinear modelling.

A15.11 Seismicity Assessment and Earthquake Prediction
The assessment of the seismic hazard to which an installation may be exposed is normally based on information about the seismicity of the area in question.

In principle, this may be complemented by information from the monitoring of ground motions and prediction of any impending earthquake. However, such prediction is not sufficiently precise to be of much use for this purpose.

A15.11.1 Seismic data and maps
There are available a number of compilations of seismic maps and other information on seismicity. They include *Seismicity of the Earth and Associated Phenomena* by Gutenberg and Richter (1954); for Europe *Seismicity of the European Area* by Karnik (1968, 1971); and for Britain *A History of British Earthquakes* by Davison (1924) and *Seismicity and seismic hazard in Britain* by Lilwall (1976).

A15.11.2 Seismic assessment
Seismic design or assessment normally takes as its starting point information on the relationship between the magnitude and frequency of earthquakes at the location of interest. In default of more specific information, use is generally made of the historical record.

The normal method is to use a relation such as the Gutenberg–Richter relation, Equation A15.2.10, from which the frequency of earthquakes of various magnitudes may be determined. Several return periods and magnitudes are selected for study.

For an earthquake of a particular magnitude and frequency the probability of occurrence may be estimated making some assumption about the probability distribution. A common assumption is that the incidence is random.

Then using a relation such as that of Donovan or Esteva, Equations A15.6.1 or A15.6.2, respectively, the peak ground acceleration can be obtained.

The approach taken is therefore statistical rather than geological. The potential benefits of a more geological approach are discussed by V.W. Lee and Trifunac (1987). They argue that estimates for the occurrence rates of earthquakes are over a time interval of some $10^5$–$10^6$ years for those based on geological structure, or ‘geological seismicity’, while those based on ‘historical seismicity’ are for intervals of the order of $10^2$–$10^3$ years.

The assessment of seismicity in Britain described below serves to illustrate the approach generally taken.

A15.11.3 Probability distributions
The frequency of earthquakes of different magnitudes is commonly obtained from the Gutenberg–Richter equation, as just described.

Use may also be made of the extreme value distribution of Gumbel (1958).

The occurrence of an earthquake of given size is commonly treated as a randomly occurring event for which the probability distribution is the Poisson distribution:

$$P = 1 - \exp(-\lambda)$$

where for an earthquake of a specified size, $P$ is the annual probability of exceedance and $\lambda$ the expected annual number of earthquakes.

The possibility of complementing this by utilizing information obtained from monitoring seismological indicators points to the possible use of the Bayesian approach.

A discussion of appropriate distributions is given by Newmark and Rosenblueth (1971).

A15.11.4 Seismicity in Britain
A study of the seismicity of Britain which is frequently quoted is that of Lilwall (1976). Figure A15.5 is one of his plots showing intensities of earthquakes with a return period of 200 years.

Lilwall divides the country into the following zones: Great Glen, Comrie and Memstrie, South Wales and Herefordshire and the remainder. The first two are areas of a seismicity relatively high for Britain. The third may be regarded as typical of a relatively active area of the country.

For the frequency of earthquakes Lilwall recasts Equation A15.2.10 as

$$\log_{10} N = a' - b' m_s$$

where $a'$ and $b'$ are constants. He obtains the following values for $a'$ and $b'$:

<table>
<thead>
<tr>
<th>Area</th>
<th>$a'$</th>
<th>$b'$</th>
<th>Surface area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>4.13</td>
<td>1.09</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>South Wales and Herefordshire</td>
<td>1.1</td>
<td>0.55</td>
<td>15000</td>
</tr>
<tr>
<td>Remainder</td>
<td>4.0</td>
<td>1.15</td>
<td>$2.3 \times 10^5$</td>
</tr>
</tbody>
</table>

The return periods for earthquakes of different magnitudes are then as follows:

A discussion of appropriate distributions is given by Newmark and Rosenblueth (1971).
For the intensity in Britain he derives, following Esteva and Rosenbueth (1964), the relation
\[ I = 6.0 + 1.5M_s - 1.9 \ln R \]  
[A15.11.5]

or, using Equation [A15.11.4]
\[ I = -2.5 + 3.1m_b - 1.9 \ln R \]  
[A15.11.6]

He uses for the estimation of \( R \) Equation A15.2.2 with \( k = 20 \).

A15.11.5 Earthquake prediction

There are a number of methods for the prediction of earthquakes. Such methods are applicable mainly to active regions. Accounts are given by Berlin (1980), Elby (1980) and Bolt (1988).

One important concept is that of the seismic gap. Essentially a seismic gap is an area which has not had an earthquake for some time and in which strain is accumulating. The argument is that due to this strain accumulation the probability of an earthquake increases with time.

The seismic gap concept has been applied to large earthquakes. Areas at the boundary of tectonic plates which have not had an earthquake for a long period are regarded as more likely to experience one than those which have had a recent event. The seismic gap approach has also been applied to lesser earthquakes.

It has been found that in some cases large, shallow-focus earthquakes tend to migrate along a fault zone.

There are a number of phenomena which are regarded as precursors of earthquakes. They range from foreshocks, seismic wave anomalies and fault creep to behaviour of animals.

There are also available several earthquake precursor models. Three principal models are (1) the dilatancy model; (2) the fault creep model; and (3) the propagating deformation front model.

Attempts to predict earthquakes have met with mixed success. There is in China an established earthquake prediction programme. One much quoted case is that of the earthquake in Liaoning Province on 4 February 1975, which had a magnitude of 7.4. Officials decided that the evidence justified the issue of a warning that a strong earthquake was probable within 24 hours. people left their houses and the earthquake in fact struck that evening. On the other hand no warning was issued for the earthquake at Tangshan in 1976, which had a magnitude of 8.0.

In an account of the prediction of earthquakes in California, Bolt (1988) stated that there is one definitive prediction. This was that a moderate earthquake was likely to occur near Parkfield, California, between 1987 and 1993. This was based on a simple linear prediction of the trend of earthquakes, which have occurred in 1901, 1922, 1934 and 1966.

A15.12 Design Basis Earthquake

In earthquake-resistant design, an installation is designed to withstand seismic events so that the frequencies at which various degrees of damage are incurred do not exceed the specified values. The choice of the design basis earthquake is governed by these frequency specifications.
The characterization of the ground motion of an earthquake has been described in Section A15.6. Essentially, there are three main approaches. These are characterization in terms of peak acceleration; of the response spectra; or of the acceleration–time profile. These three methods of characterization accord with the three main methods of analysis described in Section A15.10: static analysis, response spectra and dynamic analysis.

A15.12.1 Seismic hazard curve

There are available empirical correlations between the frequency of exceedance and magnitude of earthquakes and between their peak acceleration and magnitude, as described in Section A15.2. From these it is possible to obtain the relationship between the frequency of exceedance and peak acceleration. A plot of these two quantities is often referred to as a seismic hazard curve. A seismic hazard curve may be constructed for a region or for a particular site.

Figure A15.6 shows seismic hazard curves for the UK given by Alderson (1982 SRD R246). Curve A is based on the Gutenberg–Richter equation, Equation A15.2.10, and curve B by a method given by Hsieh, Okrent and Apostolakis (1975).

A15.12.2 Response spectra

As described in Section A15.6, there are available a number of response spectra both for real earthquakes and for simulated earthquakes.

One or more of these response spectra may be selected to define the design basis earthquake. With this method also the choice is governed by the earthquake severity, and hence the return period, for which the installation is to be designed.

Two earthquakes which figure prominently in the literature are those at El Centro in 1940 and at Parkfield in 1966. A number of response spectra for the El Centro earthquake and a comparison with that at Parkfield are given by Dowrick (1977). Further accounts of the Parkfield response spectra are given by D.W. Phillips (1982) and V.W. Lee and Trifunac (1987).

The seismic design response spectra given in Regulatory Guide 1.60 of the NRC have already been mentioned and are given in Figure A15.4. They are discussed further below.

Another set of response spectra are those developed in New Zealand, as described by Dowrick (1977).

A15.12.3 Accelerograms

For accelerograms the approach is broadly similar to that for response spectra just described. One or more accelerograms may be selected with the choice governed by earthquake severity and return period.

For accelerograms also, the 1940 El Centro and 1966 Parkfield earthquakes figure prominently in the literature. Newmark and Rosenbluh (1971) give a set of accelerograms which illustrates the distinctions which they make between different types of ground motion.

A15.13 Nuclear Installations

The seismic hazard is of particular importance for nuclear power plants and a large amount of work has been done both on seismic design and on seismic hazard assessment.

The NRC has set earthquake-resistant design criteria and has undertaken a large amount of work on seismic engineering of nuclear plants.

A15.13.1 NRC seismic design response spectra

For the purpose of nuclear plant siting, the NRC considers a fault to be active if there has been movement at least once in 35,000 years. For such a fault, it is to be assumed that the largest earthquake supported by the fault system will occur within the next 50 years.

In 1973 the NRC issued Regulatory Guide 1.60 containing its seismic design response spectra, which have already been mentioned and are shown in Figure A15.4.

Background to RG 1.60 is given by V.W. Lee and Trifunac (1987). The RG 1.60 response spectra were developed from accelerograms of some 33 earthquakes and model the shapes of spectra which can be expected at intermediate distances from medium to large earthquakes. They state that experience of the RG 1.60 response spectra since that date shows that they are
useful for straightforward cases, but meet with difficulties for responses in the near and far fields.

These authors also describe the scaling of the RG 1.60 response spectra for other distances, particularly for locations in the near field. The method generally used is based on scaling by the peak ground acceleration, although this presents some difficulties.

Lee and Trifunac discuss approaches to the improved characterization of near-source ground motion.

A15.13.2 Seismic Safety Margins Research Programme
The NRC has for some years had a major programme of work on seismic safety margins. Accounts of this work include those of Cummings (1986) and R.P. Kennedy et al. (1989).

In simple terms the seismic safety margin is the earthquake level at which with high confidence failure is extremely unlikely. An earthquake of this level is described as a seismic margin earthquake (SME). The SME is generally characterized by the peak ground acceleration (PGA).

The main body of work is that done under the Seismic Safety Margins Research Program (SSMRP). Among the reasons for the programme were uncertainty about the size of earthquakes to be expected; a lack of experimental data to guide plant design; the potential for common mode failure due to ground shaking; and the possibility that 'strengthening' might increase risk.

The SSMRP methodology involves a five-step procedure: (1) characterization of the seismic hazard; (2) determination of the response of the structure and subsystems to seismic excitation; (3) determination of the fragility functions; (4) identification of accidental scenarios; and (5) calculation of the frequency of failure and release.

The seismic hazard is characterized by seismic hazard curves, response spectra and acceleration time histories based on a combination of real earthquakes, estimates from magnitude correlations, expert judgement and other methods. The necessary computations are performed by the computer code HAZARD. The soil-structure interaction and the response of structure and subsystems to seismic excitation are treated simultaneously and are handled by the SMACS code. Seismic excitation includes forcing by an ensemble of acceleration time histories in three orthogonal directions. A third code SEISIM is used to handle the radioactive release aspects.

Most of the work in the SSMRP has been concerned with the seismic fragility of items of equipment. The fragility is a function of the seismic load and is expressed as the cumulative probability of failure with load.

A15.13.3 Seismic margin estimation
A review of methods for the calculation of the seismic margin of items of equipment is given by R.P. Kennedy et al. (1989).

The seismic margin review of a nuclear power plant requires the determination for certain components of the High Confidence of Low Probability of Failure (HCLPF) capacity. This study describes two candidate methods for doing this, the Conservative Deterministic Failure Margin (CDFM) method and the Fragility Analysis (FA) method.

The CDFM method involves a design calculation which is essentially conventional in method but which utilizes more conservative assumptions.

In the FA method, the fragility of the equipment is modelled as a double log normal distribution with three parameters: \( A_m \) the median ground acceleration; and \( \beta_R \) and \( \beta_U \), the logarithmic standard deviations representing respectively the randomness and the uncertainty in the median value. The two latter parameters may be subsumed in the combined parameter \( \beta = (\beta_R^2 + \beta_U^2)^{1/2} \).

The report describes the estimates made by four experts of the HCLPF by the CDFM and FA methods for a representative set of items, including a storage tank, a heat exchanger and an air tank. The bulk of the report consists of detailed calculations. The results are expressed as values of the PGA.

A15.14 Process Installations
There is rather less work published on the seismic design and seismic assessment of process plants, but there are some accounts available. Moreover, the methodologies developed in the nuclear industry are in large part applicable to the process industries.

The guide TID-7024 Nuclear Reactors and Earthquakes (NTIS, 1963) is quoted in the NFPA codes such as NFPA 59A: 1985 Production, Storage and Handling of Liquefied Natural Gas (LNG) for guidance on seismic loading.


Methods for seismic design are given by the NRC (1979c). There is also a good deal available for particular items. For example, for liquid storage tanks accounts have been published by Veletzos and co-workers (Veletzos and Yang, 1976; Veletzos, 1984; Veletzos and Yu Tang, 1986a, b), Haroun and Housner (1981), R.P. Kennedy (1979, 1989) and Priestly et al. (1986). Guidance on analysis of individual failure modes is given in standard texts on structures such as Timoshenko (1936), Warburton (1976), Pilkey and Chang (1978) and, for wind loads, Sachs (1978).

A15.14.1 Seismic assessment of generic plants
R. Davies (1982) has reviewed the seismic hazard for process plants in the UK. He identifies liquefied gas storage as a matter of principal concern and describes a study to assess the risk from such storage.

The study was in three parts: the assessment of seismicity in the UK; the selection of representative containment and the identification of principal failure modes; and the modelling of the seismic response of these containments.

Three levels of earthquake were defined, Levels 1–3. A Level 1 earthquake was taken as one with a return period of 150 years which would have a 0.25 probability of occurring over a plant life of 40 years. The work of
Lilwall suggests that this return period corresponds to an earthquake of body wave magnitude about 4.5, which would typically yield at 15-20 km a site intensity of around VI on the MM scale. The Level 2 earthquake was taken as one with a return period of 2000 years, magnitude of 5.25 and site intensity of VII. For the Level 3 earthquake a frequency of $10^{-4}$ events/year, or return period $10^{-4}$ years, was taken, following NFPA guidance in NFPA 59A: 1980 on the design earthquake for LNG storage.

Earthquakes corresponding to each of these three levels were identified and the accelerograms of these earthquakes were obtained. The records used were those for the earthquake at New Madrid, Missouri, on 13 June 1975 (body wave magnitude 4.3), those for that at Forgarya-Cornino, Italy, on May 11 1976 (magnitude 5.2) and the Temblor records of the earthquake at Parkfield on 27 June 1966 (magnitude 5.6).

The method of dynamic analysis used by Davies was described earlier.

Three generic types of liquefied gas storage were considered: a double skin cryogenic tank with a suspended roof, an inner shell of % nickel steel and an outer shell of mild steel to hold 20000 te of LNG; a 1250 te capacity spherical pressure storage vessel to hold 1250 te of propane; and a cylindrical pressure storage vessel, or torpedo, to hold 250 te of liquid carbon dioxide. For all three containments a foundation of hard rock was considered and the low temperature tank was also considered with a piled foundation on soft soil.

The failure modes considered were as follows. For the storage tank they were (1a) rupture of the connection between the tank shell and the floor; (1b) ripping of the tie-down strap; and (1e) excessive displacement of the base of the shell and rupture of the connection pipes. For the sphere they were (2a) tear at the connection of the shell and supporting leg; (2b) buckling of the support columns; and (2c) excessive displacement at the connecting pipe takeoff and rupture of the pipe. For the torpedo they were (3a) tear at the connection of the shell and support; (3b) rupture of straps or supports; and (3c) sliding on or rolling off support and rupture of the connecting pipes.

For the Level 1 earthquake the ratio of the seismic response stress to the seismic capacity stress was very small in each of these failure modes; the highest value of the ratio was 0.03 for the cryogenic tank tie-down strap on hard rock (mode 1b). For the Level 2 earthquake the ratio was 1.4 for the cryogenic tank tie-down strap on hard rock (1b), 0.48 for the inner shell base of the tank on hard rock (1a) and 0.21 for the inner shell base on piles (1a again). For the Level 3 earthquake these three latter values were 1.9, 0.72 and 0.29, respectively. Data on displacements are also given.

The conclusion of the study is that for liquefied gas storages of the type considered an earthquake which occurs sufficiently frequently to be likely to be felt during the life of the plant poses a negligible risk of loss of containment, but that one which approaches the maximum likely to occur in the UK could produce appreciable horizontal displacements in all types of plant and stresses in certain critical parts of some containments which exceed the dynamic design stresses allowed in current design codes.

A15.14.2 Seismic assessment of particular plants

An account of the seismic assessment of an existing process plant as part of the controls on acutely hazardous material (AHM) under the California Risk Management and Prevention Program (RMPP) under has been given by Ravindra (1992). The review covered both the site-specific geology and the engineering facilities.

He describes the investigation of the seismic characteristics of the site, including the impact of active faults; the potential for surface faulting and ground breakage, soil settlement and liquefaction, and slope instability; and local soil amplification. A seismic hazard curve was established.

The seismic capacity of the facilities was assessed by review of the design drawings and design codes used and by a walkaround of the plant.

It was found that some components had been designed using the static design method with an acceleration of 0.2 g; this acceleration is similar to that in the UBC. Detailed evaluation established that some of these items were vulnerable even though they had been designed to a building code.

The author gives examples of the seismic capacity assessed by a deterministic method given in RMPP guidelines and by the FA method and quotes values of the median ground acceleration $A_m$ and the logarithmic standard deviation of the uncertainty in this acceleration.

The failure mode determining seismic capacity in most cases is failure of the anchor bolts or anchorage. The author comments that generally this can be upgraded at minimal cost.

A15.14.3 Spherical pressure vessel

An assessment of the seismic capacity of a spherical pressure storage vessel has been described by D.W. Phillips (1982).

The vessel considered is a 15 m diameter vessel supported on 12 columns, or legs. The nominal contents of the vessel are 1200 te, the mass of the shell is 166 te and that of the legs 15.6 te. The active length of the supporting columns is 7.94 m. Each column has a flat steel plate welded to the bottom. The plate is attached by four foundation bolts to the concrete pedestal. The spacing between the bolts is 0.58 m and the inset of the bolts is 0.08 m. The bolts are 0.032 m diameter. The effective dynamic mass of the vessel itself, with a contribution from the legs, is taken as 171 te (166 + $\frac{1}{2} \times 15.6$), giving a total effective dynamic mass of 1371 te for the full vessel.

From a separate study, it is known that the natural period of the vessel for horizontal vibration is as follows:

<table>
<thead>
<tr>
<th>State</th>
<th>Mass of vessel and shell (te)</th>
<th>Natural period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>1371</td>
<td>0.75</td>
</tr>
<tr>
<td>$\frac{1}{2}$ full</td>
<td>771</td>
<td>0.58</td>
</tr>
<tr>
<td>$\frac{1}{4}$ full</td>
<td>471</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The vessel is located on a typical UK site. For such a site the seismic characteristics in terms of the free field horizontal acceleration are taken as
The method of calculation used is essentially a static analysis, but first a dynamic analysis is conducted to determine a dynamic, or resonance, correction factor. For this use, is made of the data given above on the natural period and the horizontal acceleration together with suitable response spectra. Two response spectra are used, the NRC Regulatory Guide 1.60 spectra and the Temblor–Parkfield spectra. A damping of 5% is taken as typical of welded steel at high strain and of bolted steel. For each degree of fill, the response spectra are used to obtain the acceleration from the natural frequency and damping. This value is scaled by the ratio of the maximum acceleration of the site to the maximum acceleration implied in the response spectra.

The results for the horizontal response with intact bracing are

<table>
<thead>
<tr>
<th>Return period (year)</th>
<th>Horizontal acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>1000</td>
<td>0.12</td>
</tr>
<tr>
<td>10000</td>
<td>0.25</td>
</tr>
</tbody>
</table>

\[
W_o = \left[ \sum_{i=1}^{3} W_i^2 \right]^{\frac{1}{2}}
\]

where \( W_i \) is the load in the \( i \)th direction (N) and \( W_o \) the overall load (N).

Then for the 100 year return period with horizontal acceleration of 0.05 g and incorporating the two orthogonal accelerations and the dynamic correction factor of 2, the peak horizontal seismic load of the full tank is

\[
W_s = 2^4 \times (1371 \times 10^3) \times 2 \times 0.05 \times 9.81
\]

\[
\approx 1.9 \times 10^5 \text{ N}
\]

Thus the seismic load is nearly 20 times the wind load.

Phillips gives detailed calculations for the various modes of failure and for the corresponding seismic capacities. These show that the seismic response for which the structure is weakest is the overturning couple on the column supports. The corresponding failure mode is tensile failure of the pedestal bolts. For this failure mode the safety factor has the values of 0.5, 0.2 and 0.1 for the 100, 1000 and 10000 year return periods, respectively.

The accelerations are rather greater for the Temblor–Parkfield than for the NRC response spectra. The greatest acceleration is experienced by the \( \frac{1}{4} \) full tank, but for this case the mass is much less. The dynamic correction factor chosen is 2, which corresponds approximately to the ratio of the peak ground accelerations for the site to those for the case of the full tank with the Temblor–Parkfield spectra.

The sphere did not appear to have been designed for earthquake resistance. Probably the principal horizontal force considered was wind loading. The relation for the wind load is

\[
W_w = C_D \rho_w \pi r_s^2 u_w^2
\]

where \( C_D \) is the drag coefficient, \( r_s \) the radius of the sphere (m), \( u_w \) the wind speed (m/s), \( W_w \) the wind load (N) and \( \rho_w \) the density of the air (kg/m³). At the estimated Reynolds number of 10⁷ the drag coefficient is 0.5. The wind speed with a 50 year return period would be between 18 and 32 m/s. Taking the higher value for the wind speed and \( r_s = 7.6 \) m and \( \rho_w = 1.25 \) kg/m³

\[
W_w \approx 1.1 \times 10^5
\]

The calculation of this failure mode may be summarized as follows. Figure A15.7 shows the overturning couple for which the relation is

\[
F_{sh} = \frac{1}{n} F_e \frac{l_1}{l_2}
\]

where \( F_e \) is the seismic load (N), \( F_{sh} \) the seismic tensile force on the bolts (N), \( l_1 \) and \( l_2 \) are the distances shown in Figure A15.7 (m) and \( n \) is the number of bolts resisting overturning. Taking \( l_1 = 7.94 \) m and \( l_2 = 0.66 \) m and using the seismic load for the 100 year return period

\[
F_{sh} = \frac{1}{24} (1.9 \times 10^6) \times 7.94
\]

\[
= 9.5 \times 10^5 \text{ N}
\]

Taking a bolt area of \( 8.0 \times 10^{-4} \) m² per bolt gives a bolt tensile stress of

\[
f_{sh} = \frac{9.5 \times 10^5}{8.0 \times 10^{-4}}
\]

\[
= 1.2 \times 10^9 \text{ Pa}
\]

where \( f_{sh} \) is the seismic tensile stress on each bolt (Pa). For the purpose of this assessment, tensile failure is assumed to occur at the yield stress, which for high tensile steel is some \( 0.6-0.7 \times 10^9 \) Pa. Taking the lower value of the yield stress, gives for the safety factor at the

<table>
<thead>
<tr>
<th>Return period (year)</th>
<th>Horizonal response (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sphere full</td>
</tr>
<tr>
<td>100</td>
<td>0.07</td>
</tr>
<tr>
<td>1000</td>
<td>0.17</td>
</tr>
<tr>
<td>10000</td>
<td>0.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Return period (year)</th>
<th>Horizonal response (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sphere full</td>
</tr>
<tr>
<td>100</td>
<td>0.11</td>
</tr>
<tr>
<td>1000</td>
<td>0.26</td>
</tr>
<tr>
<td>10000</td>
<td>0.54</td>
</tr>
</tbody>
</table>
100 year return period a value of $0.5 \times 10^5 / 1.2 \times 10^5$.

For none of the other failure modes considered was the safety factor less than unity at the 100 year return period, though for two others it fell to unity at the 1000 year return period and below it at the 10000 return period.

A15.14.4 Storage tank
An assessment of the seismic capacity of a flat-bottomed storage tank has been described by R.P. Kennedy (1989). The tank considered is 40 ft diameter with a shell 37 ft high and an overall height to the tank top of 43.4 ft.

The author describes in detail the use of the CDFM method. This consists of two parts, the determination of the seismic responses and the determination of the seismic capacities. There is not necessarily a one-to-one correspondence between a seismic response and seismic capacity. For a given response there may be several features resisting failure and all these must be considered.

The following responses are considered: (1) overturning moment in the tank shell immediately above the base plate of the tank; (2) overturning moment applied to the tank foundation through a combination of the tank shell and base plate; (3) base shear beneath the tank base plate; (4) combination of the hydrostatic plus hydrodynamic pressures on the tank side wall; (5) average hydrostatic minus hydrodynamic pressure on the base plate of the tank; (6) fluid slosh height. These responses are all expressed as forces except the last; for this what matters is whether the sloshing fluid hits the roof.

The author comments that the first of these responses is usually the governing one. The third is seldom governing for tanks with a radius greater than 5 m. The second, fourth and sixth seldom govern.

In investigating these responses at least two horizontal modes, the impulse and the convective, or sloshing, modes and one vertical mode should be considered.

Kennedy gives detailed calculations for the various seismic responses and for the corresponding seismic capacities. The governing response is usually the first, the overturning moment in the tank shell.

The seismic responses are determined using a value of 0.27 g for the peak ground acceleration. The overturning moment response is then estimated as 19600 kip-ft. The corresponding capacity is determined by considering (1) the compressive buckling capacity of the shell; (2) the tensile hold-down capacity of the anchor bolts, including their anchorage and attachment to the tank; and (3) the hold-down capacity of the fluid pressure acting on the tank base plate. The combined resistance of these gives an overturning moment capacity of 20800 kip-ft. The SME for this response is then calculated as 0.29 g ($0.27 \times (20800/19600)$).

This response gives the lowest value of the SME and the overall SME for the tank is thus determined as 0.29 g.

Kennedy also describes the determination of the seismic capacity in terms of the alternative FA method. Using this method the SME is found to be 0.31 g.

**Notation**

- $a$ peak ground acceleration (fraction of g); (cm/s$^2$)
- $a$, $a'$ constants in Equations A15.2.10 and A15.11.2, respectively
- $A$ median ground acceleration (fraction of g)
- $A_s$ maximum amplitude of earthquake (mm)
- $b$, $b'$ constants in Equations A15.2.10 and A15.11.2, respectively
- $c$ damping coefficient (kg/s)
- $C$ coefficient (Equation A15.9.1)
- $C_p$ drag coefficient
- $d$ peak ground displacement (cm)
- $E$ energy of earthquake (erg)
- $f_{sh}$ seismic tensile stress on bolts (Pa)
- $F$ force (N)
- $F_s$ seismic force (N)
- $F_{sh}$ seismic tensile force on bolts (N)
- $g$ acceleration due to gravity (m/s$^2$)
- $h$ focal depth (km)
- $H$ depth of soil layer (m)
- $I$ intensity of earthquake
- $I_a$ occupancy importance factor
- $I_e$ epicentral intensity of earthquake
- $k$ modifying factor for focal distance (km)
- $k$ resistance (kg/s$^2$) (Equations A15.10.2–5)
- $K$ framing factor
- $l_1$, $l_2$ active distance of support column (m)
- $l_1$, $l_2$ spacing + inset of bolts on support column base plate (m)
- $m$ mass (kg)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_b$</td>
<td>body wave magnitude of earthquake</td>
</tr>
<tr>
<td>$M$</td>
<td>magnitude of earthquake</td>
</tr>
<tr>
<td>$M_L$</td>
<td>local magnitude of earthquake</td>
</tr>
<tr>
<td>$M_s$</td>
<td>surface wave magnitude of earthquake</td>
</tr>
<tr>
<td>$n$</td>
<td>number of bolts resisting overturning</td>
</tr>
<tr>
<td>$N$</td>
<td>frequency of earthquake (y$^{-1}$)</td>
</tr>
<tr>
<td>$P$</td>
<td>annual probability of exceedance</td>
</tr>
<tr>
<td>$r$</td>
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<tr>
<td>$R$</td>
<td>focal distance (km)</td>
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<td>site factor</td>
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<tr>
<td>$S_a$</td>
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</tr>
<tr>
<td>$S_d$</td>
<td>spectral displacement (m)</td>
</tr>
<tr>
<td>$S_v$</td>
<td>spectral velocity (m/s)</td>
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<tr>
<td>$t$</td>
<td>time (s)</td>
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<tr>
<td>$T$</td>
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<tr>
<td>$T_n$</td>
<td>natural period of soil layer (s) (Equation A15.7.1)</td>
</tr>
<tr>
<td>$u_w$</td>
<td>wind speed (m/s)</td>
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<tr>
<td>$v_s$</td>
<td>velocity of shear wave (m/s)</td>
</tr>
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<td>$W_s$</td>
<td>seismic load (N)</td>
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<td>wind load (N)</td>
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<td>$x$</td>
<td>displacement (m)</td>
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<td>$Z$</td>
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<tr>
<td>$\beta_U$</td>
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<tr>
<td>$\lambda$</td>
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</tr>
<tr>
<td>$\rho_a$</td>
<td>density of air (kg/m$^3$)</td>
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<tr>
<td>$\omega$</td>
<td>damped frequency (s$^{-1}$)</td>
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<tr>
<td>$\omega_n$</td>
<td>natural frequency (s$^{-1}$)</td>
</tr>
</tbody>
</table>

**Subscripts**

- $D$: damping
- $I$: inertia
- $\text{max}$: maximum value
- $S$: elastic
Appendix

San Carlos de la Rapita

Contents

A16.1 The Camp Site A16/2
A16.2 The Road Tanker A16/2
A16.3 The Fire and Explosions – 1 A16/2
A16.4 The Emergency and the Aftermath A16/3
A16.5 The Fire and Explosions – 2 A16/3
A16.6 Some Lessons of San Carlos A16/5
At about 14.30 in the afternoon of 11 July 1978 fire and explosions from a road tanker carrying propylene occurred at a camp site at Los Afaques (The Sand Dunes) at San Carlos de la Rapita between Barcelona and Valencia in Spain. The eventual death toll was 215.

A Court of Inquiry on the disaster was held at Tarragona (Court of Inquiry, Tarragona 1982). A report was submitted to the inquiry by Carrasco (1978). Independent investigations for the HSE were been carried out by Scilly (1978) and Hymes (1983 SRD R275), for the Hampshire Fire Brigade by Stinton (1978, 1979, 1983) and for the Dutch Directorate General of Labour by Ens (1986 LPB 68). Analyses of the accident are given by V.C. Marshall (1985, 1986 LPB 72, 1987).

Selected references on San Carlos are given in Table A16.1.

Table A16.1 Selected references on San Carlos

<table>
<thead>
<tr>
<th>Reference</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrasco (1978); Stinton (1978, 1979a, b, 1983); UKAEA (1979); J. Harris (1979); Court of Inquiry, Tarragona (1982); Moodie (1982); Scilly (1983 SRD R275, 1986 LPB 61); Manas (1984); V.C. Marshall (1985, 1986 LPB 72, 1987); Ens (1986 LPB 68, 72); Foxcroft (1986 LPB 71); Bond (1987 LPB 73)</td>
<td></td>
</tr>
</tbody>
</table>

A16.1 The Camp Site

The camp site was a triangular shaped piece of land between the coast road and the sea some 3 km from the nearest town (San Carlos de la Rapita) to the north. It was 200 m in length and 10000 m² in area, tapering from about 100 m wide at the north to 30 m at the south end, and 60 m wide at the point of the accident. There was a brick wall on a concrete foundation between the road and the camp.

On the day of the accident the camp site was fully booked with some 800 people, but not all these were there at the time and in the area affected. Estimates of the number on site and of the number in the area most affected are 500 and 300–400, respectively.

A16.2 The Road Tanker

The road tanker was manufactured in 1973. It had no pressure relief valve and no pressure test certificate. It had nominal and actual capacities of 45 and 44.4 m³.

It has been alleged that the tanker had been used on previous occasions to carry ammonia, which can lead to cracking of the tank, but this has been denied.

At 12.05 the tanker took on a load of propylene at the ENPETROL Tarragona refinery. The system was that the driver would learn how much he was carrying when the vehicle was weighed at the weighbridge. There was no metering or other device to prevent overfilling. If he wished to reduce the load, he could burn some off using a device like a flamethrower. The maximum load for the vehicle was 19 te, but it was plated as suitable for a maximum load of 22 te and it was actually weighed out as a 23.5 te load. At 12.35 the vehicle left the refinery.

The driver had a recommended route, which was the motorway, and was provided with the toll money, but actually took the N340 coast road, which went past the Los Afaques camp.

A16.3 The Fire and Explosions – 1

The sequence of events at the camp site is not entirely clear, but several eyewitness accounts are available. V.C. Marshall (1987) quotes the following. A young man serving a customer in the camp shop off the main site heard a bang. He got into his car to investigate and two minutes after the first sound heard a severe explosion. A ‘fireball’ appeared on the site. A tourist in the camp restaurant heard a ‘pop’ from a tanker on the main road and saw a milky cloud drifting towards him. He ran to move his car and seconds later the cloud ignited. In one newspaper account a motorcyclist following the vehicle said that smoke and fire were issuing from the tank. In another such account a tourist walking his dog at the camp site entrance saw the tanker start to snake and then tip over; there followed almost immediately an explosion and fire.

There were conflicting reports on the last movements of the road tanker, summarized by Hymes (1983 SRD R275). They include reports to the effect that the driver stopped at the camp with the tanker already leaking; that he stopped after it sprang a leak with a sharp report at the camp; that the vehicle veered across the road and broke through the camp site wall, suffering either a small leak or complete disintegration; and that the tanker veered across the road and struck the wall a glancing blow.

Hymes gives two photographs, the first captioned as showing the ignited gas cloud and the second the cloud on fire. The latter photograph is shown in Figure A16.1. The photographer stated that the time between taking his first picture and going to the camp entrance to

Figure A16.1 The fire preceding the ‘fire ball’ at San Carlos (Hymes, 1983 SRD R275) (Courtesy of the Safety and Reliability Directorate)
take further shots was one to two minutes and that the tanker ruptured violently after a few minutes.

It is reported that until the main ‘fireball’ event people stood around watching the pall of smoke from the fire. When it did occur large numbers, many scantily clad, were burned, some running into the sea to escape or douse the flames.

The area of damage and injury, including injury outside the flame envelope, is quoted by Marshall as covering an area equivalent to that of a 125 m radius circle. Over 90% of the camp site was gutted by fire.

The explosion effects were variable. The discotheque about 75 m from the tanker was completely demolished, probably by an explosion of the gas inside it, killing four people, but in the opposite direction at a distance of only 20 m a motor cycle still stood on its footrest. Many other objects in the camp liable to be blown over by blast still stood.

The site after the event is shown in Figure A16.2.

The vehicle was torn into four main pieces. Some two-thirds of the tank, including the rear portion, flew to the north-west, landed on the ground some 150 m away and then slid and came to rest in the outer wall of a restaurant about 300 m from its starting point. The middle section travelled about 100 m to the north-east into the camp. The cab unit travelled some 60 m along the line of the road to the south. The front end cap fetched up about 100 m beyond the cab. The location of some of the fragments is shown in Figure A16.3. The front end cap is the white hemispherical object at the bottom of Figure A16.3.

**A16.4 The Emergency and the Aftermath**

For about half an hour after the fire there were some 200–300 people milling round the camp, many seriously burned and calling for help. Private cars and taxis began to ferry the injured to a hospital at Amposta 13 km away. The first ambulance came at 14.45 from the Shell oil drilling site at San Carlos. The municipal ambulances came at 15.05 and the fire brigade about 15.30.

The road was still blocked by the burning cab so that victims had to be rescued from both sides of the camp and taken north to Barcelona or south to Valencia as circumstances permitted. Those taken north to Barcelona received primary medical care at points en route, while those taken south to Valencia 165 km away did not. In the first week the death rate at Valencia was twice that at Barcelona, but over two months the death rates evened up, since most victims were too badly burned to survive.

Over 100 people died outright. Others died later from burns, so that the final figures were 215 dead and 67 injured.

Most of those treated had very serious burns. Out of 148 cases 122 had third degree burns to 50% or more of the body. Either there were fewer people only slightly burned or they received treatment elsewhere.

**A16.5 The Fire and Explosions – 2**

The Court of Inquiry held that there had been a rupture of the road tanker due to hydraulic overfill. This was the explanation given in a report submitted to it by Carrasco (1978).

Other authors have put forward alternative explanations. There appear to be three principal hypotheses concerning the initial event: (1) hydraulic rupture of the tank, (2) a small leak on the tank and (3) a road accident.

A version of the second hypothesis has been described by Hymes (1983 SRD R275). This is that a leak occurred on the tanker, that a gas cloud formed and found a source of ignition and that the flames burned back to the
tanker. There followed an engulfing fire which caused a BLEVE. The vessel was in a weakened condition and the time for the BLEVE to occur was shorter than usual. Hymes does not state how the tanker came to stop at the camp, but on this scenario it could have been to attend to the leak.

A somewhat similar account is given by Stinton (1983).

The starting point in the argument in favour of the third hypothesis, as developed by Ens (1986 LPB 68), is the need to explain how the tanker came to stop and how the tank itself failed. Relevant here is the evidence of the one eyewitness who saw smoke and flames were coming from the tanker and of the other who saw it snaking. The hypothesis is as follows. The tanker was grossly overfilled and under stress so that it was liable to burst if subjected to impact. It crashed due to a driver failure or tyre defect, causing it to break through the boundary wall into the camp site. The tank ruptured and released its contents. A gas cloud and liquid pool formed, the gas being at first too rich to burn rapidly. In due course, however, the heat vaporized the liquid pool and there was a fireball. Minor explosions may have occurred at the edges of the cloud and stronger explosions in the buildings.

With regard to the first hypothesis, that the tank suffered hydraulic rupture, attention has focused on the overfilling of the tanker and on the possible effects of this. The calculations on this aspect are very dependent on the assumptions made about the volume and temperature of the liquid when the tanker left the refinery.

Evidence was presented by Carrasco (1978) that the tank contents could have warmed up sufficiently in 2½ h for the tank to become hydraulically full. He estimates a warm-up rate of 5.6°C/h.

Carrasco's work has been criticized by Marshall and Ens. Marshall draws attention to the work of Moodie (1982) showing the need, in considering hydraulic
rupture, to allow for the expansion of the tank metal, the expansion being equivalent to between 3 and 6°C, depending on the steel used. Both authors, however, consider that it is possible that the tank had become hydraulically full. Ens suggests that this becomes credible if allowance is made for a difference between nominal and actual tanker capacity, weighing errors and warming up of the liquid in the terminal pipework. Under such biaxial stress the material would no longer be ductile but would become brittle.

V.C. Marshall (1987) gives an extensive discussion of the possible warm-up of the tank, the hydraulic overfill and physical rupture, the behaviour of the fragments and the fire. Despite his critique of Carrasco, he concludes that hydraulic rupture of the tank is the most likely cause of the incident.

He suggests that the initial bang heard was probably the tank rupture, that the later explosion was of gas which had entered a building and then exploded inside it and that the fire was a severe flash fire rather than a vapour cloud explosion or a BLEVE. The pattern of injuries, with a large proportion of dead to injured, is consistent with a flash fire.

Hymes, Ens and Marshall all give detailed accounts of the site and of the physical evidence such as the fragments, the explosion damage and the burned area.

### A16.6 Lessons of San Carlos

Among the lessons of San Carlos are the importance of

1. Equipment, procedures, supervision and training to prevent overfilling of vehicles carrying hazardous materials.
2. Provision of pressure relief on vehicles carrying flammable materials.
3. Routing of vehicles carrying hazardous materials away from populated areas and vulnerable targets.
Appendix

ACDS Transport Hazards Report

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A17.2  Substances and Activities  A17/2
A17.3  Event Data            A17/2
A17.4  Hazard Models          A17/2
A17.5  Injury Relations       A17/7
A17.6  Population Characteristics A17/8
A17.7  Rail Transport         A17/8
A17.8  Road Transport         A17/9
A17.9  Marine Transport: Ports A17/10
A17.10  Transport of Explosives  A17/13
A17.11  Risk Criteria          A17/14
A17.12  Assessed Risks        A17/16
A17.13  Risk Evaluation and Remedial Measures A17/22
A17.1 The Investigation

The Advisory Committee on Major Hazards in its Third Report (Harvey, 1984) recommended that although its terms of reference were restricted to fixed installations, the major hazard potential from the transport of hazardous materials should also receive attention. The HSC accordingly asked the relevant permanent committee, the Advisory Committee on Dangerous Substances (ACDS) to examine the matter. Its findings are presented in Major Hazard Aspects of the Transport of Dangerous Substances (ACDS, 1991) (the ACDS Transport Hazards Report).

Selected references on the ACDS Transport Hazards Report are given in Table A17.1. Its principal contents are shown in Table A17.2.

Table A17.1 Selected references on the ACDS Transport Hazards Report

<table>
<thead>
<tr>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACSD (1991); Turner (1992 LPB 101); Anon. (1992 LPB 107, p.29)</td>
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</tbody>
</table>

Table A17.2 Principal contents of the ACDS Transport Hazards Report

- Introduction
- Scope
- Method of Study
- Quantified Risk Assessment
- Risk Criteria
- QRA Results for Rail, Road and Ports
- The Peterborough Incident
- Risk Reduction and Mitigation
- Emergency Planning and Response
- Comparison of Rail and Road Transport
- Overview
- Recommendations

Appendices, including
- Appendix 3 Summary of World-wide Major Hazard Transport Accidents
- Appendix 4 Summary of Movements and Regulatory Arrangements
- Appendix 5 Modes and Consequences of Failure of Road and Rail Tankers Carrying Liquefied Gases and Other Hazardous Liquids
- Appendix 6 Criteria for Evaluating Individual and Societal Risks in Transport
- Appendix 7 Port Risks
- Appendix 8 Transport by Rail
- Appendix 9 Transport by Road
- Appendix 10 Transport of Explosives by Rail and Road
- Appendix 11 Comparison of Risks for Transport by Rail and Road
- Appendix 12 Tolerability of Risks of Rail and Road Transport and Risk Reduction and Mitigation
- Appendix 13 Emergency Planning
- Appendix 14 Management of Safety in Transport

Some of these entries are paraphrased

A17.2 Substances and Activities

The study deals with four main transport activities: (1) rail transport, (2) road transport, (3) marine transport (ports only) and (4) explosives.

The substances investigated varied as between these different modes of transport. For road and rail four substances were studied: (1) motor spirit, (2) LPG, (3) chlorine and (4) ammonia. These substances are referred to in the report, and therefore here, as the non-explosive materials.

For ports the substances considered were (1) flammable liquids, (2) flammable liquefied gas, (3) toxic liquefied gas, (4) ammonia and (5) ammonium nitrate.

The transport of explosives by rail and by road was the subject of a separate study within the report.

Excluded from the study were air transport, pipelines and radioactive substances.

A17.3 Event Data

The report contains a wealth of data on the movement of hazardous materials by rail, road and sea, on the nature and composition of loads and cargoes, and on event frequencies and probabilities.

The event frequencies cover not only land transport accidents such as vehicle and wagon impacts and fires and marine accidents such as collisions, strikings, groundings and engine room fires but also data used in the various fault trees.

The probability data include release size distributions, ignition probabilities and so on.

A17.4 Hazard Models

The study makes use of hazard models for fire, explosion and toxic release.

The fire models are for (1) a torch fire, (2) a flash fire and (3) a pool fire and the explosion models are for (1) a vapour cloud explosion, (2) a BLEVE and (3) a condensed phase explosion. The models relevant to toxic release are those for gas dispersion.

The pool fire model is required for motor spirit, the other fire models and the VCE and BLEVE models for LPG or LFG.

The hazard models fall into two sets. The first set comprises HSE models, which are used for rail and road transport, the second set models incorporated in the SAFETI code, which are used for ports. In the following account the HSE models are described first, followed by those used in SAFETI, where applicable.

A17.4.1 Gas dispersion

The gas dispersion models used are DENZ and CRUNCH for instantaneous and continuous releases, respectively. The main direct application of these models is to toxic release.

Use is also made of the parameterizations by Considine and Grint (1985) of results for flammable gas clouds obtained from DENZ and CRUNCH.

The gas dispersion model used in SAFETI is the dense gas dispersion model of R.A. Cox and Carpenter (1980).
A17.4.2 Torch fire
The torch, or jet, fire model used is that of Considine and Grint (1985), modified to give length and width and representing the flame as a cone.

Atmospheric transmissivity is determined by the method of Simpson (1984 SRD R304).

A17.4.3 Flash fire
For a flash fire use is made of the model of Considine and Grint (1985). The formation of the gas cloud is modelled using the gas dispersion models described in Subsection A17.4.1 and its combustion by assuming that it burns within the contour of the lower flammability limit.

A17.4.4 Pool fire
For a pool fire use is made of the SPREAD model, a sister model of SPILL (Prince, 1981 SRD R210), which differs from the latter in treating simultaneously the spreading and burning of the pool. The regression rate used is that of Mitzen and Eyre (1982). The other features of the model are not described but are evidently conventional.

A17.4.5 Vapour cloud explosion
The treatment of a vapour cloud explosion involves the determination of the mass of fuel in the cloud and of the overpressure resulting from explosion of this fuel.

For the mass of fuel in the cloud, for an instantaneous release the method is to take this mass as twice the flash fraction. It is assumed that no explosion occurs if the mass is less than 10 te. For a continuous release the mass of fuel in the cloud is determined by the method of Considine and Grint (1985).

The overpressure from explosion of this mass of fuel is determined from the correlation of Kingery and Pannell (1964) between mass of explosive and peak overpressure for TNT. The implication is that a TNT equivalent model is used, but further details are not given.

The VCE model used in SAFETI is the TNO correlation model.

Table A17.3 Coefficients for LPG hazard model fatal injury equation (Advisory Committee on Dangerous Substances, 1991) (Courtesy of HM Stationery Office)

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
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<td>2 kgs⁻¹ torch flame</td>
<td>332</td>
<td>3.3</td>
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<td>36 kgs⁻¹ torch flame</td>
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<td>53.4</td>
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<tr>
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<td>1850</td>
<td>0</td>
<td>0</td>
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<td>Flash fire/torch flame/BLEVE (20 te) D/5</td>
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<td>214.8</td>
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<td>0</td>
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<tr>
<td>Flash fire/torch flame/BLEVE (40 te) D/5</td>
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<td>298</td>
<td>0</td>
<td>0</td>
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<td>Flash fire/torch flame/BLEVE (20 te) F/2</td>
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<td>Flash fire/torch flame/BLEVE (40 te) F/2</td>
<td>238145</td>
<td>2016</td>
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<tr>
<td>20 te flash fire D/5</td>
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<td>0</td>
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<tr>
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<td>222</td>
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<td>0</td>
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<td>40 te flash fire D/5</td>
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<td>340</td>
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<td>0</td>
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<td>36 kgs⁻¹ VCE</td>
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</tr>
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<td>222</td>
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<td>34636</td>
<td>346</td>
<td>173</td>
<td>52916</td>
</tr>
</tbody>
</table>

A17.4.6 BLEVE
The BLEVE model used is that of A.F. Roberts (1981/82).

A17.4.7 LPG fire model
The hazard models described are used in conjunction with the release scenarios for rail and road transport to produce an overall LPG fire model.

In this overall model the number of fatalities is obtained from the relation
\[ N = D(\alpha P_{\text{id}} + b P_{\text{id}} P_{|\text{id}} + c P_{\text{id}}(1 - P_{|\text{id}}) + d) \]  [A17.4.1]

where \( D \) is the population density (persons/m²), \( N \) the number of fatalities, \( P_{|\text{id}} \) the probability of fatal injury given that the person is within the cloud, \( P_{\text{id}} \) the probability of being indoors, \( a \) and \( d \) are coefficients. The coefficients \( c \) and \( d \) are associated with vapour cloud explosions.

The model is shown in Table A17.3 in the form of the coefficients \( a \) and \( d \) to be used in Equation A17.4.1.

A17.4.8 LPG fire scenarios
The LPG fire models just described are applied in the report to the yield the hazard ranges and areas for the set of scenarios relevant to rail and road transport. These are summarized in Table A17.4.

A17.4.9 Condensed phase explosion
The condensed phase explosion model applicable depends on the type of explosive. This aspect is discussed in Section A17.10. An HDL1 explosive constitutes a mass explosion hazard, an HDL2 explosive a projection, or fragmentation, hazard and an HDL3 explosive a fire hazard.

For the estimation of the overpressure from an HDL1 explosive use was again made of the correlation of Kingery and Pannell (1964).

For the fragments from an HDL2 explosive data were supplied by the MoD from explosives trials, which allowed an estimate to be made of the density of fragments possessing a kinetic energy in excess of
### Table A17.4
Hazard ranges and areas for rail and road transport scenarios obtained from the LPG hazard model (after Advisory Committee on Dangerous Substances, 1991)

#### A. Torch flames

<table>
<thead>
<tr>
<th>Release rate (kg/s)</th>
<th>Side-on</th>
<th>End on</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>Distance to 50% lethality</td>
</tr>
<tr>
<td></td>
<td>(m)</td>
<td>(m)</td>
</tr>
<tr>
<td>2</td>
<td>12.9</td>
<td>8.5</td>
</tr>
<tr>
<td>36</td>
<td>54.6</td>
<td>33</td>
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</table>

#### B. Flash fires: instantaneous releases (rail tank wagons)

<table>
<thead>
<tr>
<th>Vessel capacity (t)</th>
<th>Distance to 50% lethality</th>
<th>Distance to 1% lethality</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>D5 (m)</td>
<td>F2 (m)</td>
</tr>
<tr>
<td></td>
<td>D5 (m)</td>
<td>F2</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
<td>50</td>
</tr>
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<td>40</td>
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<td>70</td>
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<td></td>
</tr>
</tbody>
</table>

#### C. Flash fires: instantaneous releases (road tankers)

<table>
<thead>
<tr>
<th>Vessel capacity (t)</th>
<th>Distance to 50% lethality</th>
<th>Distance to 1% lethality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>140</td>
<td>150</td>
</tr>
</tbody>
</table>

#### D. Flash fires: continuous releases

<table>
<thead>
<tr>
<th>Release rate (kg/s)</th>
<th>Area of fire</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D5 (m²)</td>
</tr>
<tr>
<td>2</td>
<td>310</td>
</tr>
<tr>
<td>36</td>
<td>7800</td>
</tr>
</tbody>
</table>

#### E. BLEVEs (rail tank wagons)

<table>
<thead>
<tr>
<th>Vessel capacity (t)</th>
<th>Fireball radius (m)</th>
<th>Fireball duration (s)</th>
<th>Distance to 50% lethality (m)</th>
<th>Distance to 1% lethality (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>76</td>
<td>12</td>
<td>110</td>
<td>175</td>
</tr>
<tr>
<td>40</td>
<td>96</td>
<td>15</td>
<td>160</td>
<td>245</td>
</tr>
</tbody>
</table>

#### F. BLEVEs (road tankers)

<table>
<thead>
<tr>
<th>Vessel capacity (t)</th>
<th>Fireball radius (m)</th>
<th>Fireball duration (s)</th>
<th>Distance to 50% lethality (m)</th>
<th>Distance to 1% lethality (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>69</td>
<td>11</td>
<td>95</td>
<td>150</td>
</tr>
</tbody>
</table>

- a This is also the distance to spontaneous ignition
- b Cloud radius 75 m

80 J, taken as the lethal value. From these data two graphs were constructed, one for persons outdoors and one for those indoors. The data are classified as confidential but the report states that the average probability of fatal injury so obtained for persons in the open at 200 m is 0.02, while that for those indoors at the same distance is an order of magnitude less.

The model used for the fire on an HD1.3 explosive is a vertical flame. Further details are not given.

**A17.4.10 Condensed phase explosion: hazard range**

It is convenient to give at this point the estimate quoted in the report of the hazard range of a condensed phase explosion.
Figure A17.1 Possible responses of an individual affected by a toxic gas cloud (Advisory Committee on Dangerous Substances, 1991) (Courtesy of HM Stationery Office)

The ranges for fatal injury by thermal radiation or overpressure are in practice about 80-85 m, being limited by the maximum permitted loads of explosive of 16 te for a lorry and 20 te for a rail wagon. These are the distances at which the proportion of fatal injuries would be about 5%.
Figure A17.2  Hazard ranges for explosives (Advisory Committee on Dangerous Substances, 1991): (a) HD1.1 explosive (mass explosion hazard); and (b) HD1.3 explosives (fire hazard) (Courtesy of HM Stationery Office)
A17.4.11 Toxic release
For toxic release use is made of the appropriate gas dispersion model to determine toxic concentration and hence, for a particular exposure period, the corresponding toxic load.

The conventional infiltration model is used to determine the indoor toxic load.

For the number of persons affected by the release, the general approach is that used in the impact model described in the next section. The concentration contours are calculated at which the probabilities of fatal injury are 1.0, 0.9, 0.5 and 0.1. This gives between these isolaths three zones with concentrations denoted \( C_1, C_2 \) and \( C_3 \) and with average probabilities of fatality taken as 0.95, 0.3 and 0.1.

For each zone there is a corresponding probability of escape indoors, the values used being 0 for \( C_1 \), 0.2 for \( C_2 \) and 0.8 for \( C_3 \).

An analysis is given of the possible responses of an individual affected by a toxic gas cloud. The results are shown in Figure A17.1.

A17.5 Injury Relations
Injury models are used in the study to relate the intensity of the physical effects to the probability of injury. These are mainly probit equations, but HSE dangerous doses are also utilized. Some use is also made of rules-of-thumb.

The injury relations fall into two sets. The first set comprises HSE models, which are used for rail and road transport, the second set relations incorporated in the SAFETI code, which are used for ports. In the following account the HSE relations are described first, followed by those used in SAFETI, where applicable. In some cases no details are given for the latter; where this is the case, it should not be assumed that they are the same as the HSE relations.

A17.5.1 Thermal radiation
For fatal injury from thermal radiation use is made of the probit equation of Eisenberg, Lynch and Breeding (1973);

\[
Y = -14.9 + 2.56 \ln(I^{4/3})
\]  \hspace{1cm} \text{[A17.5.1]}

where \( I \) is the thermal radiation (kW/m\(^2\)), \( t \) the time (s) and \( Y \) the probit.

In the SAFETI work on fireballs from hot rupture of large cargoes in port, a modification of the Eisenberg equation was used. In the region of thermal radiation above 500 kJ/m\(^2\), it was assumed that 75% of persons outdoors and 25% of those indoors are killed, either by radiation or secondary ignition effects.

A17.5.2 Fire engulfment
Injury can also occur due to engulfment in a fire. The assumptions made are that a person outdoors is killed, but that for a person indoors there is a certain probability of survival with the complementary probability \( P_i \mid | \) of becoming a fatality.

In the SAFETI work the assumptions made were that for a flash fire all persons outside within the LFL contour and 30% of those indoors within the contour are killed but that no fatalities occur beyond this contour.

A17.5.3 Explosive: explosion overpressure
An HD1.1 explosive constitutes a blast hazard. For fatal injury two equations are given, the first being used in the road and rail transport study and the second, and more up-to-date, in the port study, reflecting developments as the work progressed.

The relationship given is for fatalities amongst persons indoors and is based on data on fatal injuries from V-2 rockets in World War 2, with allowance for the effect of bomb shelters. In this situation building collapse is a more significant cause of injury that overpressure. The data are shown in Figure A17.2(a). The relation is applied also to persons outdoors in the built-up area and therefore near to buildings.

The first version of the equation is

\[
Y = 1.47 + 1.37 \ln \rho^o
\]  \hspace{1cm} \text{[A17.5.2]}

where \( \rho^o \) is the peak side-on overpressure (psi) \( Y \) the probit. The second version is

\[
Y = 2.47 + 1.37 \log_{10} \rho^o
\]  \hspace{1cm} \text{[A17.5.3]}

A17.5.4 Explosive: explosion fragments
The hazard from an HD1.2 explosive is fragments. As stated in the previous section, the lethality of a fragment is taken as a function of its kinetic energy, and thus of mass and velocity, the lethal value being taken as one in excess of 80 J.

A17.5.5 Explosive: thermal radiation
The hazard from an HD1.3 explosive is thermal radiation. Figure A17.2(b) shows the relationship given in the report for this.

A17.5.6 Chlorine toxicity
For fatal injury from exposure to chlorine use is made of the following probit equation:

\[
Y = -4.4 + 0.52 \ln(C^{2.75})
\]  \hspace{1cm} \text{[A17.5.4]}

where \( C \) is the concentration of chlorine, \( t \) the exposure time and \( Y \) the probit.

A17.5.7 Ammonia toxicity
For fatal injury from ammonia the probit equation used is

\[
Y = -12.2 + 0.8 \ln(C^2)
\]  \hspace{1cm} \text{[A17.5.5]}

where \( C \) is the concentration of ammonia, \( t \) the exposure time and \( Y \) the probit.

The SAFETI code uses for fatal injury from ammonia the probit equation.

\[
Y = -9.82 + 0.71 \ln(C^2)
\]  \hspace{1cm} \text{[A17.5.6]}

where \( C \) is the concentration of ammonia (ppm), \( t \) the exposure time (s) and \( Y \) the probit. The group \((C^2t)\) is actually computed as the time integral of the square of the concentration.

A17.5.8 Hazard impact
The method principally used in the report to estimate the impact of the hazard is as follows. The ranges are determined at which the physical effect is lethal at the 0.90, 0.50 and 0.10 probability levels. The areas within these contours are denoted \( A_{90}, A_{50} \) and \( A_{10} \) respectively. The average lethality within each area is taken as the average of the lethalties at the bounding contours.
Thus the lethality with the circle $A_90$ is 0.95 ($=(1.0-0.90)/2$), that within the annulus $(A_{95} - A_{90})$ is 0.7 and that at within the annulus $(A_{10} - A_{95})$ is 0.3. This yields the hazard impact relation

$$N = D[0.95A_{90} + 0.7(A_{95} - A_{90}) + 0.3(A_{10} - A_{95})]$$

where $A$ is an area (m²), $D$ the population density (persons/m²) and $N$ the number of fatalities.

Use is also made of variations on this basic equation.

### A17.6 Population Characteristics

In transport scenarios the characterization of the population exposed tends to be much more complex than for fixed installation scenarios. A significant proportion of the modelling described in the report is addressed to this aspect.

For the general population the report utilizes four categories of population density. These are 4210, 1310, 2120 and 20 persons/km².

The proportion of the general population outdoors is taken for the purposes of the assessment as a function of the meteorological conditions, particularly conditions D5 and F2.

This characterization of the general population essentially suffices for the assessment of fixed sites such as marshalling yards and ports but needs to be supplemented by additional models for rail and road transport. These models, which are described below, are relatively complex but this complexity is necessary to obtain a realistic estimate of the risks.

### A17.7 Rail Transport

The hazard of rail transport of non-explosive materials is considered in Appendix 8 of the report.

An account has been given in Chapter 23 of the rail transport environment in the UK. It includes data given in the ACDS report on tank wagon capacities and movements and on release frequencies and probabilities.

#### A17.7.1 Wagons and movements

For the four hazardous materials studied, the rail tank wagon capacities and movements are given in Table 23.23. The wagon capacities are for motor spirit 32 and 75 te, for LPG 20 and 40 te, for chlorine 29 te and for ammonia 53 te.

Rail movements along the major routes in the UK in 1985 are shown in Table A17.5, which also give the population densities.

#### A17.7.2 Exposed population

The population exposed to an on route rail accident considered in the report are the personnel on the trains involved, the passengers in passenger trains and the general off-track population.

For the density of the general population along the track the basic method used was to use a map to assign each square kilometre of the trackside area to one of the four population densities described in Section A17.6.

A check was made on the adequacy of using these generalized values by taking one of the rail routes and determining the population densities with circles of 300 m radius along the track from the 1981 Census enumeration districts. The process was repeated with circles of smaller and larger diameter. The results showed that in general the map and census methods gave similar results, except that the map method underestimated the urban population in a few places.

For the exposure of passengers in a passenger train (PT) or to the community (PT) to hazard from a heavy goods trains (HGT) five basic scenarios are considered. One is the involvement of a PT or to the community (PT) to hazard from a heavy goods trains (HGT) five basic scenarios are considered. One is the involvement of a PT at a stop signal in the hazard zone from a release on a HGT, the obedient train case. The other four are collision of the PT and HGT, causing a

---

**Table A17.5** Rail traffic and population densities along some major routes in the UK in 1985 (Advisory Committee on Dangerous Substances, 1991) (Courtesy of HM Stationery Office)

<table>
<thead>
<tr>
<th>Motor spirit</th>
<th>LPG</th>
<th>Ammonia</th>
<th>Chlorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>All movements, wagon km/yr</td>
<td>10,199,095</td>
<td>1,390,590</td>
<td>1,348,080</td>
</tr>
<tr>
<td>Total wagon journeys/yr</td>
<td>55,814</td>
<td>4334</td>
<td>4500</td>
</tr>
<tr>
<td>Major route</td>
<td>Merseyside-Leeds-Humberside</td>
<td>Hampshire-Midlands</td>
<td>Teesside-Scotland</td>
</tr>
<tr>
<td>Route length, km</td>
<td>223</td>
<td>329</td>
<td>262</td>
</tr>
<tr>
<td>Number of wagons on route/yr</td>
<td>5300×32 te</td>
<td>1323</td>
<td>2204</td>
</tr>
<tr>
<td>Wagon km/yr on route</td>
<td>2,051,600</td>
<td>435,267</td>
<td>530,288</td>
</tr>
<tr>
<td>% traffic in that substance</td>
<td>20</td>
<td>31</td>
<td>39</td>
</tr>
<tr>
<td>Population density (people/sq km)</td>
<td>Aggregate length of route with that population density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban (4210) both sides</td>
<td>15</td>
<td>30</td>
<td>12.5</td>
</tr>
<tr>
<td>Suburban (1310) both sides</td>
<td>36.5</td>
<td>48</td>
<td>40.5</td>
</tr>
<tr>
<td>one side only</td>
<td>1.5</td>
<td>20</td>
<td>12.5</td>
</tr>
<tr>
<td>Built-up rural (210) both sides</td>
<td>17.2</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>one side only</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rural (20) both sides</td>
<td>143.2</td>
<td>215</td>
<td>181.5</td>
</tr>
<tr>
<td>one side only</td>
<td>1.5</td>
<td>22</td>
<td>12.5</td>
</tr>
<tr>
<td>Tunnel</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates whether the population is on both sides of the railway or on one side only, the other side being rural.
release; (2) collision of a PT and an HGT, where a release has already occurred; (3) a PT entering the hazard zone of a release from an HGT; and (4) a PT entering the hazard zone of a release from an HGT and colliding, causing a further release. Two wind conditions are considered: (1) wind along the track and (2) wind perpendicular to the track.

The proportion of carriages in the PT involved is the ratio of the length of the hazard-affected zone to the length of the train.

With regard to air infiltration into a PT, the ventilation on most modern trains is controlled from the driver's cab and is set at about 13 air changes/h. The driver experiences a ventilation rate about six times this and is thus effectively out of doors.

A17.7.3 Initiating events and event frequencies
The report considers two main types of initiating event. These are puncture of a tank wagon by collision or derailment and failure or maloperation of the tank wagon equipment.

The treatment given for the frequency of these events for each of the four substances and for the probability of ignition, immediate or delayed, of flammables is described in Chapter 23.

A17.7.4 Motor spirit events
For motor spirit, the scenarios considered are instantaneous releases of 32 and 75 te and continuous releases of 25 kg/s (equivalent to a 100 mm hole).

A release of motor spirit, if ignited, results in a pool fire. The pool spread and fire model used is described in Section A17.4.

For a continuous release the times for the 32 te and 75 te wagons to empty are approximately 20 and 50 minutes, respectively. The size of pool, and pool fire, formed depends on whether ignition occurs immediately. If ignition is delayed the radius of the pool from a 32 te wagon would be some 24 m and that for a 75 te wagon some 37 m. With immediate ignition, the pool radius in both cases would be 12 m. The pool radii for instantaneous releases would be similar.

A17.7.5 LPG events
For LPG, the scenarios are instantaneous releases of 20 and 40 te and continuous releases of 2 and 32 kg/s.

If the release is instantaneous and is ignited immediately, a fireball occurs. Otherwise, a flammable cloud forms. If this cloud is ignited, there is either a flash fire or a vapour cloud explosion.

If the release is continuous and is ignited immediately, a torch fire or a BLEVE occurs. Otherwise a flammable cloud forms. If this cloud is ignited, there is either a flash fire or a vapour cloud explosion. The flash fire may be accompanied by a torch fire or a BLEVE.

The report gives event trees for these scenarios.

A17.7.6 Chlorine and ammonia events
For chlorine and ammonia, the scenarios considered are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Chlorine</th>
<th>Ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-phase release from valve (kg/s)</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Single phase release from puncture (kg/s)</td>
<td>45.1</td>
<td>33.5</td>
</tr>
<tr>
<td>Instantaneous release from catastrophic failure (te)</td>
<td>29</td>
<td>53</td>
</tr>
</tbody>
</table>

The development of these events is determined using the hazard models described.

A17.7.7 Marshalling yards
In addition to these en route events, the report also addresses releases occurring in marshalling yards. The two materials of interest in this regard are LPG and chlorine. The frequency estimates for these events for the two materials are given in Chapter 23.

The release scenarios considered are the same as for the en route case.

A17.8 Road Transport
The hazard of road transport of non-explosive materials is considered in Appendix 9 of the report.
An account has been given in Chapter 23 of the road transport environment in the UK. It includes data given in the ACDS report on tanker capacities and movements and on release frequencies and probabilities.

A17.8.1 Vehicles and movements
For the four hazardous materials studied, the road tanker capacities and movements are given in Table 23.6. The tanker capacities are for motor spirit 20–25 te, for LPG 15 te, for chlorine 17 te and for ammonia 15 te.

A17.8.2 Exposed population
The population exposed to an en route road accident considered in the report are the personnel of the vehicles involved, the other road users and the general off-road population.

The road transport situation is rather different from that of rail. In particular, it is necessary to take into account the wide variety of types of road and of road usage.

Another basic difference is that the probability of other persons becoming involved in an incident is much higher for road than for rail.

For the density of the general population along the road the method is essentially similar to that used for rail transport.

The exposure of other road users to hazard from a road tanker is treated in terms of two zones, one for users behind the tanker and one for users on the other side of the road. For the former it is assumed that traffic backs up behind the tanker and that the section of the zone ahead of it is clear. In the second zone, on the other carriageway, the population density depends on whether the traffic stops or continues to move. It is assumed that the density in this zone is half that in the first zone.
The density of the road user population backed up behind the tanker is computed as follows. The traffic is assumed to consist of 10% heavy goods vehicles (HGVs). The length of road occupied by a HGV is taken as 20 m and that occupied by other vehicles as 4 m. There are assumed to be 1.5 persons/vehicle. This yields for motorways and for other roads population densities of 0.065 and 0.05 persons/m², respectively.

The full set of eight zones defined in the report comprises four on the same side of the road as the tanker and four on the other side. Zone a is one of standard population density, Zone b one of high density, Zone c a clear zone and Zone d the zone of road users behind the tanker. Zones h, g, f and e are, respectively, the corresponding zones on the other carriageway.

With regard to air infiltration into vehicles, work by M. Cooke (1988) has shown that for a car travelling at 40 mile/h the ram effect is sufficient to give one air change/min and air ingress will be even greater if the ventilation fan is on. For a stationary car use of the ventilation fan will again give about one air change/min. Even if the fan is off, the car is not expected to provide significant protection, the volume of the air space being small.

A17.8.3 Initiating events and event frequencies

The report considers two main types of initiating event. These are puncture of a tanker by collision and failure or maloperation of the tanker equipment.

The treatment given for the frequency of these events for each of the four substances and for the probability of ignition, immediate or delayed, of flammables is described in Chapter 23.

A17.8.4 Motor spirit events

For motor spirit, the scenarios considered are instantaneous releases of 4, 8 and 12 te and a continuous release of 25 kg/s (equivalent to a 100 mm hole). The tankers contain six compartments and the instantaneous releases corresponds to spills from one, two or three of these.

A release of motor spirit, if ignited, results in a pool fire. The pool spread and fire model used is described in Section A17.4.

The pool areas obtained are

<table>
<thead>
<tr>
<th>Spill</th>
<th>Immediate ignition</th>
<th>Delayed ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 kg/s</td>
<td>314</td>
<td>908</td>
</tr>
<tr>
<td>4 te</td>
<td>707</td>
<td>1018</td>
</tr>
<tr>
<td>8 te</td>
<td>1385</td>
<td>1964</td>
</tr>
<tr>
<td>12 te</td>
<td>2124</td>
<td>3019</td>
</tr>
</tbody>
</table>

A17.8.5 LPG events

For LPG, the scenarios are an instantaneous release of 15 te and continuous releases of 2 and 32 kg/s.

If the release is instantaneous and is ignited immediately, a fireball occurs. Otherwise, a flammable cloud forms. If this cloud is ignited, there is either a flash fire or a vapour cloud explosion.

If the release is continuous and is ignited immediately, a torch fire or a BLEVE occurs. Otherwise a flammable cloud forms. If this cloud is ignited, there is either a flash fire or a vapour cloud explosion. The flash fire may be accompanied by a torch fire or a BLEVE.

The report gives event trees for these scenarios.

A17.8.6 Chlorine and ammonia events

For chlorine and ammonia, the scenarios considered are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Chlorine</th>
<th>Ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-phase release from valve</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>(kg/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single phase release from</td>
<td>45.1</td>
<td>33.5</td>
</tr>
<tr>
<td>puncture (kg/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instantaneous release from</td>
<td>17.5</td>
<td>15</td>
</tr>
<tr>
<td>catastrophic failure (te)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The development of these events is determined using the hazard models described.

A17.8.7 Lorry stopover points

In addition to these en route events, the report also addresses releases occurring at lorry stopover points. The three materials of interest in this regard are LPG, chlorine and ammonia. The frequency estimates for these events for the three materials are given in Chapter 23.

The release scenarios considered are the same as for the en route case.

A17.9 Marine Transport: Ports

The treatment of marine transport in Appendix 7 of the ACDS report is confined to the hazard at ports, which constitute fixed installations.

The study of ports was performed using the SAFETI code.

A17.9.1 Ports

There are in the UK some 42 ports with handling profiles exhibiting wide variety. The approach adopted was to study a set of three ports which had a representative set of major hazards. These ports were River Tees, the largest British chemical port complex Felixstowe, a busy port with moderate hazardous trades Shoreham, a small port with petroleum product trades

A17.9.2 Materials and movements

The principal hazardous materials and the movements of these materials through British ports are shown in Table A17.6.

A17.9.3 Exposed population and ignition sources

The model for the exposed population is that incorporated in the SAFETI code. The population is characterized in terms of the numbers of persons within 100 m grid squares. Separate distributions are used for night and day, the night-time figures being based on census data and the day-time ones on adjustments to these data.

The density of ignition sources is also modelled using the grid square method, with values of ignition probability assigned on the basis of judgement.
Table A17.6 Hazardous cargoes handled at British ports (after Advisory Committee on Dangerous Substances, 1991)

<table>
<thead>
<tr>
<th>Material group</th>
<th>Terminals</th>
<th>Visits</th>
<th>Amount per terminal (tc/year)</th>
<th>Amount per movement (tc/ship)</th>
<th>Total amount (te/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>17</td>
<td>1957</td>
<td>9244.347</td>
<td>80.291</td>
<td>157,153,891</td>
</tr>
<tr>
<td>Low flashpoint products</td>
<td>43</td>
<td>5163</td>
<td>478.261</td>
<td>39.83</td>
<td>20,365,228</td>
</tr>
<tr>
<td>High flashpoint products</td>
<td>41</td>
<td>3126</td>
<td>340.233</td>
<td>44.63</td>
<td>13,949,554</td>
</tr>
<tr>
<td>Flammable liquefied gas</td>
<td>26</td>
<td>2388</td>
<td>374.180</td>
<td>40.08</td>
<td>9,674,268</td>
</tr>
<tr>
<td>Toxic liquefied gas</td>
<td>4</td>
<td>87</td>
<td>113.926</td>
<td>52.33</td>
<td>455,303</td>
</tr>
<tr>
<td>Low flash chemicals</td>
<td>21</td>
<td>1244</td>
<td>105.689</td>
<td>17.71</td>
<td>2,205,975</td>
</tr>
<tr>
<td>High flash chemicals</td>
<td>23</td>
<td>1399</td>
<td>119.689</td>
<td>19.45</td>
<td>2,739,746</td>
</tr>
<tr>
<td>Explosive chemicals</td>
<td>19</td>
<td>258</td>
<td>14.283</td>
<td>10.52</td>
<td>271,377</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>15,662</td>
<td></td>
<td></td>
<td>207,015,342</td>
</tr>
</tbody>
</table>

A17.9.4 Initiating events and event frequencies

The report first considers the following types of marine event: (1) collision, (2) grounding, (3) striking and (4) impact. A collision occurs where two ships run into each other, a striking where a moored vessel is struck by a passing vessel and an impact where a vessel runs into a dock wall or jetty.

The starting point for the estimation of the frequency of these events at British ports was a study by the National Ports Council (1976), which was somewhat old and has known defects. The data were therefore reanalysed and supplemented by three additional data sets. The results of this analysis are given in Table A17.7, Section A.

The effects of these events were assessed separately for tankers and for gas carriers. For tankers the effects were taken to be (1) collision or striking below water, (2) collision or striking above water, (3) grounding damage or (4) impact damage. For each case a representative hole size was assigned.

For gas carriers all four marine events were assumed to have one of two effects: (1) cold leak through a hole or (2) cold rupture of the tank contents. For a cold leak the hole size was taken as that of the loading pipe connection, located at the bottom of a prismatic tank or at the mid-height of a spherical or cylindrical tank. For a cold rupture the release was taken as instantaneous from a pressurized tank or as occurring over 5 minutes from a refrigerated tank. It was assumed that 90% of the releases were leaks and 10% ruptures.

Four other events were also considered: (1) transfer spills, (2) tanker explosion, (3) gas carrier fires and (4) ammonium nitrate ship explosions.

The frequency of transfer spills was estimated from incidents reported to the HSE under NADOR in a 5.25 year period 1981–86. Transfer spills tend to be small and possibly, unreported. There were only eight spills reported, and just one for liquefied gas.

There are significant differences between cargoes and transfer arrangements which will affect the frequency of transfer spills. Differences identified included (1) cargo (liquid, pressurized liquefied gas or refrigerated liquefied gas), (2) transfer equipment (articulated hard arm or flexible hose), (3) proportion of cargoes unloaded, (4) use of vapour recovery, (5) use of ranging alarms, (6) emergency shutdown system (none, basic or advanced), (7) quick release coupling (none, pre-1987 or post-1987) and (8) environment (berth tidal or non-tidal, number of passing vessels).

The various transfer spills were condensed into four: (1) 3 minute full bore (LG only), (2) 5 minute full bore (liquid cargoes only), (3) 15 minute full bore and (4) 10 minute at 10% full bore.

Event trees were constructed to assist in estimating the proportion of each of these different outcomes. The branches in the event trees were determined by the
Table 17.7 Frequency of some marine accidents at British ports (after Advisory Committee on Dangerous Substances, 1991)

A Accidents by port type

<table>
<thead>
<tr>
<th>Port Type</th>
<th>Collision (per encounter)</th>
<th>Grounding (per km)</th>
<th>Striking (per passing)</th>
<th>Impact (per visit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sea port</td>
<td>$5.0 \times 10^{-4}$</td>
<td>$6.5 \times 10^{-5}$</td>
<td>$4.0 \times 10^{-6}$</td>
<td>$2.2 \times 10^3$</td>
</tr>
<tr>
<td>Wide estuary</td>
<td>$4.0 \times 10^{-5}$</td>
<td>$8.0 \times 10^{-6}$</td>
<td>$4.0 \times 10^{-6}$</td>
<td>$2.2 \times 10^3$</td>
</tr>
<tr>
<td>Wide river</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$9.0 \times 10^{-6}$</td>
<td>$2.1 \times 10^3$</td>
</tr>
<tr>
<td>Narrow river</td>
<td>$5.0 \times 10^{-4}$</td>
<td>$6.5 \times 10^{-5}$</td>
<td>$4.2 \times 10^{-5}$</td>
<td>$6.5 \times 10^3$</td>
</tr>
</tbody>
</table>

B Accidents by cargo group

<table>
<thead>
<tr>
<th>Cargo Type</th>
<th>Transfer accident (per cargo transferred)</th>
<th>Explosion (per visit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>$1.9 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Low flash products</td>
<td>$1.8 \times 10^{-4}$</td>
<td>$3.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>High flash products</td>
<td>$1.8 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Flammable liquefied gas</td>
<td>$7.6 \times 10^{-5}$</td>
<td>—</td>
</tr>
<tr>
<td>Toxic liquefied gas</td>
<td>$7.6 \times 10^{-5}$</td>
<td>0</td>
</tr>
<tr>
<td>Low flash chemicals</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>High flash chemicals</td>
<td>$1.5 \times 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td>Ammonium nitrate</td>
<td>0</td>
<td>$7.0 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Following three factors (1) immediate operator reaction (within one minute), (2) operation of ESD within 10 minutes and (3) effectiveness of ESD when operated.

The results of this work are the transfer spill frequencies shown in Table A17.7, Section B.

Tanker explosion frequencies were obtained from analysis of cases world-wide in Lloyd’s Casualty Returns for the period 1977–86. Table A17.7, Section B, shows the results.

The frequency of gas carrier fires was obtained from the study by Blything and Edmondson (1984 SRD R292). The data were processed to give incident rates per visit and per kilometre of approach.

It was estimated that there have been nearly 100 fire incidents but without any release of a cargo. Applying the statistics for the case of no event over a period of time, the estimate obtained for the probability of cargo release given a fire was 0.007. It was then assumed that 90% of such cases are hot leaks and 10% hot ruptures. Only the latter was considered further, the former being treated as leaks through safety valves which are consumed by the fire on the vessel.

For ammonium nitrate (AN) explosions the use of historical data was eschewed, since such incidents occurred many years ago and involved organic-coated material which is no longer used. Instead use was made of fault trees to predict the explosion frequency, the main path being a fire, probably from the engine room, entering a hold and melting part of the AN. Explosion could then be initiated by confinement, organic contamination or impact shock. The estimated frequency of AN ship explosion so obtained is $6.2 \times 10^{-8}$ per cargo.

A17.9.6 Releases of toxic liquefied gas
Releases of liquefied ammonia were modelled using the emission and dispersion models in SAFETI.

A17.9.7 Explosions of flammable liquid
For flammable liquid explosions modelling of representative events in respect of overpressure and fragments indicated that they are not in general significant beyond the vessel.

Such explosions do, however, cause casualties amongst the crew. From analysis of tanker losses in port in the period 1977–86 the following estimates were derived:

<table>
<thead>
<tr>
<th>Proportion of crew killed</th>
<th>Probability given cargo explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>0.37</td>
</tr>
<tr>
<td>0.40</td>
<td>0.11</td>
</tr>
<tr>
<td>0.65</td>
<td>0.04</td>
</tr>
<tr>
<td>1.0</td>
<td>0.04</td>
</tr>
</tbody>
</table>
A17.9.8 Ammonium nitrate explosions
Ammonium nitrate explosions are modelled using the TNT model with an appropriate value for the TNT equivalent of AN. For bagged AN this was taken as 13% of the shipment mass and for bulk AN as 33%. These values include allowance for the TNT equivalent of AN, the probable mass aboard when the explosion occurs and the efficiency of explosion for the different types of storage.

A17.9.9 Representative ports
The report gives the results of the detailed studies for the three representative ports of River Tees, Felixstowe and Shoreham.

A17.9.10 Extension to all ports
The risk results obtained for the three representative ports were applied using a 'simplified method', details of which are given in the report, to obtain an estimate of the national societal risk.

A17.10 Transport of Explosives
The hazard from the transport of explosives by rail and road is considered in Appendix 10 of the report.

A17.10.1 Categorization of explosives
The hazards presented by explosives include blast, fragments and fireball. The hazard which predominates in a particular case depends on the class of explosive.

The classification generally used in transport is the UN scheme, described in Chapter 23. The classes of explosive in this scheme which are of prime interest here are

- HD1.1 Mass explosion hazard
- HD1.2 Projection hazard
- HD1.3 Fire hazard
- HD1.4 No significant hazard

For the purpose of hazard assessment, the ACDS found it necessary to develop a categorization more adapted to this purpose, which reflects particularly the heat sensitivity of the substance or articles:

<table>
<thead>
<tr>
<th>UN class</th>
<th>ACDS category</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Heat sensitive substances in flammable packaging</td>
</tr>
<tr>
<td>HD1.1 N</td>
<td>Heat sensitive articles – not readily ignitable</td>
</tr>
<tr>
<td>P</td>
<td>Heat insensitive substances</td>
</tr>
<tr>
<td>HD1.2 Q</td>
<td>Heat sensitive articles</td>
</tr>
<tr>
<td>HD1.3 R</td>
<td>Heat sensitive substances in flammable packaging</td>
</tr>
<tr>
<td>T</td>
<td>Heat sensitive articles and substances in non-flammable packaging</td>
</tr>
<tr>
<td>HD1.4 W</td>
<td>Heat sensitive articles which present no great hazard</td>
</tr>
</tbody>
</table>

A17.10.2 Limits on loads
In the UK there are limits set to the load of explosive which can be carried. These are 16 te for a lorry and 20 te for a rail wagon, with a further limit of 40 te for a train.

A17.10.3 Rail transport of explosives: explosives and movements
The explosives moved in rail transport are predominantly (> 97%) military explosives. In the year 1988/89 BR data showed that there were 6132 movements of wagons containing explosives. The average explosives train journey is 320 km and the explosives movements are therefore $2.6 \times 10^6$ wagon km/year.

A special investigation was made of the composition of this traffic, which was found to be by Hazard Division as follows: HD1.1 21%; HD1.2 12%; HD1.3 10% and HD1.4 44%. The explosives traffic was also analysed by the HSE categorization scheme, which yielded by proportion of wagons the following dominant categories: N 10%; P 11%; Q 12%; T 10%; W 44%; N/T 3% and Q/W 4%. Some 27% of explosives wagons contained HD1.1 explosives, while 44% contained only HD1.4.

An analysis was also conducted to obtain the average values of the NEQ, effectively TNT equivalent, of the loads.

A17.10.4 Rail transport of explosives: exposed population
The population exposed to the rail transport of explosives was determined in the study using a method essentially similar to that used for the four non-explosive substances.

In the event, the assessment showed that for rail the risk is predominantly to the off-site population.

A17.10.5 Rail transport of explosives: initiating events and event frequencies
The main mechanisms identified in the report for the initiation of explosives are (1) fire, (2) impact and (3) unsafe explosives.

An analysis was made for rail and road transport of data from various sources including the minutes of the ESTC of the MoD, the annual reports of HM Inspector of Explosives and the SRD explosives data base EIDAS. There was for the UK over a 40 year period only one accident involving fatal injury, that at Peterborough in 1989 (HSE, 1990c). However, for both rail and road there were a number of dangerous occurrences, listed in Annex 2 of Appendix 10.

The report discusses in detail the methods by which it obtains its estimates of the explosive events in both forms of transport.

For rail transport it gives the following frequencies:

<table>
<thead>
<tr>
<th>Initiating mechanism</th>
<th>Frequency (events/wagon km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsafe explosives</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Fire</td>
<td>$6 \times 10^{-10}$</td>
</tr>
<tr>
<td>Impact</td>
<td>$1 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

The frequencies of events from unsafe explosives and from fire are thus assessed as broadly comparable, that assessed for events from impact being much lower.
A17.10.6 Rail transport of explosives: explosions en route
The explosion event depends, as stated earlier, on the class of explosive carried, being for HD1.1 a mass explosion, for HD1.2 fragments and for HD1.3 a fireball. The models described in Section A17.4 were applied using the hazard impact method given in that section.

A17.10.7 Rail transport of explosives: explosions in marshalling yards
The study identified one marshalling yard which handled some 50% of explosives traffic and in which explosives were present almost continuously. An outline assessment was made, although no formal estimates of individual or societal risk were produced. Application of the hazard model for the different classes of explosive showed that none of the events had a range to 10% lethality of more than 50 m. The population at this yard was beyond 110 m.

Analysis resulted in the following estimates for the frequency of initiation of an explosive load in a marshalling yard

<table>
<thead>
<tr>
<th>Initiating mechanism</th>
<th>Frequency (events/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsafe explosives</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fire</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Impact</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

A17.10.8 Road transport of explosives: explosives and movements
An investigation was made of the composition of the road explosive shipments broadly similar to that made for rail. It was found to be by Hazard Division as follows: HD1.1 94%; HD1.2 2%; HD1.3 40%. The explosives traffic was also analysed using the ACSD categorization scheme, which yielded by mileage covered the following categories: M 51%; N 23%; P 20%; Q 2%; R 3%; T 1%.

An analysis was also conducted to obtain the average values of the NEQ of the loads. The loads were classified into three bands with the load being distributed according to the following probabilities

<table>
<thead>
<tr>
<th>Band</th>
<th>Mean NEQ (kg)</th>
<th>Proportion of total mileage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>316</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>1778</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>14 125</td>
<td>14</td>
</tr>
</tbody>
</table>

A17.10.9 Road transport of explosives: exposed population
The population exposed to the road transport of explosives was determined in the study using a method essentially similar to that used for the four non-explosive substances.

In the event, the assessment showed that for road the risk is predominantly to the road users.

A17.10.10 Road transport of explosives: initiating events and event frequencies
The initiating events in road transport are the same as those for rail transport. The analysis made to obtain the frequency of the road events has been described above. The detailed methods are given in the report.

For road transport it gives the following frequencies:

<table>
<thead>
<tr>
<th>Initiating mechanism</th>
<th>Frequency (events/vehicle km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsafe explosives</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Fire</td>
<td>$2 \times 10^{-9}$</td>
</tr>
<tr>
<td>Impact</td>
<td>$2 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

The figures are somewhat similar to those for rail transport, the frequencies of events from unsafe explosives and from fire being assessed as broadly comparable, that assessed for events from impact being much lower.

A17.10.11 Road transport of explosives: explosions en route
The explosion event was modelled in a manner essentially similar to that used for rail transport. The models described in Section A17.4 appropriate to the class of explosive – HD1.1, HD1.2 or HD1.3 – were applied using the hazard impact method given in that section.

A17.10.12 Road transport of explosives: explosions at lorry stopover points
For explosives the situation at lorry stopover points is quite different from that at marshalling yards. Such points are always on premises licensed for the purpose. Lorries also stop briefly en route, but such stops are brief and are always attended. This risk was not pursued.

A17.11 Risk Criteria
The ACDS report gives in Appendix 6 a review of the principles underlying the setting of risk criteria and of the application of these to individual and societal risk.

The basic principle is that the risks should be as low as reasonably practicable (ALARP).

A17.11.1 Individual risk
With regard to individual risk to members of the public, the report refers to proposals made by the HSE. At the Hinkley Point Inquiry the HSE proposed that a fatality risk of $10^{-3}$/year is ‘intolerable’, though subsequent discussion suggested a lower level of intolerability. The HSE has also proposed a fatality risk of $10^{-6}$/year as ‘broadly acceptable’. The report adopts these criteria.

A17.11.2 Societal risk
In respect of societal risk, the ACDS criteria are formulated in term of FN curves. A distinction is made between an FN curve for risk at national level and one for risk at local level. Both types of risk occur in the study, the en route risks of rail, road and explosives transport being treated mainly as national and the risks at fixed sites such as ports, marshalling yards, lorry stopover points and unloading points as local.
Figure A17.3 FN curve risk criterion proposed by the ACDS for an identifiable community \( E - n = 10^{-6} \) (Advisory Committee on Dangerous Substances, 1991) (Courtesy of HM Stationery Office). Five concentrations are calculated at which the probabilities of fatal injury are close to 1.0 (concentrations \( C_1, C_2 \)) and 0.9, 0.5 and 0.1 (three concentrations \( C_3 \)). For each concentration there is a corresponding probability of escape indoors, the values used being 0 for \( C_1 \), 0.2 for \( C_2 \) and 0.8 for \( C_3 \).
The basic principle is illustrated in Figure 9.39, which shows an FN criterion plot for a local risk. The FN space is divided into four parts by three lines. The upper line is the tolerability line. Risks above this line are regarded as intolerable. The middle line is the scrutiny line. Risks between this line and the tolerability line may be unjustifiable and require further study. The bottom line is the negligible risk line. Risks below this line are regarded as negligible. Those between the negligible risk line and the scrutiny line should be reduced applying the ALARP principle.

For the local risk criterion FN plot the ACDS proceeds as follows. The reference point is the risks assessed at Canvey. These risks were regarded as on the borderline of tolerability. The values used by the ACDS for these risks are one third those predicted in the Second Canvey Report (HSE 1981a). This Canvey FN curve is then used as a guide both to the setting of the absolute value of the tolerability line and to its slope. This is illustrated in Figure A17.3.

The negligible risk line for the local FN plot is set three decades below the tolerability line. The arguments for this are based essentially on examination of the implications of setting it either two or four decades below. If the line were two decades down, the expectation value would be six fatalities per 1000 years. Applying a value of a life of £0.5 million gives a potential expenditure of £3000 per annum, which might justify a QRA done every ten years. It is argued that such a risk could hardly be regarded as negligible. On the other hand, if the negligible risk line were to be set four decades below the tolerability line, this would justify a potential expenditure of £30 per annum or £300 every ten years. On the basis of the cost of staff time this would barely permit even a cursory discussion, which suggests that this setting of the line is well into the negligible risk region. The slope of the tolerability line, and of the other lines, is –1, again reflecting the assessed risk at Canvey.

The treatment in the report for the national risk criterion FN plot is less firm. A tentative scrutiny line is developed for ports which is derived not from any argument based on direct combination of the number of ports and of the local criteria but rather on the implication of transferring trade from any port where the risks are already at the tolerability limit. This line is entered on the FN plot for national societal risk for ports also on other national societal risk plots as shown in the following paragraphs.

A17.11.3 Value of a life
As already mentioned, the report refers to the figure of £0.5 million for the avoidance of a statistical fatality, or the value of a life, used by the Department of Transport. It gives in Appendix 7 on ports a discussion of cost benefit analysis of proposed remedial measures in which a factor of 4 is applied to this figure, yielding a value of a life of £2 million (1991 value) to allow for ‘gross disproportion’ and uses this latter in the subsequent analysis.

A17.12 Assessed Risks
The assessed risks quoted in the study are now described. The report is careful to quote confidence bounds and to note uncertainties in, and qualifications to, the figures given. The account given here is in outline only.

A17.12.1 Rail and road transport
The assessed risks of rail and of road transport for the four non-explosive materials are presented as individual risks, as societal risks in the form of FN curves and as expectation values.

The individual risk to the public for rail transport of the four materials is assessed as negligible. For example, for a person living 50 m from the track the fatality risk from chlorine transport is predicted to be 2.4×10⁻⁷/year. For road transport, the situation is rather more complex in that there may be certain locations such as a sharp corner which have a higher than average risk. But in general the risk is assessed as negligible and as only a small fraction of the overall risk faced by road users.

The national societal risks assessed for the transport of the four materials, and for the combination of these, are shown in Figures A17.4(a) and (b) for rail and road, respectively. For rail transport the predominant risks are from motor spirit and ammonia, for road transport from motor spirit and LPG. For both modes the risk lies between the tolerability and negligible risk lines.

The expectation values of the annual number of fatalities for the rail transport of motor spirit and of ammonia are 0.074/year and 0.3/year and those for the road transport of motor spirit and LPG are 1.1/year and 0.8/year, respectively.

The report gives in Appendix 11 a comparison of the relative risks from rail and road transport. It makes the point that the choice of mode is not unrestricted. For example, motor spirit deliveries must at some stage be by road. A comparison of the rail and road risks shown in Figures A17.4(a) and (b) suggests that the risks of road transport are higher, but these graphs are for risks from actual traffic flows. Fair comparison needs to be based on a pattern of shipments which is the same for both modes. The report gives a detailed discussion but the overall conclusion is that the assessment made provides little support for a general preference for either mode on the grounds of safety.

A17.12.2 Ports
As far as regards ports, the study of the three ports found that in some limited areas near the ports individual risk was such that on the basis of the risk criteria adopted advice would be against new housing development.

The assessed societal risks are shown in Figure A17.5(a) and (b). The former shows the local societal risk for one of the ports, Felixstowe, obtained from the individual assessment for that port, and the latter the national societal risk for British ports, obtained from the simplified method described above. At none of the three ports was the local societal risk within the scrutiny zone. The national societal risk is also outside that zone.

A17.12.3 Transport of explosives
Turning to the risk from the transport of explosives, individual risk from en route transport by rail or road was not judged significant, but there was one marshalling yard where it might be.
Figure A17.4 FN curves for national societal risks from rail and road transport of four hazardous materials (Advisory Committee on Dangerous Substances, 1991): (a) rail transport; and (b) road transport. $E - n = 10^{-n}$ (Courtesy of HM Stationery Office)
Figure A17.5  FN curves for societal risks at British ports (Advisory Committee on Dangerous Substances, 1991): (a) local societal risk at Felixstowe; and (b) national societal risk (simplified method). $E - n = 10^{-n}$ (Courtesy of HM Stationery Office)
Figure A17.5 continued
Figure A17.6 FN curves for national societal risks from rail and road transport of explosives (Advisory Committee on Dangerous Substances, 1991): (a) rail transport; and (b) road transport. $E - n = 10^{-7}$ (Courtesy of HM Stationery Office)
Figure 17.6  continued
The national societal risks from rail and road transport of explosives are shown in Figures A17.6(a) and (b), respectively. The risks from road transport are higher by an order of magnitude. This is accounted for only in part by the greater volume moved; the proximity of other road users is also a factor. As Figure A17.6 shows, for explosives the principal contributor to the assessed societal risks in rail transport is the off-site population, whereas for road transport it is the road user population. For rail the fraction of the total risk contributed by the rail users is negligible, while for road the fraction contributed by the off-site population is 2-3%. For both modes the risk lies between the tolerability and negligible risk lines. The report indicates that further scrutiny would be appropriate.

A17.13 Risk Evaluation and Remedial Measures

The ACDS report gives an assessment of individual and of local and national societal risks, identifies certain activities or situations where the risks may need to be reduced or at any rate should be subject to further scrutiny and in Appendices 7, 10 and 12 makes proposals for a number of remedial measures.

One measure of general applicability is adherence to, and enforcement of, good working practice.

There are also various measures appropriate to the particular activity. For rail, it is suggested that the design and construction of tanker wagons for motor spirit and for ammonia, the improvement of communication by provision of radio telephones and the training of train drivers should receive attention.

For road, measures suggested relate to the design and construction of road tankers, use of designated routes, movement by night, provision of improved communication and availability of information in a chemical emergency and the training of drivers. Technical measures referred to for tankers are devices to monitor tyre pressure and so reduce the risk of a tyre fire; additives for middle distillates to reduce the risks from static electricity during switch loading; and cut-off devices to prevent engine overrun leading to possible ignition of vapour from spills following a tanker puncture. There may be scope for reduction of risk by the use of designated routes. Communications could be improved by provision of radio telephones. Information on the characteristics and emergency handling of chemicals carried should be available from chemical emergency information centres 24 hours a day.

For ports, the proposals made in the report include measures related to hard arm loading equipment and ESD systems, communications within the port, control of pleasure vessels and land use planning.

While many of these proposals might be made without benefit of a hazard assessment, the study provides guidance on priority areas. It identifies a number of features as meriting further scrutiny. These include the dominant contribution of motor spirit and ammonia to the en route national societal risks of rail transport and of motor spirit and LPG to those of road transport; the existence of individual risk with land use planning implications within 100 m of lorry stopover points; and the national societal risk for road transport of explosives.

At least as important as the assessed levels of risk is the improved understanding of the hazards involved. An example is the relative contributions to the national societal risk in the transport of explosives of the off-site and rail or road user populations.

Also of value are the negative results from the study. For the four non-explosive materials the report states that the risks from marshalling yards are not such as to inhibit further housing development in the zone where houses currently exist.

Notation

\( a-d \) constants
\( A \) area \((m^2)\)
\( C \) concentration
\( D \) population density \((\text{persons/m}^2)\)
\( I \) thermal radiation \((\text{kW/m}^2)\)
\( N \) number of fatalities
\( p^0 \) peak side-on overpressure
\( P_{i \mid d} \) probability of fatal injury given that a person is indoors and within the cloud
\( P_{id} \) probability that a person is indoors
\( P_{od} \) probability that a person is outdoors
\( t \) exposure time
\( Y \) probit
Equation A17.5.2
\( \psi^0 \) peak side-on overpressure \((\text{psi})\)
Equation A17.5.6
\( C \) concentration of ammonia \((\text{ppm})\)
\( t \) time \((\text{s})\)
Appendix

18

Offshore

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A18.12 Offshore Event Data A18/19
A18.13 Offshore Research A18/19
An account of loss prevention needs to include some mention of offshore oil and gas activities, even if this is necessarily brief. There is a continuous interaction between developments onshore and offshore. The treatment given here is confined to an outline of offshore activities, principally in the North Sea, written essentially for those working onshore.

Offshore installations operate in a difficult and often hostile environment. The problems not only of structures but also of processing are challenging. The solution of these problems often involves technological innovation. The significance of this for safety and loss prevention is clear.


The series of booklets by BP Petroleum Development Ltd (1990a–g) constitutes a useful starting point.

The report into the Piper Alpha disaster (Cullen, 1990) (the *Cullen Report*) provides a wealth of detail on both the design and operation of an actual platform, albeit one of the older ones, in the North Sea and on the impact on it of a major accident event.

Much useful information is also given in *Offshore Installations: Guidance on Design, Construction and Certification* by the HSE (1990b) (the HSE *Offshore Design Guide*). This gives guidance related to the Offshore Installations (Construction and Use) Regulations 1974.

Selected references on offshore are given in Table A18.1.

**Table A18.1  Selected references on offshore**

See also Table A19.1

**Offshore activities**

API (Appendix 27); ASME (Appendix 28 *Ocean Engineering, Offshore and Arctic Operations, Offshore Mechanics and Arctic Engineering*); BG (Comm. 1255, 1978 Comm. 1123, 1981 Comm. 143, 1149); IP (Oil Data Shts 7/8, 9, 10, 1978); Stephens and Stephens (1957); Frick (1962); Ranney (1979); Cairns and Rogers (1981); Carson (1981); Shyvers (1981); Shell UK Exploration and Production (1982); Skinner (1982); T.H. Dawson (1983); Gilbert (1983); Begg (1984); DoEn (1984); Frieze, McGregor and Winkle (1984); Baker-Couinsell (1985c); Waldie (1986); C. Clarke (1989); Woitge (1989); S. Brown and Freeth (1990); Cullen (1990); Steward (1990); Varery (1992); Knott (1994a, b); Leblanc (1994a, b);

**North Sea, Norwegian Sector:** Ogedal (1990, 1994); Tveit (1990, 1994); Dahle (1994); Giester (1994);

**Gulf of Mexico:** Gordon and Pope (1994); NOAA (1994); Western Geophysical (1994)

**Offshore regulatory regime**

Burgoyne (1980); Barrett, Howells and Hindley (1987); Lyons (1989); Cullen (1990); Higgs (1990); IP (1990 PUB 51, 1992 PUB 64); Petrie (1990); Friddle (1990); Barrell (1992); J.W. Griffiths (1992); HSE (1992 OTI 588); H. Hughes (1992); Lees (1992); Leiser (1992); *Certifying Authorities:* F.H. Atkinson (1989); MacLaren (1989); Fillans (1989); Thomson (1989); Cullen (1990); *Unions, safety representatives:* Cunningham (1989); Lyons (1989); Cullen (1990); Bibbings (1992); *Norwegian North Sea:* Heiberg-Andersen (1990); Ogedal (1990, 1994); Tveit (1990)

**Offshore rigs and platforms**


**Accommodation**

(1989); Terminals: Craig (1978); Duggan (1978); BP Petroleum Development Ltd (1982h, 1983b, 1984b, 1990b); Redman (1986); Pakelepa and van Berkel (1987); McGlashan and Hvingd (1992)

Offshore hazards


Offshore management
Bradig (1989); Denton (1989, 1991); Ellice (1989); Fotland and Funemark (1989); Grogan (1989); Littlejohn (1989); Macallan (1989); McKee (1989); McReynolds (1989); G. Richards (1989); R.A. Sheppard (1989); API (1990 RP 750); Cullen (1990); J. King (1992); McKeever and Lawreson (1992); S. Lewis and Donegani (1993); Jacobson (1994). Command and control: Baxendine (1989); Cullen (1990); Larkin (1992)

Offshore design


Offshore operation

Offshore emergency response, planning
Fischer (1982); Tompkins (1984); Baxendine (1989); Matheson (1989); Cullen (1990); Fitzgerald et al. (1990). R. Wilson (1992)

Offshore evacuation, escape and rescue
Booth (1989); Clayson (1989); J.D. Evans (1989); Heiberg-Andersen (1989); Jefferey (1989); Kelleher (1989); Lien (1989); McNell (1989); de la Pena (1989); Perrotti (1989); Petrie (1989); Rudd (1989); Side (1991); L.G. Wallace (1989, 1992); Cullen (1990); Owen and Spouge (1991); Forland (1992); Forster and Wong (1992)

Offshore safety
Hazard assessment offshore, inc. formal safety assessment
Fjeld, Andersen and Myklatun (1978); Borse (1979); Slater, Ramsay and Cox (1981); Pyman and Gierst (1983); Vinnem (1983); Deaves (1986); Schrader and Mowinckel (1986); Haugen and Vinnem (1987); R.A. Cox (1989d, 100, 1993); Ellis (1988); Ferrow (1989); Fleishman (1989); Gorese (1989); van der Graaf and Visser (1989); Hogh (1989); Pape (1989); Cullen (1990); Tveit (1990); Burns, Grant and Fitzgerald (1991); Rock and Butcher (1991); Diaz Correa (1992); Pape (1992); S.J. Shaw (1992); Sherrard (1992); Potts (1993); S.J. Shaw and Kristofferson (1993); Gardiner et al. (1984); K. Miller (1994); Pitblado (1994); Ramsay et al. (1994); Trbojevic et al. (1994)

Safety cases

Offshore incidents

Piper Alpha – see Appendix 19

Offshore event data – see Table A14.1

Offshore research
HSE (OTH, OTI series, 1992 OTI 589); Lane, Renwick and Al-Hassan (1994)

A18.1 Offshore Activities

Information is most readily available on the two oil provinces of the Gulf of Mexico (GoM) and the North Sea, both British and Norwegian sectors, and also on Australian developments. The account here refers primarily to the North Sea.

The oil and gas fields in the UK sector of the North Sea are shown in Plate 39.

The classic offshore development is a major oil and/or gas field with one or more large production platforms, linked by pipeline to shore and often also to other platforms.

Some wells are drilled from the platform itself, but in order to permit oil recovery beyond the range of drilling from the platform, use is also made of independent subsea wells. The fluid from these wells is brought to the platform by flowline for separation before it is sent to shore.

As the size of field declines, it becomes uneconomic to use a fixed, manned production platform in every case and necessary to resort to other methods more suited to smaller fields. Essentially these involve the use of a subsea module connected to a vessel above. When the field is exhausted, the vessel can move on. This approach permits a field to be exploited for a period of, say, 5 years, whereas a fixed platform might be amortized over a period more like 20 years.

An account of developments in the North Sea was given to the Piper Alpha Inquiry by B.G.S. Taylor (1989). They have implications for the regulatory regime in that it is increasingly necessary to allow for arrangements other than a large fixed platform.

Plates 40–47 and 57 illustrate some activities and structures in the North Sea. Plate 40 shows the Magnus platform being towed out for installation; Plate 57 the Piper Alpha platform; Plate 41 the heavy lift barge Thor used to lift a module during the construction of a platform; Plate 42 the pipelaying barge Viking Piper; Plate 43 the emergency support vessel Iolair; Plate 44 Buchan Alpha, a floating production rig; Plate 45 a bridge-linked platform; Plate 46 the Brent B platform under tow; and Plate 47 Beatrice C, an unmanned platform.

Changes in the oil price and government policies as well as exhaustion of fields and technological innovation mean that the offshore industry is in a continuous state of flux.

Accounts of some of these developments are given by Knott (1994a, b), who describes the extensive programmes of platform modification to extend the life of the Brent and Ninian fields.

A18.2 Offshore Regulatory Regime

An outline of the legislation governing oil and gas activities in the UK sector of the North Sea has been given in Chapter 3.

A summary of the principal legislation is given in Table A18.2.

A18.2.1 UK offshore regime: before 1991

Prior to the Piper Alpha disaster the regulatory body for the UK sector of the North Sea was the Department of Energy (DoEn) operating on behalf of the Health and Safety Commission under an agency agreement.

Regulations were made under the Mineral Workings Act 1971 and were complemented by guidance. Whatever the original intent, this guidance had come to be regarded as being in effect part of the regulations. In consequence, the strong tendency was to follow the guidance, even where this was done without conviction and solely for the sake of compliance and where it tended to inhibit innovation.

The regulations themselves made difficult an integrated approach. This is well illustrated by the situation pertaining in fire protection, where passive and active fire protection measures were the subject of two separate sets of regulations.

Enforcement took the form primarily of inspection of platforms. It was weak in respect of the company’s onshore organization, the safety management system (SMS), the conceptual design and formal safety assessment (FSA). The DoEn lacked expertise in a number of key areas such as the SMS, fire protection and FSA.

An operator was required to obtain certification by a Certifying Authority (CA) acting on behalf of the DoEn. The CA reviewed the design and inspected the construction to confirm compliance. The Department of Transport
Table A18.2  Selected legislation relevant to offshore

A  Acts
1934 Petroleum (Production) Act
1962 Pipelines Act
1964 Continental Shelf Act
1971 Mineral Workings (Offshore Installations) Act
1971 Prevention of Oil Pollution Act
1975 Petroleum and Submarine Pipe-lines Act
1992 Offshore Safety Act
Offshore Safety (Protection against Victimization) Act

B Statutory Instruments
1972 SI 703  Offshore Installations (Managers) Regulations
1973 SI 1842  Offshore Installations (Inspectors and Casualties) Regulations
1974 SI 289  Offshore Installations (Construction and Survey) Regulations
1976 SI 1019  Offshore Installations (Operational Safety, Health and Welfare) Regulations
1977 SI 1542  Offshore Installations (Emergency Procedures) Regulations
1978 SI 923  Submarine Pipe-lines (Diving Operations) Regulations
1977 SI 486  Offshore Installations (Life-saving Appliances) Regulations
1978 SI 611  Offshore Installations (Fire Fighting Equipment) Regulations
1980 SI 1759  Offshore Installations (Well Control) Regulations
1981 SI 399  Diving Operations at Work Regulations
1989 SI 1029  Offshore Installations (Emergency Pipe-line Valve) Regulations
1992 SI 971  Offshore Installations (Representative and Safety Committees) Regulations
1982 SI 2885  Offshore Installations (Safety Case) Regulations

(DoTp) was also involved with certain features such as the fire water system.

The operator therefore had to deal with several different regulatory bodies. Much frustration was experienced in trying to obtain agreement to deviate from the guidance, this being compounded by the multiplicity of regulators. Another aggravating factor was lack of expertise within the DoEn, which inevitably made it more difficult for it to respond to innovative proposals.

These characteristics of the regime were criticized in the Cullen Report, which recommended major changes.

A18.2.2 Burgoyne Report
Before considering these changes mention should be made of the report Offshore Safety by a committee chaired by Burgoyne (1980) (the Burgoyne Report).

The report found that several bodies were involved as regulators and recommended that there be just one, the DoEn. It placed some store on the need for a body which could speak with authority and it considered that the DoEn possessed the greatest expertise in offshore technology.

The Burgoyne Report made a number of recommendations which foreshadow those of Cullen. It placed emphasis on the quality of management, the control of pressure systems handling hydrocarbons, formal safety assessment and independent checks.

The report contained the following comment from ICI:

Experience onshore since the introduction of the Health and Safety at Work Act compared to the previous legislation seems to be that the principles of self-regulation and management control are resulting in a more responsible forward looking attitude by management. The present system of control by regulation in the North Sea could lead, it is believed, to an attitude on the part of some Employers whereby there is a primary desire to comply with the regulations rather than exert maximum effort towards total safety. Moreover, regulations are slow to form and difficult to change; they are inappropriate for complex and rapidly changing technologies, and they are capable of being abused by encouraging the attitude typified by ‘the plant must be safe because everything has been done that the regulations require’. What is needed for future projects is a more flexible system which can not only respond quickly to new problems – thereby generating improvement – but encourage a forward looking attitude and put the initial responsibility for deciding what is safe where it belongs – with the Employers. (p.239)

A18.2.3 Norwegian offshore regime
The regulatory regime operated in the Norwegian sector of the North Sea was an obvious model to consider. Evidence on this was given to the Piper Alpha Inquiry by Ognedal (1990).

Oil and gas activities in the Norwegian sector are regulated by the Norwegian Petroleum Directorate (NPD). The regime favoured by the NPD is one of goal-setting rather than prescriptive regulations and over the period 1985-92 it converted all the regulations to the former type.

Two principal elements of the regime are the systems of internal control and of risk assessment. The Guidelines for the Licencee's Internal Control 1979 describe in effect an SMS. The Regulations Related to the Licencee’s Internal Control 1985 make this a regulatory requirement.

With regard to risk assessment, the Regulations Concerning Safety Related to Production and Installation 1976 contained a requirement that if the living quarters were to be located on a platform where drilling, production or processing of petroleum was taking place, a risk evaluation should be carried out. At this date the evaluation would be largely qualitative. The move to a more quantitative approach came with the Guidelines for Safety Evaluation of Platform Conceptual Design 1981. These had as a central feature the provision of a sheltered area, required the conduct of a concept safety evaluation (CSE) and specified numerical acceptance criteria.

The Guidelines defined a design accidental event as one which does not violate any of the following three criteria:

(a) at least one escape way from central positions which may be subjected to an accident, shall normally be intact for at least an hour during a design accidental event; (b)
the shelter area shall be intact during a calculated accidental event until safe evacuation is possible; (c) depending on the platform type, function and location, when exposed to the design accidental event, the main support structure must maintain its load carrying capacity for a specified time.

The categories of event to be evaluated were specified as (1) blowouts, (2) fire, (3) explosion and similar incidents, (4) falling objects, (5) ship and helicopter collisions, (6) earthquakes, (7) other possible relevant types of accident, (8) extreme weather conditions and (9) relevant combinations of these accidents. The Guidelines gave explicit numerical criteria:

In practical terms, it may be considered necessary to exclude the most improbable accidental events from the analysis. However, the total probability of occurrence of each type of excluded situation ... should not by best available estimate exceed 10^-4 per year for any of the main functions specified...

This number is meant to indicate the magnitude to aim for, as detailed calculations of probabilities in many cases will be impossible due to lack of relevant data...

Risk assessment is now the subject of the Regulations Relating to the Implementation and Use of Risk Assessment in the Petroleum Activities 1990.

Ognedal emphasized that the NPD is flexible in its approach to risk assessment and tries to avoid its degenerating into a ‘numbers game’.

There is no equivalent in the Norwegian sector of the Certifying Authorities.

Further evidence was given by Nordgard (1990) and Tveit (1990). The latter described the practice of one of the main Norwegian operators, Statoil, of requiring that, in addition to the CSA at the conceptual stage, a further total risk analysis (TRA) be done at the detail design stage.

In a more recent account Ognedal (1995) describes a hierarchy of options for a regulatory strategy: (1) exercise of power, (2) exercise of influence, (3) provision of guidance and (4) reliance on individual responsibility (company and personal) and states that the NPD applies the lower end of these.

There is no requirement in the Norwegian sector to submit a safety case, but the NPD may ask to see the operator’s assessment.

An comparative account of the characteristics of the British and Norwegian regulatory regimes prior to Piper Alpha is contained in Safety in the Offshore Petroleum Industry: The Law and Practice for Management by Barrett, Howells and Hindley (1987).

The regime envisaged is one of goal-setting rather than prescriptive regulations and of the use of FSA to demonstrate compliance.

The report also recommended that an operator should submit a safety case and that this should be given structure by a requirement to demonstrate by QRA the integrity of a temporary safe refuge (TSR).

Another major recommendation is that the operator demonstrate, as part of the safety case, an appropriate SMS.

A further account of the report’s recommendations in relation to the evidence on the Piper Alpha disaster is given in Appendix 19.

A18.2.5 UK offshore regime: after 1991

The recommendations of the Cullen Report were accepted in toto by the government and the new regime with the HSE as the regulatory body was put in place in 1991.


Development of the new regime has been described by Barrett (1992a, b).

A18.3 Offshore Rigs and Platforms

A18.3.1 Drilling rigs

Initial exploration of a field is carried out by a mobile drilling rig. Such a unit has no processing facilities and a much smaller crew.

A typical drilling rig is shown in Plate 44. The plate shows Buchan Alpha, a semi-submersible unit, converted from its function as a drilling rig to that of a floating production platform, as described below.

A18.3.2 Production platforms

A conventional production platform comprises a steel jacket section supporting topsides which consist of a number of decks. Other platforms have concrete supports.

The purpose of a production platform is to operate the wells, separate the fluid from the wells into oil, gas condensate, gas and water, and to pump the first three of these to shore. In general, the crude well fluid cannot be passed to shore under its own pressure and current technology does not permit it to be pumped. Hence the need to separate it into its component parts. Since offshore plant is expensive, the processing done is the minimum to achieve this aim. The process plant on an offshore platform has a high throughput and operates at high pressure, but it is kept as simple as possible.

Oil is pumped to the onshore terminal through an oil pipeline. The condensate is injected into the oil and separated out again at the terminal. In the early days of development the practice in many cases was to burn the gas at the flare. Gas is now sent to shore via a gas pipeline.

The process plant has three main parts: (1) the wellhead, (2) the production separators and (3) the gas compression. The process is described further below.

This activity is supported by a power generation plant, workshops and accommodation.

Plate 48 is an exploded view of the Magnus platform. Noteworthy features include the drilling derrick and
drilling facilities; the separation and processing plant and the flare; the utilities, including gas turbines and generators; the helideck, accommodation and lifeboats.

Plates 49, 50 and 51 show a wellhead module, a separation module and a gas compression module, respectively, and Plate 52 a set of main oil line pumps.

Some statistics on typical platforms are given in Tables A18.3 and A18.4.

A18.3.3 Wellhead
The lines from the individual well terminate at the wellhead, each line being topped by a 'Christmas tree'. A line is provided with a hydraulic master valve (HMV) to allow flow to be shut off in an emergency. The well fluid then passes into a manifold from which it is taken off to the production separators through wing valves. Further protection for a well is provided by its down-hole safety valve (DHSV).

Drilling and wellhead equipment is covered by the API in a number of publications, including Spec. 6A: 1989 (well head equipment and valves), Spec. 7: 1994 (drilling equipment) and the RP 14 series (safety valves).

The main hazard from a well is that of a blowout, which is liable to occur during workover of the well. A workover is an operation performed on a producing well. It is generally a complex operation which requires careful control.

Protection against a blowout may be provided in the form of a blowout preventer (BOP), which is installed on top of the well. A typical blowout preventer is shown in Plate 56. Accounts of this aspect of the technology are given in Blowout Prevention by Goins and Sheffield (1983) and Blowout Prevention by F.G. Mills (1984). Blowout prevention systems are the subject of API RP 53: 1984.

A18.3.4 Production facilities
As described, the well fluid is passed to the separators, where it is separated into the four components mentioned. The oil is pumped to shore by the main oil line (MOL) pumps. The gas is first compressed by centrifugal compressors. It is let down in pressure, so that its temperature falls and condensate forms, which is separated out; the simplest method is a Joule–Thomson expansion. The gas is dried and purified. It is then compressed to a higher pressure by reciprocating compressors. Some is used on the platform at the wells and for power generation and the rest is piped to shore, with a small amount flared.

The essential elements of the production plant are therefore the production separators, the main oil line pumps, centrifugal and reciprocating compressors, the gas drying and purification system, and the condensate handling system.

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**Table A18.3** Some statistical data on gas and oil production platforms (Courtesy of BP Petroleum Development Ltd)

<table>
<thead>
<tr>
<th></th>
<th><strong>West Sole WB</strong> (gas)</th>
<th><strong>Forties</strong> (oil)</th>
<th><strong>Buchan</strong> (oil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height from seabed to helideck</td>
<td>56.8 m</td>
<td>167.6 m</td>
<td>35.3 m</td>
</tr>
<tr>
<td>Clearance of deck above lowest sea level</td>
<td>24.4 m</td>
<td>144.8 m</td>
<td>144.8 m</td>
</tr>
<tr>
<td>Tower section weight at float out (excluding piles)</td>
<td>700 te</td>
<td>15,600 te</td>
<td>15,600 te</td>
</tr>
<tr>
<td>Deck dimensions</td>
<td>42.5 m × 36.5 m</td>
<td>53.3 m × 51.8 m</td>
<td>53.3 m × 51.8 m</td>
</tr>
</tbody>
</table>

**Table A18.4** Some manning data on gas and oil production platforms

<table>
<thead>
<tr>
<th></th>
<th><strong>West Sole WB</strong> (gas)</th>
<th><strong>Forties</strong> (oil)</th>
<th><strong>Buchan</strong> (oil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company:</td>
<td>Management</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Production</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Maintenance/support21</td>
<td>52</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Drilling</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Subtotal</td>
<td>29</td>
<td>99</td>
<td>48</td>
</tr>
</tbody>
</table>

Sources: BP Petroleum Development Ltd (1982a, 1983a, c)

a These figures give the number of people on board at any one time.

b With drilling in progress.
This basic plant is supported by a number of facilities, which include (1) the blowdown, vent and flare systems and (2) the methanol injection system.

Facilities have to be provided which allow within a matter of minutes blowdown of the main gas inventories. The blowdown system is therefore a major facility. Depending on its pressure, gas is burnt at the low pressure or high pressure flare. The main, high pressure flare needs to have the capacity to flare the gas coming from the wells. While flaring of the full gas flow occurs only during plant modifications or emergency conditions, in the early days before the gas was exported this mode of operation was normal on many platforms.

In any event, the gas flow and heat generation during full flaring are massive. The flare system is therefore a prominent feature of an offshore platform. Much of the work on the modelling of flare flames has been done with offshore applications in view.

Plate 55 shows a Kaldair flare system. This device exploits the Coanda effect to obtain high throughput with low smoke levels.

Another key facility is the methanol injection system. The formation of hydrates of gas condensates is a major cause of blockage problems and is countered by the injection of methanol. A methanol injection system is shown in Plate 53.

Accounts of hydrates are given in Gas Hydrates by Berecz and Balla-Achs (1983) and Natural Gas Hydrates by J.L. Cox (1983). Evidence on the potential for formation of hydrates at various points in the process plant on Piper Alpha was given by S.M. Richardson (1989a) and Saville (1989c). The quantity of methanol required to be injected to counter such hydrates was addressed by these authors and by Paterson (1989), who did the original calculations. Further evidence on hydrate behaviour in the plant was given by A.G. Clark, Cottam, J. Drysdale, Grieve and Henderson (all 1989).

A18.3.5 Pipelines

The transport of oil and gas from offshore platforms to shore is through pipelines. The system in the North Sea is shown in Plate 39. In some cases the connection between sections of the pipeline system between a given platform and shore is made on another platform, so that the pipeline from the first platform passes onto the second platform where the connection is made.

Gas pipelines operate at high pressures, of the order of 2000 psi (140 bar), and the inventories of both gas and oil pipelines are large. A gas pipeline may contain several thousand tons of gas.

One consequence of the large inventory in a gas pipeline is that depressurization of the line takes a day or more. This is too long a time scale for emergency depressurization to reduce significantly the inventory which participate in an incident.

A pipeline is kept clear by passing through it a ‘pig’. The onshore and platform ends of the lines are provided with pig launchers/receivers, or traps. The need to pig a pipeline places certain constraints on the pipeline configurations which are practical.

A18.3.6 Risers

The section of the pipeline entering or leaving a platform is known as a riser. As Piper Alpha demonstrated, a gas riser is a major hazard.

A riser is provided with an emergency shutoff valve (ESV). Prior to Piper Alpha the common practice was to locate such ESVs high on the platform close to the pig trap. This location keeps the valve clear of the sea, but introduces the possibility of a riser rupture on the seaward side against which the valve offers no protection.

Following Piper Alpha the most urgent action taken by the DoEn was to bring in regulations, the Offshore Installations (Emergency Pipe-line Valve) Regulations 1989, requiring operators to fit ESVs closer to sea level or subsea, retrofitting if necessary.

An alternative is to locate the ESV subsea. This eliminates the possibility that the riser is burnt through on the seaward side but at a price. A subsea isolation valve (SSIV) is expensive in capital cost, of equipment and installation, and is not easy to maintain. Evidence on the features of SSIVs was given to the Inquiry by A.J. Adams (1989), Broadbribb (1989) and Gilbert (1989).

Since Piper Alpha the industry has installed a large number of SSIVs.

The more fundamental approach would be to try to eliminate gas risers altogether. Evidence on the scope for this was given to the Piper Alpha Inquiry by Willatt (1989). In general, the scope for eliminating risers appears limited, although there are some expedients which may be used in particular cases such as use of a separate riser platform.

A18.3.7 Accommodation

Personnel on a production platform are normally housed in one or more accommodation modules. The accommodation is designed to act in some degree as a safe haven.

Application of the principle of inherently safe design points to the reduction of exposure of personnel by removal of the accommodation from the vicinity of the processing plant and risers altogether. Some of the options for this were described to the Inquiry by Spouge (1989). They include the use of a separate accommodation platform, possibly bridge-linked, or of a floating hotel, or flootel.

One factor which has to be taken into account in assessing the relative risks of different accommodation configurations is the risk of helicopter accidents. This is such as to affect significantly the risk for those configurations where such transport is necessary.

If the accommodation is located on the production platform, it needs to be protected against fire and explosion. The most fundamental form of protection is by layout which separates the accommodation from the process modules. However, since the wellhead, production and gas compression functions are all potential sources of hazard, this is not easy to achieve.

Apart from the general separation of the accommodation from the hazard sources, measures may be taken to protect it from certain quite specific hazards such as a flame from a ruptured riser, as described below. It is common to provide the accommodation with protection in the form of fire or blast walls.

Another aspect of protection of the accommodation is the maintenance within it of breathable air. This has two aspects. One is provision of pure air. The other is exclusion of smoke and other contaminants. The latter involves various measures to prevent ingress of smoke.
by any route, whether through the regular air intake or through opened doors or broken windows.

Suitably protected, the accommodation can serve as a safe haven or temporary safe refuge, as described below.

A18.3.8 Vessels
A fixed platform is attended by a number of different kinds of vessel. It is a legal requirement that a platform have a standby vessel in permanent attendance to assist in an emergency.

The platform is supplied by a flow of supply vessels, which bring to it the drill rods, the plant equipment, the provisions and a variety of other materials.

On occasions, other types of vessel may be present. One type is the flot, which may be used to supplement the accommodation on the platform during a period of heavy construction work load. Another is an emergency support or fire-fighting unit, which also may sometimes be used as a flot. A third is a pipe-laying vessel. A large vessel such as an emergency support unit will be attended by several anchor-handling vessels.

A18.3.9 Subsea wells
As already indicated, many new developments involve subsea systems. In some cases the well fluid from the subsea system passes through a flow line to a fixed
Subsea systems: (a) a subsea wellhead; and (b) a subsea system showing wellhead, manifold and template, and riser and pipeline systems (after BP Petroleum Development Ltd, 1983a)

production platform while in others it is taken up to a vessel above.


The conventional arrangements are illustrated by those in the Magnus field, shown schematically in Figure A18.1.

Some features of typical subsea systems are illustrated in Figure A18.2. Figure A18.2(a) shows a single subsea wellhead and Figure A18.2(b) a subsea system with wellheads, manifold and template, connected to a floating production platform.

As it happens, the first exploitation of North Sea oil was by means of subsea systems, in 1971 in the Ekofisk field and in 1975 in the Argyll field. Important subsea developments were Exxon’s submerged production station (SPS) in the GoM in 1974 and Shell/Esso’s underwater manifold centre (UMC) in the North Sea in 1982. The UMC was a multiwell template which was used to test a number of new technologies. Subsea development received impetus from the large template manifold systems installed in the Highlander and Scapa fields.

Connections from a subsea well to a platform are now feasible over a distance of some 30 km or more.

Floating production systems

As described above, the trend is towards the floating production system (FPS), of which there are several types.

These include (1) the dynamically positioned tanker (DPT), (2) the buoy-moored system and (3) the moored barge system. The differences between these systems lie mainly in the technique used to keep the vessel on station, the methods used being, as the names indicate, dynamic positioning, mooring to a single buoy and mooring by multiple lines to the seabed, respectively. The DPT system is the most versatile, being able to operate in severe weather conditions, cyclone areas and deep water. The buoy-moored system is suitable for less severe weather and less deep water. The moored barge system is a low-cost option for shallow water and tranquil conditions.

A variety of approaches have been used to implement an FPS. One is the floating production platform exemplified by Buchan Alpha shown in Plate 44, which is a converted semi-submersible exploration rig. The rig is connected to the subsea manifold by a riser system consisting of eight production risers which bring the well fluid up, an export riser down which the separated oil is pumped to the export pipeline on the seabed, together with two service risers. The system is subject to weather-related constraints, limiting hawser tensions.
being specified for the 'stop exporting' and 'cast off' conditions.

In other systems use is made of a tanker or barge. An arrangement increasingly favoured is the floating production, storage and offloading system (FPSO). Figure 18.3 shows an arrangement for loading the oil from an FPS such as Buchan Alpha to a shuttle tanker. The main vessel remains on station near the subsea well and takes on board the fluid flowing from the well, processing it and storing the oil until it can offload it to a shuttle tanker.

A18.3.11 Onshore terminal
The crude oil pipelines pass from the platforms to an onshore terminal for separation, purification and storage. Scottish terminals are Sullom Voe in the Shetlands, Flotta in the Orkneys, Nigg Bay and Cruden Bay.

The gas pipelines go to separate onshore terminals. The Scottish gas terminal is St Fergus.

A18.4 Offshore Hazards
An offshore rig or platform is exposed to a unique combination of hazards.

The principal hazards are

(1) structural failure
   (a) ship collision;
   (b) severe weather;
   (c) earthquake;
(2) falling objects;
(3) blowout;
(4) fire/explosion.

Some of the hazards to be taken into account are treated in the HSE Offshore Design Guide.

Section 11 of the Guide on environmental conditions deals with the meteorological and oceanographic, or metocean, variables to be considered which are (1) winds, (2) waves, (3) water depths and sea variations, (4) currents, (5) air and sea temperatures, (6) snow and ice, (7) marine growths and (8) combinations of these.

For each variable a set of parameters is defined. For example, for winds the parameters are (1) extreme wind speed and direction, (2) vertical profile and (3) gust speeds and spectra. Values for the intensity of these parameters are defined principally in terms of return period. The Guide gives extensive information in the form of maps, tables and equations to assist in the determination of the metocean parameters.

The loads to which an installation may be subject are treated in Section 15, which covers (1) dead loads, (2) imposed, or operational, loads, (3) hydrostatic loads, (4) environmental loads, (5) deformation loads, (6) accident loads and (7) loads in combination. The environmental loads are those just discussed. The accidental loads include vessel collision.

A18.5 Offshore Management
An offshore platform has both marine and process characteristics. It shares with marine vessels the hazards of severe weather and of collision and in extremis those of escape to the sea. At the same time it contains high pressure plant processing oil and gas. The platform is also a self-contained community with its own power plant, accommodation and other facilities.

The senior manager on the platform is the offshore installation manager (OIM). The OIM is required in large part to combine the skills of a ship's captain with those of a refinery manager and to exercise command and control in an emergency.

In the early days of the North Sea many OIMs had a nautical background. This has now given way to appointment of OIMs from a variety of disciplines.

The Cullen Report gives a good deal of material on offshore management.
A18.6 Offshore Design

A18.6.1 Inherently safer design
The processing of hydrocarbons is the raison d'être of an offshore platform. This clearly sets certain limitations on the practice of inherently safer design. Nevertheless, this design principle is just as applicable offshore.

Three examples will suffice. One is reduction in the oil inventory in the production separators. The separators constitute a major oil inventory on the platform and it was the separators which fed the oil pool fire on Piper Alpha. Separators are now in use which have much reduced inventories.

It may be noted in passing that evidence on the hydrocarbon inventory on Piper Alpha was given to the Inquiry by M.R. Clark (1989).

A second example is adoption of a layout which minimizes the possibility of an oil pool forming near a gas riser.

A third example concerns the potential for a jet flame from a gas riser to impinge on the accommodation. Following Piper Alpha, Shell reviewed their platforms to establish whether in each case this was a possibility (Chamberlain, 1989). In those cases where it was, action was taken.

A18.6.2 Friendly plant
Closely related is the design of plant which is friendly to the process operator. In oil and gas extraction there are strong pressures to maintain production. In these circumstances, it is highly desirable that there be fall-back states of plant operation to which the operator can resort, without facing the all-or-nothing choice of continuing normal production or effecting total shut down.

A case in point is the confidence which the operator has that shutting down the gas plant will not lead to loss of power on the main generators. Evidence at the Piper Alpha Inquiry appeared to indicate that in some systems fuel changeover on the generators, from gas to diesel, could not be fully relied on. If this situation exists, it puts a greater pressure on the operator to keep going.

A18.6.3 Plant layout
Offshore production platforms carry large amounts of equipment held in a small space. Space and weight are both at a premium, since they are difficult and expensive to provide. Spacing between equipment in a module has to be less generous than in onshore plants. Where a 15 m distance is widely used in the latter, the distance offshore is often half that.

The design of separators for minimum space and weight has been discussed above.

It is also necessary to ensure that the layout is such that the centre of gravity of the total mass of equipment is at the centre of the supporting structure. CAD packages for plant layout provide a powerful tool for achieving a layout which meets this requirement.

The decks of the platform are divided into modules. The modules are separated by fire walls which inevitably reduce the ventilation.

Layout design seeks to separate sources of hazard from vulnerable targets. The application of this principle is seen on many platforms by the separation of the accommodation from the wellhead.

A18.6.4 Platform systems
There are a number of basic systems which are critical for safe operation of the platform. The account given here of these systems is limited to a brief overview. It is convenient to cast it as a description of the systems on Piper Alpha. The Cullen Report gives a detailed description of those systems and of their behaviour on the night of the disaster.

A18.6.5 Electrical power systems
The first of the systems is the electrical power supply system. Basic power is supplied by a pair of main turbine-driven generators with dual fuel firing, gas being the normal fuel with diesel fuel as standby. As backup, there is an emergency generator, turbine-driven and diesel fuelled. Changeover of fuel on the main generator and start up of the emergency generator are automatic. Drilling is served by a separate power supply from a diesel-driven generator with its own emergency generators.

The emergency generator for the main supply is designed to provide supply to critical services, which include HVAC, instrumentation and valves, and emergency lighting. Further backup is provided by an uninterruptible power supply (UPS) drawn from batteries designed to provide power during the momentary interruption while the emergency generator starts up and, if necessary, for a period in the event of total failure of the main supply.

Electrical systems for offshore production platforms are the subject of API RP 14F: 1991.

A18.6.6 Fire protection system
The fire protection system comprises a number of complementary elements. These are (1) the hazardous area classification, (2) the fire walls, (3) fire and gas detection system, (4) the fire water deluge system, (5) the fire pumps, (6) the foam system, (7) the halon systems and (8) the fire fighting arrangements.

Fire prevention and control on offshore production platforms is covered in API RP 14G: 1986.

The first line of defence against fire is the use of hazardous area classification to reduce the risk of ignition of any flammable leak which may occur. This was formerly covered by API RP 500B: 1973, specific to offshore, which is now replaced by the general onshore and offshore code RP 500: 1991.

The traditional form of active fire protection is the water deluge system. This is covered by the Construction and Use Regulations 1974 and the associated guidance in the Offshore Design Guide. The plant is divided into reference areas with a specified quantity of water to be delivered over each area. In order to limit the size of the reference areas use is made of firewalls. There are firewalls between the main production modules, namely the wellhead, separation and gas compression modules. These provide basic passive fire protection. They are not necessarily designed as blast walls.

There is an extensive fire and gas (F&G) detection system, with sensors in the main production modules and elsewhere, utilizing both combustible gas detectors and fire detectors.

A fixed water deluge system with distribution throughout the main modules and at the risers furnishes a basic level of active fire protection. Water for the deluge
system is drawn from the sea by fire pumps operating off the main power supply but with diesel-driven pumps as standby. A set of fire pumps is shown in Plate 54.

At locations where an oil pool fire may occur, such as the production separators, foam injection is provided.

Certain closed volumes may be provided with a halon total flooding system. Enclosures which may be protected in this way include the centrifugal compressor enclosures, the generator area, the electrical switchgear room and the control room. Where, as in the latter case, operators may be present, a non-toxic agent is used and there is prior alarm.

These fixed systems are supplemented by the fire fighting teams.

A18.6.7 Emergency shutdown system

The platform is provided with an emergency shutdown (ESD) system, the main functions of which are (1) to shut down the flow from the reservoir, (2) to shut off the flow through the pipelines entering and leaving the platform, (3) to shut down the main items of equipment and (4) to initiate blowdown of the inventories to flare.

There are various levels of ESD, some involving only individual items of equipment and others a full platform ESD, or PESD.

Physically, PESD may be activated from the control room or from any of a number of emergency pushbuttons around the platform.

As important as the hardware are the procedures which govern operation of the PESD system. It bears emphasis that the protection apparently afforded can be negated if there are cultural, organizational or human factors which inhibit initiation of the system in a real emergency.

A18.6.8 Communications system

The communications system provides for both internal and external communication. Communication on the platform itself is by telephone, radio and public address system.

One form of external communication is provided by means of telecommunications links, using both a tropospheric scatter system and a direct line-of-sight microwave radio. Another form is the use of the safety of life at sea (SOLAS) radio, high frequency ship-to-shore (HH/SSB) radio and very high frequency (VHF) radio.

A18.6.9 Evacuation, escape and rescue system

The evacuation, escape and rescue (EER) system is built around the three main means of leaving the platform, which are (1) helicopter, (2) lifeboat and (3) liferaft.

The emergency procedure is for personnel to collect at designated muster points. In the vast majority of cases evacuation is by helicopter, personnel being summoned to the helideck from their muster points.

There are a number of reasons, however, why evacuation by helicopter may be impractical. They include high winds and smoke from the platform, which can prevent landing. Another is the time taken to reach the platform. A helicopter already in or near the field may arrive relatively quickly but in many locations it takes about an hour for a helicopter to travel from an onshore base.

If helicopter evacuation is not practical, the other main means of getting off the platform is by lifeboat. The use of lifeboats is also subject to limitations. Lifeboats may sometimes be difficult to reach and have limitations in high seas. Even if the conditions do not actually prevent use, they may increase the risk of injuries.

If the lifeboats cannot be used, resort is had to escape to the sea, by launching liferafts and climbing down knotted ropes. The use of knotted ropes requires a certain degree of fitness and is not without risk.

One area of development has been improved lifeboat systems. Prominent among these is the freefall lifeboat, which is launched with its complement straight into the water, as opposed to being lowered from davits. These have been in use on Norwegian platforms and are the method used on the replacement for Piper Alpha, Piper Bravo.

A variety of devices have become available for escape, ranging from individual packages which can be hooked onto a guard rail to chutes and slides.

Another aspect is the integrity of the escape routes from locations where personnel are likely to be to the means of escape. Escape routes need therefore to be designed against a variety of scenarios. Of particular importance are the routes to the lifeboats from the accommodation, where at any given time a large proportion of the personnel will be. One approach is to locate lifeboats in a protected area integral with the accommodation.


Work in this area has been described by Bellamy and Harrison (1988), Forland (1992), Forster and Wong (1992) and I.G. Wallace (1992).

A18.6.10 Fire protection

As just indicated, the traditional means of fire protection has been passive protection by firewalls and active protection by a uniform water deluge.

Alternative approaches have tended to be inhibited by the need to comply with the two separate sets of regulations covering fire, one requiring passive and the other active fire protection measures.

In addition to the trade-off between passive and active fire protection, there may also be a trade-off between ventilation and active fire protection. If a module is well ventilated, gas from a leak is less likely to accumulate in the first place.

A plea for greater flexibility was made to the Piper Alpha Inquiry by Brandie (1989b), who advocated a scenario-based approach in which specific fire hazards are identified and water deluge arrangements directed more specifically to these scenarios. The Cullen Report recommended this approach within the context of FSA.

There are a number of issues related to fire protection. One is the availability of standard fire tests for hydrocarbon, as opposed to building, fires, such tests being needed for design of fire walls. Another is the use of
passive fire protection on risers, which might involve a risk of corrosion beneath the lagging.

Another long-standing issue, which relates to active fire protection, is the availability of the fire pumps.

There is generally a strong argument for the use of passive fire protection in that once installed it appears less subject to human failings. The matter is not, however, straightforward. Thus, for example, in some applications corrosion may occur under fireproofing, which may both promote the corrosion and conceal it.

There is now considerable activity in the investigation of fire events on platforms, covering oil pool fires and jet flames; impingement of flames on vulnerable targets such as risers and passive protection of these targets. Further details are given in Section A18.12.

A18.6.11 Explosion protection
In many cases there has been little protection against explosion over and above that against fire, partition walls being designed as firewalls rather than as blast walls.

This situation no longer pertains and much effort is being devoted to explosion protection. CFD simulation is being used to study the overpressures generated by explosions in modules, with particular reference to the enhancing effect of obstacles and to the mitigating effects of venting and of water spray systems.

Evidence on the mitigation of explosions was given to the Piper Alpha Inquiry by Chamberlain (1989) (explosion venting) and Vasey (1989) (water sprays).

A large amount of work has been done on the development and venting of explosions in modules and other obstructed spaces. Much of the work using CFD explosion simulation codes has been directed to the offshore module problem. Representative work using such codes is that of Hjertager (1982a, 1986, 1991), Bakke et al. (1989), Catlin (1990) and Hjertager et al. (1994). Examples of work on module explosions includes that described by Solberg, Pappas and Skramstad (1980, 1981), A.J. Harrison and Eyre (1987b), Catlin (1991), Brenton, Thomas and Al-Hassan (1992), Samuels (1992, 1993), Catlin, Manos and Tite (1993) and Catlin et al. (1993). A fuller account is given in Chapter 17.

A18.6.12 Explosion protection: blast walls
An increasingly common method of explosion protection is the use of blast walls.

The design of a blast wall is partly a matter of formulating suitable accident scenarios and predicting by simulation the resultant overpressure and partly one of engineering the wall so that it fulfils its protective function even if it deforms somewhat.

An account of the design of the blast walls on the Kitiwake platform was given to the Piper Alpha Inquiry by Doble (1989). The engineering of blast walls was described by van Beek (1989).

A18.6.13 Smoke minimization and protection
Another area of work is the investigation of the hazard presented by smoke, particularly that from an oil pool fire. Aspects of this are the generation and movement of smoke and the exclusion of smoke from the accommodation.

Smoke ingress into the accommodation was addressed at the Piper Alpha Inquiry by Dalzell (1989).

Accounts of work on smoke include those of Chamberlain (1994) and Kandola and Morris (1994).

A18.6.14 Design basis accidents
The design of plant to cope with accidental events requires that there be defined a set of design basis accidents. The concept is that the plant is then designed to withstand the design basis accidents in each category but does not have to be designed for events more severe than this. The selection of the design basis accidents is therefore closely linked with the estimates for the frequency of such events, so that overall risk in the design is an appropriate one.

A18.6.15 Reliability engineering
Offshore operations are a fruitful field for the application of reliability engineering and a number of accounts are available. They include overviews by Shyvers (1981) and Lloyd and Catchpole (1988) and treatments of specific topics by Bello and Avogadri (1982) (pipelines), J.N.P. Gray and McDonald (1982) (dynamic positioning system), Signoret and Leroy (1985) (deepwater drilling), Grillo and Qureshi (1988) (platforms) and ThoF-Christensen and Sorensen (1987) (structural joints).

A18.7 Offshore Design: HSE Offshore Design Guide
The regulations governing the design and construction of an offshore platform have long been the Offshore Installations (Construction and Survey) Regulations 1974. Associated guidance is given in the Offshore Design Guide already referred to, issued in its earlier editions by the DoEn (1977a, 1984) and its current edition by the HSE (1990b).

The principal contents of this guide are shown in Table 18.5.

Much of the Guide deals with marine and structural matters which are not of prime concern here, but several sections are of interest.

Section 13 deals with fire protection, the two main topics treated being fire testing and passive fire protection; active fire protection is not considered, reflecting the same limitation in the set of regulations which the Guide supports.

This section defines the classes of fire division utilized offshore. Two types of test are used, a standard fire test and a hydrocarbon fire test. In essence, Class A-60 divisions are required to prevent the passage of smoke and flame for 60 minutes in a standard fire test, Class B-15 to prevent the passage of flame for 30 minutes in a standard fire test (with a 15 minute temperature limitation on the unexposed face) and Class H-120 to prevent the passage of smoke and flame for 120 minutes in a hydrocarbon fire test.

Section 91 covers the ESD system, in a treatment which is one of the most comprehensive on this topic. An outline of the contents is given in Table 18.6.

A18.8 Offshore Operation
In general, the principles of safe operation offshore are those which apply onshore, but there are a number of features which are specific to or of particular importance offshore.
Table A18.5 Principal contents of the HSE Offshore Design Guide (HSE, 1990b)

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Appendix

B References and Bibliography

a Other section numbers contain no entries
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The need for safe systems of work and effective communication between personnel applies offshore as it does onshore, but the penalty of failure can be particularly serious offshore. Piper Alpha highlighted the importance of (1) handover procedures and (2) the permit-to-work system.

There is no counterpart onshore to two of the offshore activities of (3) drilling and (4) diving. There can also be in the confined environment of the platform a high level of (5) construction work. Supplies of all kinds coming onto the platform have to be lifted up by crane so that there is a substantial activity of (6) load handling.

Table A18.6 Principal contents of the HSE Offshore Design Guide: Section 91 Emergency Shutdown Systems (HSE, 1990b)

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The accommodation is integral with the platform so that at all times there is a substantial (7) population at risk. The hazards of the platform require a high state of readiness for (8) the fire protection system and (9) the evacuation, escape and rescue system. The personnel are in large proportion (10) contractors. The effectiveness of operational activities and of the emergency systems depends on (11) continuing training. The platform has its own management but some decisions involve (12) management onshore.

A18.8.1 Handover procedures

Communication between shifts is by means of a handover system in which each person hands over to his 'back-to-back', giving information such as ongoing activities and states of critical equipment. It is essential that there be in place effective handover procedures and a formal system is required to ensure this.

A18.8.2 Permit-to-work system

Another equally important means of communication is the permit-to-work system. For some tasks there may be a dozen or more persons who need to be kept informed of the activity and this is done through the PTW system.

The other main function of the PTW system is to ensure safe systems of work. A crucial aspect of this is the systems for isolation of the plant.

A particular danger arises if the work load on the platform becomes so heavy that the PTW system is put under stress.

A18.8.3 Drilling
Drilling is a major activity on the platform which has no counterpart onshore. One aspect of this activity is the ever-present hazard of a well blowout.

Another aspect which can impinge on the operation of the platform as a whole is the need to avoid loss of power such that the drill becomes stuck.

A18.8.4 Diving
Diving is another activity specific to an offshore platform. For the most part it does not impinge to any major extent on other activities except in so far as precautions are necessary to ensure the safety of the divers. At the time of the explosion on Piper Alpha the fire pumps had been turned to manual start to prevent sudden start-up of the pumps with consequent danger of a diver being drawn into the pump water inlet. This was not the policy on the sister platform Claymore, run by the same operator and in the same field.

A18.8.5 Construction work
Both onshore and offshore construction is an almost continuous activity. On a platform construction work may be necessary on the process plant, the utilities, the accommodation or other facilities. Another source of work is the tie-in of a satellite field, bringing the riser from the field onto the platform. For the most part production is continued during construction work, but management has to consider whether, in a given case, the level of work is so high that continuation of production is not justifiable.

A18.8.6 Load handling
Supplies of all kinds brought onto the platform have to be lifted up by crane from supply vessels with the risk that a load will be dropped or will crash against the platform. The hazard of a dropped load is present on onshore plants also but the problem bulks larger offshore.

A18.8.7 Population at risk
Management of operations on the platform has to bear in mind continuously the fact that there is a large permanent population at risk.

A18.8.8 Fire protection system
A platform is provided with a full fire protection system, but whether this is effective in the event depends in large part on operation and maintenance factors.

The fire and gas detection sensors need to be well maintained. The detection system should be subject to a discipline which avoids numerous false alarms. The fire water pipework should be kept clear so that it is capable of delivering the intended water flows.

The platform cannot call on an outside fire brigade but must rely on itself. Fire response is by fire fighting teams. Training and exercises are needed to keep these teams at full readiness.

A18.8.9 Evacuation, escape and rescue system
Likewise, it is necessary that the evacuation and escape system be maintained in a state of readiness and personnel be familiar with it by training and drills.

A18.8.10 Contractors
The proportion of contractors on a platform may well be of the order of 70% or more. Typically specialist teams such as drillers and divers are contractors with one person from the operating company as liaison. Some contractors may remain on a platform for long periods, others come and go.

The operating company attempts to ensure the quality of contractors admitted to the platform by means of a quality assurance system. Personnel from the company visit the contractor company onshore and make the usual quality assurance audit.

It is the responsibility of a contractor to ensure that its personnel are properly trained in offshore emergency procedures as well as in safe systems of work and PTW systems.

However, there may well be features of the systems operated on a platform which are particular to that platform. The operator needs, therefore, to ensure that contractors within its system are familiar with them. Failure to do this was held to have contributed to the leak on Piper Alpha.

A18.8.11 Training
As the foregoing indicates, both company and contractors personnel require a good deal of training. In fact the proportion of time spent offshore on training is quite appreciable. The issue is the quality of the training, which needs to be based on clear objectives, and with emergency training, on a full range of scenarios.

A18.9 Offshore Emergency Planning
Offshore emergency planning has the same broad features as that for onshore. In principle, they include the detection of the incident, the assessment of its nature and seriousness and if necessary, the declaration of the emergency, the assumption of command and control, and the implementation of the emergency plan.

However, the emergency may not present in this ideally structured form. It may well take the form of an emergency shutdown initiated automatically or by personnel in the control room or at one of the shutdown buttons scattered throughout the platform.

A18.9.1 Emergency scenarios
The first step in emergency planning is the definition of the set of scenarios on which the plan is to be based. A wide range of scenarios needs to be considered if the plan is to be robust.

It is not uncommon for an incident to require the evacuation of the platform, but in the vast majority of cases this will be by helicopter and management may well feel it has not done as well as it might if even one person is injured.

At the other extreme is the sort of situation which arose on Piper Alpha where there was no prospect of an evacuation by any of the conventional means and where escape to the sea was the only option. This implies that
the person in command explicitly instruct personnel to make their own escape.

A18.9.2 Assessment of the emergency
Whatever the initial events in the emergency, an appropriate response depends on correct assessment.

In many cases both assessment and action are liable to be severely hindered by fire and smoke. A platform has a number of levels. Whereas onshore personnel operate mainly at ground level, offshore they are likely to be exposed to flames and smoke coming up from below.

This makes it all the more important to consider in advance the assessment of the emergency.

The scale of the disaster on Piper Alpha was due in large part to inadequate assessment of the situation.

A18.9.3 Interaction with other platforms
It is common for a platform to be linked by gas and/or oil pipelines with one or more other platforms. If the emergency shut down of the platform includes shut off of the connecting pipelines this may impose a forced shut down on these other platforms. Such forced shutdown is highly undesirable. Hence one policy is to provide separately activated shut offs for some of the pipelines. On Piper Alpha the shut off of the three gas pipelines was separate from the main ESD system and was effected by three separate buttons in the control room.

A18.9.4 Communications in an emergency
The maintenance of communications is always an important aspect of emergency planning, but this is particularly the case offshore. The emergency plan needs to have regard to communications on the platform itself and with vessels lying off the platform, with other platforms in the field and with shore.

A18.9.5 Emergency on an connected platform
The emergency plan for a given platform should cover events not only on that platform but on interconnected platforms. The plan should cover scenarios which include shut downs and fires/explosions on the other platforms and should allow for loss of communications.

A18.9.6 Integrity of accommodation
The emergency plan should include measures to ensure the integrity of the accommodation. As already stated, the essential requirements are to exclude smoke and to maintain breathable air. An appropriate emergency discipline is needed to ensure that ingress of smoke through external doors and windows is minimized and that internally fire doors are kept closed.

A18.9.7 Evacuation, escape and rescue
As already stated, emergency planning should cover a wide range of scenarios. One aspect of these scenarios is the assessment of the options available for evacuation, escape and rescue.

A18.10 Offshore Safety
The foregoing account provides the background for consideration of safety offshore.

A18.10.1 Goal-setting regulations
The basic framework operated in the new offshore safety regime is that of regulations which are goal-setting rather than prescriptive.

The first set of regulations of the new offshore regime are the Offshore Installations (Safety Case) Regulations 1992.

Before considering these, it is interesting to note that the first regulations issued, by the DoEn, in the wake of the Piper Alpha disaster were the Offshore Installations (Pipe-line Valve) Regulations 1989, which require the operator to fit EIVs to the pipelines connected to the platform and are thus prescriptive. The Cullen Report explicitly endorsed this, in effect considering that exceptionally this case met the conditions for adopting a prescriptive regulation.

A18.10.2 Safety case
The Offshore Installations (Safety Case) Regulations 1992 implement Recommendation 1 of the Cullen Report that the operator should submit to the regulator a safety case.

For major hazard installations onshore a requirement for a safety case already existed under the CIMAH Regulations 1984. Evidence on the onshore safety case was given to the Piper Alpha Inquiry by Setton (1989) and V.C. Marshall (1989d).

The offshore safety case is largely modelled on the onshore case, but has three features not explicitly contained in the latter.

A18.10.3 Safety management system
One of these is the requirement, the subject of Cullen’s Recommendation 2(i), on the operator to demonstrate that it has a safety management system (SMS) which will assure the safety of the project through the design and operation. The SMS is thus part of the safety case rather than a free-standing requirement.

Evidence given to the Piper Alpha Inquiry tended to address aspects of safety management rather than an SMS as such. It included that from Denton (1989) (total quality management), Elllice (1989) (OIMs), McKeel (1989) and R.A. Sheppard (1989) (both safety management).

The indications are that the adoption offshore of a formal requirement concerning the SMS will influence developments in safety management onshore also.

A18.10.4 Temporary safe refuge
The second distinguishing feature of the offshore safety case, following Cullen’s Recommendation 2(iii), is the requirement that the platform have a temporary safe refuge (TSR), normally the accommodation, which should provide protection for a defined period.

Evidence on a safe haven and TSR was given to the Piper Alpha Inquiry by Brandle (1989a), Dalzell (1989) and Nordgard (1989).

Design of a TSR involves the definition of the events against which it is to provide protection and specification both of the endurance period and the conditions which constitute failure.

A18.10.5 Quantitative risk assessment
The third distinguishing feature of the offshore safety case is the requirement to use QRA, which is introduced in Cullen’s Recommendations 2(ii) and 4(iii).
Evidence on the application of QRA to offshore installations was presented to the Piper Alpha Inquiry by R.A. Cox (1989) and Hogh (1989), and on the HSE’s view of its role by Ellis (1989) and Pape (1989).

Essentially the QRA is a matter for the operator. The Cullen Report does, however, propose that one aspect of it be specified by the regulator:

The Safety Case involves a demonstration that the frequency of events which threaten the endurance of the accommodation, or TSR, will not exceed a certain value. In order to provide at least one fixed point in the regime, both the minimum endurance and the frequency with which there is a failure of such endurance should be specified by the regulatory body, at least in the first instance. (para 17.57)


A18.10.6 Costs of safety
In the wake of Piper Alpha the offshore industry has incurred major expenditure to enhance safety. Much of this was incurred in response to the disaster itself and before the Cullen Report appeared.

The HSE itself has made a comparison of the quantifiable costs and benefit of safety measures in the UK North Sea expressed as Net Present Value over 15 years (HSC, 1992). It attributes the bulk of both costs and benefits to the Safety Case Regulations, the costs being estimated at £1200–2500 million and the benefits at £2600–4600 million.

A commentary on these estimates is given by Potter (1994).

A18.11 Offshore Incidents

A18.11.1 Sea Gem
On 27 December 1965 the drilling rig Sea Gem collapsed, capsized and sank. The rig was in the position where it had been placed some six months before. The collapse involved the widespread disintegration of the structure. Of the 32 men on board 13 died.

The inquiry (R.J. Adams, 1967) found that having regard to the brittle properties of the steel used in the tie bars a simple lowering of the temperature to +3°C was sufficient to account for the failure.

A18.11.2 Ekofisk Bravo
On 22 April 1977 an uncontrolled blowout of oil and gas occurred on well B64 on the Ekofisk Bravo platform in the Norwegian Sector of the North Sea. The blowout occurred during workover of the well. The well was not stopped until April 30. There were no casualties but there was some damage to the platform and a large oil slick formed.

Oil issued at the rate of 3000 ton/d and created an oil slick which eventually covered some 900 square miles. By the time the well was capped estimated losses were 22,500 tons of oil and 60 million cubic feet of gas.

A workover was being carried out on the well involved. In this case the workover took the form of pulling some 10,000 ft of production tubing from the well. It involved the removal of the Christmas tree and installation of a blowout preventer.

The blowout occurred while the Christmas tree was off. Insufficient effort had been made to minimize the time when the well was without either the Christmas tree or the BOP. The immediate cause of the blowout was the failure of a down-hole safety valve, which had been incorrectly installed; it was thrown onto one of the decks of the platform. The BOP was not ready for immediate installation, being on the deck still in two parts.

The inquiry (Gjerde, 1977–78) found that there had been a failure of management and of safe systems of work. It also considered the personnel involved inadequately qualified.

It pointed out that prior to the blowout there has been two events which should have served as warnings that one might be imminent.

A18.11.3 Alexander L. Kielland
On 27 March 1980 in the Ekofisk field the accommodation platform Alexander L. Kielland overturned with 212 men on board, killing 123 of them.

The weather was bad with high winds and high seas. Column D of the structure broke off and the platform listed; after some 20 minutes keeled over.

It was found by the inquiry (Naesheim, 1981) that there had been a fatigue failure.

A18.11.4 Ocean Ranger
On 15 February 1982 the semi-submersible drilling unit Ocean Ranger capsized and sank on the Grand Banks, St John’s, Nova Scotia, with loss of all 84 men on board.

Investigations were conducted by both the US and Canadian authorities. The Ocean Ranger was registered in the USA and was investigated by the NTSB (1983 NTSB-MAR-83–02). Some 69 of the crew were Canadian citizens and the Canadian authorities also held an inquiry (Hickman, 1984).

The Canadian inquiry, which had the NTSB work available to it, found that the loss was due to a combination of severe storm conditions, design inadequacy and lack of knowledgeable human intervention. The ballast control room was located too close to the water line and the port lights were of inadequate strength. The ballast control system was unnecessarily complex. These defects might have been overcome if the crew had been more knowledgeable.

A18.11.5 Piper Alpha
On 8 July 1988 a gas leak occurred on the Piper Alpha platform in the British sector of the North Sea. There followed an oil fire which burnt through a gas riser, resulting in a massive jet flame which engulfed the platform. 167 men died.

The Piper Alpha disaster is described in Appendix A19.

A18.11.6 Ocean Odyssey
On 22 September 1988 an explosion and fire occurred on the drilling rig Ocean Odyssey. One man died and 66 escaped by lifeboat.
A18.11.6 Brent Spar
The Brent Spar fiasco in June 1995 was a quite different kind of incident. The platform had reached the end of its useful life. The structure contained some 130 tones of noxious materials, including toxic metals. The operator, Shell, assessed the best practical environmental option to be deep sea disposal in the Atlantic, in which it had the support of the British Government. However, as the company began to tow the platform across the North Sea, a high profile campaign by Greenpeace led to a boycott at the company’s filling stations in Continental Europe and to pressure from European governments; that from consumers in the UK was much weaker. The chairman of German Shell described the short-term impact as being as serious as anything which had happened in the history of the company. Wrong-footed, Shell backed down and agreed not to proceed with deep sea disposal of the platform; its ultimate fate is so far undecided. Although the company clearly felt it had the weight of scientific opinion on it side, it nevertheless ran up against the determination of the public that the seas should not be used as dumping ground.

A18.12 Offshore Event Data
As for onshore installations, information on offshore events is of two main types: (1) incident data and (2) equipment failure data.

The World-wide Offshore Accident Database (WODAD, 1988) enumerates the principal accidents involving offshore structures involved in oil and gas activities.

There is also a need, particularly in hazard assessment, for more detailed information on events such as leaks, fires and explosions, which help to validate the models. Recommendation 39 of the Cullen Report was that the regulatory body should maintain a database of hydrocarbon leaks, spills and ignitions to which the industry would contribute and which it could use. The HSE has responded by creating the HCR database, as described by Bruce (1994).

An indication of the profile of hydrocarbon releases and ignitions on Piper Alpha was given in evidence to the Inquiry by Wottge (1989). He referred to some 88 recorded but 87 identified leaks, 5 in the period prior to 1983 and 8, 7, 12, 29, 16 and 10, respectively, in the years 1983–1987 and the part-year 1988. By fluid there were 50 leaks of gas, 20 of condensate, 8 of oil and one of water-oil mixture; 9 were unclear, but probably 5 were gas and one water-oil mixture. By location, 8, 13, 26 and 1 were in modules A, B, C and D, respectively, 28 in the gas conservation module (GCM), 9 on the deck support frame with two assigned to the ‘other’ category. By type the leaks were characterized as follows: flanges 27; valves 13; nipples 4 (fatigue) + 1 (corrosion) + 21 (unknown); pipework 4 (weld/fatigue) + 2 (chloride stress corrosion cracking) + 1 (sand erosion) + 1 (overpressure); pump/bearing/rapid 2; overheating 1; maintenance failure 2; procedure failure 1; and ‘other’ 7. These events included an explosion in a heat exchanger in 1984, a leak from a 4 in. vent valve which was left open and leaks from a 1 in. condensate line, a ¾ in. seal oil line, a 3 in. gas nipple and a high pressure gas hose.

Equipment failure data collection is the subject of a major co-operative exercise carried out under the aegis of OREDA and initiated some years before Piper Alpha. This is described in Appendix 14.

A18.13 Offshore Research
Activity offshore is supported by a substantial research effort, which has redoubled following the Piper Alpha disaster and the advent of the new offshore regime.

The environment offshore is a hostile one and in some respects, the work has been devoted to marine and structural topics. Piper Alpha has resulted in an increase in work on the fire and explosion hazards from hydrocarbons and other aspects which played a part in the disaster.

Studies related to the safety case include work on hazop (Rushton et al., 1994) and QRA (Sherrard, 1992) and Goodner et al. (1994).

Models have been developed to predict conditions in a vessel, particularly the drop in temperature, during blowdown (Haque, Richardson and Saville, 1992; Haque et al., 1992; S.M. Richardson and Saville, 1992).

A major project on fire and explosion study has been led by the Steel Construction Institute. This is focused on fire and explosion loading of structures, the response of structures and mitigatory measures.


Other work published in this area includes that on ventilation (Ronold, 1992); flares and jet flames (Chamberlain, 1987); passive fire protection against jet flames (Lev, 1991; Shirvill, 1992); jet flames in modules (Chamberlain, 1994); smoke (Kandola and Morris, 1994); and accommodation/safe haven protection (Dalzell and Melville, 1992).

Another area of research has been human factors. Studies have been conducted relevant to platform design (Bellamy, Geyer and Astley, 1991) and evacuation systems (Fitzgerald et al., 1990).
Appendix 19

Piper Alpha

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A19.1 The Company, the Management and the Personnel
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A19.7 Some Lessons of Piper Alpha
A19.8 Recommendations on the Offshore Safety Regime
At 10.00 p.m. on 6 July 1988 an explosion occurred in the gas compression module of the Piper Alpha oil production platform in the North Sea. A large pool fire took hold in the adjacent oil separation module, and a massive plume of black smoke enveloped the platform at and above the production deck, including the accommodation. The pool fire extended to the deck below, where after 20 minutes it burned through a gas riser from the pipeline connection between the Piper and Tartan platforms. The gas from the riser burned as a huge jet flame. Most of those on board were trapped in the accommodation. The lifeboats were inaccessible due to the smoke. Some 62 men escaped, mainly by climbing down knotted ropes or by jumping from a height, but 167 died, the majority in the quarters.

The Piper Alpha explosion and fire was the worst accident which has occurred on an offshore platform.

Following the disaster a Public Inquiry was set up under the Public Inquiries Regulations – Offshore Installations Regulations 1974 presided over by Lord

**Table A19.1 Selected references on Piper Alpha**

**Report of the Public Inquiry**
Cullen (1990)

**Part 1 Evidence**

**Part 2 Evidence**
A19.2 The Field and the Platform

The Piper Alpha platform was located in the Piper field some 110 miles north-east of Aberdeen. The platforms in the field and the pipeline connections between them are shown in Figure A19.1. The Piper platform separated the fluid produced by the wells into oil, gas and condensate. The oil was pumped by pipeline to the Flotta oil terminal in the Orkneys, the condensate being injected back into the oil for transport to shore. The gas was transmitted by pipeline to the manifold compression platform MCP-01, where it joined the major gas pipeline from the Frigg Field to St Fergus.

There were two other platforms connected to Piper Alpha. Oil from the Claymore platform, also operated by Occidental, was piped to join the Piper oil line at the Claymore T. Claymore was short of gas and was therefore connected to Piper Alpha by a gas pipeline so that it could import Piper gas. Oil from Tartan was piped to Claymore and then to Flotta and gas from Tartan was piped to Piper and thence to MCP-01.

Elevation views of the Piper Alpha platform, the layout of the production deck at the 84 ft level and the layout of the deck below, the 68 ft level, are shown in Figures A19.2, A19.3 and A19.4, respectively. A view of the platform showing the west face and pipe deck is given in Plate 57. The production deck level consisted of four modules, Modules A-D. A Module was the wellhead, B Module the oil separation module, C Module the gas compression module and D Module the power generation and utilities module. A view of C Module, looking east, is given in Plate 58.

A Module was about 150 ft long east to west, 50 ft wide north to south and 24 ft high. The other modules were of approximately similar size. There were firewalls between A and B Modules, between B and C Modules, and between C and D Modules (the A/B, B/C and C/D firewalls, respectively); these firewalls were not designed to resist blast.

The pig traps for the three gas risers from Tartan and to MCP-01 and Claymore were on the 68 ft level. Also on this level were the dive complex and the JT flash drum, the condensate suction vessel and the condensate injection pumps.

There were four accommodation modules: the East Replacement Quarters (ERQ), the main quarters module; the Additional Accommodation East (AAE); the Living Quarters West (LQQ); and the Additional Accommodation West (AAW).
The control room was in a mezzanine level in the upper part of D Module. It was located about one quarter of the way along the C/D firewall from the west face.

There were two flares on the south end of the platform, the east and west flares, and there was a heat shield around A Module to provide protection against the heat from the flares.

Platform systems included the electrical supply system, the fire and gas detection system, the fire water deluge system, the emergency shutdown system, the communications system and the evacuation and escape system.

Electrical power was supplied by two main generators which normally ran off the gas supply but could be fired by diesel. There was a diesel-fired emergency generator and also a drilling generator and an emergency drilling generator. In addition, there were uninterrupted power supplies for emergency services.

The main production areas were equipped with a fire and gas detection system. In C Module the gas detection system was divided into five zones: C1 and C2 in the west and east halves of the module and C3–C5 at the three compressors, respectively.

The fire water deluge system consisted of ring mains which delivered foam in A–C Modules and part of D module and at the Tartan and MCP-01 pig traps and water at the condensate injection pumps. The fire pumps were supplied from the main electrical supply but there were backup diesel-driven pumps.

The hydrocarbon inventory in the pipelines was approximately as follows. The main oil line was 30 in diameter and 30 miles long and held some 70,000 te of oil. The gas line from Tartan was 18 in. diameter and 11.5 miles long and held some 450 te; the gas line to MCP-01 was 18 in diameter and 33.5 miles long and held 1280 te; and the gas line to Claymore was 16 in. diameter and 21.5 miles long and held 260 te.

**A19.3 The Process and the Plant**

The fluid from the wellhead, containing oil, gas, condensate and water, passed through the wellhead ‘Christmas trees’ to the two separators where the gas was separated from the oil and water. The oil was then pumped into the main oil line. The gas was compressed first in three centrifugal compressors to 675 psia, with some gas being taken off at this point as fuel gas for the main generators, and then boosted in the first stage of two reciprocating compressors to 1465 psia. Condensate was removed and the gas was then further compressed in the second stage of the reciprocating compressors to
1735 psia. The gas then went three ways: to serve as lift gas at the wells, to MCP-01 as export gas or to flare. The plant could be operated in two modes, which affected the method of removing condensate. In the normal, or phase 2, mode, the gas passed from the first stage of the reciprocating compressors to the Gas Conservation Module (GCM), where it was dried. The gas was then cooled by reducing the pressure across a turbo-expander so that condensate was knocked out by the expansion and returned to the outlet of the JT flash drum, which was also the inlet of the second stage of the reciprocating compressors. Condensate from the GCM was passed to the JT flash drum. The process could also revert to the original, or phase 1 mode, dating from a period before the GCM was installed to produce export quality gas, in which the GCM was isolated and gas from the first stage of the reciprocating compressors was let down in pressure across the JT valve into the JT flash drum so that condensate was knocked out by the Joule–Thomson (JT) effect and then passed as before into the second stage of the reciprocating compressors.

Condensate from the JT flash drum passed first to two parallel centrifugal condensate booster pumps and then to two reciprocating condensate injection pumps
Figure A19.3 The Piper Alpha platform: the production deck on the 84 ft level (Sylvester-Evans, 1991) (Courtesy of the Institution of Chemical Engineers)

Figure A19.4 The Piper Alpha platform: the 68 ft level (Sylvester-Evans, 1991) (Courtesy of the Institution of Chemical Engineers)
which pumped the condensate into the main oil line. There was normally one condensate injection pump line operating and one on standby.

Each condensate injection pump was protected from overpressure on the delivery side by a single pressure safety valve (PSV). The PSV was on a separate relief line from the delivery head of the pump rather than on the delivery line itself. The valve on A pump was PSV 504 and that on B pump PSV 505. These valves were located in C Module, the relief line running up from the 68 ft level, where the pumps were located, to the PSVs in C Module and back down to the condensate suction vessel on the 68 ft level.

In accordance with standard practice, methanol was injected into the process at various points to prevent formation of hydrates which would tend to cause blockages.

**A19.4 Events Prior to the Explosion**

On 6 July there was a major work programme on the platform. This included the installation of a new riser for the Chanter field and work on a prover and metering loop.

The extra accommodation for the workforce was provided on the Tharos, a large floating fire fighting vessel anchored near the platform. Also near the platform were the standby vessel, the Silver Pit, a pipeline vessel, the Lowland Cavalier, and Maersk anchor handling vessels for the Tharos.

The GCM was also out of service for changeout of the molecular sieve driers. In consequence, the plant operation had started to the phase 1 mode so that the gas was relatively wet.

The resulting increased potential for hydrate formation was recognized by management onshore. The increased methanol injection rates required were calculated and communicated to the platform together with suggestions for the configuration of the methanol pumps. The methanol injection rates needed were some twelve times greater than for normal phase 2 operation.

However, there was an interruption of the methanol supply to the most critical point, at the JT valve, between 4.00 and 8.00 p.m. that evening.

The operating condensate injection pump was B pump. The A pump was down for maintenance. There were three maintenance jobs to be done on this pump: (1) a full 24 month preventive maintenance (PM), (2) repair of the pump coupling and (3) recertification of the pressure safety valve, PSV 504. In order to carry out the 24 month PM, the pump had been isolated by closing the gas operated valves (GOVs) on the suction and delivery lines but slip plates had not been inserted. Work on the coupling, which was suffering from a vibration problem, would not involve breaking into the pump.

With the pump in this state, with the GOVs closed but without slip plate isolation, access was given to remove PSV 504 for testing. It was taken off in the morning of July 6 by a two-man team from the specialist contractor Score UK Ltd. They were not able to restore the PSV that evening. The supervisor in this team came back to the control room some time before 6.00 p.m. to suspend the permit-to-work (PTW) and the team then went off duty, intending to put the PSV back the next day.

At about 4.50 p.m. that day, just at shift changeover, the maintenance status of the pump underwent a change. The maintenance superintendent decided that the 24 month PM would not be carried out and that work on the pump should be restricted to the repair of the pump coupling.

About 9.50 p.m. that evening B pump on the 68 ft level tripped out. The lead production operator and the phase 1 operator attempted to restart it but without success. The loss of this pump meant that with A pump also down condensate would back up in the JT flash drum and within some 30 minutes would force a shut down of the gas plant. There was a possibility that if the gas supply to the main generator was lost and if the changeover to the alternative diesel fuel failed, the wells also would have to be shut down. It would then be necessary to undertake a ‘black start’.

The lead operator came up to the control room. He talked on the telephone with the lead maintenance hand and it was agreed to attempt to start A pump. The lead operator signed off the permit for A pump so that it could be electrically deislated and restarted, and went back down to the pumps. The lead maintenance hand came down to the control room to organize the electricians to deisolate the pump. It is uncertain precisely what action the lead operator and the phase 1 operator took. They were observed at the pumps by the phase 2 operator and an instrument fitter, but the evidence of these witnesses was inconclusive. However, there was no doubt that the lead operator intended to start A pump.

About 9.55 p.m. the signals for the tripping of two of the centrifugal compressors in C Module came up in the control room. This was followed by a low gas alarm in C3 zone on C centrifugal compressor. Then the third centrifugal compressor tripped. Before the control room operator could take any action a further group of alarms came up: three low gas alarms in zones C2, C4 and C5 and a high gas alarm. The operator had his hand out to cancel the alarms when he was blown across the room by the explosion.

Just prior to the explosion personnel in workshops in D Module heard a loud screeching sound which lasted for about 30 seconds.

**A19.5 The Explosion, the Escalation and the Rescue**

The initial explosion occurred at 10.00 p.m. It destroyed most of the B/C and C/D firewalls and blew across the room the two occupants of the control room, the control room operator and the lead maintenance hand.

The emergency shutdown (ESD) system operated, closing the emergency shut-off valve (ESV) on the main oil line and starting blowdown of the gas inventories to flare. The ESVs on the gas pipelines were not designed to close on platform TSD; this would impose an undesirable forced shut down on the other platforms connected to Piper. Instead there were three separate shutdown buttons for these ESVs in the control room.

The explosion was followed almost immediately by a large fireball which issued from the west side of B Module and a large oil pool fire at the west end of that module. The explosion and fire were witnessed by personnel on the vessels lying off the platform. It so
happened that one witness on the Tharos was standing with camera at the ready. He took a sequence of shots of the development of the fireball, of which that shown in Plate 59 is the first.

The large oil pool fire gave rise to a massive smoke plume which enveloped the platform from the production deck at the 84 ft level up. Some idea of the size of the plume may be obtained from Plate 60 taken soon after from a vessel lying off the platform.

The offshore installation manager (OIM) made his way to the radio room and had a Mayday signal sent.

The Tharos effectively took on the role of On-Scene Commander. The Coast Guard station and Occidental headquarters onshore were informed. Rescue helicopters and a Nimrod aircraft for aerial on-scene command were dispatched. The flight time for the helicopters was about an hour.

Most of the personnel on the platform were in the accommodation, the majority in the ERQ. Within the first minute flames appeared on the north face of the module also and the module was enveloped in the smoke plume coming from the south. The escape routes from the module to the lifeboats were impassable.

At the 68 ft level divers were working with one man underwater. They followed procedure, got the man up and briefly through the decompression chamber. They were unable to reach the lifeboats, which were inaccessible due to the smoke. They therefore launched liferafts and climbed down by knotted rope to the lowest level, the 20 ft level.

The drill crew also followed procedure and secured the wellhead.

The oil pool in B Module began to spill over onto the 68 ft level where a further fire took hold. There were drums of rigwash stored on that level which may have fed the fire.

The fire water drench system did not operate. There was only a trickle of water from the sprinkler heads.

The explosion disabled the main communications system which was centred on Piper. The other platforms were unable to communicate with Piper. They became aware that there was a fire on Piper, but did not appreciate its scale. They continued for some time in production and pumping oil. This pumping would have caused some additional oil flow from the leak at Piper.

After some 20 minutes from the initial explosion the fire on the 68 ft level led to the rupture of the Tartan riser on the side outboard of the ESV. This resulted in a massive jet flame which enveloped much of the platform. The rupture of the Tartan riser is shown in Plate 61.

The emergency procedure was for personnel to report to their lifeboat, but in practice most evacuations would be by helicopter and personnel would be directed from the lifeboats to the dining area on the upper deck of the ERQ and then to the helideck. Personnel in the ERQ found the escape routes to the lifeboats blocked and waited in the dining area. The OIM told them that a Mayday signal had been sent and that he expected helicopters to be sent to effect the evacuation. In fact the helideck was already inaccessible to helicopters.

Some 33 minutes into the incident the Tharos picked up the signal ‘People majority in galley. Tharos come. Gangway. Hoses. Getting bad’.

No escape from the ERQ to the sea was organized by the senior management. However, as the quarters began to fill with smoke individuals filtered out by various routes and tried to make their escape.

Some men climbed down knotted ropes to the sea. Others jumped from various levels, including the helideck at 174 ft. One man who had arrived only that afternoon on his first tour jumped from a high level. One standing on pipes protruding from the pipe deck was pushed off by another behind him who could no longer stand the heat of the pipes.

The vessels around the platform launched their fast rescue craft (FRCs). The first man rescued, by the FRC of the Silver Pit, was the oil laboratory chemist, who, on experiencing the explosion, simply walked down to the 20 ft level and was picked up without getting his feet wet. Most survivors, however, were rescued from the sea. Much of the rescue operation took place after the rupture of the Tartan riser. Plate 62 shows a rescue craft at the platform at some time after this event.

The FRC of the another vessel, the Sandhaven, was destroyed with only one survivor. The FRC of the Silver Pit made repeated runs to the platform; eventually it was blown out of the water, and began to sink, but returned to the platform and then finally sank, its crew being themselves rescued by helicopter.

At about 10.50 p.m. the MCP-01 riser ruptured and about 11.18 p.m. the Claymore riser ruptured. The pipe deck collapsed and the ERQ tipped. By 12.15 a.m. on 7 July the north end of the platform had disappeared. By the morning only A Module, the wellhead, remained standing.

A19.6 The Investigation

An investigation of the disaster was immediately undertaken by the Department of Energy (DoEn) headed by Mr Petrie. Two reports were issued, an interim report (the Petrie Interim Report, or simply, the Petrie Report) and a final report (the Petrie Final Report); the latter included appendices on various technical studies commissioned.

The Petrie Report put forward two scenarios for the hydrocarbon leak which led to the explosion: a leak from the site of PSV 504 (Scenario A) and a leak due to ingestion of liquid into the reciprocating compressors (Scenario B).

The Inquiry was presided over by a Scottish judge, Lord Cullen, assisted by three Technical Assessors. There was a legal Counsel to the Inquiry assisted by technical Consultants to the Inquiry. Parties to the Inquiry included Occidental, the DoEn, groups representing survivors and the trade unions, the contractors, the specialist contractor Score, several equipment manufacturers, and for the second part, the UK Oil Operators Association (UKOOA). Part 1 of the Inquiry dealt with the disaster and its background, Part 2 with the future. The Inquiry heard some 280 witnesses in 180 days of evidence and received some 840 productions, or documents.

It began by considering whether to advise that the debris of the platform should be raised from the sea bed. It was clear at an early stage that the size of leak sought was of the order of 10 mm². The evidence was that the operation presented a number of problems and hazards, would involve considerable delay and might well not
provide much useful information. The Inquiry decided not to pursue the matter.

In seeking to find the cause of the leak, the Piper Alpha Report begins with the evidence on the explosion itself. It concludes that the explosion was at 10.00 p.m., that it was in C Module and in the south-east quadrant of that module, that the fuel involved was condensate, that the leak gave rise to a gas cloud filling less than 25% of the module, that the mass of fuel within the flammable region was some 30–80 kg, that the explosion was a deflagration rather than a detonation, that the maximum peak overpressure was in the range 0.2–0.4 bar, and that the ignition source could not be identified. Evidence for these findings included the gas alarms in C Module; the screeching noise heard just prior to the explosion; testimony of and photographs taken by observers on the surrounding vessels of the fires just after the explosion; the effects of the explosion, including the damage to the two firewalls in C Module; the effects of the explosion on the control room and its occupants; the lack of damage to the heat shield on A Module; and estimates of overpressure based on some of the explosion effects, such as firewall damage and bodily translation of persons.

It was not initially clear how a gas cloud of sufficient size could develop without setting off certain gas alarms which according to the evidence had not been triggered. In particular there was a gas detector in the roof above the site of PSV 504 or PSV 505 (the two valves were close together) and another some 2–3 ft above floor level among the heat exchangers between the reciprocating and centrifugal compressors; both these detectors were in C2 zone. However, the first gas alarm was in C3 zone at C centrifugal compressor. Accordingly, wind tunnel tests were commissioned from BMT Fluid Mechanics to explore the pattern of gas alarms for different types of leak. Scenarios investigated included leaks of natural gas and of condensate, the one a buoyant and the other a heavy gas; leaks from various points in the modules; and leaks from various types of source, including a leaking flange and an open pipe. It was concluded by the investigator that of the scenarios studied only a leak from the site of PSV 504 or PSV 505 fitted the pattern of gas alarms and, further, that this leak was a two-stage leak, the first stage being small and the second relatively large. It would have been this second stage which gave rise to the gas cloud sought.

The experimental run of main interest simulated a leak of 100 kg/min from PSV 504. Figure A19.5 shows the contours of the lower flammability limit of the gas cloud formed after 30 seconds from such a leak. The cloud would not set off either of the gas detectors mentioned. Figure A19.6 shows the mass of gas within the flammable limit as a function of the leak flow rate after 30 seconds and at infinite time. These results were

Figure A19.5 The flammable gas cloud for a leak of 100 kg/min in the BMT wind tunnel tests: LEL contours at 30 seconds (Cullen, 1990)
subject to a number of reservations but indicated that a gas cloud of sufficient size could be formed.

The next question considered was whether the explosion of such a gas cloud could cause the damage observed. It was estimated that the B/C firewall would fail at an overpressure of 0.1 bar and the C/D firewall at an overpressure of 0.12 bar.

Simulations of the explosion of flammable mixtures in the module had been commissioned prior to the Inquiry at the Christian Michelsen Institute (CMI) by the DoEn and other parties. The simulations were performed using the FLACS computer code. Following the wind tunnel work, the Inquiry commissioned a single further run for a gas cloud in the south-east quadrant of C Module and containing some 45 kg of propane within the flammable limit. The simulation was subject to a number of reservations but indicated that such an explosion could cause the firewall damage observed.

Simulations of the general type presented to the Inquiry are shown in Plate 28.

The simulation also provided an explanation of a point which had seemed puzzling. The two occupants of the control room were thrown across it by the explosion and experienced a rush of cold air, not hot gas. The simulation showed that in the early stages of the explosion the control room wall would be subject to a positive overpressure and intrush of air, but that by the time the hot combustion products approached the control room, the negative phase of the pressure pulse had set in, the velocity vectors had reversed and the direction of air flow was out of the control room into C Module.

The two-stage nature of the leak also presented another point of difficulty. Isolation of A pump was by the closure of the GOVs on the suction and the delivery lines. The suction GOV was electrically isolated and it was uncertain whether power to it had been restored by the time of the initial explosion. In any event restoration of the valve would involve reconnecting a pneumatic line to the valve, which could quickly be done by an operator. It was concluded that this connection was made and that probably the operator gave it a tweak to make sure the valve movement was restored. This would have had the effect of admitting condensate to the relief line to PSV 504, but not of filling it with condensate liquid, thus giving rise to the early, smaller leak. Subsequent opening of the valve and filling of the relief line with condensate liquid could then have caused the later, larger leak.

Evidence was also heard on tests on leaks from blind flanges. The flange at PSV 504 was a ring-type joint (RTJ) flange. Three methods of tightening up were investigated: flogging up with a flogging spanner and hammer; hand tightening with a combination spanner; and finger tightening. The results showed that a flange in good condition which had been flogged up or hand tightened did not leak. Even deterioration of the flange would be unlikely to give the leak sought unless the deterioration was gross. However, a finger-tightened flange could give a leak which was directionally downwards and was of the flow rate sought.

The Inquiry concluded that the explosion had been caused by ignition of a gas cloud containing some 45 kg of hydrocarbon within the flammable range, arising from a two-stage leak, in the first stage perhaps some 4 kg/min and in the second stage some 110 kg/min lasting some 30 seconds, coming from an orifice of equivalent diameter some 8 mm².

There was no obvious explanation why the blind flange was not leak-tight. Much evidence was led to the effect that an experienced and competent fitter would not make up a blind flange which was not leak-tight. The Inquiry noted, however, that the decision not to proceed with the

Figure A19.6 Mass of fuel in the flammable range in the BMT wind tunnel tests: (a) variation with time; and (b) variation with leak rate (Cullen, 1990)
full 24 month PM on A pump was taken just as shift handovers on the platform were starting so that some personnel may have been ignorant of this change in intent and that the lack of leak-tightness of the blind flange may have been connected with the status of A pump.

The lead production operator had clearly had the intention to start A pump. It was difficult to explain this given the fact that its sole PSV was off. The Inquiry concluded that the lead operator was indeed ignorant of this, even though this meant a serious breakdown of communications about the work. It implied that the fact that the PSV was off was not communicated in the handovers of the lead maintenance hand, the phase 1 operator and the lead production operator and that the lead operator did not learn of it through the PTW system.

When he found that he was unable to put the PSV back that evening, the Score supervisor came up to the control room to suspend the permit. He was on his first tour as a supervisor and had had no training in the operation of the PTW system in use on the platform. Whom he spoke to and what transactions took place were obscure. It was unclear how he knew that the procedure in filling out the permit for suspension was to write 'SUSP' in the gas test column.

In any event the Score supervisor did not make a final inspection of the job site before going off work and evidently the lead production operator did not inspect the job site either, although in both cases good practice required that this be done.

Further, the leak would not have occurred if there had been a more positive isolation of the pump by means such as the use of a blind plate.

The explanation just described is that adopted in the Piper Alpha Report but several other scenarios for the leak were also explored. One group of scenarios was concerned with explanations of the leak from the blind flange following admission of condensate into A pump other than lack of leak-tightness. They include the possibilities of auto-ignition, shock loading, low temperature brittle fracture, and overpressurization by methanol injection. All of these were quickly ruled out except auto-ignition by compression of a flammable mixture formed in the relief line. The line had been left open for an hour before the blind flange was put back on. It was not possible to calculate whether auto-ignition would have occurred due to lack of data on auto-ignition properties of the multi-component mixture at the high pressures involved, some 300 bar. Moreover, company documentation on the rating of the pipework was inconsistent so that it was uncertain whether the flange was a 900 lb or 1500 lb one. The expert evidence was that if auto-ignition had occurred and the lower rating applied, a leak was possible, although whether it would have had the required characteristics was another matter. An account of this work on auto-ignition has been given by S.M. Richardson, Saville and Griffiths (1990).

The scenario was considered that condensate liquid had backed up in the JT flash drum and thence into the reciprocating compressors. There was evidence that on loss of B pump steps had been taken to reduce the condensate make by unloading and recycling these compressors. The report concludes that there had been insufficient time for back-up to occur before the initial explosion and that in addition both the conditions around the compressors and the expected action of protective instrumentation were against this scenario.

A further scenario which emerged in the Inquiry was that the leak occurred from PSV 505 and that it was caused by hydrate blockage. The interruption to the methanol supply to the JT valve lent credibility to this scenario. Experimental work commissioned showed that hydrates would form under the conditions pertaining at the JT valve during the partial loss of methanol supply if the temperature at the valve fell below a critical value; it had in fact been below this temperature on 5 July. The expert evidence was that hydrates could pass through to the condensate injection pumps and cause blockage there some two hours after restitution of the full methanol supply. There were several versions of the scenario all leading to blockage of hydrate at PSV 505 and overrunning of the pump so that the delivery pressure rose to a value high enough to cause rupture of the valve, which was the weakest point in the line. The report does not rule out this scenario, but regards it as less likely than the preferred one.

Finally, the Consultants to the Inquiry reviewed a large number of other scenarios which were not purely theoretical but had some link with the information available at the time, which included a hazop study, past equipment failures and process conditions that evening. None was found convincing by the Inquiry.

Turning to the escalation, the causes of the oil pool fire and the fireball which occurred in B Module within seconds of the explosion in C Module were unclear. The Inquiry heard evidence on the type, number, velocity and impact effects of the projectiles which would have resulted from the destruction of the B/C firewall. The condensate injection line ran from C Module through into B Module where it joined the main oil line. The report concludes that probably the fireball was caused by a missile rupturing this line near the main oil pumps at the west face of B Module.

Estimates of the size of the oil pool fire indicated that the supply of oil to the fire probably exceeded the oil inventory of the separators and that there was a leak of oil from the main oil line through the main oil line EVS which was not fully closed. This leak would be aggravated by continued pumping of oil by the other platforms.

The fire water deluge system did not work. The initial explosion knocked out the main power supplies. It may also have damaged the water pumps and the water mains. In any event it was the practice on Piper to put the pumps on manual start when divers were in the water and thus in possible danger of being sucked into the pump intakes and they were on manual start that evening. The start controls were at the pumps themselves. After the explosion occurred an attempt was made to get through to the pumps to start them by personnel wearing breathing apparatus, but to no avail. Further evidence was given of quite extensive blockage caused by corrosion products in the fire water deluge system, which operated on sea water, a problem which had persisted for some years.

The initial explosion caused the operation of the platform ESD. This could have occurred through loss of the main power supply and/or rupture of a pneumatic ring main. Also although dazed by the explosion the
control room operator pressed the platform ESD button. He did not, however, press the buttons to close the ESVs on the three gas pipelines. Evidently these did close but their closure was due rather to the effects of the initial explosion on power supplies to the valves.

Following the initial explosion a period of extended flaring occurred which greatly exceeded that to be expected from the flaring of the gas inventory on the platform. The report accepted that the most probable explanation was a failure of the Claymore ESV to close fully.

The main communications for the Piper field were centred on Piper. The system was knocked out by the initial explosion, so that the other platforms were unable to communicate with Piper and had difficulty communicating with the shore.

The report details a number of management weaknesses. There were severe and numerous defects in the PTW system. For example, it violated more than half of the main points in the code of practice on permits-to-work issued by the Oil Industry Advisory Committee (OIAC). The system was operated rather casually. The training of the specialist contractors supervisor in the permit system operated on the platform was found to be inadequate.

With regard to handovers, the company had been prosecuted only a year before for a fatality and had pleaded guilty. The report takes the view that a failure in handover procedures was a factor in that accident.

A number of different types of audit were performed by the company, by its partners, by loss prevention specialists, and so on. None of these had revealed the defects in the PTW which became apparent very quickly in the Inquiry.

The report is critical of the handling of the emergency by the senior management on the platform and in particular of the failure to recognize that helicopter evacuation was not possible and to take command of the situation and organize escape from the ERQ.

The decision to keep the platform operating despite the large workload is another matter of which the report is critical.

The report states that the company had no system to ensure that all projects were subject to formal safety assessment. Certain techniques such as hazop were used on some projects and quantitative estimates had been made in some studies, but the approach was unsystematic. The report takes the view that as a consequence the hazards presented by the hydrocarbon inventory on the platform and particularly in the pipelines had not been systematically addressed.

Part 2 of the Inquiry was concerned with the future offshore safety regime. The context was not only the Piper Alpha disaster but also the changes taking place in the North Sea oil province. The exploitable oil and gas fields were becoming smaller and the technology to develop them was becoming more varied.

The evidence in Part 1 revealed serious weaknesses in the company management. It was an issue why the DoEn had not discovered these weaknesses. The report is critical of the relative lack of emphasis placed by the Department on the assessment of management and management systems.

In contrast to the British onshore and Norwegian offshore regimes, which had both moved increasingly towards goal-setting regulations, the British offshore regime relied excessively on prescriptive regulations, and associated guidance.

The deficiencies of such a regime were illustrated in the regulations concerning fire protection, which had a number of defects. Passive and active fire protection were covered by two separate sets of regulations. The regulations, and associated guidance, for active fire protection led in practice to systems based on delivery of a uniform quantity of water over large areas of a platform, deluge systems prone to blockage and massive water pumps. Fire protection was not integrated with explosion protection.

The report states that the approach taken by the DoEn to the control of the major hazards from hydrocarbons at high pressure did not impress as an effective one. Further the inspectorate had relatively little expertise in this area.

Following the Piper Alpha disaster the DoEn brought in regulations to require ESVs to be placed nearer to sea level and for the valves to be of full ESV standard. The report notes that of the 400 risers covered by the regulations, some 70 required modification in the latter respect.

The regime made little use of formal safety assessment (FSA). This was in contrast to the regulatory use of FSA onshore, and in particular the onshore safety case. The DoEn had in fact explicitly rejected the concept of an offshore safety case. This policy also contrasted with the situation in the Norwegian sector, where a concept safety evaluation (CSE) was required. Quantitative risk assessment is required in a CSE and is often necessary to fulfil the requirements of a safety case.

Considerable evidence was heard on quantitative risk assessment (QRA). The burden of this evidence was that QRA is in regular use in many companies as an aid to decision-making both for onshore and offshore installations and that there was no serious impediment to this from any problems of overall methodology, frequency estimation, consequence modelling or risk criteria.

In contrast to the HSE, the DoEn was not well equipped to operate a regime based on goal-setting regulations and FSA. It had no experts in FSA or fire protection.

A number of recommendations which would have met some of the points on which the DoEn was criticized had been made in the Burgoynes Report (Burgoyne, 1980), but had not been implemented.

A19.7 Some Lessons of Piper Alpha

A19.7.1 Some lessons

Lessons from the Piper Alpha disaster are considered in this section with the exception of the recommendations of the report on the offshore safety regime which are considered in Section A19.8. A list of some of the lessons is given in Table A19.2. Many apply particularly to offshore installations, but others are of more general applicability.

Regulatory control of offshore installations

The Piper Alpha disaster exposed weaknesses in the offshore regulatory regime which have already been
Table A19.2  Some lessons of Piper Alpha

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described. The lessons drawn are seen in the recommendations given in Section A19.8.

Quality of safety management

The Piper Alpha Report is critical of the quality of management, and particularly safety management, in the company.

It was not that the company did not put effort into safety. On the contrary, there were numerous meetings and much training on safety. The problem was the quality of these activities.

Many managers had come up through the ranks and had minimal qualifications. The culture tended to be somewhat in-grown and insufficiently self-critical.

These defects manifested themselves in various ways such as in the toleration of poor practices in plant isolation and operation of the PTW system; in the failure to appreciate the ineffectiveness of the audits done; in the failure to address the major hazard problem and to use FSA. The report comments:

Senior management were too easily satisfied that the PTW system was being operated correctly, relying on the absence of any feedback of problems as indicating that all was well. They failed to provide the training necessary to ensure that an effective PTW system was operated in practice. In the face of a known problem with the deluge system they did not personally become involved in probing the extent of the problem and what should be done to resolve it as soon as possible. They adopted a superficial response when issues of safety were raised by others, ... They failed to ensure that emergency training was being provided as they intended. Platform personnel and management were not prepared for a major emergency as they should have been. (para 14.52)

A crucial weakness was failure to appreciate that absence of feedback to management about problems is almost certainly an indicator not that there are no problems but that there are, and they could be serious. Of one OIM the report states: ‘His approach seemed to be, in his own words, “surely that is all you are concerned with about the permit system... If the system is working and no problems are identified... then you should be reasonably happy with it, surely?” .... He had been surprised by the number of deficiencies in the operation of the permit system which had been revealed in the Inquiry. He had checked this out and found it to be true.’ Of another manager it states that he said ‘he knew that the system was monitored on a daily basis by safety personnel. By the lack of feedback he “knew that things were going all right and there was no indication that we had any significant permit to work problems”’. (para 14.26)

Safety management system

Onshore the quality of the management and the management system are of prime concern to the HSE in its inspections in general and in the safety case in particular. In submitting a safety case a company will often give extensive documentation on its systems. Nevertheless, in the regulations the formal requirements on management are fairly minimal.

The Inquiry heard evidence in favour of the assurance of safety through the use of quality assurance to standards such as BS 5750 and ISO 9000. It also heard evidence on the need for better qualified management, including a proposed requirement for all OIMs to be graduates.

The concept of a safety management system goes part way towards these insofar as the system itself is based on principles similar to those of quality assurance and covers the question of management quality.

Documentation of plant

The discrepancies in the documentation concerning the rating of the flange on PSV 504 have already been mentioned. The Inquiry in fact heard of a number of other defects in the documentation of the plant. Failure to maintain correct records can have serious consequences.

Fallback states in plant operation

The loss of the working condensate pump on Piper created a situation where operating personnel were under some pressure to start the other pump and avoid a gas plant shut down with its possible escalation to a total shut down, loss of power and the need for a ‘black start’. In this case the pressure was created partly by the view which an individual took of the probability that the changeover of the main generators from gas to diesel would fail. This illustrates the desirability of ensuring that plants have fallback states short of total shut down. In this case the problem was in the reliability of changeover, a type of problem which may lie with design or with maintenance.

Permit-to-work systems

The defects in the PTW system have already been described. These defects led directly to a situation where condensate was admitted to a pump from which the PSV
had been removed and hence to the disaster. The Piper Alpha Report devotes considerable attention to the need for an effective system.

Isolation of plant for maintenance
The Piper Alpha Report states that the disaster would not have occurred if a pump had been positively isolated so that condensate could not be admitted. Positive isolation is not achieved by shutting a valve but requires means such as insertion of a slip plate or removal of a pipe section.

Training of contractors’ personnel
The proportion of contractors’ personnel on an offshore installation can be as high as 70%. The offshore scene therefore exemplifies in extreme form a problem which applies to onshore plants also. This is the need to train contractors’ personnel in the company’s operating and emergency systems and procedures. Failure to train a contractor’s supervisor in the operation of the PTW system on Piper meant that he was unfamiliar with a feature of the system which turned out to be a critical one.

Disabling of protective equipment by explosion itself
The initial explosion on Piper disabled large parts of the protective systems, including power supplies and fire water supplies. It illustrates the importance of taking this factor into account in design and in FSA.

Offshore installations: control of pressure systems for hydrocarbons at high pressure
An offshore production platform contains a large amount of plant containing hydrocarbons at high pressure. The feed to this plant is from the wells, which can sometimes behave in an unpredictable way. The pipelines connected to the platform contain large quantities of hydrocarbon, the high pressure gas pipelines constituting a particularly serious hazard.

There needs therefore to be a comprehensive system for the control of the total pressure system, covering design, fabrication, installation, operation, inspection, maintenance and modification and including control of such features as materials of construction, lifting of loads, and so on and personnel need to be trained in the purposes and operation of system.

Offshore installations: limitation of inventory on installation and in its pipelines
The scale of the Piper disaster was due primarily to the large inventory of the three high pressure gas pipelines connected to the platform. The Inquiry heard evidence on the practicalities of reducing the number of gas pipelines connected to a platform. There are many technical problems involved, but the point has been made that such reduction should be a design objective.

The main inventory of hydrocarbons in process on a platform is in the separators. The massive oil pool fire on Piper was fed from the separators. The Piper Alpha Report recommends that methods of dumping this inventory be explored.

Evidence was also heard that in some cases the main inventory of hydrocarbons on a platform might be the diesel fuel.

The alternative method of preventing the hydrocarbon inventory from feeding a fire is emergency isolation, which is considered next.

Offshore installations: emergency shutdown system
The ESD system on Piper operated, shut down ESVs and blew the gas inventory on the platform down to flare.

Nevertheless, the accident drew attention to a number of problems in effecting isolation, some specific to offshore platforms and some more generally applicable.

The Tartan riser ruptured on the outboard side of the ESV so that closure of this valve was of no avail. It is clear that an ESV needs to be located as close to the sea level as practical in order to minimize this risk.

It is possible to go one step further and install a subsea isolation valve, but this is for consideration on a case-by-case basis.

Both types of isolation valve received considerable attention in the Inquiry. However, neither will be effective unless it achieves tight shut off. The evidence that the main oil line and the Claymore gas line ESVs did not shut off tightly emphasizes the importance of this feature.

Moreover, in order to be effective the ESD system has to be activated. The fact that on Piper closure of the three gas line ESVs was not part of the platform ESD but had to be effected for each line separately by manual pushbutton, that these buttons were not pushed, and that closure only occurred due to loss of power, shows that this problem also is not a trivial one.

Offshore installations: fire and explosion protection
An offshore installation is not in general able to call on outside assistance comparable with that available from the fire brigade to an onshore plant. It must be self-reliant.

This implies that both protection against, and mitigation of, fire and explosion on the one hand and fire fighting on the other are of particular importance and that both the hazard assessment and the design and operation of the plant must be of high quality.

Offshore installations: temporary safe refuge
It is clear from the Piper disaster that there needs to be a temporary safe refuge (TSR) where personnel can shelter in an emergency and where the emergency can be controlled and evacuation organized.

This TSR will normally be the accommodation. In most cases it will be on the production platform itself, but it may be on a separate accommodation platform.

The protection of the TSR from ingress of smoke and fumes from outside and from generation of fumes by fires playing on the outside needs careful attention. Measures require to be taken to prevent smoke ingress through doors and through the ventilation system.

Offshore installations: limitation of exposure of personnel
The concept of a TSR is a particular application of the more general principle of limitation of exposure of personnel. The Inquiry also heard evidence of the application of the principle to other aspects such as the location of workshops.
Offshore installations: formal safety assessment
The evidence showed that many companies which operate installations onshore and offshore have formal systems for safety assessment and practise FSA routinely, that FSA has considerable benefits in the design and operation of plant, and that it provides a suitable basis for dialogue between the company and the regulatory body.

Offshore installations: safety case
A safety case is a particular form of FSA. The evidence indicated that a safety case is as applicable offshore as onshore and that it is a suitable means for the company to demonstrate to the regulatory body that it has identified the major hazards of its installation and has them under control.

Offshore installations: use of wind tunnel tests and explosion simulations in design
Wind tunnel tests and explosion simulations were used in the Inquiry to investigate the cause of the explosion, but evidence was also heard of their value in platform design.

Wind tunnels may be used to assess the effectiveness of ventilation and of the gas detection system in a module, the wind conditions at the helideck and the movement of smoke from oil pool fires. Explosion simulations may be used to investigate the effect of different module layouts on explosion overpressures and to assess the effectiveness of blast walls.

The explosion and fire phenomena
The Piper disaster drew attention to several important aspects of explosion and fire on offshore installations. These include explosions in semi-confined modules, oil pool fires and jet flames.

Explosions in semi-confined and congested modules are a hazard which assumes particular significance offshore. Although major progress has been made in the last decade in simulating such explosions and developing design methods, this remains an area where further work is needed.

Oil pool fires onshore are relatively well understood, but this does not apply to the behaviour of such a pool fire on an offshore platform. Aspects of some importance are design to prevent accumulation of an oil pool in the first place and the massive smoke plume from such a fire.

Jet flames, including jet flames from risers, are particularly important for offshore platforms. In this case there are available a number of models developed for flares and flames on onshore plant, including pipelines, which can be applied offshore.

Evidence given indicated that in considering the hazard of a jet flame from a riser, the worst case was not necessarily a full bore rupture but a partial rupture, since the latter is sustained for a longer period.

Publication of reports in accident investigation
The Inquiry heard that the company had a policy of severely restricting circulation of accident investigation reports.

Likewise the DoEn did not make public reports on major offshore accidents. This contrasts markedly with the HSE policy of issuing reports on major accidents, many of which are referred to in this book.

A19.7.2 An accident model
The following outline of a model of the accident highlights the role played by some of the features just mentioned:

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<td>Hazard identification, assessment and management</td>
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<td>Escalation 2: oil pool fire</td>
<td>Explosion mitigation</td>
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<tr>
<td>Escalation 3: riser rupture</td>
<td>Hazard identification, assessment and management</td>
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<td>Escalation 4: accommodation failure</td>
<td>Fire protection of risers</td>
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<td>TSR fire and smoke protection</td>
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<td>Emergency command and control</td>
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A19.8 Recommendations on the Offshore Safety Regime
The *Piper Alpha Report* makes recommendations for fundamental changes in the offshore safety regime.

The basis of the recommendations is that the responsibility for safety should lie with the operator of

Table A19.3 Some elements of the safety management system

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<tbody>
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<td>Organizational structure</td>
</tr>
<tr>
<td>Management personnel standards</td>
</tr>
<tr>
<td>Training, for operations and emergencies</td>
</tr>
<tr>
<td>Safety assessment</td>
</tr>
<tr>
<td>Design procedures</td>
</tr>
<tr>
<td>Procedures, for operations, maintenance, modifications and emergencies</td>
</tr>
<tr>
<td>Management of safety by contractors in respect of their work</td>
</tr>
<tr>
<td>Involvement of the workforce (operator’s and contractors’) in safety</td>
</tr>
<tr>
<td>Accident and incident reporting, investigation and follow-up</td>
</tr>
<tr>
<td>Monitoring and auditing of the operation of the system</td>
</tr>
<tr>
<td>Systematic re-appraisal of the system in the light of experience of the operator and industry</td>
</tr>
</tbody>
</table>
the installation and that nothing in the regime should detract from this.

The offshore regime envisaged in the recommendations is one in which the emphasis is on the operator demonstrating to the regulatory authority the safe design and operation of its installation rather than demonstrating mere compliance with regulations. In this regime the preferred form of regulations is goal-setting rather than prescriptive.

The recommendations envisage that FSA will play a major role. It may be used to demonstrate compliance with a goal-setting regulation or with the general requirements of the HSWA.

A central feature of the regime proposed is the safety case for the installation. This safety case is broadly similar to that required for onshore installations but there are some important differences. In the offshore safety case it is required that the operator should demonstrate that the installation has a TSR in which the personnel on the installation may shelter while the emergency is brought under control and evacuation organized.

Further, it is recommended that this demonstration should be by QRA. This means that there must be criteria which define the failure of the TSR and criteria for its endurance time and its failure frequency. The criteria may then be met by reducing the frequency of accidental events, by increasing the durability of the TSR, or by some combination of these.

The recommendation on the safety case includes a requirement that the operator should demonstrate that it has a safety management system (SMS) to ensure the safe design and operation of the installation. This SMS should draw on quality assurance principles similar to those of BS 5750 and ISO 9000. The elements of the SMS should include those listed in Table A19.3. They include management personnel standards.

Various measures related to hardware were urged on the Inquiry. These included the provision of separate accommodation platforms, the installation of subsea isolation valves and blast walls, the use of freefall lifeboats and purpose-built standby vessels. The report takes the view, however, that in accordance with its basic philosophy such matters should be dealt with as part of the demonstration of safe design and operation.

The report considers that the then current regulatory body, the DoEn, is unsuitable as the body to be charged with implementing the new regime and recommends the transfer of responsibility for offshore safety to the HSE.

These recommendations were accepted immediately by the government and the new regime under the HSE began in April 1991.
Appendix

Nuclear Energy

20

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A20.1 Radioactivity A20/3
A20.2 Nuclear Industry A20/4
A20.3 Nuclear Reactors A20/5
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A20.6 Nuclear Pressure Systems A20/7
A20.7 Nuclear Reactor Operation A20/8
A20.8 Nuclear Emergency Planning A20/8
A20.9 Nuclear Incident Reporting A20/9
A20.10 Nuclear Incidents A20/9
The energy industries in general have much in common with the process industries in terms of the management, the plant and the hazards. This is true even of the nuclear industry, although this also has a number of unique features. Historically, the nuclear industry has often had to face particular problems before they have impinged on the process industries and has had to devise solutions to them. In consequence, there are a number of areas where work in the nuclear industry is relevant to the process industries.

In this appendix a general account is given of nuclear energy, essentially with reference to those features which are common to, or have impact on, the process industries. Accounts of the accidents at Three Mile Island and at Chernobyl and of the Rasmussen Report are given in Appendices 21–23, respectively.

Some topics common to both industries have been dealt with already in other chapters. The account of major hazard control in Chapter 4 covers nuclear hazards. The treatment of management and management systems in Chapter 6 is applicable to nuclear as well as process systems.


Frequent reference is made in this appendix to two reports issued following the accident at Three Mile Island. These are The Report of the President Commission on the Accident at Three Mile Island (the Kemeny Report) (Kemeny, 1979) and TMI-2 Lessons Learned Task Force Final Report (the Task Force Report) (NRC, 1979d).

Selected references on the nuclear industry are given in Table A20.1.

### Table A20.1 Selected references on nuclear energy. See also Appendix 28, Section B (Nuclear Regulatory Commission)

#### Nuclear energy and technology

ASME (Appendix 28 Nuclear Safety); HSE (Appendix 28 Nuclear Installations, 1979 HA 4); AICHe (1954-67/101-118, 1972/119); McCullough (1957); J.H. Bowen and Masters (1959); Kopelman (1959); Tipton (1960); El-Wakil (1962); Foard (1963); Gill (1964); T. Thompson and Beckerley (1964); Lumarsch (1965); Zudan, Yen and Steigelman (1965); Shaw (1967); Glassstone (1968); F.R. Farmer (1969a); Glassstone and Sesonks (1969); ENEA (1970); Ramey (1970); Wechsler (1970); Berry (1971); CEGB (1971); T.J. Thompson (1971); A.E. Green and Bourne (1972); R.V. Moore (1972); Holdren and Herrera (1973); Jaeger (1973, 1975); Inglish (1973); ACRS (1974); Allardice and Trapnell (1974); Bupp and Derian (1974); Cochran (1974); Willrich and Taylor (1974); Flood (1976); Hafner et al. (1976); S.E. Hunt (1976); RCEP (1976 Rep. 6); ASTM (1977 STP 616); S. Fawcett (1977); IMechE (1977/38, 1982/64, 1984/82, 1988/99, 1992/143); Pocock (1977); Pedersen (1978); Duderstadt (1979); J. Hill (1979a); Kaplan (1979); Cottrell (1981); Knief (1981); IBC (1982/24); IAEA (1983); W. Marshall (1984); Rahn et al. (1984); Stahlkopf and Steele (1984); Bennett (1985); Wilkie and Berkowitch (1985); Wilkie (1986); Kletz (1986c, 1987g, 1991c); Inhaber (1987); UKAEA (1987); Varey (1987); Bindon (1988); Lewins (1988); G. Lewis (1988); V.C. Marshall (1988b); Gittus (1988); Bennett and Thomson (1989); NFP (1991 NFPA 801, 1995 NFPA 803); Nowlen (1992); Hicks (1993) ANSI N series

#### Inherently safer design

Kletz (1988b); Forsberg et al. (1989)

#### Sizewell B


#### Nuclear waste, fuel reprocessing

I.K.G. Williams (1979); Bennett (1981); R. Smith and Hartley (1982); J.A. Williams (1982); Bennett (1983); IBC (1985/64, 1986/70, 1987/73); Heafield (1986); N.J. James, Rutherford and Sheppard (1986); Elliot and King (1987); N. James, Sheppard and Williams (1987)

#### Reactivity and radioactive contamination

NRPB (Appendix 28); Moelwyn-Hughes (1961); W.J. Moore (1962); Yen Wang (1969); Coggle and Noakes (1972); McDonald, Darley and Clarke (1973); Sternglass (1973); AEC (1975); Brodine (1975); MRC (1975b); G.N. Kelly, Jones and Hunt (1977); R.H. Clarke (1980); Whicker and Schultz (1982); Foo-Sun Lau (1987); NRPB (1989, 1995)

#### BS (Appendix 27 Reactivity)

#### Nuclear hazard assessment and control

HSE (Appendix 28 Nuclear Installations, 1977c, 1979d, f, 1979 HA 5, 1983/8, 1992/16); AEC (1957, 1975); Sinclair (1963); F.R. Farmer (1967a, b, 1969a, b, 1970, 1971); Bourgeois (1971); Dale and Harrison (1971); F.R. Farmer and Gilby (1971); Hanauer and Morris (1971); Kirk and Taylor (1971); Ylarrondo, Solbrig and Ibsen (AICHe 1972/119); Hosemann, Schikarski and Will (1973); EPA (1974); Karam and Morgan (1974); N.C. Rasmussen (1974, 1981); Chicken (1975, 1982, 1986); Bridenhaugh, Hubbard and Minor (1976); Flood (1976); Freudenthal (1976); Rust and Weaver (1976); Ford (1977); Fussell and Burdick (1977); Comey (1977); HM Chief Inspector of Nuclear Installations (1977); G.N. Kelly, Jones and Hunt (1977); NRC (1977a-c); UCS (1977); Higson (1978); R.J. Parker (1978); E.E. Lewis (1979); Windscale Local Liaison Comm. (1979); Alvareas and Hasegawa (1979/80); Joksimovic and Vesely (1980); Strong and Menzie (1980); Charlesworth, Gronow and Kenny (1981); Fleming et al. (1981); Sagan (1981); Allan, Adraktas and Campbell (1982); NRC (1982); Openshaw (1982); I.B. Wall (1982); Amendola (1983a, b); D.E. Bennett (1983); Frenlin (1983); Heudorf and Hartwig (1983); Brooks (1984); CEC (1985/2); Lois and Modares (1985); Frank and Moieni (1986); C.D. Henry and Brauer (1986); Ronen (1986); Anon. (1987p); Ashworth and Western (1987); Durant and Perkins (1987); Gittus (1987); Mullins and Clough (1990 SDR R509); J. Singh, Cave and...
McBride (1990); Ang (1992); IAEA (1992); Wu and Apostolakis (1992); Hofmeister (1993); J.R. Thomson (1994)

**NRC studies**


**Benchmark studies**

TUV (1979); NEA (1984)

**Detailed studies**

Coxon (1971); Kazarians and Apostolakis (1978); Apostolakis and Mosleh (1979); Rasmussen, Wilson and Burdick (1979); Apostolakis and Kazarians (1980); Aupied, Cogoque and Procaccia (1983); M.G.R. Evans and Parry (1983); Hendrickx and Lannoy (1983); Coudray and Mattei (1984); NRC Steam Explosion Rev. Gp (1985); Bley and Reuland (1987); Ashurst and Davidson (1993 LPB 112)

**Emergency planning**


**Incidents**

Chamberlain (1959); Anon. (1962c); Norman (1975); Anon. (1976g); HM Chief Inspector of Nuclear Installations (1977); V.C. Marshall (1979c); Bertini et al. (1980); Curtis, Hogan and Horowitz (1980); J.G. Fuller (1984); May (1989); Mosey (1990); Ashurst and Davidson (1993 LPB 112); Anon. (1994 LPB 119, p. 13)

**Windscale**


**Browns Ferry**

AEC (1975); Ford, Kendall and Tye (1976); NRC (1976); Anon. (1982 LPB 47, p. 13); May (1989)

**Severe accident risks**

Pickard, Lowe and Garrick (1983); NRC (1987a, b, 1989); Wheeler et al. (1989)

**Precursor events**

Minarick and Kukiellka (1982); Cottrell et al. (1984); Minarick et al. (1985)

### A20.1 Radioactivity

Accounts of radioactivity and of ionizing radiations are given by Glashon (1968), Glashon and Dolan (1979), Knie (1981), Foo-Sun Lau (1987) and in many texts on physical chemistry such as Moelwyn-Hughes (1961) and W.J. Moore (1963).


#### A20.1.1 Types of radiation

There are three main types of radioactive particle or ray: (1) α-particles, (2) β-rays or particles and (3) γ and X-rays.

α-particles are helium nuclei, or protons. Their mass is relatively large and their range correspondingly short. An air gap of about 8 cm or a sheet of paper may suffice to stop them. Generally, they present little external radiation hazard, but they are dangerous if they get inside the body.

β-rays, or particles, are electrons. They have a much smaller mass and greater penetrating power. Their range in air is about 10 m, but they are usually stopped by a few millimetres of solid material.

γ and X-rays are electromagnetic radiations, or photons, which differ from each other only in respect of source and wavelength. They have a range of several hundred metres, but can be stopped by a few millimetres of lead or 0.5–1 m of concrete.

Both β-rays and γ and X-rays constitute an external radiation hazard.

Ionizing radiation may be classified as direct or indirect. The former consists of particles and thus includes α-particles (protons) and β-particles (negatively charged electrons) and positrons (positively charged electrons), while the latter includes γ and X-rays (both photons) and also neutrons.

#### A20.1.2 Units of radiation

The units of activity of a radioactive source are bequerel (Bq) and curie (Ci).

1 Bq = 1 disintegration/s
1 Ci = 3.7 × 10^{10} Bq

Another unit of source strength is the roentgen (R), which defines the ionization effect of γ and X-rays.

1 R produces in 1 cm² air ions carrying a charge of 1 electrostatic unit (esu)

For γ and X-ray radiation 1 R is equivalent to the absorption of 87 erg/g of air. However, for other types of radiation and targets the equivalences are significantly different.

Units of absorbed dose are rads and grays (Gy), the latter being the modern unit.

1 rad = 100 erg/g = 0.01 J/kg
1 Gy = 1 J/kg = 100 rad

The effect on man of a given absorbed dose D is a function of the type of radiation, for which a quality factor Q is defined. The value of Q is unity for γ and X-rays and electrons, but has other values for other types of radiation. The value for Q for α-particles is 20. The quality factor is also referred to as the relative biological effectiveness (RBE).

The dose equivalent H is the product of the absorbed dose and the quality factor:

\[ H = D \times Q \]  

Units of effective dose, or dose equivalent, are rems and sieverts (Sv), the latter being the modern unit.
1 rem = 1 rad × Q
1 Sv = 1 Gy × Q
1 Sv = 100 rem

Thus the roentgen is the unit of total dose, the rad or gray that of absorbed dose and the rem or sievert that of effective dose.

In the context of discussion of biological effects effective dose is frequently referred to simply as dose.

A20.1.3 Radioactive decay

Specific Activity and Half Life

The basic equation for radioactive decay is

\[ \frac{dn}{dt} = -\lambda n \]  \hspace{1cm} \text{[A20.1.2]}

where \( n \) is the number of radioactive atoms, \( t \) time and \( \lambda \) the radioactive decay constant (s\(^{-1}\)). Then from Equation A20.1.2

\[ \frac{n}{n_0} = \exp(-\lambda t) \]  \hspace{1cm} \text{[A20.1.3]}

where \( n_0 \) is the number of radioactive atoms at arbitrary time zero.

The half-life \( \tau \) is defined by the relations

\[ \frac{n}{n_0} = \frac{1}{2} = \exp(-\lambda \tau) \]  \hspace{1cm} \text{[A20.1.4]}

\[ \tau = \ln 2 / \lambda = 0.693 / \lambda \]  \hspace{1cm} \text{[A20.1.5]}

But

\[ n_0 = N_0 / M_a \]  \hspace{1cm} \text{[A20.1.6]}

where \( M_a \) is the atomic weight and \( N_0 \) is Avogadro’s constant (\( = 6.024 \times 10^{23} \)). Then from Equations A20.1.2, A20.1.3 and A20.1.6 at arbitrary time \( t = 0 \) \((n = n_0)\)

\[ \frac{dn}{dt} = \frac{\lambda N_0}{M_a} = \frac{\ln 2 N_0}{\tau M_a} \]  \hspace{1cm} \text{[A20.1.7]}

Energy release

The release of energy during radioactive decay is governed by the relation of Einstein

\[ E = mc^2 \]  \hspace{1cm} \text{[A20.1.8]}

where \( c \) is the velocity of light, \( E \) the energy release and \( m \) the mass.

The energy may be calculated from the decay equation by determining the difference in mass of the two sides. An atomic mass unit (amu) is equivalent to 931 MeV.

For example, for the decay of polonium 210 to lead 206 and helium nucleus, or \( \alpha \)-particle, the decay equation is

\[ ^{210}\text{Po} \rightarrow ^{206}\text{Pb} + ^{4}\text{He} \]

and the atomic mass balance is

<table>
<thead>
<tr>
<th>LHS</th>
<th>Atomic mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{210}\text{Po})</td>
<td>210.049</td>
</tr>
<tr>
<td>(^{206}\text{Pb})</td>
<td>206.034</td>
</tr>
<tr>
<td>(^{4}\text{He})</td>
<td>4.004</td>
</tr>
<tr>
<td>Total RHS</td>
<td>210.038</td>
</tr>
<tr>
<td>Mass loss</td>
<td>0.011</td>
</tr>
<tr>
<td>Energy</td>
<td>931 \times 0.011 = 10.2 MeV</td>
</tr>
</tbody>
</table>

A20.1.4 Radioactivity health effects

An account of health effects from radiation is given in Living with Radiation by the National Radiation Protection Board (NRPB) (1989). An account in the specific context of Chernobyl is given by the Watt Committee on Energy (1991).

Potential health effects of radiation at relatively low doses are short term: (1) birth defects from radiation received by the foetus; (2) thyroid cancers from radioactive iodine; from 3 years onwards: (3) leukaemia; over a period 5–40 years: (4) cancers; and over a generation: (5) genetic effects.

Recommendations for radiation protection standards are given in Radiological Protection Bulletin 141 1993 by the NRPB (1993). Details are given in Chapter 25.

A20.2 Nuclear Industry

A20.2.1 Nuclear industry regulation

Public control of the nuclear industry is discussed in Chapter 4. In the UK the regulatory body is the Nuclear Installations Inspectorate (NII), which is part of the HSE. In the USA it changed in the mid-1970s from the Atomic Energy Commission (AEC) to the Nuclear Regulatory Commission (NRC).

A20.2.2 Nuclear industry advisory committees

In the UK there is a standing committee, the Advisory Committee on the Safety of Nuclear Installations (ACSNI) which advises on nuclear safety. In the USA there is an Advisory Committee on Reactor Safety (ACRS).

Advice on radiological protection in the UK is the responsibility of the National Radiological Protection Board (NRPB).

A20.2.3 International bodies

Bodies operating at the international level include the International Atomic Energy Agency (IAEA) in Vienna and the International Committee on Radiological Protection (ICRP). The IAEA was set up in 1957 as an intergovernmental organization linked to the UN.

A20.2.4 Nuclear industry research

Work for the nuclear industry is a main source of support for a number of major research laboratories and organizations whose output is also of interest to the process industries. In the UK these include the UK Atomic Energy Authority (UKAEA), which operates laboratories at Harwell. The Systems Reliability Directorate (SRD) is part of the UKAEA.

In the USA major laboratories with a nuclear interest include the Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Electric Power Research Institute (EPRI), Lawrence Livermore National Laboratory (LLNL), Oak Ridge National Laboratory (ORNL) and Sandia Laboratories (SL).

A20.2.5 Nuclear industry accidents

Early perceptions of the hazard from the nuclear industry were coloured by the image of an explosion from a nuclear weapon. A major accident in the nuclear industry, a core meltdown, is quite different. There would not be the initial intense blast and radiation
effects, but rather a dispersion of radioactive material at the site and from the site by the wind.

Such an accident occurred at Chernobyl.

A20.2.6 Nuclear industry debate

Virtually from its inception the nuclear industry has been the subject of debate. Some principal conflicts are Nuclear Power by Patterson (1976), Soft Energy Paths by Lovins (1977), The Risks of Nuclear Power Reactors by the Union of Concerned Scientists (UCS) (1977), Nuclear or Not? by Foley and van Buren (1978), Coverup by Grossman (1980), The Fast Breeder Reactor by Sweet (1980), The PWR Decision by Camell and Chadleigh (1984), Going Critical by Patterson (1985) and Nuclear Politics by T. Hall (1986).

A20.3 Nuclear Reactors


Treatments by the HSE include PWR (HSE, 1979d), Safety Assessment Principles for Nuclear Reactors (HSE, 1979b) and Sizewell B (HSE, 1982b).

A20.3.1 Nuclear reactor types

Some principal types of nuclear reactor are

1. Gas-cooled reactors:
   a. Magnox reactor;
   b. Advanced gas-cooled reactor (AGR);
   c. High temperature gas-cooled reactor (HTGR);
2. Light water reactors (LWRs):
   a. Pressurized water reactor (PWR);
   b. Boiling water reactor (BWR);
3. Heavy water reactors:
   a. CANDU reactor;
   b. Steam generating heavy water reactor (SGHWR);

Accounts of reactor types are given in Nuclear Power Reactors by the UKAEA (1987) and by Patterson (1976) and Lewins (1988).

In the UK the first reactors were the gas cooled Magnox reactors. The next generation were the advanced gas cooled reactors. The first pressurized water reactor came much later, at Sizewell B.

Elsewhere, notably the USA and France, the vast majority of reactors installed have been PWRs.

A20.3.2 Reactor design features

In a nuclear reactor energy is released by a chain reaction involving neutrons. The reaction is sustained by those neutrons which are absorbed. Slower neutrons are absorbed in larger proportion than faster ones. Use is made, therefore, of a ‘moderator’ to slow down the neutrons. In some designs the moderator is graphite, e.g. the Magnox reactor, while in others it is water, e.g. the PWR.

The power output of the reactor is controlled by movement of control rods, containing materials which are strong absorbers of neutrons, and the reactor is shut down by their full insertion. Emergency shut down, or scram, is effected by dropping in the rods.

Even when shut down the reactor has a certain output of heat, due to radioactivity in the core. This decay heat needs to be removed if the core is not to overheat. The removal of the decay heat is one of the main problems which have to be handled in reactor design.

The reactor core is cooled by a coolant which in the AGR is carbon dioxide and in the PWR is water.

A20.3.3 Advanced gas-cooled reactors

The underlying concept of the advanced gas-cooled reactor (AGR) is that if forced convection circulation of the gas coolant is lost, natural convection will still effect a degree of cooling. To this extent, the reactor is an application of inherently safer design.

A20.3.4 Pressurized water reactors

The majority of nuclear reactors installed world-wide are PWRs. In the PWR design the core is cooled by water which also doubles as the moderator.

A PWR is provided with multiple systems to inject cooling water into the reactor to keep the core cool and with numerous protective systems to ensure the operation of this backup cooling. The reactor is vulnerable in the event of the failure of these instrument and cooling systems. On a PWR an emergency can escalate within a relatively short time scale.

In a PWR the fuel is inside three sets of containment. The first is the fuel rods. The second is the reactor pressure vessel (RPV) in which the fuel rods are held. The third is the containment building which encloses the reactor vessel.

The reactor is vulnerable to loss of coolant and much attention has focused on the large loss of coolant (LOCA) accident.

A20.3.5 Inherently safer design

In view of the nature of the hazard from a nuclear reactor, there is interest in inherently safer design. Mention has already been made of the inherent safety aspects of the AGR.

An review of approaches to inherently safer design of nuclear reactors is given in Proposed and Existing Passive and Safety-related Structures, Systems and Components (Building Blocks) for Advanced Light Water Reactors by Forsberg et al. (1989).

Some examples are discussed by Kletz (1988h). The high temperature gas reactor (HTGR) is a small reactor cooled by high pressure helium. The reactor is designed to withstand a high temperature and to have an adequate heat loss by radiation and natural convection if the coolant should fail. The Swedish process-inherent ultimate safety (PIUS) reactor is a water cooled reactor immersed in boric acid solution, so that if the coolant pumps fail this solution is drawn through the core by natural convection.

Another aspect of inherent safety is the reliability of the overall system for the control and protection of the reactor, which includes both the automatic control and protection and the process operator. As already mentioned, a PWR is vulnerable to equipment failure in the
instrument and coolant systems which protect it. It is therefore vulnerable also to operator actions which render this protection ineffective.

This feature is discussed by Franklin (1986) in these terms:

When operators are subject to conditions of extreme emergency arising from a combination of unforeseen circumstances they will react in ways which lead to a high risk of promoting accidents rather than diminishing them. This is materially increased if operators are aware of the very small time margins that are available to them.

A20.4 Nuclear System Reliability

A20.4.1 Pressure systems

The integrity of the pressure system is critical to the safety of a nuclear reactor such as the PWR. Much attention has therefore focused on the potential for pressure vessel failure.

Pressure vessel failure is considered in the Rasmussen Report. It is also discussed by Bridenbaugh, Hubbard and Minor (1976) and Cottrell (1977).

It was a principal issue at the Sizewell B inquiry, and an account is given in Appendix 26.

The treatment given in Chapter 12 of failure rates of pressure vessels draws heavily on estimates made with nuclear applications in mind.

A20.4.2 Protective systems

From the start the nuclear industry made extensive use of instrumentation, and particularly of instrumented protective systems. Accounts of this work are given in Reliability Assessment of Protective Systems for Nuclear Installations by Eames (1965 AHSH(S) R99) and Safety Assessment with Reference to Automatic Protective Systems for Nuclear Reactors by A.E. Green and Bourne (1966 AHSH(S) R136).

This work led to interest in reliability technologies, including fault trees and dependent failure.

Since it was necessary to have a target to aim for in the design of such protective systems, this also prompted the development of risk criteria.

A20.4.3 Reliability engineering

The nuclear industry joined the defence and aerospace industries in developing reliability techniques. An treatment of reliability engineering from the viewpoint of the nuclear industry and with special reference to protective systems, is Reliability Technology by A.E. Green and Bourne (1972).

A20.4.4 Failure and event databases

The practice of reliability engineering created the need for failure and event databases. This is illustrated by the development of the database of the UKAEA Systems Reliability Service (SRS) (Ablitt, 1973 SRS/GR/14). The development of this database is described in Appendix 14.

A20.4.5 Fault trees

The need to identify failure paths and to estimate failure frequencies for systems with multiple layers of protection has led in the nuclear industry to extensive use of fault tree analysis. It is the basic method used for frequency estimation in the Rasmussen Report. The technique is described in Reliability and Fault Tree Analysis by Barlow, Fussel and Singpurwalla (1975) and in Fault Tree Handbook by Vesely et al. (1981).

Associated with this work are the fault tree analysis computer codes PREP and KITT (Vesely and Narum, 1970).

A20.4.6 Event trees

Likewise, the nuclear industry has made much use of event trees, both to identify and quantify the effects of certain failures, such as those of the power supply, and the outcomes of a release to atmosphere.

A20.4.7 Dependent failures

Nuclear reactors rely on extensive protective systems to give a very high degree of reliability, and it is characteristic of such systems that they are liable to be defeated by dependent failure. In some cases different assumptions about dependent failure can result in a dramatic increase in the estimated frequency of an accident. The nuclear industry has therefore put much effort into the study of this problem.

The problem of dependent failure bulks large in the analyses in the Rasmussen Report and in the critiques of that report.

An account is given in Defences against Common-mode Failures in Redundant Systems by Bourne et al. (1981 SRD R196).

A20.5 Nuclear Hazard Assessment

A20.5.1 Probabilistic risk assessment

The nuclear industry has for long made use of probabilistic risk assessment (PRA), or probabilistic safety assessment (PSA), as a means of ensuring that its hazards are identified and under control and as a basis for dialogue on this with the regulatory authority. Guidance is given in PRA Procedures Guide by the NRC (1982). A more recent treatment is Procedures for Conducting Probabilistic Safety Assessment of Nuclear Power Plant by the IAEA (1992).

The Rasmussen Report, described in Appendix 23, is one well known generic PRA. Another is the Deutsche Risikostudie Kernkraftwerke by the Technische Uberwachungsverein (TUV) (1979).

A20.5.2 Accident sequences and scenarios

In a nuclear PRA considerable effort is devoted to the treatment of the accident sequences, or scenarios.

Thus a large proportion of the IAEA document just referred to is devoted to procedures for the identification of accident initiators and of accident sequences, for the classification of accident sequences into plant damage states and for the determination of the frequency of the accident sequences.

A20.5.3 Rare events

There are a number of natural and man-made threats which may hazard a nuclear plant. Examples of these two types of event are, respectively, an earthquake and an aircraft crash. Such events, their consequences and
frequency, have therefore been the subject of much study by the nuclear industry.

A20.5.4 Explosions
One type of the event which may put a nuclear plant at risk is an explosion. The industry has examined various kinds of explosion, including vapour cloud explosions, and certain types of particular interest to it such as steam explosions and hydrogen explosions.

A20.5.5 Hydrogen explosions
The fuel elements in the reactor core are held in metal cladding tubes. At high temperatures the zirconium metal used for this cladding can react with steam to produce hydrogen, with the risk of a hydrogen explosion.

A20.5.6 Missiles
Studies of some relevance to process plants are those on missiles such as the work reported by Baum (1984, 1991).

A20.5.7 Earthquakes
Of rare natural events, the earthquake hazard bulks large both in plant design and in risk assessment. The nuclear regulator has put much effort into defining the type of earthquake which the plant should be required to withstand. Guidance is given in Design Response Spectra for Seismic Design of Nuclear Power Plants by the NRC (1973).

Then, given such a design earthquake, it is possible to specify equipment to withstand it, as described below.

A20.5.8 Expert judgement
Where hard information is lacking, resort may be had to the use of expert judgement. Thus expert judgement may be used to obtain estimates of failure and event rates. It may also be applied to other aspects such as the formulation of accident sequences. Guidance on this approach is given in Eliciting and Analysing Expert Judgement: a Practical Guide by M.A. Meyer and Booker (1990).

A20.5.9 Computer error
A modern nuclear power station operates under computer control. The control computer, both hardware and software, is therefore a safety critical system.

The quality assurance of the computer software is a particularly intractable problem. An account of this aspect of the Sizewell B computer system is given by Hunns and Wainwright (1991).

A20.5.10 Human error

A20.5.11 Source terms
Each accident scenario needs to be associated with a defined source term, so that the dispersion of radioactive materials may be modelled.

A20.5.12 Emission models
The nuclear industry was one of the first to develop a sustained interest in two-phase flow, both flow within the plant and flow of leaks from it. An example of work from a nuclear background is Two-Phase Flow and Heat Transfer by Butterworth and Hewitt (1977).

A20.5.13 Gas dispersion models
Much of the work on gas dispersion modelling has been in support of work on the consequences of a nuclear accident. This is illustrated by one of the early texts, Meteorology and Atomic Energy 1968 by Slade (1968).

A20.5.14 Severe accident risk
A focus to work on PRA has latterly been provided by the Severe Accident Risk study, for which the basic document is NUREG-1150 Reactor Risk Reference Document of the NRC (1987).

A20.5.15 Risk criteria
The quantification of risks from nuclear reactors has necessarily led to the need for risk criteria by which to judge these risks. Some of the first risk comparisons were those given in the Rasmussen Report.

Since then, there has been a wide-ranging debate of risk criteria for man-made hazards of all kinds. Nuclear risk criteria emerging from this are given in The Tolerability of Risk from Nuclear Power Stations by the HSE (1988b), and associated comments (HSE, 1988a).

A20.6 Nuclear Pressure Systems

A20.6.1 Quality assurance
All aspects of the design and operation of nuclear power plant need to be carried out to high standards. There has to be, therefore, a system of quality assurance to ensure that these standards are met.

This aspect is described in NUREG-1055 Improving Quality and the Assurance of Quality in the Design and Construction of Commercial Nuclear Power Plants (NRC, 1984).

A20.6.2 Inspection
High-quality inspection is an essential part of the nuclear industry’s armoury. It has a special interest in non-invasive techniques of monitoring and inspection. These include acoustic emission monitoring, ultrasonics and leak detection methods.

Methods of leak detection are described in NUREG/CR-4813 Assessment of Leak Detection Systems for LWRs (NRC, 1987).

The industry has also developed risk-based inspection. An account is given in NUREG/CR-5371 Development and Use of Risk-based Inspection Guides (NRC, 1989).

A20.6.3 Fracture mechanics
One of the most powerful inspection techniques for pressure systems is fracture mechanics and the nuclear industry has been in the van in developing such
methods. They include the CEGB R6 system described in R/H/R6 Assessment of the Integrity of Structures Containing Defects by Milne et al. (1986).

A20.6.4 Seismic qualification
One of the principal external hazards to which a nuclear plant is vulnerable is an earthquake. There is therefore a requirement that equipment crucial to safe operation be able to withstand an earthquake of specified intensity. This is implemented by a system of seismic qualification of equipment. An account is given in NUREG-1030 Seismic Qualification of Equipment in Operating Nuclear Power Plants by the NRC (1987).

A20.6.5 Ageing
Another aspect which the nuclear industry has explored in some detail is ageing of equipment, and residual, or remanent, life assessment.

An account of basic principles is given in NUREG/CR-5314 Life Assessment Procedure for Major LWR Components (NRC, 1990). There are studies on specific equipment such as electric motors, diesel generators, instrument air systems, motor operated valves, etc.

A20.7 Nuclear Reactor Operation
The Kemeny Report and, even more, the Task Force Report on TMI contain numerous recommendations on nuclear reactor operation, particularly on the design of display and alarm systems and of control rooms generally, operating and emergency procedures, and operator training.

A20.7.1 Human factors
A considerable effort is made to apply human factors on nuclear power plants, a practice reinforced by the Kemeny Report's emphasis on people-related problems.

Some typical titles which illustrate the application of human factors on nuclear power plants are as follows: NUREG/CR-3331 A Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control (NRC, 1983); NUREG/CR-3371 Task Analysis of Nuclear Power Plant Control Room Crews (NRC, 1984); and NUREG-1122 Knowledge and Abilities Catalog for Nuclear Power Plant Operators (NRC, 1987).

Three reports on human factors in nuclear power plant operation have been issued by the ACSNI Study Group on Human Factors. Reference has already been made to the second report, on human reliability assessment (ACSN, 1991). The other two are First Report on Training and Related Matters (ACSN, 1990) and Third Report: Organising for Safety (ACSN, 1993).

A20.7.2 Process operator
The problems, and modellings, of the process operator have been the subject of extensive studies, notably the work described in Information Processing and Man–Machine Interaction by Rasmussen (1986).

A20.7.3 Display and alarm systems
Early developments in computer aids for the process operator were the alarm analysis systems developed at Wyllia and Oldbury nuclear power stations, described by Welbourne (1965) and Patterson (1968), respectively. The purpose of these systems is to assist the operator in interpreting the large number of alarms which tend to come up in a plant emergency.

One of the perceived problems at TMI was the difficulty experienced by operators in assessing the safety status of the plant. A recommendation of the Task Force Report was that every reactor should have a plant safety status display.

TMI also illustrated the alarm interpretation problem just mentioned and the report recommended that the feasibility be explored of developing a suitable aid, which it termed a disturbance analysis system (DAS).

A20.7.4 Control room design
A large proportion of the studies conducted on control rooms have been in the nuclear industry, and these have contributed to the development of understanding of human factors and human error.

In the aftermath of TMI control room design in general was also an issue. This illustrated in NUREG-0700 Guidelines for Control Room Design Reviews (NRC, 1981).

A set of studies of the Sizewell B control room are described by Ainsworth and Pendlebury (1994), Umbers (1994) and Whitfield (1994).

A20.7.5 Operating procedures
In the operation of nuclear power plants particular emphasis is placed on written operating procedures and on the training of operators in these. An account is given in NUREG/CR-3968 Study of Operating Procedures in Nuclear Power Plants (NRC, 1987).

A20.7.6 Emergency procedures
Operating procedures for dealing with an emergency assume particular importance on nuclear power plants. The Kemeny Report and the Task Force Report make recommendations on the emergency procedures.


A20.7.7 Operator training
Process operators on nuclear power plants undergo extensive training, for which the industry makes appreciable use of simulators.

The need for such training is a principal theme of both the Kemeny Report and of the Task Force Report on TMI. It is also the subject of the first report of the Study Group on Human Factors of the ACSNI (1990). Simulator training is treated in NUREG/CR-3725 Nuclear Power Plant Simulators for Operator Licensing and Training (NRC, 1984) and numerous other reports.

A20.8 Nuclear Emergency Planning
An emergency plan, covering both on-site and off-site aspects, is an integral part of the arrangements at a nuclear power plant.

A20.8.1 Accident management plans
There has been growing emphasis on the need to plan for and to manage an emergency.
Relevant work is that described in NUREG/CR Management of Severe Accidents by the (NRC, 1985) and NUREG/CR-5543 A Systematic Process for Developing and Assessing Accident Management Plans by the NRC (1991).

A further account is given by Ang (1992).

A20.8.1 Off-site emergency plans

Off-site emergency planning has been a feature of the nuclear industry from its earliest days. An account is given in Emergency Plans for Civil Nuclear Installations by the HSE (1986b).

A20.9 Nuclear Incident Reporting

In most regulatory regimes the nuclear industry is required to report to the regulator the occurrence of specified types of incidents.

A20.9.1 Licensee Event Reports

In the USA the system is that described in the NUREG/CR-2000 Licensee Event Report (LER) compilation.

A20.9.2 Precursors to severe accidents

The LERs record some events which are of such a nature that they could well have escalated into more severe events, even though in the particular case this has not occurred. These events are precursors of more serious incidents and serve as warnings. Periodic analyses are made of such precursors such as NUREG/CR-4674 Precursors to Potential Severe Core Damage Accidents 1990: Status Report by the NRC (1991).

A20.10 Nuclear Incidents

There have been a number of incidents on nuclear plants which are instructive for the process industries also. In addition to TMI and Chernobyl, they include Windscale and Browns Ferry.

Accounts of incidents include those in Nuclear Power by Patterson (1976), The Nugget File by the UCS (1979) and Nuclear Lessons by Curtis et al. (1980); later incidents are covered by May (1989).

A20.10.1 Radioactive sources

Although the incidents of prime interest here are those involving nuclear plant, other nuclear sources should not be neglected. The following case, believed to be the worst of it kind to date, illustrates the hazard from equipment containing a radioactive source.

In 1985 in Goiania, Brazil, a radiotherapy institute moved premises, leaving behind a unit containing a caesium-137 source in a stainless steel container and without notifying the licensing authorities. Subsequently the building was partially demolished. Some two years after the institute’s departure, on 13 September 1987, two men entered and tried to dismantle the machine for scrap, one taking home the steel cylinder; both fell ill. However, some five days later one broke open the steel cylinder and the caesium spilled out. A train of events ensued which resulted in 249 people being exposed to radiation, of whom four died.

A20.10.2 Military reactors and weapons plants

Hanford, the Green Run, 1949

On 2 December 1949 at Hanford, Washington State, there occurred one of a series of releases from an installation of eight nuclear reactors producing plutonium for the Manhattan Project. This was the Green Run, an experiment conducted to investigate monitoring methods which would be useful in intelligence work on the nuclear capabilities of other countries. The release formed a plume 200 miles x 40 miles in dead calm conditions and involved 20000 Ci of xenon and 7780 Ci of iodine-131.

Rocky Flats, Colorado, 1957

On 11 September 1957 at Rocky Flats, Colorado, a fire occurred in a glove box at an atomic weapons plant. Plutonium shavings ignited spontaneously, workers tried to put the fire out and explosions occurred which blew out the ventilation filters. For half a day there was a release of plutonium contaminated smoke. On 11 May 1969 there occurred another glove box fire. All new weapons production was shut down for six months.

Idaho Falls, Idaho, 1961

On 3 January 1961 at Idaho Falls, Idaho, an incident occurred on a prototype military nuclear power plant, the Stationary Low Power Reactor SL-1, one of 17 reactors at the AECs National Reactor Test Station (NRTS). The reactor was shut down and control rods had been disconnected to install additional instrumentation. The emergency started with the sounding of alarms. As it developed, three men working on the control rods were found to be missing. One was discovered dead, pinned to the ceiling by a control rod, another was also dead and the third died soon after. The precise sequence of events is uncertain. One explanation given is that the central control rod was partially withdrawn and there was a power surge, generating steam which lifted the lid of the pressure vessel, causing it to rise 9 ft and then drop back.

A20.10.3 Windscale

Accounts of the Windscale incident are given in Windscale Fallout by Breach (1978) and Windscale 1957 by L. Arnold (1992) and by May (1989).

On 10 October 1957 at Windscale, UK, an incident occurred which led to a serious radioactive release. The installation consisted of two simple air-cooled, graphite-moderated, atomic piles used for the production of plutonium. The graphite was subject to deformation and build-up of energy due to neutron bombardment, the so-called Wigner effect. A procedure had been established to release the Wigner energy by turning off the fans, making the pile critical and letting heat build up. On 7 October 1957, this procedure had been followed, but it appeared that not all the Wigner energy had been released, so the pile was heated up again. The sensors then showed an abnormal temperature rise and the power was reduced. By 9 October conditions seemed normal except that there was a hot spot. However, on 10 October a rise in radioactivity was detected at the filters in the chimney. An attempt was made to inspect the core using a remote scanner, which jammed. Staff removed a charge plug and looked in. All the fuel channels which
they could see were on fire and a fuel cartridge had burst. The air movement caused by the fans was now fanning the blaze. Despite fears that it might lead to a hydrogen–oxygen explosion, the decision was taken to use water to put out the fire, which it did. As a result of the incident, workers on the site were exposed to radiation and milk from cattle in the area had to be discarded. The release was mitigated by the presence of the filters, installed at the insistence of Sir John Cockcroft, prominent at the top of the chimney, and known locally as 'Cockcroft's Folly'. The piles were decommissioned and set in concrete.

A20.10.4 Civil nuclear reactors and reprocessing plants

Chalk River, Ontario, 1957

On 12 December 1957 at Chalk River, Ontario, there was a loss of control on a nuclear reactor leading to damage of the core so that it had to be removed and buried. In outline the initial sequence of events was as follows. Outside the control room, a supervisor found that an operator was opening valves which caused the control rods to withdraw. He immediately set about shutting the valves, but some of the rods did not drop back. He telephoned the operator in the control room, intending to ask him to push a button which would drop control rods in, but by a slip of the tongue actually referred to a button which would withdraw rods. In order to comply, the operator moved away from the phone so that the supervisor temporarily lost touch with him. The operator in the control room soon recognized from the rising reactor temperature that there was something wrong and pressed the scram button, but events had been set in train which led to core damage.

Detroit, Michigan, 1966

On 5 October 1966 near Detroit, Michigan, the Enrico Fermi reactor experienced an incident. The reactor was the first commercial fast breeder reactor in the USA. It was being started up for a series of tests when abnormalities were observed and some of the control rods were found not to be in their expected positions. Tests on the sodium coolant showed it to be contaminated, suggesting that part of the fuel core had melted, but the cause was unknown. The authorities were alerted and went on standby for evacuation. Subsequent investigation found that separation had occurred of parts from a steel cone at the bottom of the vessel, installed so that in a meltdown the fuel would spread out and not reach critical mass. In a last-minute modification, zirconium plates had been put onto the cone. One plate had worked loose, had been forced into the core by the sodium coolant and had blocked coolant flow to two of the fuel assemblies.

An account of this incident is given in We Almost Lost Detroit by Fuller (1984).

Browns Ferry, Alabama, 1975

Prior to TMI one of the US incidents which received particular attention was that on 22 March 1975 at Browns Ferry. Accounts are given in the Rasmussen Report and in Browns Ferry: the Regulatory Failure by Ford, Kendall and Tye (1976). The incident is described in Appendix 23.

Beloyarsk, USSR, 1978

On 30–31 December 1978 at Beloyarsk, USSR, there occurred an incident which until Chernobyl was the most serious in the nuclear industry. The complex was 50 km from Sverdlovsk and housed two RMBK reactors and a BM600 fast breeder reactor. A serious fire broke out in the machine hall, causing steel girders and the concrete roof to collapse, opening up a huge hole above No. 2 Generator and disabling the fire protection system. Emergency procedures called for both RMBK reactors to be shut down. But as it was close to –50°C outside, it was feared the reactor cooling system would freeze and the cores would overheat. Attempts were made to keep No. 1 Reactor and its turbine running, but despite the fire the turbine froze. There followed an extended emergency which eventually, with the arrival of fire fighters from outside, was brought under control.

Cap la Hague, France, 1981

On 6 January 1981 at Cap la Hague, Normandy, France, in a nuclear fuel reprocessing facility there occurred the most serious of a series of incidents. Fire broke out in a spent fuel dry waste silo. Ignition occurred in cotton waste, soaked in solvent and in contact with uranium and magnesium. The cotton waste had been used in a decontamination operation there several weeks earlier. The fire was attacked first by water, which formed steam, and then by liquid nitrogen. Radioactivity was released inside and outside the plant.

New York State, 1982

On 25 January 1982 in New York State the Ginna reactor experienced tube rupture, due to corrosion, in the steam generator, causing contamination of the secondary, clean steam circuit by the radioactive water from the primary water circuit cooling the core. High pressure in the steam circuit caused a pressure relief valve to open, initially in five minute bursts and then by sticking open for 50 minutes. Another PRV on the primary circuit was deliberately opened to reduce the pressure in that circuit but also stuck open. A steam bubble formed, but it proved possible to correct it by pumping in more water.

Frankfurt, FRG, 1987

On 16–17 December 1987 at Frankfurt, FRG, the Biblis A nuclear reactor experienced an incident involving the low pressure injection (LPI) system. It was a requirement that this system remain isolated to prevent (1) leakage of primary coolant out through it and (2) overpressure of the system itself by the primary coolant. During start up the main valve TH22 S006 on the pipe between the LPI system and the primary circuit had been left open; there were also two secondary valves on the line. The status of the main valve was shown by a red light on the control panel, but the operators assumed that the fault was on the light itself. There were two changes of shift before it was realized that valve TH22 S006 was open. The operators took two hours to decide on a plant shut down and then ten minutes later changed their minds and tried an alternative, and hazardous, procedure. They decided to initiate flow through valve TH22 S006, expecting that the valve would then be shut by its trip system. They controlled the flow by cracking open one
of the secondary valves and primary coolant started to escape, but valve TH22 S0006 did not shut, and after a few seconds they desisted. The operators then shut the reactor down.

**Notation**

- $H$ dose equivalent (Sv)
- $m$ mass
- $M_a$ atomic weight
- $n$ number of radioactive atoms
- $n_0$ number of radioactive atoms at time zero
- $N_A$ Avogadro's number
- $Q$ quality factor
- $t$ time
- $\lambda$ radioactive decay constant ($s^{-1}$)
- $\tau$ half-life (s)
- $c$ velocity of light
- $D$ absorbed dose (Sv)
- $E$ energy
Appendix

Three Mile Island

21

Contents

A21.1 The Company and the Management A21/2
A21.2 The Site and the Works A21/2
A21.3 The Process and the Plant A21/2
A21.4 Events Prior to the Excursion A21/4
A21.5 The Excursion – 1 A21/4
A21.6 The Emergency and the Aftermath A21/7
A21.7 The Excursion – 2 A21/7
A21.8 The Investigations A21/8
A21.9 Some Lessons of Three Mile Island A21/12
At 4.00 on 28 March 1979 a transient occurred on Reactor No. 2 at Three Mile Island, near Harrisburg, Pennsylvania. A turbine tripped and caused a plant upset. The operators tried to restore conditions, but, misinterpreting the instrument signals, misjudged the situation and took actions which resulted in the loss of much of the water in the reactor and the partial uncovering of the core. Radioactivity escaped into the containment building.

The accident at Three Mile Island (TMI) (also referred to initially as Harrisburg) was the most serious accident which had occurred in the US nuclear industry.

The President set up a commission to investigate the accident. Their work is described in The Report of the Presidents Commission on the Accident at Three Mile Island (the Kemeny Report) (Kemeny, 1979).

The NRC carried out an investigation, reported in Investigation into the March 28, 1979 Three Mile Island Accident by Office of Inspection and Enforcement (the NRC Report) (NRC, 1979b). It also set up a task force, the findings of which are given in TMI-2 Lessons Learned Task Force Final Report (the Task Force Report) (NRC, 1979d).

Another report is Analysis of Three Mile Island - Unit 2 accident by the Nuclear Safety Analysis Center (NSAC) of EPRI (1979a).

Hearings were also held by the US Congress (US Congress, 1979) at which evidence was taken from managers, engineers, process operators and others.

The Accident at Three Mile Island gives the initial response of the HSE (1979a).

The Three Mile Island accident was a watershed in the development of nuclear power in the US and worldwide. After 1979 the number of new nuclear power stations in the US virtually dried up. Elsewhere TMI has at the least heightened awareness of nuclear hazards.

In addition to the official reports mentioned, accounts of the TMI accident have been given in Three Mile Island by Stephens (1980) and by J.F. Mason (1979), Rubinstein (1979a, b), Collier and Davies (1980), Dunster (1980), H.W. Lewis (1980), Rogovin (1980), Schneider (1980) and Kletz (1982, 1988h). A detailed timetable of the events during the accident is given by the NRC (1979b) and by J.F. Mason (1979).

Selected references on Three Mile Island are given in Table A21.1.

### Table A21.1 Selected references on Three Mile Island

<table>
<thead>
<tr>
<th>Reference</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRC (1979b, d); Douglas (1979); EPRI (1979a); Ferrara (1979); HSE (1979a); Kemeny (1979); J.F. Mason (1979); Rubinstein (1979a, b); Savage (1979); US Congress (1979); Brookies and Siddall (1980); Cobb and Marshall (1980); Collier and Davies (1980); Dunster (1980); Lanouette (1980); Levy (1980); H.W. Lewis (1980); Rogovin (1981); Stephens (1980); Torrey (1980); Jaffe (1981); Moss and Sills (1981); Schneider (1981); Starr (1981); Straus (1981); Wolf (1981); Kletz (1982, 1983, 1988h); Sills, Wolf and Shelansky (1982); Sear, Long and Jones (1983); Anon. (1984kk); Ural and Zalosh (1985); Ballard (1988); Philley (1992)</td>
<td>Mr G. Miller, Mr J. Logan, Mr G. Kunder, Mr W. Zewe, Mr F. Scheimann, Mr E. Frederick, Mr C. Foust, Mr J. Herbein, Mr L. Rogers</td>
</tr>
</tbody>
</table>
Figure A21.1  Simplified flow diagram of TMI 2 nuclear power plant (Kemeny, 1979)
injection system which operates at 2.8 MPa. This takes water either from a large tank of borated water or from the dump of the containment building and is thus capable of keeping up recirculation indefinitely.

The reactor, the primary cooling circuit and the steam generators are housed in a containment building which is leak-tight. The containment is designed to retain the contents of the primary circuit in the event of a major leak.

The containment building has a spray system containing dilute sodium hydroxide. The spray is triggered by high containment pressure and is intended in the event of a loss of coolant accident to cool down the contents of the containment and to scrub out iodine.

The turbogenerator set is housed in a separate building which also contains the condensate and water treatment plants. Feedwater for the secondary circuit is from the condenser. The condensate water is purified by ion exchange in a condensate polishing system, a package unit.

The water converted to steam on the secondary side in the steam generators is supplied to them by the main feedwater pumps. These are backed up by auxiliary, or emergency, feedwater pumps. Both sets of feedwater pumps are housed in the turbine building.

The control room is a typical one and is shown in Figure A21.2.

A21.4 Events Prior to the Excursion

Some two days prior to the incident routine testing had been done on the valves on the auxiliary feedwater pumps. Two of the valves, the ‘twelve valves’, had inadvertently been left shut.

For some 11 hours before the incident the operators had been trying to clear a blockage in the condensate polishing system. In order to do this use was made of compressed air. The service air line used for this purpose was cross-connected to the instrument air line. The pressure of the air in the instrument line was less than that of the water in the units and some water got into the instrument air line, despite the presence of a non-return valve on that line. This water found its way to some of the plant instruments.

Another feature was a persistent slight leak from either the regular safety valves or the PORV.

A21.5 The Excursion – 1

An account is now given of the events which constituted the excursion. A timetable of the events is given in Table A21.2, Sections A and B showing the events and phases, respectively. The trend records of the RCS parameters are shown in Figure A21.3.

At the time of the incident on 28 March the reactor was operating under automatic control at 97% of its rated output of 961 MWe. The incident began when water which had entered the instrument air line caused the isolation valves on the condensate polishing system to drift shut and the condensate booster pump to lose suction pressure and trip out. The main feedwater pumps in the secondary circuit then tripped and almost immediately the main turbine tripped. The time was 4.00.37.

Valves allowing steam to be dumped to the condenser opened and the auxiliary feedwater pumps started up. At the steam generators the removal of heat from the RCS fell and the pressure of the RCS rose. Within 3–6 seconds the PORV set pressure of 15.5 MPa was reached and the valve opened, but this was insufficient to relieve the pressure and at 8 seconds in, pressure rose to 16.6 MPa, the set point for reactor trip. The control rods were driven into the core to stop the reaction.

The RCS pressure now fell below the PORV set pressure, but the valve failed to shut. However, the

![Figure A21.2 Control room at TMI 2 (Kemeny, 1979)](image-url)
### Table A21.2  Timetable of events at Three Mile Island

**A  Timetable (first hours) (after Dunster, 1980)**

<table>
<thead>
<tr>
<th>Absolute Time into Incident</th>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.01 zero</td>
<td></td>
<td>Feed water pump fails</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure rise occurs in primary circuit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relief valves open</td>
</tr>
<tr>
<td></td>
<td>8 s</td>
<td>Reactor shut down</td>
</tr>
<tr>
<td></td>
<td>13 s</td>
<td>PORV fails to close but indicates closure in the control room</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extra cooling water (normal) injected by the operator</td>
</tr>
<tr>
<td>4.02 1 min 45 s</td>
<td></td>
<td>Steam generators dry out</td>
</tr>
<tr>
<td>4.03 2 min</td>
<td></td>
<td>Pressure in primary circuit falls and emergency cooling water injection started</td>
</tr>
<tr>
<td>4.04 5 min 30 s</td>
<td></td>
<td>Indication of high level of water in the pressurizer causes operator to shut off one emergency cooling pump</td>
</tr>
<tr>
<td>4.06 5 min 30 s</td>
<td></td>
<td>Steam generated in the core</td>
</tr>
<tr>
<td>4.11 11 min</td>
<td></td>
<td>Alarm indication of a high level of water in the containment building sump</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sump water being pumped to auxiliary building</td>
</tr>
<tr>
<td>4.39 39 min</td>
<td></td>
<td>Sump pumps stopped by operator</td>
</tr>
<tr>
<td>5.00 60 min</td>
<td></td>
<td>Primary coolant pumps vibrating due to presence of steam</td>
</tr>
<tr>
<td>5.14 1 h 14 min</td>
<td></td>
<td>Two primary pumps stopped by operator</td>
</tr>
<tr>
<td>5.45 1 h 45 min</td>
<td></td>
<td>Two remaining primary pumps stopped by operator</td>
</tr>
<tr>
<td>5.50 1 h 50 min</td>
<td></td>
<td>Temperature in outlet ducts high enough to show presence of superheated steam – significance not recognized</td>
</tr>
<tr>
<td>6.22 2 h 22 min</td>
<td></td>
<td>Block valves on the relief valve lines closed by operators</td>
</tr>
<tr>
<td>7.00 3 h</td>
<td></td>
<td>Site emergency declared</td>
</tr>
<tr>
<td>7.20 3 h 20 min</td>
<td></td>
<td>Indication of 800 rem/h in containment building</td>
</tr>
<tr>
<td>7.24 3 h 24 min</td>
<td></td>
<td>General emergency declared</td>
</tr>
<tr>
<td>8.00 4 h</td>
<td></td>
<td>Containment building isolated automatically but operators continue to transfer primary let-down water to tanks in the auxiliary building</td>
</tr>
<tr>
<td>8.25 4 h 25 min</td>
<td></td>
<td>Local radio carried item concerning general emergency</td>
</tr>
</tbody>
</table>

**B  Phases (Collier and Davies, 1980)**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turbine trip 0–6 min</td>
</tr>
<tr>
<td>2</td>
<td>Loss of coolant</td>
</tr>
<tr>
<td>3</td>
<td>Continued depressurization 20 min-2 h</td>
</tr>
<tr>
<td>4</td>
<td>Heat-up transient 2–6 h</td>
</tr>
<tr>
<td>5</td>
<td>Extended depressurization 6–11 h</td>
</tr>
<tr>
<td>6</td>
<td>Repressurization and ultimate establishment of stable cooling mode 13–16 h</td>
</tr>
<tr>
<td>7</td>
<td>Removal of hydrogen bubble 1–8 d</td>
</tr>
</tbody>
</table>

*Absolute times are approximate; the turbine trip was at 4.00.37*  

Valve position indicator in the control room, which actually indicated not the position of the valve but the signal sent to it, showed the valve as closed. The RCS continued to lose water through the open PORV.

In the secondary circuit condensate was no longer being returned to the steam generators, because the valves on the condensate polishing system had closed. The auxiliary feedwater pumps were running, but the valves between the pumps and the steam generators were also, inadvertently, closed. At 1 min 45 s into the incident the steam generators boiled dry.

Meanwhile the RCS pressure was dropping. At 2 min the pressure fell to 11 MPa at which point the first of the ECCS systems, the HPI system, came on and injected high pressure water. The liquid level in the pressurizer, however, was rising.

The display of liquid level was an indicator of the level of fluid in the pressurizer, but no longer of the mass of water; the liquid now contained steam bubbles and had thus been rendered less dense. To this extent the level display had become misleading.

The operators became concerned that the HPI system was increasing the inventory of water in the RCS, that the steam bubble in the pressurizer would be lost and that the circuit would become full of water and thus go ‘solid’. At 4 min 38 s they therefore shut down one of the HPI pumps and throttled back the other.

With water passing through the PORV the pressure in the reactor coolant drain tank built up and at 7 min 45 s the reactor building sump pump came on, transferring water to the waste tanks in the auxiliary building.

At 8 min the operators realized that the steam generators were dry. They found that the auxiliary feedwater system valves were closed and opened them, thus restoring feedwater to the steam generators.

At 60 min the operators found that the RCS pumps were vibrating. This was due to the presence of steam, though they did not realize this. At 1 h 14 min they shut
Figure A21.3 Trend records of reactor cooling system parameters at TMI 2 (Collier and Davies, 1980): (a) parameters in minutes following turbine trip; and (b) parameters in hours following turbine trip.
off the two pumps in Loop B to prevent damage to the pumps and pipework, with possible loss of coolant, and at 1 h 40 min shut off the two pumps in Loop A.

At 2 h 18 min the PORV block valve was at last shut off, thus stopping the loss of water from the RCS. The RCS pressure then began to rise.

In the two hours since the turbine trip periodic alarms had warned of low level radiation in the containment building. At about 2 h in, there was a marked increase in the radiation readings. By 2 h 48 min in, high radiation levels existed in several areas of the plant. At 2 h 55 min a site emergency was declared.

Attempts were made to restart the RCS pumps. One pump in Loop B operated for some 19 min but was shut down again by vibration trips at 3 h 13 min.

Meanwhile, high radiation levels had been measured in the containment building. At 3 h 30 min a general emergency was declared.

At some point, perhaps about 4 h in, the station manager appears to have realized that the reactor core had suffered damage.

From 4 h 30 min attempts were made to collapse the steam bubbles in the RCS loops, but without success and at 7 h these efforts were abandoned.

The operators then tried to bring in the lower pressure cooling system by reducing pressure in the RCS. They began at 7 h 38 min by opening the PORV block valve. At 8 h 41 min the pressure fell to 4.1 MPa at which point the core flooding system operated.

One consequence of the exposure of the core was that a steam–zirconium reaction occurred, generating hydrogen. During the depressurization hydrogen from the RCS was vented into the containment building. At 9 h 50 min there occurred in the containment building what was apparently a hydrogen explosion. There was a thud and a pressure spike of 0.19 MPa occurred. The sprays came on for some 6 min. However, the nature of the event was not immediately understood.

By this time the reactor had been stabilized, although it had suffered core damage.

When the significance of the event in the containment building became appreciated, concern grew about a possible explosion of a hydrogen bubble there.

A21.6 The Emergency and the Aftermath

As already described, a site emergency was declared at 7.00 on 28 March. At 7.24 a general emergency was declared. The emergency which then unfolded over the next week or so is described in the Kemeny Report.

The plant was contacted by the local WKBO radio station. The radio station asked what kind of emergency it was. They were told by the company manager of communications services that it was a general emergency, a 'red-tape' sort of thing required by the NRC when certain conditions exist, but that there was no danger to the public.

The emergency did not end with the establishment of stable operation. The following day the core damage was found to be more serious than first thought. The hydrogen bubble problem persisted over the next 8 days and caused particular concern. There were also a number of other problems, mainly associated with the large quantities of water contaminated with low level radioactivity. The levels of radioactivity in the atmosphere around the plant were monitored continuously.

The handling of the emergency in respect of evacuation developed into a protracted saga, of which only highlights need be mentioned. In addition to the company and the NRC, the state governor and the President became involved. On 29 March meetings were held to decide whether to recommend evacuation. On 30 March a radiation reading outside the plant, later found to be erroneous, led NRC officials to recommend evacuation. The local director of emergency preparedness was notified to stand by for an evacuation; he notified fire departments and had a warning broadcast that an evacuation might be called. Then the NRC chairman assured the Governor that an evacuation was not necessary. Later the Governor decided that pregnant women and pre-school children should be evacuated. Meanwhile, people around the plant had started to make their own arrangements, and many left. By 1 April the NRC had concluded that the hydrogen bubble posed no threat but failed to announce this properly.

Operations to restore the situation at TMI-2 have lasted over a period of years (Masters, 1984).

A21.7 The Excursion – 2

The operators in the TMI-2 control room made a number of errors. Some of these were failures to make a correct diagnosis of the situation, others were undesirable acts of intervention.

The first was the failure to realize that the PORV had stuck open. The operators had an indication that the PORV had shut again, in the form of a status light. However, this light showed now the shutter signal sent to the valve, not the valve position itself. They were also misled by the reading of high water level in the pressurizer.

There were several contra-indications, however, which pointed to the fact that the PORV was open. One was that the PORV outlet pipe was at a higher temperature than usual, 140°C instead of 90°C. Another was that the temperature and pressure in the pressurizer were lower than usual. The third was that there was a high level in the containment building sump. Later, the vibration of the primary coolant pumps was another indication.

Closely connected with this first diagnostic failure was the failure to recognize that the mass of primary coolant water had fallen. Here the operators were misled by the level measurement.

Turning to the interventions, at 2 minutes into the incident the HPI pumps tripped in automatically, because the mass of water in the primary circuit was falling. Thirty seconds later, the operators, fearing that the system would fill right up with water and go ‘solid’, shut the HPI pumps off. This was the wrong action, because the primary circuit then continued to lose water.

Another counterproductive action was the shutting down of the primary coolant pumps. About 60 minutes into the incident the pumps began vibrating. This was another clue that the primary circuit fluid was now a two-phase mixture of steam and water. The operators had been trained not to allow violent vibration of the pumps, which could damage them or the piping, and they shut the pumps down. The forced flow of cooling water through the reactor core ceased.
These failures of diagnosis and the fear of the system going solid have frequently been characterized as illustrations of mindset.

The operators were poorly served by the displays and alarms in the control room. Mention has already been made of the fact that some of the indicators did not actually display the variable of direct interest. There were a large number of alarms which were difficult to interpret.

A21.8 The Investigations

Principal investigations into the accident are the NRC Report, the Kemeny Report and the US Congressional hearings. These are described in this section. Recommendations given in the Kemeny Report and the Task Force Report are outlined in Section A21.9.

A21.8.1 NRC Report

The NRC Report gives a detailed account of the TMI accident with a full chronology for the first 16 hours containing 676 entries. There was little dispute about the basic facts. The investigations are significant mainly for their probing of the deeper causes.

A21.8.2 Congressional hearings

Hearings on the incident which are replete with information were held by the US Congress; they repay study.

Of particular interest here are the sessions dealing with the display and alarm systems. Extracts from the record on these two topics are given, respectively, in Tables A21.3 and A21.4, and are self-explanatory.

Table A21.3 The display problem at Three Mile Island: evidence given to Congressional committee (after Lees, 1980, based on US Congress, 1979)

| Weaver | I just want to say that is an extremely important point because one of the things we wanted to find out was how well they were in control. So you are raising the issue, I think, that because these gauges were off at one side they did not see them. Is that a possibility?  
| Eisenhut | It is certainly a possibility. In fact, that is why I said that is an area – the reason I highlighted it, it is a question area as to what happened to the pilot-operated relief valve, what kind of indications they had that the valve was still open.  
| Weaver | But they could have seen them?  
| Eisenhut | There were at least a couple of other instruments they could have used if those instruments were working. I do not know whether they were.  
| Weaver | The indications are that they did not see them for several hours; is that correct?  
| Eisenhut | At least a couple of hours.  
| [p.27] |

| Carr | We were told the other day that there was no direct level indicator in the reactor at the level of the coolant, that that had to be inferred from looking at other data, say the pressurizer pressure. Now we are saying that there is no direct indication of this valve at the top of the pressurizer, that we only got an indication, a direct indication on its mechanism rather than on its functioning, and that there were some backup inferences you could draw from other instruments which would lead someone to assemble some data. I suppose jumping way, way ahead of ourselves here I am wondering, is this a special feature of Babcock & Wilcox plants that on their gaging and instrumentation they do not use direct data, and then use the other stuff for backup? Or is this something throughout the nuclear industry, where there is a lot of data points and it leaves it to the operator to sort of assemble all of this, what is happening inside that building, in his head.  
| Stello | Valve positions normally are indicated by a mechanism which looks at the travel of the stem, which is to some degree on indirect reference to what the valve is actually doing, but a more direct method than you would get from looking at the solenoid which starts the event.  
| [p.30] |

| Stello | But as I tried to understand the accident, I reduced the number of program meters that I really wanted to know about to very few to try to make the judgement of what was going on. I think the operators can do that....  
| Carr | You can reduce the number that you really need to focus on to try to understand the event that you have had to relatively few. For example if you had a major LOCA, he would know very quickly what program meters that he ought to focus his attention on. He would have very quickly a response in the reactor building that says I have a discharge of a lot of high-energy fluid. I either have a break in my secondary system in the reactor building or the primary system. I immediately look at my primary system meters. Then I can tell if that was a primary system rupture. If it is a primary system rupture, I then know what program meters to track. So there is a hierarchy of logic built into the very many alarms that you see that point him at the right direction....  
| Carr | But this whole family of alarms and gages that you see, there is a hierarchy of logic built into it that, as you are trained to be an operator, you know what critical program meters to look for very quickly and eliminate or focus your attention in the right direction.  
| Carr | In the location of the alarms and gages and buzzes and switches and all that stuff, does the location on the panel follow that logic?  
| Stello | Yes.  
| [p.31] |

| Vento | One other thing before we go on to the other problem in the secondary system, which you did next. This relief valve, of course, is a key part of this, apparently. But there were some tailpipe temperature and some other indicators there that were also available. Who was responsible for watching those at this particular point? The tailpipe temperature?  
| Frederick | What you are talking about is the outlet temperature of the relief valve.  
| Vento | There is also a tank that this goes to that is not shown on here, and that has an indicator on it and a temperature and so forth. There is a thermocouple on
here, and who was responsible for watching those in this particular process? It was just a generally shared thing?

**Frederick:** The points that you are talking about are not displayed. They are not on the console. They are in the computer. You have to manually call them up.

**Vento:** You have to call those things up. But were they not called up during this procedure at all?

**Frederick:** No.

**Weaver:** How many minutes are we in now? Where are we?

**Faust:** It is not a normal thing.

**Frederick:** About an hour.

**Faust:** We did not know a problem like that existed at the time.

**Frederick:** If the valve indicated shut, there is no reason to look at the downstream temperature.

[p.135]

.....

**Reis:** It is a broad question, but as well as you can answer it, do you think that the control room provided you, in a timely fashion, in an easy-to-read fashion, the information you wanted and needed? And alternatively, in the course of the accident, were the communications in the control room such so that when someone at the panel needed conceptual information, in other words, this instrument, that instrument, and this gage are reading things that do not jibe together, that you had that sort of immediate access to an engineer? When did you get it?

Did it work well, so that you were able to figure out what was really going on?

**Frederick:** The answer to the first question, the instruments, in my opinion, were not adequate. I can come up with a million questions on how to change them and the availability of additional input from the engineering staff.

It was not available to me, because I did not seek it out. I would give whatever question I had to the supervisor, and he would refer them to whoever he could as far as more operators, more engineers, to get more information. And he would bring back whatever suggestions there were if there were any.

If things were that confusing, that I had to turn and ask somebody a question, I would wait for their response and their instructions on what to do next and then take the prescribed action according to what they suggested rather than what was on the panel.

**Faust:** I would say – well, I cannot change it much from what he said – we would continue to feed changes that we were seeing in the plant, to the supervisor; as well as if we thought we knew something that should be done, we would be saying that, too.

**Reis:** In terms of the layout of the plant, in general, do you think there could be some significant changes that would make your job a lot easier?

**Frederick:** Yes.

**Faust:** Definitely.

[p. 155]

.....

**Cheney:** It seems to me that is a key point. Has this ever been questioned before, whether or not the pressurizer level was an accurate reflection of the reactor coolant level, in a general sense, in terms of the basic design of the reactor?

**McMillan:** I think a lot of people have asked that question. What does the pressurizer level indicate to you?

**Cheney:** I would just like to come back to that basic question: Whether or not those operators at Three Mile Island on that day were trained to read that pressurizer level as anything other than indicating reactor level, coolant level in the reactor?

**McMillan:** Let us trace that through and see if we can find what evidence

**Cheney:** Do you think that is some flaw in the design of the reactor?

**McMillan:** No, sir.

**Cheney:** Why not have a coolant level indicator from within the reactor itself?

**McMillan:** That has been suggested by a number of people, post Three Mile Island.

**Weaver:** Mr McMillan, how do you measure the level of water in the reactor vessel?

**McMillan:** You do not measure the level of water in the reactor vessel.....

**Weaver:** But is that not an important thing to know? Why do you not have something that tells us the level of the water?

**McMillan:** Well, I think –

**Cheney:** I guess I would like to follow up on this.

[p. 232]

.....

**Weaver:** Are you opposed, Mr McMillan, to water level measurement in the reactor vessel?

**McMillan:** It is a difficult problem, yes. But I am not at this point saying it is insurmountable...

**Weaver:** I would say the first thing I was going to do, if I were going to design a nuclear plant, is to make sure we knew what the water level was.

[p. 237]

* In addition to the personnel identified in Section A21.1, the transcript extracts given above refer to the following: Mr Cheney, Mr Vento, Mr Weaver, all Congressmen; Mr Reis, Congressional staff; Mr D.Eisenhut, Deputy Director, Division of Operating Reactors, Office of Nuclear Reactor Regulation, NRC; Mr MacMillan, Vice-President, Nuclear Power Generation Division, Babcock and Wilcox Co.

**Table A21.4** The alarm problem at Three Mile Island: evidence given to Congressional committee (after Lees, 1980a, based on US Congress, 1979)

<table>
<thead>
<tr>
<th>Weaver</th>
<th>The plant manager told me he thought 100 audio alarms were going off at one time.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stello</td>
<td>Is that what he told you?</td>
</tr>
<tr>
<td>Weaver</td>
<td>Yes</td>
</tr>
<tr>
<td>Stello</td>
<td>I would not be surprised.</td>
</tr>
</tbody>
</table>

.....

**Weaver:** All occurring in the control room?

**Mattson:** Yes.

**Carr:** And there is no instrumentation that helps the operator sort out the order of importance of these alarms, or the order of importance of gages or lights or switches; right?

**Mattson:** Only the training.
Carr: Only the training to assemble all of these instruments and react in split seconds.
[p. 31]

.....

Weaver: How are people able to differentiate between these various alarms?
Michelson: I am not a human factors engineer. I have never studied control rooms enough to understand that area at all. It is a very good question. I have asked it sometimes myself.
[p. 47]

.....

Higgins: There were a lot of short-term problems that were being addressed also; that is, equipment problems, loss of power, additional alarms that continued throughout the day, and we did not mention the number of alarms; there were a large number of equipment starts and stops, large number of individual problems...
[p. 97]

Weaver: Would you describe the alarms that were going off? Were they going just constantly or was it...
Higgins: One would occur; the operators would address that. And then another one, perhaps a little bit later another one, or if you have a particular event, a specific event, for example the hydrogen burning in the containment might generate several, or a particular release of radioactivity from an area in the auxiliary building might generate several related alarms.

Like generally there are a lot of indicators of a particular event as Mr Michelson described, on relief valve. You have got a relief valve tailpipe temperature alarm; you have got an alarm in the reactor drainpipe, I believe; level indications, and perhaps alarms associated with those system pressure alarms.

All this has to do with one relief valve lifting, so when a particular event occurs, you may get several related alarms, all of which have to be addressed.
[p. 99]

.....

Higgins: If you have a scram, many alarms do come in as a result of that. Some are normal; some indicate things not being normal. And it is up to the operator by his training to distinguish which ones he expects, which ones not to expect, that type of thing.
[p. 100]

.....

Higgins: There was a tremendous amount of activity going on in the control room. A lot of people were involved with a lot of the different problems, and that was one of many things. Operators were – alarms were going off; pumps were being started and stopped; valves were being cycled, and this was just one of a myriad of those things that was occurring throughout the entire day. And I was thoroughly not able to follow what was going on. And I did not pick it up at all.
[p. 111]

*A spike on a recorder probably indicating a hydrogen burn – FPL.*

.....

Frederick: The alarms – this is a big problem. There is only one audible alarm in the control room for the 1,600 alarm windows that we have, in other words, the ones that are displayed on the front of the console along with the ones on the reverse panel. So that during the emergency, I made a point of announcing that I did not want anybody to acknowledge the alarm, that is, push the acknowledgement to silence the alarm, because that would make all the windows stop flashing, and I wanted to read them all to see what was happening. As we began to run out of ideas, I wanted to review all of the alarms that we received to see if anything was happening that we could not see.

.....

Frederick: There are several steps in the alarm process. As the alarm comes in, it sounds an alarm and a flashing light. As long as the alarm stays in – and you push the button, and the light will go solid. If in the meantime the alarming condition clears itself or goes away and you push the button, the light will go out and you will not be able to tell that it ever came in. If you have three or four alarms at the same time, only one may stay lit out of the three or four. We had probably 100 or 200 alarms flashing within the first few minutes.

.....

Frederick: I would not be able to establish the chronology. I just wanted to see what systems were affected by the transient and if we could see something. There are some alarms you expect to get. If you read over them, you just discount them as being normal. But there may be a few that come in that you had not expected, and those are the ones I was looking for.
[p. 136]

.....

Frederick: No. The sequence of alarms that comes out of the computer that they were able to read later on was backlogged. The alarms came in 100 at a time. The computer, the IBM typewriter just types them out one at a time. So as they were coming in rapidly, probably 10 or 15 per second, it just could not keep up. So there was a backlog of maybe 2 or 3 hours.

Faust: I do not know what time this fits into, but we had problems with the alarm typewriter, too, at this time. I do not know what it was, but the easiest way for me to say it is, it sort of started eating the paper. In other words, it got off the track.
[p. 137]

.....

Vento: Obviously the proper procedure here would have said that 300° or 280° in the tailpipe should have been an indication.

Frederick: That is the point he is talking about. In other words, what came out of the computer on the typewriter was an alarm that said: Temperature hot. But we could not see that, because the alarm typewriter was backlogged several hours.
[p. 139]

.....

Weaver: Now I am troubled by the newspaper reports. One report, early on, had it that there was just page after page of computer printout of question marks.

Miller: Looking back – and we can come back to you with further information, but there was a period of time in the first 2 to 3 hours where the computer failed, I believe.

Zeev: Yes, for over an hour period, it did not give us any information.

Cheney: You mean you would query it and nothing would happen?

Zeev: No. The question marks, periods, and so forth, the computer had hung up, where it really did not scan the
parameters and print on in a fashion where we could interpret it.

Cheney: It was unusable.
Miller: I thing Bill would back this up. He was not using that totally. He was just using his console to operate the plant, so when that went out, he just had to go away from it.

Weaver: What caused this? What was going on? What happened? We have it here in the chronology that 1 hour 13 to 2:57 – in other words –

Miller: I think, in fairness, the machine has got a tape, disc, and that sort of thing. It has experienced problems. It is not a vital piece of equipment to Bill’s use of the emergency procedures or operations of the plant, so I would guess Bill would just simply have told an electrical engineer to call someone in and go on with the console.

Weaver: You do not have to have it in any way?
Zewe: No, it is just an operator’s tool, but it is not anything that is really that critical to the operation.
[p. 175]

* In addition to the personnel identified in Section A21.1 and Table A21.3, the transcript extracts given above refer to the following: Mr Carr, Congressman; Mr Stello, Director, Division of Operating Reactors, Office of Nuclear Reactor Regulation, NRC; Mr Mattson, Division of System Safety, Office of Nuclear Reactor Regulation, NRC; Mr Michelson, Nuclear Engineer, Tennessee Valley Authority; and Mr Higgins, Region I, Office of Inspection and Enforcement, NRC.

A21.8.3 Kemeny Report
The Kemeny Report gives an account of the accident, from 29 March to 2 April, presents findings and makes recommendations. Some findings are described in this section.

The reports starts with what it calls ‘people-related problems’. It states

Popular discussions of nuclear power plants tend to concentrate on questions of equipment. Equipment can and should be improved to add further safety to nuclear power plants, and some of our recommendations deal with this subject. But as the evidence accumulated, it became clear that the fundamental problems are people-related problems and not equipment problems.

When we say that the basic problems are people-related, we do not mean to limit this term to shortcomings of individual human beings – although these do exist. We mean more generally that our investigation has revealed problems with the ‘system’ that manufactures, operates and regulates nuclear power plants. There are structural problems in various organizations, there are deficiencies in various processes, and there is a lack of communication among key individuals.

We are convinced that if the only problems were equipment problems, this Presidential Commission would never have been created. The equipment was sufficiently good that except for human failures, the major accident at Three Mile Island would have been a minor incident. But, wherever we looked, we found problems with the human beings who operate the plant, with the management that runs the key organization, and with the agency that is

charged with assuring the safety of nuclear power plants. (p. 8)

The form frequently taken by this problem is described as follows: ‘In the testimony we received, one word occurred over and over again. That word is “mindset”.’ (p. 8)

The report is critical of the approach taken to control of the industry, stating:

We note a preoccupation with regulations. It is, of course, the responsibility of the Nuclear Regulatory Commission to issue regulations to assure the safety of nuclear power plants. However, we are convinced that regulations alone cannot assure safety. Indeed, once regulations become as voluminous and complex as those regulations now in place, they can serve as a negative factor in nuclear safety. The regulations are so complex that immense efforts are required by the utility, by its suppliers and by the NRC to assure that regulations are complied with. The satisfaction of regulatory requirements is equated with safety. This Commission believes that it is an absorbing concern with safety that will bring about safety – not just the meeting of narrowly prescribed and complex regulations. (p. 9)

The report makes various criticisms of the NRC, of which a sample, changed in order, are:

We found serious managerial problems within the organization. These problems start at the very top... It is not clear to us what the precise role of the five NRC commissioners is, and we have evidence that they themselves are not clear what their role should be... NRC’s primary focus is on licensing and insufficient attention has been paid to the ongoing process of assuring safety... NRC is vulnerable to the charge that it is heavily equipment-oriented, rather than people oriented... We are extremely critical of the role the organization played in the response to the accident... NRC has sometimes erred on the side of the industry’s convenience rather than carrying out its primary mission of assuring safety... (pp. 19–21)

The Commission identifies an over-concentration on large accident hazards:

We find a fundamental fault even with the existing body of regulations. While scientists and engineers have worried for decades about the safety of nuclear equipment, we find that the approach to nuclear safety has a major flaw. It was natural for the regulators and the industry to ask: ‘What is the worst kind of equipment failure that can occur?’ Some potentially serious scenarios, such as the break of a huge pipe that carries the water cooling to the nuclear reactor, were studied extensively and diligently, and were used as the basis for the design of plants. A preoccupation developed with such large-break accidents as did the attitude that if they could be controlled, we need not worry about the analysis of ‘less important’ accidents. (p. 9)

A potentially insignificant incident grew into the TMI accident, with severe damage to the reactor. Since such combinations of minor equipment failures are likely to occur much more often than the huge accidents, they deserve extensive and thorough study. (p. 9)

The report is critical of organizational failure to follow through safety issues:
We find that there is a lack of ‘closure’ in the system – that is, important safety issues are frequently raised and may be studied to some degree of depth, but are not carried through to resolution; and the lessons learned from these studies do not reach those individuals and agencies that most need to know about them. (p.11)

The report reopens the issue of the influence of the operator in a developing reactor emergency. The conventional approach has been that any action taken by the operator is likely to be beneficial. It gives this view as an example of designers’ mindset: ‘They concentrated on equipment, assuming that the presence of operators could only improve the situation – they would not be part of the problem’. (pp.8–9)

On the handling of the emergency the Commission comments:

We are disturbed both by the highly uneven quality of emergency plans and by the problems created by multiple jurisdictions in case of a radiation emergency. Most emergency plans rely on prompt action at local level to initiate a needed evacuation or to take other protective action. We found an almost total lack of detailed plans in the local communities around Three Mile Island. It is one of the many ironies of this event that the most relevant planning by local authorities took place during the accident. In an accident in which prompt defensive steps are necessary within a matter of hours insufficient advance planning could prove extremely dangerous. (p.15)

The report contains a number of supplemental views by individual members of the commission, one of which is by Professor T.H. Pigford. He is critical of the NRC’s approach to safety, which he characterizes as lacking in experienced personnel; failing to take a comprehensive approach with quantified safety objectives and rational priorities; and prone to introduce arbitrary requirements. He calls it ‘A stifling approach. The existing process inhibits the interchange of technical information between the NRC and industry. It discourages innovative engineering solutions’.

On human factors aspects he states

The emphasis in this report upon equipment versus people obscures the fact that the equipment itself is only one product of the defense-in-depth or multiple-barrier design approach, which also encompasses the analysis of how components must perform and how systems of equipment must operate. The accident demonstrated that this system of equipment performed better than expected.

The nature of the people-related problem needs clarification. One such problem – and a most serious one – was the errors made by the operators and the operator-supervisors, whose training was insufficient in scope and understanding. Another was failure of many individuals to respond adequately to earlier experience from other reactors and to other advance information that might have alerted the operators and avoided the accident.

### A21.9 Some Lessons of Three Mile Island

#### A21.9.1 Kemeny Report recommendations

The *Kemeny Report* and the *Task Force Report* both give extensive recommendations. The heads of these recommendations are shown in Table A21.5, in Sections A and B, respectively.

The *Kemeny Report* recommends that the NRC be restructured as a new independent agency in the executive branch and that the ACRS be strengthened.

The report states: To the extent that the industrial institutions we have examined are representative of the nuclear industry, the nuclear industry must dramatically change its attitude towards safety and regulations. It goes on ‘The industry should establish a program that specifies appropriate safety standards including those for management, quality assurance, and operating procedures and practices, and that conducts independent evaluations’. Improvements in operator training are called for, with particular emphasis on the use of simulators.

Under the heading of technical assessment, the report deals with equipment for information display in the control room and for mitigating the consequences of accidents and recommends a formal safety assurance programme involving hazard identification and assessment.

The report recommends that there should be a requirement for an emergency response plan. It also makes recommendations on worker and public health in relation to nuclear hazards and on the public’s right to information.

#### A21.9.2 Task Force Report recommendations

The recommendations of the *Task Force Report* are summarized in Section B of Table 21.5. They deal particularly with operator training and with the man-machine interface.

<table>
<thead>
<tr>
<th>Table A21.5</th>
<th>Heads of some principal recommendations on Three Mile Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Presidents Commission (Kemeny, 1979)</td>
</tr>
<tr>
<td>Nuclear Regulatory Commission</td>
<td>Utility and it suppliers</td>
</tr>
<tr>
<td>Training of operating personnel</td>
<td>Technical assessment</td>
</tr>
<tr>
<td>Worker and public health and safety</td>
<td>Emergency planning and response</td>
</tr>
<tr>
<td>Public’s right to information</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>‘Lessons Learned’ Task Force (Nuclear Regulatory Commission, 1979b)</td>
</tr>
<tr>
<td>Personnel qualifications and training</td>
<td>Staffing of control room</td>
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<td>Working hours</td>
<td>Emergency procedures</td>
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<td>Verification of correct performance of operating activities</td>
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<td>Man–machine interface</td>
<td>Reliability assessments of final designs</td>
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<tr>
<td>Review of safety classifications and qualifications</td>
<td>Design features of core-damage and core-melt accidents</td>
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<tr>
<td>Safety goal for reactor regulation</td>
<td>Staff review objectives</td>
</tr>
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<td>NRR Emergency Response Team</td>
<td></td>
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</tbody>
</table>
The report calls for a thorough review of control room design and for development of aids to assist the operator in assessing the status of the plant and in analysing disturbances and alarms. It proposes the development both of a plant safety status display system and of a disturbance analysis system (DAS).

On the former the report states

Each licensee should be required to define and adequately display in the control room a minimum set of plant parameters (in control terminology, a state vector) that defines the safety status of the nuclear power plant.

The minimum set of plant parameters should be annotated for sensor limits, process limits, and sensor status. The annotated set of parameters should be presented to the operator in real time by a reliable, single-failure-proof system located in the control room. (p.A-12)

### A21.9.3 Some lessons

The Three Mile Island incident yields numerous lessons. Some of these are listed in Table A21.6. Many of these lessons are drawn in the reports just described.

<table>
<thead>
<tr>
<th>Table A21.6 Some lessons of Three Mile Island</th>
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<tbody>
<tr>
<td>Regulatory control of major hazard installations</td>
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<td>People-related versus equipment-related problems</td>
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<td>Formal safety assurance</td>
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<td>Relative importance of large and small failures</td>
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<td>Influence of operator in an emergency</td>
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<td>Fault diagnosis by the process operator</td>
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<td>Accident management for major hazard installations</td>
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<td>Follow-up of safety issues</td>
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<tr>
<td>Learning from precursor events</td>
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<tr>
<td>Package and other ancillary units</td>
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<tr>
<td>Display of variable of interest</td>
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<tr>
<td>Plant status display and disturbance analysis systems</td>
</tr>
<tr>
<td>Abuse of instrument air</td>
</tr>
<tr>
<td>Limitations of non-return valves</td>
</tr>
</tbody>
</table>

showed that this is not necessarily so, and that operator action can be detrimental.

**Fault diagnosis by the process operator**

The incident highlighted the problem of fault diagnosis by the process operator under stress. It showed the limitations of fixed operating rules in dealing with abnormal situations and the dangers of tunnel vision, or mindset. In other words, it showed the inadequacy of rule-based behaviour and the need for knowledge-based behaviour and for training based on development of the latter.

**Accident management for major hazard installations**

TMI shows that a major accident poses a number of difficult problems and that it needs to be managed. This implies that accident management must be recognized as a specific requirement and planned in advance.

The handling of an emergency in the control room is one aspect of the problem, but there are many others. They include the identification, mobilization, direction and co-ordination of the necessary resources; planning for an emergency, both on site and off site; and handling of the media.

**Follow-up of safety issues**

The Kemeny Report is critical of the follow-up of safety issues, referring to a lack of closure. Safety issues which are raised and agreed to be valid need to be followed through to resolution. Personnel who most need to know should be informed.

**Learning from precursor events**

There had been previous incidents in which a PORV had been stuck in the open position, but the management of the TMI plant had no systematic approach to learning from such incidents.

**Package and other ancillary units**

Turning to some more detailed aspects, the incident started with a fault in the condensate polishing system, a package unit. It illustrates the point that the ancillary equipment and services should receive their due share of attention, starting with specification and continuing right through to operation.
Display of variable of interest
If a process variable is critical, it is highly desirable that the quantity which is displayed should be the variable of direct interest. At TMI there were two cases where this was not done. One is the water level in the pressure vessel. The other is the status of the PORV. The display showed the signal to the valve rather than the actual valve position.

Plant status display and disturbance analysis systems
TMI was a dramatic illustration of the difficulties faced regularly by process operators in interpreting displays and alarms, and of way in which these can be compounded by information overload. It highlighted the scope for the development of improved display and alarm systems and for the exploitation of computers to this end. The principal aids proposed were plant safety status display systems and disturbance analysis systems.

Abuse of instrument air
The air used to clear the blockage on the condensate polishing system was instrument air. It is bad practice to connect instrument air to the process, which can cause it to become contaminated.

Limitations of non-return valves
The entry of water into the instrument air system illustrates the limitations of a non-return valve. Such a valve is intended to stop bulk flow of fluid; it will not necessarily prevent the passage of trace quantities.
Appendix

Chernobyl

Contents

A22.1 The Operating Organization and the Management A22/2
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A22.9 The Later Aftermath A22/11
A22.10 Some Lessons of Chernobyl A22/11
On Monday 28 April 1986 a worker at the Forsmark nuclear power station in Sweden put his foot in a radiation detector for a routine check and registered a high reading. The station staff thought they had had a radioactive release from their plant and the alarm was raised. However, as reports came in of high radioactivity in Stockholm and Helsinki, the source of the release was identified as the Soviet Union. In fact, an accident had occurred on Unit 4 at Chernobyl in the Ukraine some 800 miles from Sweden on Saturday 26 April.

At 1.24 on that day an experiment to check the use of the turbine during rundown as an emergency power supply for the reactor went catastrophically wrong. There was a power surge in the reactor, the coolant tubes burst and a series of explosions rent the concrete containment. The graphite caught fire and burnt, sending out a plume of radioactive material. Emergency measures to put out the fire and stop the release were not effective until 6 May.

The Soviet Government set up an investigatory team headed by N.I. Ryzhkov, President of the USSR Council of Ministers, to investigate. A report The Accident at the Chernobyl Nuclear Power Plant and its Consequences by the USSR State Committee on the Utilisation of Atomic Energy (1986) (the USSR State Committee Report) was presented in August 1986 to a meeting of experts at the IAEA in Vienna by V. Legasov.


Table A22.1 Selected references on Chernobyl

| NRC (Appendix 28 Chernobyl); BNES (1986); Franklin (1986); Hawkes et al. (1986); IAEA (1986); IBC (1986/69); USSR State Committee on the Utilization of Atomic Energy (1986); Watt Ctte on Energy (1986, 1991); Collier and Davies (1987); Gittus et al. (1987); Hall, Hall and Nixon (1987 LPB 76); Hamman and Parrott (1987); NEA (1987); NRC (1987b); F. Allen (1988); Ballard (1988); Haynes and Bojcum (1988); Kletz (1988h); Marples (1988, 1991); V.C. Marshall (1988 LPB 81); Mould (1988); Wheeler (1988); Worley and Lewins (1988); Gudiksen, Harvey and Lange (1989); Konstantinov and Gonzalez (1989); Parmentier and Nenot (1989); Voznyak, Kovalenko and Troitsky (1989); Hass et al. (1990); Ryin et al. (1990); Ottewell (1991); Segerstahl (1991); Read (1993) |

Selected references on Chernobyl are given in Table A22.1.

A22.1 The Operating Organization and the Management

Little information has become available concerning the organization operating the Chernobyl plant or about its management.

A22.2 The Site and the Works

The Chernobyl nuclear power station is situated in a region which at the time was relatively sparsely populated. There were some 135 000 people within a 30 km radius. Of these 49 001 lived in Pripyat to the west of the plant’s 3 km safety zone and 12 500 in Chernobyl 15 km to the south-east of the plant.

There were four nuclear reactors on the site. The first pair had been built in the period 1970–77 and the second pair were completed in 1983.

A22.3 The Process and the Plant

Unit 4 at Chernobyl was designed to supply steam to two turbines each with an output of 500 MWe. The reactor was therefore rated at 1000 MWe or 3200 MWT.

Unit 4 was an RBMK-1000 reactor, which is a standard design widely used in the Soviet Union. The RBMK-1000, shown in Figure A22.1, is a boiling water pressure tube, graphite moderated reactor. The reactor is cooled by boiling water, but the water does not double as the moderator, which is graphite.

The design of the reactor avoided the use of a large pressure vessel. Instead, use was made of much smaller individual pressurized fuel channels. The reactor had 1661 fuel channels. There was in each one a fuel assembly, divided into two subassemblies, each containing 18 fuel elements.

The reactor contained 192 t of uranium enriched to 2%. The subdivision of the uranium into a large number of separately cooled fuel channels greatly reduced the risk of total core meltdown.

The reactor was cooled by water passing through the pressure tubes. The water was heated to boiling point and partially vaporized. The steam–water mixture with a mass steam quality of 14% passed to two separators where steam was flashed off and sent to the turbines, while water was mixed with the steam condensate and fed through downcomers to pumps which pumped it back to the reactor. There were two separate loops each with four pumps, three operating and one standby. This system constituted the multiple forced circulation circuit (MFCC).

The moderator used was graphite. The reactor contained a stack of 2488 graphite blocks with a total mass of 1700 t.

An emergency core cooling system (ECCS) was provided to remove residual heat from the core in the event of loss of coolant from the MFCC.

The reactor was provided with a control and protection system (CPS). The control system incorporated a control computer. There was a control system which controlled the power output of the reactor by moving the control rods in and out. Automatic protective systems included a
**Key**

1. Reactor
2. Fuel-channel standpipes
3. Steam/water riser pipes
4. Steam drums
5. Steam headers
6. Downcomers
7. Main circulating pumps (MCP)
8. Group distribution headers
9. Reactor inlet water pipes
10. Burst-can detection system
11. Upper biological shield
12. Side biological shield
13. Lower biological shield
14. Irradiated fuel storage pond
15. Fuelling machine
16. Bridge crane

*Figure A22.1* Simplified flow diagram of Chernobyl Unit 4 (Nuclear Regulatory Commission, 1987b)
trip to bring in the ECCS and reactor shut down trips. Reactor shut down was effected by the insertion of control rods and conditions which would trigger shut down included loss of steam to the turbines and loss of level in the separators.

The reactor was housed in a containment built to withstand a pressure of 0.45 MPa. There was a ‘bubble’ condenser designed to condense steam entering the containment from relief valves or from rupture of the MFCC.

An important operating feature of the reactor was its reactivity margin, or excess reactivity. Below a certain power level the reaction would be insufficient to avoid xenon poisoning. It was therefore necessary to operate with a certain excess reactivity. This reactivity could be expressed in terms of the number of CPS control rods which would need to be inserted to counter it. The operating instructions stated that a certain excess reactivity was to be maintained; the equivalent number of control rods was 30.

Another important operating characteristic was the reactor’s ‘positive void coefficient’. An increase in heat from the fuel elements would cause increased vaporization of water in the fuel channels and this in turn would cause increased reaction and heat output. There was therefore an inherent instability, a positive feedback, which could be controlled only by manipulation of the control rods. Control of the reactor at normal power output presented little problem, but this feature made the reactor highly sensitive at low outputs.

A22.4 Events Prior to the Release

The origin of the accident was the decision to carry out a test on the reactor. Electrical power for the water pumps and other auxiliary equipment on the reactor was supplied by the grid with diesel generators as back-up. However, in an emergency there would be a delay of about a minute before power became available from these generators. The objective of the test was to determine whether during this period the turbine could be used as it ran down to provide emergency power to the reactor. A test had already been carried out without success, so modifications had been made to the system, and the fresh test was to check whether these had had the desired effect.

A programme for the test was drawn up. It included provision to switch off the ECCS during the test, apparently to prevent its being triggered during the test.

At 1.00 on 25 April the reduction of power began. At 13.05 Turbogenerator 7 was switched off the reactor. At 14.00 the ECCS was disconnected. However, a request was received to delay shutting down since the power output was needed. It was not until 23.10 that power reduction was resumed.

At some stage the trip causing reactor shut down on loss of steam to Turbogenerator 8 was disarmed, apparently so that if the test did not work the first time, it could be repeated. This action was not in the experimental programme.

The test programme specified that rundown of the turbine and provision of unit power requirements was to be carried out at a power output of 700–1000 MWe, or 20% of rated output. The operator switched off the local automatic control, but was unable to eliminate the resultant imbalance in the measurement function of the overall automatic controls and had difficulty in controlling the power output, which fell to 30 MWe. Only at 1.00 on 26 April was the reactor stabilized at 200 MWe, or 6% of rated output. Meanwhile the excess reactivity available had been reduced as a result of xenon poisoning.
It was nevertheless decided to continue with the test. At 1.03 the fourth, standby pump in one of the loops of the MFCC was switched on and at 1.07 the standby pump in the other loop.

A22.5 The Release – 1

With the reactor operating at low power, the hydraulic resistance of the core was less and this combined with the use of additional pumps resulted in a high flow of water through the core. This condition was forbidden by the operating instructions, because of the danger of cavitation and vibration. The steam pressure and water level in the separators fell and other process parameters changed. In order to avoid triggering the trips which would shut down the reactor on these parameters, the trips were disarmed.

The reactivity continued to fall and at 1.22.30 the operator saw from a printout of the reactivity evaluation program that the available excess reactivity had fallen below a level requiring immediate reactor shut down. Despite this the test was continued.

At 1.23.04 the emergency valves on Turbogenerator 8 were closed. The reactor continued to operate at about 200 MWt, but the power soon began to rise. At 1.23.40 the unit shift foreman gave the order to press the scram button. The rods went down into the core, but within a few seconds shocks were felt and the operator saw that the rods had not gone fully in. He cut off the current to the servo drives to allow the rods to fall in under their own weight.

Within four seconds, by 1.23.44, the reactor power had risen, according to Soviet estimates, to 100 times the nominal value.

At about 1.24, according to observers outside Unit 4, there were two explosions, the second within some 3 seconds of the first, and debris and sparks shot into the air above the reactor.

It is thought that the fuel fragmented, causing a rapid rise in steam pressure as the water quenched the fuel elements, so that there was extensive failure of the pressure tubes. The explosive release of steam lifted the reactor top shield, exposing the core. Conditions were created for reaction between the zirconium and steam, producing hydrogen. An explosion, involving hydrogen, occurred in and ruptured the containment building, and ejecting the debris and sparks were seen.

Some 30 fires broke out.

The accident was aggravated by the fact that the 200 t crane fell onto the core and caused further bursts of the pressure tubes.

The stricken reactor is shown in Figure A22.2.

Table A22.2 Timetable of events at Chernobyl

<table>
<thead>
<tr>
<th>A</th>
<th>Events prior to initial explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 April</td>
<td>1.00 Reduction of power started</td>
</tr>
<tr>
<td></td>
<td>13.05 Turbogenerator 7 disconnected</td>
</tr>
<tr>
<td></td>
<td>14.00 ECCS disconnected</td>
</tr>
<tr>
<td></td>
<td>23.10 Power reduction resumed</td>
</tr>
<tr>
<td>26 April</td>
<td>00.28 Operator switches off local automatic control, but is unable to eliminate resultant imbalance in measurement function of the overall automatic controls</td>
</tr>
<tr>
<td></td>
<td>1.00 Reactor stabilized at 200 MWt (6% rated output)</td>
</tr>
<tr>
<td></td>
<td>1.03 Standby pump switched on in one loop of MFCC</td>
</tr>
<tr>
<td></td>
<td>1.07 Standby pump switched on in other loop of MFCC</td>
</tr>
<tr>
<td></td>
<td>1.19 Trips on low steam pressure and low water level disabled</td>
</tr>
<tr>
<td></td>
<td>1.22.30 Printout confirming fall in excess reactivity</td>
</tr>
<tr>
<td></td>
<td>1.23.04 To begin test, stop valve on steam to Turbogenerator 8 closed</td>
</tr>
<tr>
<td></td>
<td>1.23.40 Scram button pressed to drop control rods</td>
</tr>
<tr>
<td></td>
<td>1.23.44 Operator hears banging noises and sees rods stopping before they reach bottom; disengages servo drives to allow rods to fall under own weight</td>
</tr>
<tr>
<td></td>
<td>1.23.48 First explosion – extensive failure of pressure tubes, explosive release of steam, top lifted off reactor</td>
</tr>
<tr>
<td></td>
<td>1.24 Second explosion – explosion within reactor space, possibly involving hydrogen, pressure increase to several MP, rupture of containment building</td>
</tr>
<tr>
<td></td>
<td>Numerous fires</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>Events after initial explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 April</td>
<td>2.54 Fire fighting units from Pripyat and Chernobyl arrive</td>
</tr>
<tr>
<td></td>
<td>3.34 Most of fires in turbine room roof out</td>
</tr>
<tr>
<td></td>
<td>3.54 Fire on reactor building roof out</td>
</tr>
<tr>
<td></td>
<td>5.00 All fires, other than those in core, out</td>
</tr>
<tr>
<td></td>
<td>Unit 3 shut down</td>
</tr>
<tr>
<td>27 April</td>
<td>1.13 Units 1 and 2 shut down</td>
</tr>
<tr>
<td>27 April</td>
<td>Start of smothering operation using helicopters</td>
</tr>
<tr>
<td>6 May</td>
<td>Discharge of radioactivity drops to several hundred Ci/h</td>
</tr>
</tbody>
</table>
The timetable of these and the following events is shown in Table A22.2.

**A22.6 The Emergency and the Immediate Aftermath**

The fire brigades from Pripyat and Chernobyl set out at 1.30. The fires in the machine hall over Turbogenerator 7 were particularly serious, because they threatened Unit 3 also. These therefore received priority. By 5.00 the fires in the machine hall roof and in the reactor roof had been extinguished.

However, the heating up of the core and its exposure to the air caused the graphite to burn. The residual activity of the radioactive fuel provided another source of heat. The core therefore became very hot and the site of raging fire.

During the next few days the fire raged and a radioactive plume rose from the reactor. The accident had become a major disaster. It was necessary to evacuate the population from a 30 km radius round the plant and deal with the casualties and to take a whole range of measures to dampen and extinguish the fire, to cover and enclose the core, and to deal with the radioactivity in the surrounding area.

Three evacuation zones were established: a special zone, a 10 km zone and 30 km zone. The latter zone is shown in Figure A22.3. A total of 135000 people were evacuated.

Accounts of the evacuation are incomplete and sometimes contradictory, but what appears to have happened is as follows. Within a few hours of the accident an emergency headquarters was set up in Pripyat. About 14.00 on 26 April there was an evacuation of some 1000 people from Pripyat, within a 1.6 km zone around the plant. A much larger evacuation took place about 14.00 next day, when about 1000 buses were brought in and within two hours had evacuated some 40000 people. However, it was not until some nine days later that the authorities in Moscow ordered complete evacuation from a 30 km zone around the site.

First reports from Kiev spoke of no apparent concern, but as the nature of the disaster became known, parents hastened to send their children out of the city to relatives elsewhere.

A medical team was set up within 4 hours of the accident and within 24 hours triage of the 100 most serious cases had been effected.

A system was set up to control movements between the zones. People crossing the zone boundaries had to change clothing and vehicles were decontaminated.

In the immediate aftermath of the accident steps were taken to obtain the measurements essential to the control of the emergency. These included the measurement not only of the radioactivity in and around the plant, but also of conditions in the reactor relevant to bringing it under control. The latter was made more difficult by the fact that the regular measurement system had been disabled.

A decision had to be made whether to let the fire burn itself out or to smother it. In view of the hazard to the surrounding area, the latter course was chosen. A specialist team was assembled who began to cover the damaged reactor with compounds of boron, dolomite, sand, chalk and lead. Between 27 April and 10 May some 5000 te of material were dropped on the reactor by helicopter. By May 6 the release of radioactivity had decreased to a few hundred Ci/d and had ceased to be a major factor.

At the same time the core temperature was tackled by pumping nitrogen under pressure from the compressor station into the space beneath the reactor vault. This reduced the oxygen concentration and the temperature. By 6 May the temperature rise had been halted and the temperature began to decline.

Meanwhile Soviet experts were concerned about the hazard of the large amount of water directly beneath the reactor. If the core were to come into contact with this water, there could be massive and explosive vaporization into steam. Engineers went down through dark passages flooded with radioactive water and succeeded in opening two large valves to allow the water to drain out.

Next an attempt was made to put a large concrete slab fitted with cooling coils beneath the core to prevent material from the core contaminating the ground and watercourses beneath it. Tunneling in the soil at this point was difficult and it was necessary to resort to freezing the soil using liquid nitrogen, a method used in building the Leningrad Metro. The construction of this concrete bed was complete by the end of June.

Subsequently the reactor was entombed in concrete.

There was also intense activity to counter the effects of radioactivity in the surrounding area. 7000 wells were sealed. The water supply to Kiev could no longer be taken from water near the plant and a new water supply for the city had to be constructed. A system of dikes was constructed to catch radioactive rain water from the area around the plant. A system of bore holes and barriers was created to prevent contamination of water courses.

Decontamination measures were also set in train. The site itself was divided into zones. The measures taken were to remove debris and contaminated equipment, decontaminate roofs and outer surfaces of buildings, remove a 5–10 cm layer of soil into containers, lay where necessary concrete or fresh earth on the ground, and coat certain surfaces with film-forming compounds.

Decontamination of the area outside the site was complicated by the fact that the distribution of the radionuclides changed with time according to the terrain, particularly during the first 3–4 months. Hence the full value of measures to decontaminate a particular area is generally obtained only temporarily. Buildings were hosed down and the earth around them then removed. Measures were developed to allow the contaminated land to be used for agriculture: these included changes to methods of cultivation and harvesting and the use of dust-suppression materials.

The accident was the subject of intense press interest world-wide, although hard facts were difficult to come by. Interest centred on satellite photographs of the burning core, evacuation measures taken or not taken, the assistance given by an American bone marrow transplant surgeon, potential fallout in other countries and implications for nuclear power generally.

The fire in the reactor was readily seen from above and satellite photographs appeared on the world’s television screens. These were soon supplemented by Soviet pictures of the stricken reactor.

The death toll from Chernobyl cannot be known with certainty, since most deaths will be excess cancers. Two men died dealing with the accident itself. By the end of
September the toll of dead in the USSR was 31 with 203 injured. The casualties are discussed further in Section A22.8.

Other European countries were also affected. Radioactive contamination was measured across Europe and many countries banned particular products for a period.

A22.7 The Investigations

A22.7.1 USSR State Committee Report

In the West the main source of information on the accident was initially the investigation described in the USSR State Committee Report.

Part I of the report gives a brief description of the reactor and describes the accident itself. The seven appendices of Part II describe the reactor system, the detailed design of the reactor, the measures to deal with the consequences, the quantity of radioactivity released, the dispersion of the radioactive plume and the radioactive deposition, the radio-ecological contamination caused, and the medical and biological consequences.

An important feature of the investigation was a simulation of the accident using a mathematical model. This was assisted by the fact that the control computer had a program which logged several hundred critical parameters with a minimum cycle time of one second.

According to the simulation a power surge occurred in the reactor which took the output to 530 MWt within three seconds. There was intense steam formation and then nucleate boiling in the fuel channels and abrupt pressure increase, causing bursting of the channels.

The primary explosion was therefore bursting of the fuel channels by high pressure steam. The formation of steam and the rapid rise in core temperature created conditions for the steam-zirconium and other reactions. These reactions gave rise to hydrogen and carbon monoxide. After the reactor space had been vented and destroyed these mixed with air and burnt causing an explosion.

The report criticises both the experimental programme and the conduct of the test. It states

The quality of the programme was poor and the section on safety measures was drafted in a purely formal way... Apart from the fact that the programme made essentially no provision for additional safety measures, it called for shutting off the reactor’s emergency core cooling system.

Because the question of safety in these experiments had not received the necessary attention, the staff involved were not adequately prepared for the tests and were not aware of the possible dangers. Moreover, as we shall see in what follows, the staff departed from the programme and thereby created the conditions for the emergency situation.

The report highlights the positive void coefficient as a problem feature of the reactor design. It lists six violations of the operating instructions by the operators and gives the motivation for and consequences of each.

The test programme specified that the ECCS should be disconnected. In addition, the reactor shut down trip based on turbogenerator shut down was disarmed. During the actual test the reactor shut down trip based on coolant parameters was disarmed. These three actions were all taken to facilitate the test. The three other violations were the reduction in the reactivity margin, the switch from local automatic power control to manual control and the switching on of the standby pumps. The first was connected with attempts to deal with the poisoning problem and it rendered the protective system ineffective. The second was an operator error and it made the reactor much more difficult to control. The third was done to make doubly sure of adequate cooling and it resulted in loss of level in the separator and the decision to disable the reactor shut down trip based on coolant parameters.

The report also points out that at low power levels the measurement of power density in the core is less accurate.

The report gives an account of the release from the damaged reactor and of the emergency measures taken.

The report records a number of measures being taken to prevent a repetition. They include changes to the organization responsible for the reactors and to the inspection organization and intensification of research on safety aspects.

An important design modification mentioned is the use of uranium fuel enriched to 2.4% rather than 2% in order to try to avoid the positive void coefficient problem.

In presenting the report to the IAEA Legasov is reported as saying that the plant was one of the best in the country with good operators who were so convinced of its safety that they ‘had lost all sense of danger’.

A22.7.2 Other reports

As described at the start of the section, there have been a number of other reports on Chernobyl. The coverage of these reports is broadly as follows:

<table>
<thead>
<tr>
<th>IAEA</th>
<th>NRC</th>
<th>NEA</th>
<th>Watt Ctee 1</th>
<th>Watt Ctee 2</th>
<th>UKAEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of RBMK reactors</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>General account of events</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Chronology of events</td>
<td>X</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>Radioactive release, source terms</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Radioactive dispersion, Health effects</td>
<td>X</td>
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<td>X</td>
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</tr>
<tr>
<td>Environmental effects, decontamination</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td></td>
</tr>
<tr>
<td>Emergency response</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Safety issues</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>
A22.8 The Release – 2

Estimates of the amount of radiation released are given in the USSR State Committee Report and several of the other reports mentioned. Table A22.3, Section A, based on figures given by Konstantinov and Gonzalez (1989), gives one such estimate of the total release, while Section B, based on the USSR State Committee Report, gives an estimate of the rate of release, showing the fall-off after 6 May.

According to the USSR State Committee Report, on 26 April the area around the site was in a low gradient pressure field with a slight wind varying in direction. At an altitude of about 1 km the wind speed was 5–10 m/s in a northerly direction.

The most intense plume observed was during the first 2–3 days in a northerly direction. Radiation levels in this stream at 5–10 km from the reactor and at 200 m altitude were 1000 mR/h on 27 April and 500 mR/h on 28 April. According to aircraft monitoring data on 27 April the height of the stream exceeded 1200 m in a northerly direction and the radiation level at this height was 1 mR/h. During the following days the height of the stream did not exceed 200–400 m.

Information on the radiation levels experienced at and around the site is patchy. The report states that those at

Table A22.3 Estimated radioactive release from Chernobyl Unit 4

A  Core inventory and estimated fraction released (after Konstantinov and Gonzalez, 1989)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Core inventorya (EBq)</th>
<th>Estimated fraction releasedb (%)</th>
<th>Half-life</th>
</tr>
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<tbody>
<tr>
<td>Kr-85</td>
<td>0.033</td>
<td>100</td>
<td>10.72 year</td>
</tr>
<tr>
<td>Xe-133</td>
<td>1.7</td>
<td>100</td>
<td>5.25 d</td>
</tr>
<tr>
<td>I-131</td>
<td>1.3</td>
<td>20</td>
<td>8.04 d</td>
</tr>
<tr>
<td>Te-132</td>
<td>0.32</td>
<td>15</td>
<td>3.26 d</td>
</tr>
<tr>
<td>Cs-137</td>
<td>0.29</td>
<td>13</td>
<td>30.0 year</td>
</tr>
<tr>
<td>Cs-134</td>
<td>0.19</td>
<td>10</td>
<td>2.06 year</td>
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<tr>
<td>Sr-89</td>
<td>2.0</td>
<td>4</td>
<td>50.5 d</td>
</tr>
<tr>
<td>Sr-90</td>
<td>0.2</td>
<td>4</td>
<td>29.12 year</td>
</tr>
<tr>
<td>Zr-95</td>
<td>4.4</td>
<td>3</td>
<td>64.0 d</td>
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<tr>
<td>Mo-99</td>
<td>4.8</td>
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<td>2.75 d</td>
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<td>Ru-103</td>
<td>4.1</td>
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<td>Ru-106</td>
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<td>2.9</td>
<td>6</td>
<td>12.7 d</td>
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<td>0.14</td>
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<td>2.36 d</td>
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<td>0.001</td>
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<td>87.74 year</td>
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<td>Pu-239</td>
<td>0.0008</td>
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<td>24065 year</td>
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<tr>
<td>Pu-240</td>
<td>0.001</td>
<td>3</td>
<td>6537 year</td>
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<tr>
<td>Pu-241</td>
<td>0.17</td>
<td>3</td>
<td>14.4 year</td>
</tr>
<tr>
<td>Cm-242</td>
<td>0.026</td>
<td>3</td>
<td>163 d</td>
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B  Estimated daily release rates (after USSR State Committee, 1986)

<table>
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<th>Date</th>
<th>Time after accident (d)</th>
<th>Radioactivity releaseda (MCi)</th>
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<tr>
<td>Apr. 26</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.4</td>
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<td></td>
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<td>2.6</td>
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<td></td>
<td>4</td>
<td>2.0</td>
</tr>
<tr>
<td>May 1</td>
<td>5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>5.0</td>
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<td></td>
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<td></td>
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<td></td>
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<td>0.01</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>20 × 10⁻⁵</td>
</tr>
</tbody>
</table>

a Decay corrected to 6 May 1986, 1 EBq = 10¹⁸ Bq
b Stated accuracy ±50% except for noble gases
the site exceeded 100 mR/h. The report also gives the following additional activities:

15 days after the accident at 30–40 km north:
35–40 mR/h
15 days after the accidents at 50–60 km west: 5 mR/h
At beginning of May in Kiev: 0.5–0.8 mR/h

Maps of the radioactive fallout in the Chernobyl region are given in the Second Watt Committee Report and by Read. Figure A22.3 from the former shows the boundary of the zone contaminated to the level of 0.5 μSv/h on 10 May 1986.

Accounts and maps of the radiation dispersion patterns over Europe and over the UK are given in the UKAEA
Figure A22.4  Radiation dispersion pattern across Europe 3 May 1986 (Gittus et al., 1987)
Report and in the two Watt Committee Reports and by Apsimon and Davison (1986), Wheeler et al. (1989) and Hass et al. (1990).

Figure A22.4 from Gittus et al. (1987) shows the estimated radiation dispersion pattern across Europe on 3 May 1986.

According to the Second Watt Committee Report, of the 4% of the core inventory dispersed, the distribution was approximately 0.3–0.5% on the reactor site, 1.5–2.0% within 20 km and 1.0–1.5% beyond 20 km. The most significant isotopes outside the USSR were I-131, Cs-134 and Cs-137.

In Europe the highest dose equivalents in the year after the accident were 0.76, 0.67 and 0.59 mSv in Bulgaria, Austria and Greece, respectively, while that in the UK was 0.03 mSv.

A22.9 The Later Aftermath

Of those on site at the time, two died on site and a further 29 in hospital over the next few weeks. A further 17 are permanent invalids and 57 returned to work but with seriously affected capacity. The others on site, some 200, were affected to varying degrees. There is apparently no detailed information on the effects on the military and civilian personnel brought in to deal with the accident.

Potential health effects at relatively low doses are discussed in Appendix 20. A detailed discussion of such effects from Chernobyl is given in the Second Watt Committee Report. For EC countries the estimates of the NRPB in 1986 were 100 fatal thyroid cancers and 2000 fatal general cancers, or 2100 fatal cancers. For the USSR the situation is much more complex, but the report quotes an estimate by Ryin et al. (1990) of 1240 fatal leukaemia cases and 38000 fatal general cancers.

Measures to reduce the hazard from Unit 4 reactor have continued long after the events described, involving devoted and heroic work to limit the harm to their fellows, not only in the USSR but elsewhere.

A22.10 Some Lessons of Chernobyl

Some of the lessons of Chernobyl apply specifically to the nuclear industry and these are not considered here, but the more important ones are equally applicable to the process industries. A list of some of these is given in Table A22.4.

These lessons are now considered.

Management of, and safety culture in, major hazard installations

The management of the organization at the Chernobyl plant were clearly inadequate for the operation of a major hazard installation.

The defects highlighted particularly in the foregoing account are a weak safety culture and overconfidence, a potentially lethal combination.

Adherence to safety-related instructions

Closely linked to this is the lesson which most commentators have highlighted as the principal one, the need to adhere to safety-related instructions. At Chernobyl a number of such instructions were violated by the operators. These violations included disconnecting the ECCS and disabling two sets of trip systems.

Table A22.4 Some lessons of Chernobyl

<table>
<thead>
<tr>
<th>Management of, and safety culture in, major hazard installations</th>
<th>Adherence to safety-related instructions</th>
<th>Inherent safer design of plants</th>
<th>Sensitivity and operability of plants</th>
<th>Design of plant to minimize effect of violations</th>
<th>Disarming of protective systems</th>
<th>Planning and conduct of experimental work on plants</th>
<th>Accidents involving human error and their assessment</th>
<th>Emergency planning for large accidents</th>
<th>Mitigating features of accidents</th>
</tr>
</thead>
</table>

Inherently safer design of plants

The Chernobyl reactor had a low degree of inherent safety, due particularly to the positive temperature coefficient.

The reactor did have some features, however, which might be claimed to be inherently safer. Thus by avoiding the use of a single large pressure vessel the design eliminated the hazard of catastrophic rupture of such a vessel and by subdividing the fuel into individually cooled channels it reduced the risk of total core meltdown.

On the other hand in addition to the sensitivity inherent in the positive temperature coefficient, the design also involved massive graphite blocks which could burn.

Chernobyl thus also illustrates the fact that inherently safer design does not have a single dimension, but is multi-dimensional.

Sensitivity and operability of plants

Closely related to inherently safer design is the sensitivity and operability of plants. The nuclear reactor at Chernobyl had a regime, that of low excess reactivity, at which it was close to instability and difficult to control. This is an undesirable characteristic in any plant. This fact is recognized in the recommendation made that the uranium fuel enrichment be increased to 2.4%.

Design of plant to minimize effect of violations

At Chernobyl it was necessary to avoid operating the plant with a power output less than 20% of the rated value. Where there is a feature which is so critical, it is arguable that the plant should be designed to ensure that it cannot be violated. This is another aspect of inherently safer design.

The practicality of such an approach can only be decided in the light of the particular case. As Franklin argues, it is not practical to design against all conceivable violations.

Disarming of protective systems

The disarming of protective systems is a permissible practice in certain cases, but these need to be well defined and there must be proper procedures for doing
so. At Chernobyl protective systems were disarmed which should not have been.

Planning and conduct of experimental work on plants
When work is to be done on a plant, whether engineering work or experimental testing, it is necessary, particularly if the work involves modification to safety-related features such as the disarming of trips, to review the potential hazards and to have specific authorized arrangements for the safe operation of the plant.

Once the test is under way, unauthorized modifications should not be made to the equipment or to the test procedure itself which have potential safety implications.

Accidents involving human error and their assessment
The Chernobyl disaster was caused by a series of actions by the operators of the plant. It appears to be a case of human error which is virtually impossible to foresee and prevent. No doubt the probability of any one of the events would have been assessed as low and that of their combination is virtually incredible. But there was a common factor, namely the determination to carry out the test.

There is a need for the development of techniques, both for design and for hazard assessment of plant, for identifying potentially hazardous operator intervention sequences.

Emergency planning for large accidents
The scale of the accident at Chernobyl was such that the resources required to deal with the emergency exceeded those available locally. In the event, the authorities responded by mobilizing resources on a military scale. Large numbers of military and civilian personnel were drafted in to work on the reactor itself, on evacuation and on decontamination. The evacuation on 27 April required some 1000 buses.

Mitigating features of accidents
In terms of the effect of the accident on the population near the site there were several factors which mitigated the effect of the accident at Chernobyl, although the full value of these was partially lost due to hesitation in carrying out the evacuation. These mitigating features are discussed by Hawkes et al. (1986).

The accident occurred at night so that fewer people were exposed on site and the population outside were mostly indoors. The intense fire created the conditions for the radioactive plume to rise high and carry the release away. There was little wind so that the plume was not prevented from rising and such wind as existed was away from the large centres of population to the south. The weather was dry so that the radioactivity was not washed down on the nearby population.
Appendix

Rasmussen Report

Contents

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A23.2 Risk Assessment Methodology A23/2
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A23.5 Event Trees A23/4
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A23.11 Population Characteristics A23/7
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A23.13 Injury Relations A23/9
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A23.17 Browns Ferry Incident A23/12
A23.18 Critical Assumptions A23/14
A23.19 Critiques A23/15
A comprehensive hazard assessment of nuclear power plants in general is the Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants by the Nuclear Regulatory Commission (NRC) (1975). The work was done by a team led by Professor N.C. Rasmussen and is often referred to as the Rasmussen Report. It is also known as the Reactor Safety Study (RSS) and also as WASH 1400. It is referred to in this appendix as the Reactor Safety Study but elsewhere as the Rasmussen Report.

This study was a major exercise involving some 70 man years of work and costing $4 million. The report is a document of nine volumes some 15 cm thick.

The Reactor Safety Study constituted a watershed in probabilistic risk assessment. It not only brought the PRA approach to the fore as an aid in decision-making, but created a framework and brought together the various techniques needed to carry out such a study.

The work is of interest in respect of its methodology, its treatment of particular problems in risk assessment, its compilations of failure data and its presentation and evaluation of risks. Also of interest are the critiques of the report.

The methodology is based on the extensive use of fault trees and event trees and addresses the problem of uncertainty in the results obtained.

The report has been followed by further reports which have developed the methodology. In particular, a treatment of overall PRA methodology is given in the PRA Procedures Guide of the NRC (1982) and of human factors methodology in the Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications. Final Report by Swain and Guttmann (1982).

Selected references on the Reactor Safety Study are given in Table A23.1.

### A23.1 Earlier Studies

The RSS, or WASH 1400, was not the first study of this subject. There were several earlier reports on nuclear reactor safety.

The first of these was the report Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants by the Atomic Energy Commission (AEC) (1957). The work was done by the Brookhaven National Laboratory and is often referred to as the Brookhaven Report and also as WASH 740.

WASH 740 considered as a pessimistic accident scenario, or maximum credible accident, a situation where a reactor was nearing time for refuelling and thus contained its largest inventory of fission products and suffered an accident involving loss from containment of half the core inventory in weather conditions which would carry the cloud towards a town of one million people 50 km away. It was estimated that this accident could result in 3400 deaths, 43,000 injured and $7 billion property damage.

The report did not give an estimate of the frequency of such an event and stated in effect that the methodology to do so did not exist.

A study to update WASH 740 was carried out by Brookhaven National Laboratory. The study was essentially complete by 1965 but was published only in 1973. It considered an even more pessimistic scenario of a large accident in a city and gave estimates of 45,000 deaths and 70,000 injuries.

Another report on reactor safety was The Safety of Nuclear Power Reactors (Light Water Cooled) and Related Facilities by the AEC (1973), or WASH 1250. This report included both accounts of policy and collections of data and contained some of the early results of WASH 1400.

### A23.2 Risk Assessment Methodology

The report provides a framework for probabilistic risk assessment. The overall methodology described is based on selection of a set of release scenarios; estimation of the frequency of each scenario using fault trees and of the frequency of each associated set of outcomes using event trees; estimation of the consequences using hazard models for the physical phenomena and models of population exposure, mitigation of exposure by shelter and by escape and evacuation and injury from radioactivity; and evaluation of these results using risk criteria.

Table A23.2, Section A, indicates the subjects covered by the various volumes of the report and Section B some of the specific topics. Reference to the report is frequently made here, in particular with respect to (1) failure and event data; (2) lognormal distribution; (3) fault trees; (4) event trees; (5) common mode failure; (6) human error; (7) evacuation; (8) shelter; (9) FN curves; and (10) risk evaluation.

The RSS gives risk assessments of both PWRs and BWRs, but the account given here is largely confined to the former.

### A23.3 Event Data

The RSS contains a compilation of a large amount of failure and event data. These are based primarily on nuclear industry experience supplemented by other sources.

Most of the data refer to two years experience at 17 nuclear plants which were operational in the US in 1972. The average plant in the sample was some four years old.

Data for equipment are given as failure rates or probabilities of failure on demand.
### Table A23.2 Reactor Safety Study: principal contents

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<td>I</td>
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<td>VI 6-1, B-1</td>
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<td>VI 10-1</td>
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<td>VI 11-25</td>
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<td>Mitigation of early exposure</td>
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<td>VI 11-3, App. J</td>
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<td>Shelter, ventilation and inside dosage</td>
<td>VI 11-6</td>
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<td>Mitigation of long-term exposure</td>
<td>VI</td>
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<td></td>
<td>Interdiction</td>
<td>VI 11-15</td>
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<tr>
<td></td>
<td>Decontamination</td>
<td>VI 11-15, App. K</td>
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<td></td>
<td>Doses of radioactivity</td>
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<td>Radioactivity dose-response relations</td>
<td>VI 9-1, Apps F-I</td>
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<td></td>
<td>Radiation dose criteria</td>
<td>VI 11-11</td>
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<td>Fate of radionuclides in environment</td>
<td>VII-37, 45</td>
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<td>XI 10-1</td>
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<td></td>
</tr>
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<td>Contribution of various radionuclides</td>
<td>VI 13-1</td>
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<td></td>
<td>Risks from natural and man-made hazards</td>
<td></td>
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<tr>
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<td>Early fatalities</td>
<td>MR</td>
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<tr>
<td></td>
<td>Earthquakes</td>
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<tr>
<td></td>
<td>Hurricanes</td>
<td>MR 10, 107, 116, 124</td>
</tr>
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<td></td>
<td>Tornadoes</td>
<td>MR 10, 106, 115, 122</td>
</tr>
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<td>Meteors</td>
<td>MR 10, 106, 123</td>
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<td>MR 10, 107, 125</td>
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<td></td>
<td>Dams</td>
<td>MR 10, 108, 114, 129</td>
</tr>
<tr>
<td></td>
<td>Explosions</td>
<td>MR 108, 118, 128</td>
</tr>
<tr>
<td></td>
<td>Toxic gas releases</td>
<td>MR 10, 108, 117, 127</td>
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<tr>
<td></td>
<td>Aircraft crashes</td>
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<td></td>
<td>FN curves</td>
<td>MR 119</td>
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<td></td>
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  Frequency  XI 5-1
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It is assumed that the failures are random and that the exponential failure distribution is applicable. The possibility of failure due to ageing was considered but excluded. The report states:

It should be recognized that the study did not include extreme ageing consideration since the applicability of its results is limited to only the next five years.

The data on failure rates and probabilities are given not as point values but as ranges. Most of these data are presented in terms of the 90% confidence range and are correlated using the lognormal distribution with values quoted for the lower and upper bounds, median, and error factor. This use of the lognormal distribution reflects the large amount of uncertainty in the data so that for many items it was possible to give only order of magnitude values for the failure rate or probability.

It is convenient to use as one of the parameters which describe the lognormal distribution the median. The report therefore quotes median values for much of the data.

In addition to data on failures, data for test and repair times are also given. These times are also correlated using the lognormal distribution.

It is worth emphasizing that in the report the lognormal distribution is not used to correlate times to failure. These are assumed to be exponentially distributed so that they are described by a constant failure rate. The lognormal distribution is used to describe the spread of these failure rates. On the other hand the lognormal distribution is indeed used to characterize test and repair times.

There are special studies of pipework failure and power supply failure. Reactor pressure vessel failure is also considered.

Some of the failure and event data in the RSS are given in Appendix 14.

A23.4 Fault Trees
The RSS makes extensive use of fault trees. The need to do this arises because the accident events considered can occur only if there are failures of a number of protective systems and because such failures are rare and insufficient historical data for them are available.

The volume of the report which deals with the fault trees contains some 150 figures, most of them fault tree diagrams.

The computer codes PREP and KITT were used to calculate the frequencies of the top events from those of the base events.

The PWR function unavailabilities obtained from the fault tree analyses are summarized in Table A23.3.

A23.5 Event Trees
The basic accident sequence considered is an initiating event followed by system failure and then containment failure.

The RSS makes extensive use of event trees for the accident sequences.

A summary of the event trees is given in Table A23.4.

A23.6 Common Mode Failure
Common mode failures are recognized in the RSS as a factor which may greatly increase the frequency of the hazard.

Several techniques are used to handle such common mode failures. For similar events which may in some way be coupled, such as human actions to calibrate an instrument or open a valve, lower and upper bound probabilities of failure are defined. The lower bound probability \( p_l \) is the probability calculated assuming complete independence of the events. The upper bound probability \( p_u \) is the probability calculated assuming complete coupling between the events. The actual probability \( p \) is then taken as the geometric mean, or lognormal median

\[
p = (p_l p_u)^{1/2}
\]  [A23.6.1]

The example given is the reclosing of two valves. The probability of failing to close one valve is taken as \( 10^{-2} \). Then the lower bound is \( 10^{-4} \) \((10^{-2} \times 10^{-2})\) and the upper bound \( 10^{-2} \) \((10^{-2} \times 1 \)\). While the probability given by Equation A23.6.1 is \( 10^{-3} \) \((10^{-4} \times 10^{-2})\).

The method of handling coupled events in a fault tree is described below.

Other common mode failures may occur as the result of a common event such as a fire or earthquake. The treatment of such external threats is considered below.

The RSS concludes that common mode failures do not make a large contribution to the overall frequency of core melt failure.

A23.7 Human Error
The report gives an extensive treatment of human error and estimates for error rates for a number of types of error. It also deals with problems such as non-independence of, or coupling between, errors.

The treatment of human error in the RSS and the Handbook of Human Reliability Analysis are described in Chapters 9 and 14 and some of their error rate estimates given.
Table A23.3 Reactor Safety Study: PWR function unavailabilities from fault trees (Nuclear Regulatory Commission, 1975)

<table>
<thead>
<tr>
<th><strong>System</strong></th>
<th>$Q_{upper}$</th>
<th>$Q_{median}$</th>
<th>$Q_{lower}$</th>
<th><strong>Major contributors (point estimates)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electric power</strong></td>
<td>$1.0 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>Hardware: $2.2 \times 10^{-5}$, Test and maintenance: $1.0 \times 10^{-5}$, Human: $3 \times 10^{-5}$, Common-mode: $1 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Reactor protection</strong></td>
<td>$1.0 \times 10^{-4}$</td>
<td>$3.6 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary feedwater</strong></td>
<td>$3.0 \times 10^{-4}$</td>
<td>$3.7 \times 10^{-5}$</td>
<td>$7.0 \times 10^{-6}$</td>
<td>Hardware: $2.0 \times 10^{-6}$, Test and maintenance: $3.2 \times 10^{-6}$, Human: $3 \times 10^{-5}$, Common-mode: $1 \times 10^{-3}$</td>
</tr>
<tr>
<td>0-8h after small LOCA</td>
<td>$2.6 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>8-24h after small LOCA</td>
<td>$2.8 \times 10^{-3}$</td>
<td>$4.5 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Containment spray injection</td>
<td>$7.8 \times 10^{-3}$</td>
<td>$2.4 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

**Consequence limiting control**

<table>
<thead>
<tr>
<th><strong>System</strong></th>
<th>$Q_{upper}$</th>
<th>$Q_{median}$</th>
<th>$Q_{lower}$</th>
<th><strong>Major contributors (point estimates)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>High single train</td>
<td>$7.2 \times 10^{-2}$</td>
<td>$2.8 \times 10^{-2}$</td>
<td>$1.4 \times 10^{-2}$</td>
<td>Hardware: $2.0 \times 10^{-2}$, Test and maintenance: $3.2 \times 10^{-3}$, Human: $1.0 \times 10^{-3}$, Common-mode: $4.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Hi-both trains</td>
<td>$4.8 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$4.8 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Hi-Hi single train</td>
<td>$2.6 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>$7.2 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Hi-Hi both trains</td>
<td>$3.2 \times 10^{-3}$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$4.1 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

**Emergency coolant injection**

<table>
<thead>
<tr>
<th><strong>System</strong></th>
<th>$Q_{upper}$</th>
<th>$Q_{median}$</th>
<th>$Q_{lower}$</th>
<th><strong>Major contributors (point estimates)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulators</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$9.5 \times 10^{-4}$</td>
<td>$6.2 \times 10^{-4}$</td>
<td>Hardware: $4.9 \times 10^{-4}$, Test and maintenance: $3.2 \times 10^{-4}$, Human: $7.0 \times 10^{-4}$, Common-mode: $4.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Low pressure injection</td>
<td>$7.4 \times 10^{-3}$</td>
<td>$4.7 \times 10^{-3}$</td>
<td>$3.1 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>High pressure injection</td>
<td>$2.7 \times 10^{-2}$</td>
<td>$8.6 \times 10^{-3}$</td>
<td>$4.4 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

**Safety injection control**

<table>
<thead>
<tr>
<th><strong>System</strong></th>
<th>$Q_{upper}$</th>
<th>$Q_{median}$</th>
<th>$Q_{lower}$</th>
<th><strong>Major contributors (point estimates)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Single train</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$5.8 \times 10^{-3}$</td>
<td>$3.3 \times 10^{-3}$</td>
<td>Hardware: $3.0 \times 10^{-3}$, Test and maintenance: $2.2 \times 10^{-3}$, Human: $4.5 \times 10^{-5}$, Common-mode: $6.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Both trains</td>
<td>$2.7 \times 10^{-3}$</td>
<td>$9.9 \times 10^{-5}$</td>
<td>$5.4 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Containment spray recirculation</td>
<td>$9.0 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-3}$</td>
<td>$2.5 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Containment heat removal</td>
<td>$3.0 \times 10^{-4}$</td>
<td>$8.5 \times 10^{-5}$</td>
<td>$3.0 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Low pressure recirculation</td>
<td>$3.1 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$4.4 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>High pressure recirculation</td>
<td>$2.2 \times 10^{-2}$</td>
<td>$9.0 \times 10^{-3}$</td>
<td>$4.3 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

**Containment leakage**

<table>
<thead>
<tr>
<th><strong>System</strong></th>
<th>$Q_{upper}$</th>
<th>$Q_{median}$</th>
<th>$Q_{lower}$</th>
<th><strong>Major contributors (point estimates)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure reduced to $&lt; \frac{1}{2}$ psi</td>
<td>$7.5 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$8.4 \times 10^{-5}$</td>
<td>Hardware: $1.3 \times 10^{-4}$, Test and maintenance: $8.8 \times 10^{-4}$, Human: $1.0 \times 10^{-4}$, Common-mode: $6.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Pressure not reduced to $\frac{1}{2}$ psi</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$2.0 \times 10^{-3}$</td>
<td>$6.0 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Sodium hydroxide addition</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$5.9 \times 10^{-3}$</td>
<td>$3.6 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

---

a Also human error.
b Containment pressure must be reduced to $< \frac{1}{2}$ psi to isolate containment spray injection system.

c Common mode resulting from human error.
d Point estimate value obtained only.

NA. Not applicable to combined systems.
### Table A23.4 Reactor Safety Study: PWR accident sequences from event trees (Nuclear Regulatory Commission, 1975)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Intermediate to large LOCA</td>
</tr>
<tr>
<td>B</td>
<td>Failure of electric power to ESFs</td>
</tr>
<tr>
<td>B’</td>
<td>Failure to recover either on-site or off-site electric power within about 1 to 3 h following an initiating transient which is a loss of off-site a.c. power</td>
</tr>
<tr>
<td>C</td>
<td>Failure of the containment spray injection system</td>
</tr>
<tr>
<td>D</td>
<td>Failure of the emergency core cooling injection system</td>
</tr>
<tr>
<td>F</td>
<td>Failure of the containment spray recirculation system</td>
</tr>
<tr>
<td>G</td>
<td>Failure of the containment heat removal system</td>
</tr>
<tr>
<td>H</td>
<td>Failure of the emergency core cooling recirculation system</td>
</tr>
<tr>
<td>K</td>
<td>Failure of the reactor protection system</td>
</tr>
<tr>
<td>L</td>
<td>Failure of the secondary system steam relief valves and the auxiliary valves and the auxiliary feedwater system</td>
</tr>
<tr>
<td>M</td>
<td>Failure of the secondary system steam relief valves and the power conversion system</td>
</tr>
<tr>
<td>Q</td>
<td>Failure of the primary system safety relief valves to reclose after opening</td>
</tr>
<tr>
<td>R</td>
<td>Massive rupture of the reactor vessel</td>
</tr>
<tr>
<td>S</td>
<td>A small LOCA with an equivalent diameter of about 5 to 15 cm</td>
</tr>
<tr>
<td>T</td>
<td>Transient event</td>
</tr>
<tr>
<td>V</td>
<td>Failure of low-pressure injection system check valve</td>
</tr>
<tr>
<td>α</td>
<td>Containment rupture due to a reactor vessel steam explosion</td>
</tr>
<tr>
<td>β</td>
<td>Containment failure resulting from inadequate isolation of containment openings and penetrations</td>
</tr>
<tr>
<td>γ</td>
<td>Containment failure due to hydrogen burning</td>
</tr>
<tr>
<td>δ</td>
<td>Containment failure due to overpressure</td>
</tr>
<tr>
<td>ε</td>
<td>Containment vessel melt-through</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sequence designation</th>
<th>Event tree failure(s)</th>
<th>Containment event tree failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A</td>
<td>Large rupture only</td>
<td>None</td>
</tr>
<tr>
<td>2. A-β</td>
<td>Large rupture only</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>3. AH-α</td>
<td>ECCS recirculation</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>4. AH-β</td>
<td>ECCS recirculation</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>5. AH-ε</td>
<td>ECCS recirculation</td>
<td>Melt-through</td>
</tr>
<tr>
<td>6. AHI-α</td>
<td>ECCS recirculation plus sodium hydroxide</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>7. AHI-β</td>
<td>ECCS recirculation plus sodium hydroxide</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>8. AHI-ε</td>
<td>ECCS recirculation plus sodium hydroxide</td>
<td>Melt-through</td>
</tr>
<tr>
<td>9. AG-δ</td>
<td>Containment heat removal</td>
<td>Overpressure</td>
</tr>
<tr>
<td>10. AHG-δ</td>
<td>ECCS recirculation plus containment heat removal</td>
<td>Overpressure</td>
</tr>
<tr>
<td>11. AHG-ε</td>
<td>ECCS recirculation plus containment heat removal</td>
<td>Melt-through</td>
</tr>
<tr>
<td>12. AHF-α</td>
<td>ECCS recirculation plus containment spray recirculation</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>13. AHF-β</td>
<td>ECCS recirculation plus containment spray recirculation</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>14. AHF-ε</td>
<td>ECCS recirculation plus containment spray recirculation</td>
<td>Overpressure</td>
</tr>
<tr>
<td>15. AHF-γ</td>
<td>ECCS recirculation plus containment spray recirculation</td>
<td>Melt-through</td>
</tr>
<tr>
<td>16. AD-α</td>
<td>ECCS injection</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>17. AD-β</td>
<td>ECCS injection</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>18. AD-ε</td>
<td>ECCS injection</td>
<td>Melt-through</td>
</tr>
<tr>
<td>19. ADI-α</td>
<td>ECCS injection plus sodium hydroxide</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>20. ADI-ε</td>
<td>ECCS injection plus sodium hydroxide</td>
<td>Melt-through</td>
</tr>
<tr>
<td>21. ADG-α</td>
<td>ECCS injection plus containment heat removal</td>
<td>Melt-through</td>
</tr>
<tr>
<td>22. ADG-ε</td>
<td>ECCS injection plus containment heat removal plus sodium hydroxide</td>
<td>Melt-through</td>
</tr>
<tr>
<td>23. ADF-α</td>
<td>ECCS injection plus containment spray recirculation</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>24. ADF-ε</td>
<td>ECCS injection plus containment spray recirculation</td>
<td>Melt-through</td>
</tr>
<tr>
<td>25. ACD-β</td>
<td>Containment spray injection plus ECCS injection</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>26. ACD-ε</td>
<td>Containment spray injection plus ECCS injection</td>
<td>Melt-through</td>
</tr>
<tr>
<td>27. ACDGI-α</td>
<td>All except electric power and containment spray recirculation</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>28. ACDGI-β</td>
<td>All except electric power and containment spray recirculation</td>
<td>Containment leakage</td>
</tr>
<tr>
<td>29. ACDGI-ε</td>
<td>All except electric power and containment spray recirculation</td>
<td>Overpressure</td>
</tr>
<tr>
<td>30. ACDGI-γ</td>
<td>All except electric power and containment spray recirculation</td>
<td>Melt-through</td>
</tr>
<tr>
<td>31. AB-α</td>
<td>Electric power</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>32. AB-β</td>
<td>Electric power</td>
<td>Hydrogen combustion</td>
</tr>
<tr>
<td>33. AB-ε</td>
<td>Electric power</td>
<td>Melt-through</td>
</tr>
<tr>
<td>34. S2C-α</td>
<td>Small LOCA plus containment spray injection</td>
<td>Vessel steam explosion</td>
</tr>
<tr>
<td>35. S2C-β</td>
<td>Small LOCA plus containment spray injection</td>
<td>Overpressure</td>
</tr>
<tr>
<td>36. TMLB-α</td>
<td>Transient plus feedwater plus electric power</td>
<td>Hydrogen combustion</td>
</tr>
<tr>
<td>37. TMLB-β</td>
<td>Transient plus feedwater plus electric power</td>
<td>Overpressure</td>
</tr>
<tr>
<td>38. TMLB-ε</td>
<td>Transient plus feedwater plus electric power</td>
<td>Vessel steam explosion</td>
</tr>
</tbody>
</table>
A23.8 Rare Events

An important rare event considered in the RSS is failure of the reactor pressure vessel. The report states:

"Potentially large ruptures in the vessel were considered that could prevent effective cooling of the core by the ECCS. Since certain of these ruptures appeared to be capable of causing missiles (such as the reactor vessel head) with sufficient momentum to rupture the containment, this area was explored with some care. ... There is some small probability that a large vessel missile could in fact impact directly on the containment and penetrate through the wall. This type of rupture could involve a core meltdown in a non-intact containment.

A study by the Advisory Committee on Reactor Safeguards (ACRS) concluded that "the disruptive failure probability of reactor vessels designed, constructed and operated according to code is even lower than $1 \times 10^{-6}$ per vessel year." The figure used in the RSS is $1 \times 10^{-7}$/vessel year.

The effect of this low estimate of reactor pressure vessel failure rate is to take this event out of consideration as a cause of release. The RSS states:

"Gross vessel rupture would have to be at least about 100 times more likely than the value estimated in order to contribute to the PWR core melt probability."

A23.9 External Threats

The RSS considers external threats such as fire, earthquakes and sabotage.

"The prediction of earthquakes is highly uncertain and the report emphasizes this. It nevertheless states that a 'reasonable estimate of core melt due to earthquake' is $10^{-7}$ per reactor year'."

The RSS acknowledges the threat posed by sabotage, but does not take this into account in the risk estimates made. These estimates apply to bona fide accidents and exclude those due to sabotage.

A23.10 Release Scenarios

The consequences of a core degradation or meltdown depend on (1) core inventory; (2) fraction released; (3) dispersion and deposition; (4) population exposed; (5) mitigating features (evacuation, shelter); and (6) injury relations.

A schematic outline of the consequence models is shown in Figure A23.1.

The initial radioactivity of the radionuclides in the reactor core is given in Table A23.5 and the reactor core inventory in Table A23.6.

The release scenarios are shown in Tables A23.7 and A23.8.

The release from the reactor is used in the report as the source term for a plume gas dispersion model. This model takes into account the deposition of solid radionuclides.

A23.11 Population Characteristics

The population at risk was characterized by a composite model based on the 68 actual sites holding the first 100 reactors. Six composite sites of different types were defined.

The population density was determined as follows. The first type of site was an Atlantic coastal site and 14 of the reactors were assigned to this composite site. The actual
Table A23.5  Reactor Safety Study: initial activity of radionuclides in reactor core (Nuclear Regulatory Commission, 1975)

<table>
<thead>
<tr>
<th>No.</th>
<th>Radionuclide</th>
<th>Radio inventory source (curies × 10⁻⁹)</th>
<th>Half-life (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cobalt-58</td>
<td>0.0078</td>
<td>71.0</td>
</tr>
<tr>
<td>2</td>
<td>Cobalt-60</td>
<td>0.0029</td>
<td>1920</td>
</tr>
<tr>
<td>3</td>
<td>Krypton-85</td>
<td>0.0056</td>
<td>3950</td>
</tr>
<tr>
<td>4</td>
<td>Krypton-85m</td>
<td>0.24</td>
<td>0.183</td>
</tr>
<tr>
<td>5</td>
<td>Krypton-87</td>
<td>0.47</td>
<td>0.0528</td>
</tr>
<tr>
<td>6</td>
<td>Krypton-88</td>
<td>0.68</td>
<td>0.117</td>
</tr>
<tr>
<td>7</td>
<td>Rubidium-86</td>
<td>0.00026</td>
<td>18.7</td>
</tr>
<tr>
<td>8</td>
<td>Strontium-89</td>
<td>0.94</td>
<td>52.1</td>
</tr>
<tr>
<td>9</td>
<td>Strontium-90</td>
<td>0.037</td>
<td>11100</td>
</tr>
<tr>
<td>10</td>
<td>Strontium-91</td>
<td>1.1</td>
<td>0.403</td>
</tr>
<tr>
<td>11</td>
<td>Yttrium-90</td>
<td>0.039</td>
<td>2.87</td>
</tr>
<tr>
<td>12</td>
<td>Yttrium-91</td>
<td>1.2</td>
<td>39.0</td>
</tr>
<tr>
<td>13</td>
<td>Zirconium-95</td>
<td>1.5</td>
<td>65.2</td>
</tr>
<tr>
<td>14</td>
<td>Zirconium-97</td>
<td>1.5</td>
<td>0.71</td>
</tr>
<tr>
<td>15</td>
<td>Niobium-95</td>
<td>1.5</td>
<td>35.0</td>
</tr>
<tr>
<td>16</td>
<td>Molybdenum-99</td>
<td>1.6</td>
<td>2.8</td>
</tr>
<tr>
<td>17</td>
<td>Technetium-99m</td>
<td>1.4</td>
<td>0.25</td>
</tr>
<tr>
<td>18</td>
<td>Ruthenium-103</td>
<td>1.1</td>
<td>39.5</td>
</tr>
<tr>
<td>19</td>
<td>Ruthenium-105</td>
<td>0.72</td>
<td>0.185</td>
</tr>
<tr>
<td>20</td>
<td>Ruthenium-106</td>
<td>0.25</td>
<td>366</td>
</tr>
<tr>
<td>21</td>
<td>Rhodium-105</td>
<td>0.49</td>
<td>1.5</td>
</tr>
<tr>
<td>22</td>
<td>Tellurium-127</td>
<td>0.059</td>
<td>0.391</td>
</tr>
<tr>
<td>23</td>
<td>Tellurium-127m</td>
<td>0.011</td>
<td>109</td>
</tr>
<tr>
<td>24</td>
<td>Tellurium-129</td>
<td>0.31</td>
<td>0.048</td>
</tr>
<tr>
<td>25</td>
<td>Tellurium-129m</td>
<td>0.053</td>
<td>0.340</td>
</tr>
<tr>
<td>26</td>
<td>Tellurium-131m</td>
<td>0.13</td>
<td>1.25</td>
</tr>
<tr>
<td>27</td>
<td>Tellurium-132</td>
<td>1.2</td>
<td>3.25</td>
</tr>
<tr>
<td>28</td>
<td>Antimony-127</td>
<td>0.061</td>
<td>3.88</td>
</tr>
<tr>
<td>29</td>
<td>Antimony-129</td>
<td>0.33</td>
<td>0.179</td>
</tr>
<tr>
<td>30</td>
<td>Iodine-131</td>
<td>0.85</td>
<td>8.05</td>
</tr>
<tr>
<td>31</td>
<td>Iodine-132</td>
<td>1.2</td>
<td>0.0958</td>
</tr>
<tr>
<td>32</td>
<td>Iodine-133</td>
<td>1.7</td>
<td>0.873</td>
</tr>
<tr>
<td>33</td>
<td>Iodine-134</td>
<td>1.9</td>
<td>0.0366</td>
</tr>
<tr>
<td>34</td>
<td>Iodine-135</td>
<td>1.5</td>
<td>0.280</td>
</tr>
<tr>
<td>35</td>
<td>Xenon-133</td>
<td>1.7</td>
<td>5.28</td>
</tr>
<tr>
<td>36</td>
<td>Xenon-135</td>
<td>0.34</td>
<td>0.384</td>
</tr>
<tr>
<td>37</td>
<td>Cesium-134</td>
<td>0.075</td>
<td>750</td>
</tr>
<tr>
<td>38</td>
<td>Cesium-136</td>
<td>0.030</td>
<td>13.0</td>
</tr>
<tr>
<td>39</td>
<td>Cesium-137</td>
<td>0.047</td>
<td>11000</td>
</tr>
<tr>
<td>40</td>
<td>Barium-140</td>
<td>1.6</td>
<td>12.8</td>
</tr>
<tr>
<td>41</td>
<td>Lanthanum-140</td>
<td>1.6</td>
<td>1.67</td>
</tr>
<tr>
<td>42</td>
<td>Cerium-141</td>
<td>1.5</td>
<td>32.3</td>
</tr>
<tr>
<td>43</td>
<td>Cerium-143</td>
<td>1.3</td>
<td>1.38</td>
</tr>
<tr>
<td>44</td>
<td>Cerium-144</td>
<td>0.85</td>
<td>284</td>
</tr>
<tr>
<td>45</td>
<td>Praseodymium-143</td>
<td>1.3</td>
<td>13.7</td>
</tr>
<tr>
<td>46</td>
<td>Neodymium-147</td>
<td>0.60</td>
<td>11.1</td>
</tr>
<tr>
<td>47</td>
<td>Neptunium-239</td>
<td>16.4</td>
<td>2.35</td>
</tr>
<tr>
<td>48</td>
<td>Plutonium-238</td>
<td>0.00057</td>
<td>32500</td>
</tr>
<tr>
<td>49</td>
<td>Plutonium-239</td>
<td>0.00021</td>
<td>8.9 × 10⁶</td>
</tr>
<tr>
<td>50</td>
<td>Plutonium-240</td>
<td>0.00021</td>
<td>2.4 × 10⁶</td>
</tr>
<tr>
<td>51</td>
<td>Plutonium-241</td>
<td>0.034</td>
<td>5350</td>
</tr>
<tr>
<td>52</td>
<td>Americium-241</td>
<td>0.000017</td>
<td>1.5 × 10⁶</td>
</tr>
<tr>
<td>53</td>
<td>Curium-242</td>
<td>0.0050</td>
<td>163</td>
</tr>
<tr>
<td>54</td>
<td>Curium-244</td>
<td>0.00023</td>
<td>6600</td>
</tr>
</tbody>
</table>

Population around each of these reactors was determined from census data for a distance of 50 miles. For each actual site 16 sectors were defined, making 224 sectors in total. These 224 sectors were then ranked in order of population density and 16 representative sectors were determined for the composite site.
Table A23.6  Reactor Safety Study: reactor core inventory (Nuclear Regulatory Commission, 1975)

<table>
<thead>
<tr>
<th>Location</th>
<th>Total inventory (curies)</th>
<th>Fraction of core inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel</td>
<td>Gap</td>
</tr>
<tr>
<td>Core&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.0 × 10&lt;sup&gt;8&lt;/sup&gt;</td>
<td>1.4 × 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Spent fuel storage pool (max.&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>1.3 × 10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>1.3 × 10&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Spent fuel storage pool (av.&lt;sup&gt;c&lt;/sup&gt;)</td>
<td>3.6 × 10&lt;sup&gt;8&lt;/sup&gt;</td>
<td>3.8 × 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Shipping cask&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2.2 × 10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>3.1 × 10&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Refueling&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.2 × 10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>2 × 10&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Waste gas storage tank</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Liquid waste storage tank</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup>  Core inventory based on activity 1 h after shutdown.

<sup>b</sup>  Inventory of 1/3 core loading; 2/3 core with three day decay and 1/3 core with 150 day decay.

<sup>c</sup>  Inventory of 1/3 core loading; 2/3 core with 150 day decay and 1/3 core with 60 day decay.

<sup>d</sup>  Inventory based on 7 FWR or 17 BWR fuel assemblies with 150 day decay.

<sup>e</sup>  Inventory for one fuel assembly with three day decay.

Data from a time use study by J.P. Robinson and Converse (1966) were used to determine the fraction of time spent at different locations and hence the probability that a person was inside shelter.

A23.12 Mitigation of Exposure

Factors which mitigate the exposure of the population include shelter and evacuation.

The RSS uses a single exponential stage evacuation model. This model is based on a study of actual evacuations by Hans andSell (1974).

Measures to mitigate long-term exposure include interdiction of the contaminated zone and decontamination of this zone.

The effect of shelter on concentration is modelled using a single exponential stage model for ventilation.

A23.13 Injury Relations

The effects of radioactivity on people are complex and are both short-term, or prompt, and long-term.

In order to determine these effects it is first necessary to estimate the doses of radioactivity received and then to apply a dose–response relation.

The RSS gives a detailed treatment of all these aspects and the report contains a large number of tables and graphs showing early and late fatalities and injuries due to different modes of injury and the contribution to these of individual radionuclides.

It also deals with the contamination of land.

A23.14 Uncertainty in Results

An attempt is made in the report to put bounds on the errors of the estimates.

A number of methods are used. Failure rates and probabilities are taken not as single values but as a range of values with a lognormal distribution, as described above.

The inputs to the fault trees are therefore not single values of frequency or probability but distributions of these. The frequency or probability of the top event is then computed, also as a distribution, by sampling from the distributions of these individual events using Monte Carlo simulation.

Such simulation may also be used to take account of common mode failures by arranging coupling between the failure rates or probabilities in question.

A23.15 Presentation of Results

The risks from reactor accidents are presented in the main report principally in the form of tables of frequency-consequence results.

The results for 100 reactors are for the mix of both PWR and BRW reactors considered in the study. The risks for an individual PWR are higher than for a BWR and those for a composite single reactor based on the mix are close to those for a PWR.

Table A23.9, Section A shows the societal risk of early effects from one reactor and Section B those from later effects. The report gives another table showing the societal risk from 100 reactors, the frequencies simply being greater by a factor of 100. Table A23.10 shows the individual and average societal risk from 100 reactors.

The results are also given in graphical form. Figure A23.2 gives a histogram of PWR release categories. Figure A23.3 is the frequency-consequence curve, or FN curve, for early fatalities from a single reactor. The graph shows curves for a PWR, a BWR and the composite reactor.

Figure A23.4 is the frequency-consequence curve for areas in which relocation of people and decontamination would be required.

A23.16 Evaluation of Results

The RSS evaluates the risk from the 100 nuclear reactors by making comparisons with those from other hazards.
<table>
<thead>
<tr>
<th>Accident category and frequency $f_j$</th>
<th>Description of accident category</th>
<th>Duration of release (h)</th>
<th>Elevation of release (m)</th>
<th>Energy release rate (Btu/h)</th>
<th>Fraction of core inventory released</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR1a 9 x 10^7 yr^-1</td>
<td>Core melt-down and failure of containment spray and heat removal systems. 1a-steam explosion after containment failure due to overpressure; 1b-steam explosion ruptures containment</td>
<td>0.5</td>
<td>25</td>
<td>$20 \times 10^6$ (1a) $520 \times 10^6$ (1b)</td>
<td>Xe-Kr  I  Cs=Rb  Te-Sb  Ba-Sr  Ru, Rh, Co, Mo, Tc  Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm</td>
</tr>
<tr>
<td>PWR2 8 x 10^-5 yr^-1</td>
<td>Core melt-down, failure of containment spray and heat removal systems. Containment fails through overpressure after commencement of core melt-down</td>
<td>0.5</td>
<td>0</td>
<td>170 x 10^6</td>
<td>0.9  0.7  0.5  0.3  0.06  0.02  3 x 10^-3</td>
</tr>
<tr>
<td>PWR3 4 x 10^-5 yr^-1</td>
<td>Failure of containment due to overpressure before core melt-down</td>
<td>1.5</td>
<td>0</td>
<td>6 x 10^6</td>
<td>0.8  0.2  0.2  0.3  0.02  0.03  3 x 10^-3</td>
</tr>
<tr>
<td>PWR4 5 x 10^-5 yr^-1</td>
<td>Core melt-down and failure of containment system properly to isolate; failure of containment spray system</td>
<td>3.0</td>
<td>0</td>
<td>1 x 10^6</td>
<td>0.6  0.09  0.04  0.03  5 x 10^-3  3 x 10^-3  4 x 10^-4</td>
</tr>
<tr>
<td>PWR5 7 x 10^-5 yr^-1</td>
<td>As PWR4, but containment spray systems operate to reduce release to atmosphere</td>
<td>4</td>
<td>0</td>
<td>3 x 10^-5</td>
<td>0.3  0.03  9 x 10^-3  5 x 10^-3  10^-3  6 x 10^-4  7 x 10^-5</td>
</tr>
<tr>
<td>PWR6 6 x 10^-5 yr^-1</td>
<td>Core melt-down, failure of containment sprays. Containment maintains integrity but core melts through base</td>
<td>10.0</td>
<td>0</td>
<td>0</td>
<td>0.3  8 x 10^-4  8 x 10^-4  9 x 10^-8  9 x 10^-5  7 x 10^-5  10^-5</td>
</tr>
<tr>
<td>PWR7 4 x 10^-5 yr^-1</td>
<td>As PWR6, but containment sprays operate</td>
<td>10.0</td>
<td>0</td>
<td>0</td>
<td>6 x 10^-3  2 x 10^-5  10^-5  2 x 10^-5  4 x 10^-6  10^-6  2 x 10^-7</td>
</tr>
<tr>
<td>PWR8 4 x 10^-5 yr^-1</td>
<td>Large pipe break, containment fails properly to isolate, all other engineered safeguards work, no core melt-down</td>
<td>0.5</td>
<td>0</td>
<td>2 x 10^-3</td>
<td>2 x 10^-3  4 x 10^-4  5 x 10^-4  10^-6  10^-8  0  0</td>
</tr>
<tr>
<td>PWR9 4 x 10^-5 yr^-1</td>
<td>As PWR8, but all engineered safeguards function as designed. Essentially PWR design basis accident</td>
<td>0.5</td>
<td>0</td>
<td>3 x 10^-6</td>
<td>6 x 10^-7  10^-9  10^-11  0  0</td>
</tr>
</tbody>
</table>

**Table A23.7** Reactor Safety Study: PWR release scenarios ± 1 (Nuclear Regulatory Commission, 1975)
Table A23.8  Reactor Safety Study: PWR release scenarios – 2 (Nuclear Regulatory Commission, 1975)

<table>
<thead>
<tr>
<th>Fission product</th>
<th>Gap release fraction</th>
<th>Meltdown release fraction</th>
<th>Vaporization release fraction&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Steam explosion fraction&lt;sup&gt;e&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe, Kr</td>
<td>0.030</td>
<td>0.870</td>
<td>0.100</td>
<td>((X) (Y) 0.90)</td>
</tr>
<tr>
<td>I, Br</td>
<td>0.017</td>
<td>0.883</td>
<td>0.100</td>
<td>((X) (Y) 0.90)</td>
</tr>
<tr>
<td>Ca, Rb</td>
<td>0.050</td>
<td>0.760</td>
<td>0.190</td>
<td>–</td>
</tr>
<tr>
<td>Te&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.0001</td>
<td>0.150</td>
<td>0.850</td>
<td>((X) (Y) 0.60)</td>
</tr>
<tr>
<td>Sr, Ba</td>
<td>0.000001</td>
<td>0.100</td>
<td>0.010</td>
<td>–</td>
</tr>
<tr>
<td>Ru&lt;sup&gt;b&lt;/sup&gt;</td>
<td>–</td>
<td>0.030</td>
<td>0.050</td>
<td>–</td>
</tr>
<tr>
<td>La&lt;sup&gt;c&lt;/sup&gt;</td>
<td>–</td>
<td>0.003</td>
<td>0.010</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup> Includes Se, Sb  
<sup>b</sup> Includes Mo, Pd, Rh, Tc  
<sup>c</sup> Includes Nd, Eu, Y, Ce, Pr, Pm, Sm, Np, Pu, Zr, Nb  
<sup>d</sup> Exponential loss over 2 h with half-time of 30 min. If a steam explosion occurs prior to this, only the core fraction not involved in the steam explosion can experience vaporization.  
<sup>e</sup> X = Fraction of core involved in the steam explosion. Y = Fraction of inventory remaining for release by oxidation.

Table A23.9  Reactor Safety Study: societal risk from one reactor (Nuclear Regulatory Commission, 1975)

A  Early effects

<table>
<thead>
<tr>
<th>Chance per reactor-year</th>
<th>Early fatalities</th>
<th>Early illness</th>
<th>Total property damage ($10^9$)</th>
<th>Decontamination area (~ square miles)</th>
<th>Relocation area (square miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One in 20000&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>One in 100000</td>
<td>&lt; 1.0</td>
<td>300</td>
<td>0.5</td>
<td>2000</td>
<td>130</td>
</tr>
<tr>
<td>One in 1000000</td>
<td>119</td>
<td>3000</td>
<td>3</td>
<td>3200</td>
<td>250</td>
</tr>
<tr>
<td>One in 10000000</td>
<td>900</td>
<td>14000</td>
<td>8</td>
<td>–</td>
<td>290</td>
</tr>
<tr>
<td>One in 100000000000</td>
<td>3300</td>
<td>45000</td>
<td>14</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup> This is the predicted chance of core melt per reactor year.

B  Cancer and genetic effects

<table>
<thead>
<tr>
<th>Chances per reactor-year</th>
<th>Latent cancer&lt;sup&gt;b&lt;/sup&gt; fatalities (per year)</th>
<th>Thyroid nodules&lt;sup&gt;b&lt;/sup&gt; (per year)</th>
<th>Genetic effects&lt;sup&gt;c&lt;/sup&gt; (per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One in 20000&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>One in 100000</td>
<td>170</td>
<td>1400</td>
<td>25</td>
</tr>
<tr>
<td>One in 1000000</td>
<td>460</td>
<td>3500</td>
<td>60</td>
</tr>
<tr>
<td>One in 10000000</td>
<td>860</td>
<td>6000</td>
<td>110</td>
</tr>
<tr>
<td>One in 1000000000</td>
<td>1500</td>
<td>8000</td>
<td>170</td>
</tr>
<tr>
<td>Nuclear incidence</td>
<td>17000</td>
<td>8000</td>
<td>8000</td>
</tr>
</tbody>
</table>

<sup>a</sup> This is the predicted chance of core melt per reactor year.  
<sup>b</sup> This rate would apply to the first generation born after a potential accident. Subsequent generations would experience effects at a lower rate.

Table A23.10  Reactor Safety Study: individual and average societal risk from 100 reactors (Nuclear Regulatory Commission, 1975)

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Societal</th>
<th>Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early fatalities&lt;sup&gt;b&lt;/sup&gt;</td>
<td>$3 \times 10^{-3}$</td>
<td>$2 \times 10^{-10}$</td>
</tr>
<tr>
<td>Early illness&lt;sup&gt;b&lt;/sup&gt;</td>
<td>$2 \times 10^{-4}$</td>
<td>$1 \times 10^{-8}$</td>
</tr>
<tr>
<td>Latent cancer fatalities&lt;sup&gt;c&lt;/sup&gt;</td>
<td>$7 \times 10^{-2}$/yr</td>
<td>$3 \times 10^{-10}$/yr</td>
</tr>
<tr>
<td>Thyroid nodules&lt;sup&gt;b&lt;/sup&gt;</td>
<td>$7 \times 10^{-2}$/yr</td>
<td>$3 \times 10^{-10}$/yr</td>
</tr>
<tr>
<td>Genetic effects&lt;sup&gt;c&lt;/sup&gt;</td>
<td>$1 \times 10^{-7}$/yr</td>
<td>$7 \times 10^{-1}$/yr</td>
</tr>
<tr>
<td>Property damage ($)</td>
<td>$2 \times 10^{6}$</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on 100 reactors at 68 current sites.  
<sup>b</sup> The individual risk value is based on the 15 million people living in the general vicinity of the first 100 nuclear power plants.  
<sup>c</sup> This value is the rate of occurrence per year for about a 30-year period following a potential accident. The individual rate is based on the total US population.  
<sup>d</sup> This value is the rate of occurrence per year for the first generation born after a potential accident; subsequent generations would experience effects at a lower rate. The individual rate is based on the total US population.
The main report gives numerous tables showing risks from various natural and man-made hazards such as earthquakes, hurricanes, tornadoes, meteorites, fires, dams, explosions, toxic gas releases, and aircraft crashes.

One of the principle comparisons made is the FN curve for the 100 reactors and for other hazards. Figures A23.5 and A23.6 show, respectively, the FN curve for early deaths for natural hazards and for man-made hazards together with the curve for 100 reactors.

The overall conclusion of the report is that the risks to the public from 100 nuclear reactors are very much less than those from other natural and man-made hazards.

The report has a slim Executive Summary which describes the report as a whole and gives a presentation and evaluation of the results. This summary does not include the societal risk estimates given in Table A23.9 and in general tends both to play down the risks and gloss over many qualifying assumptions.

**Figure A23.2** Reactor Safety Study: histogram for frequency of PWR release categories (Nuclear Regulatory Commission, 1975)

**A23.17 Browns Ferry Incident**

The incident at Browns Ferry is widely regarded as a near miss and the RSS could hardly avoid reference to this incident.

On 22 March 1975 a fire started in the electrical control cables at the plant. Following a plant modification a candle was used to detect air leaks at a point where a set of electrical cables passed through a wall. The fire burned out of control for seven and a half hours and badly damaged 1600 cables of which 618 were cables related to the safety systems.

The power interruption caused disturbances on the reactors and the operators, hindered by dense smoke, had to struggle to bring them back under control. Unit 2 was shut down and stabilized without great difficulty but Unit 1 was out of control for some hours and was stabilized only after the fire was put out. Control of Unit
1 was only achieved by the use of equipment which was not part of the safety system.

The fire disabled all five emergency core cooling systems in Unit 1.

At the point when control was lost 7 out of 11 of relief valves were failed. The fire disabled the other 4. The

RSS gives an analysis of the probability that these four valves would in fact be disabled in a fire without any of the valves, from the set of 7 or the set of 4, being repaired over the duration of the fire. The probability estimated was 0.003.
**Figure A23.4** Reactor Safety Study: frequency-consequence curve for areas requiring relocation and decontamination for one reactor (Nuclear Regulatory Commission, 1975)

### A23.18 Critical Assumptions

The results obtained in the RSS depend upon the validity of a number of assumptions. Some of the more critical assumptions are:

- Plant standards are not seriously below average
- Failures are random rather than wearout
- Reactor pressure vessel operating conditions are closely controlled
- Site is not subject to unusually severe earthquakes
Figure A23.5 Reactor Safety Study: FN curves for early fatalities for 100 reactors compared with natural hazards (Nuclear Regulatory Commission, 1975)

Population density around site is not unusually high
Emergency plans exist and are exercised
Medical facilities exist to handle large numbers of injured
Also
Sabotage is not considered

A23.19 Critiques

The RSS has been the subject of much comment and criticism. Three principal critiques are the comments included as Appendix XI of the report itself, the Risk Assessment Review Group Report (H.K. Lewis, 1978) and The Risks of Nuclear Power Reactors by the Union of Concerned Scientists (UCS) (1977).

There are also reviews by the EPA (1976) and the American Nuclear Society (1980) and a series of reports by the Electric Power Research Institute (EPRI) (EPRI, 1975; Leverenz and Erdmann, 1975, 1979; Erdmann et al., 1977).

Some of the principal topics addressed in the critiques are indicated in Table A23.11.

Some of the comments made in the Review Group Report and the UCS review are now described.

Figure A23.6 Reactor Safety Study: FN curves for early fatalities for 100 reactors compared with man-made hazards (Nuclear Regulatory Commission, 1975). Note: car accidents caused at the time of the report about 50,000 deaths per year in the US. These fatalities are not shown because data for large multiple-fatality accidents are not available

A23.19.1 Review Group Report

The review found the RSS 'inscrutable'. It was difficult to follow the detailed thread of any calculation and difficult therefore to carry out a peer review.

The group were also critical of the Executive Summary which they felt did not give a good summary of the findings of the Main Report and was thus misleading.

The review is nevertheless sympathetic in principle to the attempt to quantify the frequency of events using fault tree and event tree methods and the consequences using hazard and injury models.

It states that it is incorrect to say that the use of fault trees and event trees is fundamentally flawed: it is just an implementation of logic.

On the other hand the practical application of the methodology involves various difficulties, including the availability of data, the statistical treatment of the data and the selection of appropriate models.

The group draw attention to the fact that the methodology is based on converting situations which are essentially continuous into discrete events and that this involves quite drastic simplification.
Table A23.11 Reactor Safety Study: some principal topics raised in critiques

<table>
<thead>
<tr>
<th>Topic</th>
<th>Reactor safety study</th>
<th>Review group</th>
<th>Union of concerned scientists</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report format and scrutability</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Feasibility of peer review</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Report scope</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Reactor design adequacy</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Risk assessment methodology</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Completeness of identification</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fault tree analysis</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Database</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Frequency of accident sequences</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Common cause failures</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Human error</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Reactor pressure vessel rupture</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Steam explosion</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Hydrogen combustion</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Emergency core cooling reliability</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>External hazards</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Earthquakes</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sabotage</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Core meltdown analysis</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Core inventory and release</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Evacuation</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decontamination</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doses of radioactivity received</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Dose–response relations</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fate of radionuclides</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changes between draft and final versions</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presentation and evaluation of results</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Browns Ferry</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other warning events</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is suggested that the problem of data is such that in some areas it is not appropriate to give absolute risk values but only bounding values.

The report criticizes the study for not always distinguishing clearly between different sources of values quoted: historical data, subjective judgements and models.

The review is sympathetic in principle to the use of values determined from expert judgment. Such judgements can be rather accurate as studies of betting demonstrate. It is necessary, however, to stay within the domain of expertise of the expert and not require him to make estimates of events of which he has no experience.

The log-normal distribution is used to fit much of the data. The group are somewhat critical of some of the fits obtained, particularly for sparse data, but they accept the use of this distribution.

With regard to the use of the median rather than the mean of this distribution, they state that this is more a matter of presentation than of substance and caused people to infer incorrectly that the study was predicting a lower failure rate than it actually did.

They are much more critical of the use made of the geometric mean, or square root bounding, and quote as an example the estimation of the probability $p$ of failure of three adjacent BWR control rods. This probability is calculated as described above using Equation A23.6.1, where the values of the bound probabilities are the following functions of the failure probability $p_\alpha$ ($= 10^{-4}$) of a single rod

$$p_1 = p_\alpha^3 = 10^{-12}$$

$$p_0 = 0.01p_\alpha = 10^{-6}$$

so that

$$p = 10^{-9}$$

An alternative model is the arithmetic mean which gives

$$p = 10^{-6}$$

There is thus a large difference.

The review devotes considerable attention to the problem of common mode failures. Such failures can cause individual equipment failures, can compromise redundant systems and can activate low probability accident sequences. The principal causes of such failure listed by the group are power supply failure, human error and external threats such as fire, explosion, earthquake and sabotage. They were unconvinced that the problem had been fully dealt with in the study and suggest that the best way to handle such events is to mount a defence against them at the start and so eliminate their effects.

It is suggested in the report that the treatment of earthquakes is inadequate. Attention is drawn to the work of Hsieh and Okrent (1976) showing that design...
and construction errors can greatly reduce the safety factors thought to be present in a design.

Another problem discussed at some length in the review is human factors and human error. The report expresses some disappointment that there were few comments on the human factors aspects of the study. Human factors affect the study in that human error can initiate an accident, can disable protective systems and can cause escalation, while on the other hand human action can mitigate an accident situation. The report recognizes that the human factors aspects of the study remain pioneering work and were well executed, but draws attention to the lack of data. The main thrust of the group’s comments, however, is to the effect that the study probably gives too little credit for the effectiveness of human action in averting an accident.

The group identified various sources of uncertainty in the work, some biased towards conservativism and some to nonconservativism. Among the former factors were pervasive regulatory influence towards the use of certain parameter values and reluctance to claim full credit for effective human adaptability during accidents. Among the latter factors were questions of completeness and common cause failure. They were therefore unable to determine whether the accident frequencies estimated were high or low, but were convinced that the error bounds had been greatly underestimated.

The report discusses the problem of the completeness of the identification of the hazards. The probability of core melt predicted in the study is two orders of magnitude less than the upper bound value which may be estimated from the number of melt-free reactor years accumulated. The report suggests that if there are unidentified accident sequences which can lead to core melt, some precursors events in these sequences should probably be occurring, although they may remain unrecognized. They suggest it is important to subject potentially significant sequences and precursors, as they occur, to the kind of analysis given in the study.

The report suggests that the results of the study cannot be applied directly to particular reactor sites. Application to a specific site would require more detailed study of the site characteristics such as topology and meteorology.

The report gives an account of the Brown’s Ferry accident.

A23.19.2 Union of Concerned Scientists report

The review of the RSS by the UCS is more critical.

In the view of the UCS publicly available documents on the study suggest that it was not sufficiently independent of the nuclear industry, that its results were largely predetermined, that critical reviews were suppressed and that certain sensitive issues were avoided.

The report starts with a fundamental critique of the basic methodology. It reviews experience of fault tree analysis in the aerospace industry. It quotes an example the use of the technique to estimate the reliability of the Apollo Service Propulsion System or SPS engine. One of the authors of the UCS report, W.M. Bryan, was in charge of reliability assessment during the testing of this engine. The estimated failure probability of the engine based on fault tree analysis was $10^{-4}$ while that estimated after testing was $4 \times 10^{-7}$ so that the theoretical analysis gave an underestimate by a factor of 40.

The authors state that fault tree analysis for Apollo also failed to assure completeness of hazard identification. Many failures in the programme resulted from events which had not been identified as ‘credible’ and came as complete surprises. Some 20% of ground test failures and more than 35% of in-flight failures were not identified as credible prior to their occurrence.

The report states

Fault trees, mathematical models and event trees were developed over 20 years ago and were [later] discarded . . . by NASA and . . . by the AEC as viable tools for estimating reliability/safety quantitative values.

It lists techniques which are used probabilistic design analysis, propagation of error techniques, reliability estimation from small samples, malfunction simulation models, and others.

The methodology used in the study is to synthesize accident sequences from failure data for single items.

The UCS suggest that this approach fails to utilize information which is available on multiple failure accident sequences which have actually happened.

The review draws attention to the database used in the RSS, which was described above. The average age of the plants used in the study was four years. Two difficulties which arise from this are that often data collection was not well established and that failures due to ageing would scarcely have begun to appear.

The UCS criticize the assumption of random failure and suggest that failure rates may be significantly affected by ageing.

Attention is drawn to the danger of using historical failure data. The example is cited of the Skybolt rocket motor. A minor modification was made to the welding procedure for this motor. This resulted in flaws which were not revealed by quality assurance procedures but which caused the unit to explode under pressure and led to mission failures of the first two operationally launched vehicles.

An example is given where the study may have underestimated failure probabilities. For the High Pressure Coolant System (HPCS) the study uses a failure probability of 7.8 $\times 10^{-3}$/demand. The report quotes data for four reactors in which there were 10 failures in 47 tests, a failure probability of 0.21.

Such instances also suggest that at some plants standards may be generally lower and the probability of an accident correspondingly higher, perhaps by an appreciable factor.

The report is critical of the use made in the study of the log-normal distribution to express the uncertainty in failure rate data. It suggests that it is not at all clear that this is the correct choice.

The report quotes the following comments by Yellin (1976):

The basic fault tree model therefore begins from estimates of the logarithms of the component failure probabilities, rather than from the probabilities themselves. In view of this use of the log-normal input distributions, one should also evaluate the accuracy of roughly 10–20% in their estimates of these output logarithms of failure
probabilities, while it is suggested here that the evidence presented in WASH-1400 is in fact consistent with uncertainties of order 50%. This difference of opinion is crucial, since for a typical failure probability of $10^{-4}$, an accuracy of 10–20% results in an overall uncertainty factor of 10 in probability, while an accuracy of 50% results in an overall uncertainty factor of 1000.

The use of the median instead of the mean of the log-normal distribution is also criticized as incorrect. The former is some 2.5 times less than the latter. The authors believe that its use results in the study in underestimation of the risks by this factor.

The assumption of independence of events is criticized by the report, which devotes considerable space to the problem of common-mode failures.

The report suggests that the RSS underestimates the importance of failures which occur in accident sequences as the result of previous failures and also of failures due to incorrect design.

The RSS found that common-cause failures do not make a significant contribution to the overall risk, but the UCS suggest that this contribution may have been underestimated. The example given is the miscalibration of four instruments in turn. The probability $p$ of miscalibration of a single instrument is given in the study as $3 \times 10^{-3}$. For dependent failures of this kind the overall probability $p$ of failure would be calculated using the study methodology as the geometric mean of the case for four independent failures, and for tight coupling between failures. For the latter case, which gives the upper bound, the probability $p_u$ is

$$p_u = 3 \times 10^{-3} \times 10^{-1} \times 1 = 3 \times 10^{-4}$$

The last three terms are based on tight coupling. Then the estimated probability $p$ is

$$p = [(3 \times 10^{-3})^4 \times 3 \times 10^{-4}] = 2 \times 10^{-7}$$

Thus the estimated ratio of the probability of the common cause failure ($2 \times 10^{-7}$) to the probability of the single failure ($3 \times 10^{-4}$) is approximately $10^{-3}$. The UCS compare this figure with their own estimate obtained by examining the common causes failures in the RSS database. Out of 303 failures 33 are identified as common cause. They take three of these failures as common-cause multiple miscalibration failures and thus obtain an estimate of $10^{-2}$ for the probability ratio referred to. This differs from the RSS estimate by a factor of 100.

The review gives the following breakdown of the 33 common cause failures in the RSS

<table>
<thead>
<tr>
<th>Failure</th>
<th>No. of failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift of instruments, etc.</td>
<td>4</td>
</tr>
<tr>
<td>Miscalibration of instruments, etc.</td>
<td>5</td>
</tr>
<tr>
<td>Design error</td>
<td>6</td>
</tr>
<tr>
<td>Component failure</td>
<td>9</td>
</tr>
<tr>
<td>Environmental effects</td>
<td>6</td>
</tr>
<tr>
<td>Human error</td>
<td>2</td>
</tr>
<tr>
<td>Unknown</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
</tr>
</tbody>
</table>

The review refers to an incident on the Oak Ridge Research Reactor where the reactor had to be operated for five hours without emergency cooling protection due to seven sequential common mode failures, each involving three parallel elements, making a total of 21 failures in all.

The review also considers what it calls common event failure which may lead to common mode failures. These events include fire, turbine missiles, earthquakes and sabotage. The UCS give an alternative analysis of the probability of core meltdown in the Brown’s Ferry fire based on the relief valve failures and obtains a value of 0.03 instead of the RSS value of 0.003.

The review draws attention to the problem of design adequacy. The equipment may be reliable in the sense that it functions, but it may not be capable of fulfilling its task. For the Emergency Core Cooling System (ECCS) the RSS assigned a probability of failure of less than 0.1. The UCS argue that ECCS systems have not been tested under accident conditions and may well lack the basic capability and thus have a higher failure probability.

Also in the context of design adequacy the UCS take issue with the value used in the RSS for the failure frequency of the reactor pressure vessel. The RSS used a figure of $10^{-7}$/year. The UCS argue that for non-nuclear pressure vessels the failure frequency is approximately $10^{-5}$/year and that there is no justification for using a value 100 times less. They base their argument partly on the fact that the failure rates of components in nuclear plants are not greatly different from those in non-nuclear plants. They quote Professor Rasmussen

Probably one of the most serious issues that the [nuclear power plant] intervenors can raise today, with good statistics to back their case, is that nuclear power plants have not performed with the degree of reliability we would expect from machines built with the care and attention to safety and reliability that we have so often claimed.

The UCS also refer to comments made by Sir Alan Cottrell, formerly Chief Scientific Adviser to the British Government, emphasizing the problem of dealing with deterioration of the vessel in a situation where, being radioactive, it is extremely difficult to replace. The UCS review includes an appendix by Cottrell on reactor pressure vessel integrity.

They also quote the following qualifications given in the Marshall Report with respect to such reactor pressure vessels:

That it is essential to confine the operational transients to unusually narrow limits in order to avoid excessive crack growth by metal fatigue.

That emergency core cooling water should be injected at an unusually high temperature in order to minimize the risk of fracture by thermal shock.

The UCS list a number a safety issues which are addressed inadequately or not at all in the RSS. These include the hazards of loss of containment through electrical penetration seals, of earthquakes and of sabotage as well as the ageing problem already mentioned.
The UCS consider that the RSS dismisses too readily the risk from earthquakes. They give a number of quotations on the inability of seismologists to predict earthquakes. Thus C.R. Allen (1967):  

Almost every large earthquake that has occurred in California has proved to be surprising in terms of what would have been expected by geologists, seismologists, and engineers at the time.

and Greensfelder (1971):  

Thus the San Fernando earthquake occurred in an area which has had relatively low seismicity and was not caused by movement on a major, historically active fault, such as the San Andreas or one of its branches. In fact, portions of the fault associated with this shock were not previously mapped…

The UCS argue that at the least the earthquake hazard introduces a much larger uncertainty than the RSS allows. The review includes an appendix on the earthquake hazards at the Diablo Canyon nuclear reactor site.

On sabotage the UCS argue that it is indeed difficult to quantify but that it is a relevant factor in considering nuclear safety. They draw attention to the fact that the saboteur may be able to deliberately defeat many of the factors which normally operate to mitigate an accident.

The review makes a number of criticisms of the gas dispersion model, of the models of population exposure and of the relations for injury from radioactivity.

The UCS are doubtful about credit claimed for evacuation. Among their reasons are lack of emergency plans and failures in specific emergencies. They quote the failure to evacuate at Browns Ferry.
Figure A23.7  continued

A number of criticisms are made by the UCS of the handling of the results from the RSS. One criticism centres on the tendency to present the results simply as showing the risks of nuclear power to be very low and to play down the qualification and the uncertainties. Another is that the way the study was handled did not allow an effective process of peer review.

The large changes made between the draft and final reports also attract criticism. In some cases these changes exceeded the uncertainty bounds given in the draft report.

The Executive Summary is criticized as overoptimistic and misleading.

The UCS conclude that the RSS is not usable for policy decisions.

The review gives an alternative statement of the risks, the differences being partly of substance and partly of presentation. The UCS estimate of the frequency of a major release is 1 in 10,000 per reactor year, which is 20 times that of the RSS. The upper bound based on the number of incident free reactor years was 1 in 300. The estimate of the consequences of such a release is that the early fatalities and injuries would be ten time greater than in the RSS. In individual cases the consequences might be 100 or 1000 fold worse than the RSS predicts.

The UCS estimate of the FN curve for early deaths is shown in Figure A23.7(a).

The UCS also estimate that the late deaths are underestimated in the RSS by a factor of 2 to 5 and further argue that the FN curve should show the total deaths. Figure A23.7(b) shows the curve which they give for this.

Notation

$\rho$  probability of failure

Subscript

1  lower bound

u  upper bound
Appendix

ACMH Model Licence Conditions
The Second Report of the Advisory Committee on Major Hazards (Harvey, 1979b) presents in an appendix a set of model controls for a major hazard installation in the form of ‘Model Conditions for a Possible Licensing Scheme for Selected High Hazard Notifiable Installations’, although the report leaves open the question of whether the use of licensing or regulations is the best method of implementing such controls.

The appendix is prefaced by the statement:

The conditions outlined in this appendix have been written to give guidance as to the range and scope of the requirements that might be required if a licensing scheme of control were adopted for major hazard installations with the highest hazard potential. … The Committee is not yet in a position to say if certain installations should be regulated in this way until more information is available, particularly from the proposed Hazardous Installations (Notification and Survey) Regulations. It is, however, clear that there is a gradation of hazard with size and complexity of plant, and as this is increased there should be a greater degree of control and surveillance by the organisation in control of such activities. Thus this appendix has a wider application than the possible requirements for a licensing system of control. It is recommended that any organisation operating a major hazard plant, particularly one at the highest level of hazard potential, should review and satisfy itself that it could demonstrate that the requirements given below are adequately met.

The full text, which is reproduced by courtesy of the Health and Safety Executive and HM Stationery Office is as follows:

MODEL CONDITIONS FOR A POSSIBLE LICENSING SCHEME FOR SELECTED HIGH HAZARD NOTIFIABLE INSTALLATIONS

With regard to a possible licensing system it is recognized that a licence is the most stringent form of control under the Major Hazards arrangements and would be applied only to those Notifiable Installations which present the greatest hazard potential. The licence would be granted to the organization which operates the installation and would be valid only for the specified location.

The approach adopted to licensing would be that foreshadowed by the Robens Committee and embodied in the Health and Safety at Work etc. Act 1974, namely that safety is the responsibility of the organization which should demonstrate that it is taking appropriate measures to ensure effective control of the hazards.

The licensing procedure might be in two stages. At the first stage the organization would provide the Health and Safety Executive with a statement of intent covering the nature of the proposed installation, the hazards and the features of the design and operation intended to control the hazards. At the second stage the organization would provide HSE with design and operating information to show how the statement of intent is implemented.

The documentation required might be in two parts corresponding to these two stages and consist of

Part 1
(a) The Systems Documentation

(b) The Preliminary Design Document
Part 2
(a) The Background Documentation
(b) The Design Document
(c) The Operating Document.

The Systems Documentation, which is relevant to Licence Conditions 1–9, would be concerned with the general systems which the organization has set up to ensure safety and could be used in support of more than one licence application provided that it is up-to-date.

Details of the Preliminary Design Document are given in Licence Condition 10.

The purpose of the Preliminary Design Document would be to show the general nature of the installation and of any associated hazards. The onus would be on the organization to draw attention at this stage to any special features which might have an important bearing on the granting of a licence.

The Background Document would be documentation on the implementation of Licence Conditions 1–9, in relation to the particular installation.

Details of the main Design Document and the main Operating Document are given in Licence Condition 10.

The main Design Document would be essentially a more up-to-date and detailed version of the Preliminary Design Document, including additional details, such as materials of construction for the main plant items.

The main Operating Document, which incorporates the Operating Manual, would give details of the personnel structure for the operation of the installation.

A licence would be granted for a particular installation on a given site. The licence would not itself deal with questions of siting, but the issue of a licence is an indication that an installation meets certain standards and this is relevant to siting considerations.

The licensee would be required to inform HSE of significant changes which are proposed in any of the matters within the scope of the licence.

Conditions for a Licence

The conditions for the issue of a licence are that the Licensee shall demonstrate to the Health and Safety Executive that the design, construction, operation, maintenance and modification of his installation are or will be to the standard appropriate to the installation and in particular that the following features of his organization are to such a standard:

1. The management system
2. The safety system
3. The Responsible Persons
4. The arrangement for the identification of hazards
5. The arrangements for the assessment of hazards
6. The arrangements for the design and operation of pressure systems
7. The arrangements for the minimization of exposure of personnel
8. The arrangements for the administration of emergencies
9. The arrangements for reporting of and learning from incidents
10. The design and operating documentation.
1. Licence Condition: The Management System

The organization should show that it has and supports a management system and staff structure which combine to ensure continuing effective control of the installation and its hazards.

The staff concerned include contractors and consultants. This aspect is considered further in Licence Condition 3.

The organization should show the management structure, making clear the distinction between executive and advisory functions, and should give a brief job description for each post.

The management system should give full support to the personnel who are responsible for the design and operation of the installation. Important elements include a suitable and well understood management structure; adequate human resources including coverage of absences, vacancies and emergency situations; recruitment, training and career planning; and effective communications.

The management system should in particular provide satisfactory arrangements in the areas which are the subject of Licence Conditions 2–9. There should be comprehensive, formal and documented set of systems and procedures.

The management should define the objectives of its system of documentation in respect of immediate a communication and of record-keeping and should specify the extent of the documentation required and the procedures for producing it.

The management system should provide for thorough initial and continuing training of personnel in their work generally and in safety in particular.

Full use should be made of appropriate standards and codes of practice. Where there are standards or codes which have statutory backing or which are commonly recognized within the UK as constituting sound practice, these should be applied as a minimum. Where there are no approved or accepted standards or codes the situation should be covered by the adoption of sound practice and the use of in-house codes.

The management system should include formal procedures for the control of modifications made to the plant or to the process, whether during design or during operation.

The management system should require the independent assessment of features which are critical to the safe operation of the installation. This independent check is essential for inspection of pressure systems and for reliability assessment of instrument trip systems. The guiding principle is that the feature is critical to safe operation of the installation. It is acceptable that the check be done by an in-house authority provided that this is genuinely independent of the interested party. Thus pressure system inspection, for example, must be done by an authority independent of the operating authority, as described by Licence Condition 6.

The management system should contain a variety of arrangements for the periodic audit both of the continuing appropriateness of systems and of the continuing effectiveness of their implementation.

Background

It is considered that in the case of major hazard installations the control of the plant and its hazards requires a considerable degree of formalization of communications through written systems and procedures, standards and codes of practice. This is essentially to encourage, and where appropriate enforce, collective and personal discipline by the use of operating methods which have been carefully thought out and which contain an appropriate level of checks and counterchecks to obviate problems and reduce errors.

It is recognized that there is always the problem of over-administration through paperwork and what at times seems like 'going through the motions' without apparently contributing anything useful. However, it is considered that a careful review of incidents will, time and again, illustrate that there was a loss in discipline because appropriate procedures either did not exist or were not observed.

There should be an interlocking set of systems and procedures to ensure safety through sound engineering and management practices. There is no upper limit to the number of procedures which can be formalized, but there is nothing to be gained by deliberately trying to maximize the number. The optimum number is that which leaves no obvious gaps but avoids creating confusion by overlapping.

Many of the required procedures are implicit in the various Licence Conditions which follow. It is evident that key procedures include those for the identification of hazards, the assessment of hazards, the control of maintenance through permits-to-work, the control of modifications to process or plant, the inspection of equipment, the operation of the process (normal and emergency), the control of access, the conduct of safety audits, the reporting of incidents.

Self-auditing features should be built into the management system in the form of formal instructions for periodic checks on those parts of the system which may become degraded unnoticed. The operation of a permit-to-work system, for example, should be subjected to regular audit by some means such as an instruction, not merely an exhortation, to the plant manager to sample a proportion of permits each week.

2. Licence Condition: The Safety System

The organization should show that within the management system there is a safety system which is appropriate to the level of hazard inherent in the installation.

The safety system should in particular provide for satisfactory arrangements in the areas of the safety organization, safety objectives and assessment, safety consultative committees, and safety training.

The organization should show that it has people competent to operate the safety system.

Background

Most of the aspects of the safety system mentioned are already legal requirements, but it is the object of this section to review their adequacy in relation to the major hazard installation.

A distinction can be drawn between the technological and human sides of safety. On a major hazard plant the technological features are obviously particularly important. The responsibility for these aspects rests primarily with the qualified technical staff in the design and operations areas. There should be no neglect, however, of the human side. On the contrary, on a major hazard
plant it is more important than ever to run a 'tight ship' as far as safety is concerned.

The authority of the safety staff should be made clear, particularly in relation to the more technical aspects of the installation. Attention should be paid to the means of ensuring that the safety officers/advisers are effective and are seen to be so.

The safety objectives set for management and the assessment of the performance in meeting these objectives should be indicated. This may not be a simple matter of accident statistics. For major hazard installations there is an additional problem of avoiding rare but catastrophic events. This makes it important to monitor both the occurrence of 'near misses' and the degree of adherence to procedures and rules.

The programme of safety training provided for employees at all levels should be outlined.

Attention is also drawn to Licence Condition 9 which is concerned with the system of reporting of and learning from incidents.

3. Licence Condition: The Responsible Persons

The organization should nominate Responsible Persons who are in charge of the design and operation of the installation.

The term 'Responsible Person' has a specific meaning in the context and is explained below.

The organization should show the management structure down to the lowest level of executive technical management, making clear the distinction between executive and advisory functions. There should be a job description for each post; the job descriptions for the posts held by Responsible Persons are particularly important.

The level of seniority held by the Responsible Person should normally be either the lowest or second lowest level of technical executive management.

It is envisaged that persons immediately senior to the Responsible Persons will themselves normally have been or be qualified to be a Responsible Person on major hazard installations, though not necessarily on those processes of which they are now in charge.

The organization should show that a person nominated as a Responsible Person is qualified to hold the post by reasons of his academic qualifications, practical training and recent relevant experience.

On the operations side this experience should be experience in the operation of the actual process or of a similar process. Experience limited to design of the process or of similar processes and/or to operation of dissimilar processes is not acceptable. On the design side the experience should be in the design of similar processes.

Where the process incorporates features of considerable technical novelty as a result of which no person has first-hand experience of operation of relevant full-scale plant even greater regard must be paid to the level of competence of the individual and normally experience of pilot plant operation would be required.

Where the installation is to be designed in part or in whole by an outside contractor it is the responsibility of the organization which will operate the installation to satisfy itself and to demonstrate to HSE that the design is to an appropriate standard. The minimum requirement is that there be a nominated Responsible Person in the operating company who has the duty of liaison with the contractor. Where practical it is also desirable to have nominated Responsible Persons in charge of design in the contracting company.

For convenience reference is made here only to design and operation. The organization should enumerate all the project activities such as fabrication, construction, inspection, commissioning and satisfy itself and HSE that there are nominated Responsible Persons responsible for these activities.

It is emphasized that the ultimate responsibility for the safety of the installation lies with the organization which operates it.

Background

The concepts of 'Responsible' and 'Authorized' Persons occur in various management systems. Our usage of these words is that 'Responsible' relates to a job, e.g. plant manager, and 'Authorized' to a task, e.g. signing a permit-to-work.

We have considered various models for Responsible Persons. These include those in the Mines and Quarries Act, the Merchant Shipping Act, the Factories Act (radioactive substances), the Explosives Act, the Medicines Act.

We have also considered the arrangement whereby the Department of the Environment advised by the Institution of Civil Engineers recommends individuals for the design of reservoirs.

Competence to do a job must depend on the definition of the job and its relation to other jobs. We began, therefore, with a consideration of management structures and reviewed possible general models for a large and a small firm. It became apparent, however, that this was not a particularly helpful approach and it was not pursued. However, in a concrete situation we do consider the presentation of such a management structure and job descriptions desirable.

With regard to the level of seniority we started with the proposition that the Responsible Person should be at the lowest level of the executive technical management. However, this could give rise to problems in some areas. For example, it is necessary to train for succession and by definition trainees must be at a lower level. Such additional lower levels are not normal in existing practice, would be wasteful and would not offer job satisfaction. We therefore prefer to leave a degree of flexibility. But we do attach importance to ensuring that the responsibility is real rather than nominal and is at the lowest practical level.

Thus we envisage that the Responsible Person on the operations side would usually be capable of 'stepping down' and carrying out the job at the next level down.

With regard to selection of Responsible Persons we consider academic qualifications, practical training and recent relevant experience essential.

We think it is desirable that the person chosen should have the sort of broad scientific and technological education which a first degree in science or engineering usually gives. We consider that such a degree should normally be a necessary qualification. Exceptionally, however, people without a degree may be considered. We also attach importance to the ability of the person to recognize problems outside his sphere of competence.
and to his willingness to seek the advice of other experts.

We consider that although the Flixborough disaster has emphasized the importance of the integrity of the plant, there may be other major hazards where the integrity of the process is of at least equal importance. Thus, whilst it is probable that the Responsible Person will normally be an engineer there will be cases where he will be a scientist, e.g. chemist.

We attach particular importance to the selection of Responsible Persons on the operations side.

We lay particular emphasis on recent relevant experience. There is obviously room for discussion as to the ‘relevance’ of experience or the ‘similarity’ of processes. It is up to the organization to convince HSE on these points.

We stress, however, that we would not want this emphasis on recent relevant experience in any way to inhibit technological innovation or normal career development.

We accept that technological progress requires specialization. The professional institutions already recognize this and are considering a register of persons considered competent to design and operate major hazard installations. We are maintaining contact, although, whilst welcoming their interest, we see a number of difficulties in this approach.

The requirement to nominate Responsible Persons should not be seen as detracting in any way from the necessity for a team effort by management to achieve high standards of safety in plants which have major hazards.

4. Licence Condition: The Arrangements for the Identification of Hazards

The organization should show that it uses appropriate methods of hazard identification at all stages of the project.

The terms ‘hazard identification’ and ‘safety audit’ refer to mainly qualitative techniques which review the existence of a hazard.

The application of the techniques should be matched to the stages of the project, starting with coarse scale investigations and progressing to fine scale studies to discover detailed faults.

The management system should contain a formal requirement for the use of such methods, should specify the documentation required arising from this use and should monitor this use.

The organization should show that it has people competent to implement these methods of hazard identification.

Background

The first objective of hazard identification is to reveal the substances or processes which have a hazard potential. The second objective is to identify all conceivable threats to the installation or its processes which might lead to loss of containment.

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<th>Table A24.1 Some methods of hazard identification</th>
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As technology has progressed identifying hazards has become in some ways more difficult. In particular, there are many hazards which are not revealed by traditional visual inspection. It has become necessary, therefore, to develop additional methods of hazard identification.

An illustrative list of methods is given in Table A24.1.

Since every human enterprise involves the possibility of error it follows that the soundness of the management of the potentially hazardous installation is the predominating factor and that the first essential in all cases is an audit of the management system as a whole.

It is recognized that there is a wide variety of methods of hazard identification in use in industry and that different techniques are applicable to different situations. There is no intention of imposing any particular method.

It is necessary that the use of these methods be a requirement of the management system, which also should specify the degree of recording and documentation required and should contain a mechanism for auditing the application of the techniques to ensure that they are used.

The people who have to implement these techniques must be competent to do so. HSE should be able to advise on opportunities for training in this area.


5. Licence Condition: The Arrangements for the Assessment of Hazards

The organization should show that the hazards identified by the means described in the preceding section have been removed or that the associated risks have been reduced to a minimal level.

In this context ‘minimal’ means the probability that an employee or member of the public will be killed or injured or that property will be damaged is at least as low as in good modern industrial practice.

The method of demonstrating that the risks are at a minimal level should be comprehensive and logical.

The method may consist of

(a) The use of codes of practice generally recognized in the industry
(b) The use of special testing
(c) The use of calculations based on appropriate data.

In many cases it will be sufficient to show for all or at least some aspects of the hazard that a generally recognized and accepted code of practice is applicable and has been followed.

Where there is any aspect of the hazard, the risk of which cannot be reduced to a minimal level by following a recognized code of practice or by special testing, then, whenever meaningful quantitative methods should be used to demonstrate that the risk has been reduced to a minimal level. These quantitative methods will normally consist of three steps:

(a) An estimate of the consequence to employees and the public.
(b) An estimate of the frequencies with which hazardous situations will occur.

(c) Comparison of (a) and (b) with the other risks to which people are normally exposed in order to show that the risk under consideration is relatively small.

The management system should contain a formal requirement that such methods of hazard assessment should be applied.

The organization should show that it has access to people competent to implement these methods.

Background

Having identified hazards, as described in the previous sections, it is necessary to know that the associated risks have been reduced to a minimal level.

It is envisaged that the method of demonstrating that the risks are at a minimal level will normally be based on a fault tree approach, but that a detailed development of all parts of the tree will not generally be required.

Sometimes it is possible to remove a hazard completely, for example, by replacing a flammable or toxic raw material by a non-flammable or non-toxic one.

More often, the hazard cannot be eliminated completely, though the risk can be reduced to any desired level by the use of protective equipment. For example, the risk that a particular vessel will burst because of overpressure can be reduced by fitting a relief valve suitable for the duty, adequately sized and properly maintained. This does not eliminate the hazard completely as there is a small probability that the relief valve will fail to lift when required. Even if two relief valves are fitted, there is still a very small probability of coincident failure.

In many cases codes of practice provide generally recognized and accepted methods of reducing a hazard to a minimum level. For example, in the case just considered, it would normally be sufficient to show that the vessel is fitted with a relief valve, adequately sized and properly maintained, as relief valves have been generally recognized for many years as an accepted way of reducing to a minimal level the probability that a vessel will burst.

Similarly, if fracture of pipework has been identified as a hazard, it would be sufficient to show that the pipework has been designed and constructed and will be operated and maintained in accordance with a recognized and relevant code of practice.

Codes of practice should not be used outside their area of applicability. Codes of practice for pipework, for example, do not cover fracture by projectiles and if it is necessary to take the latter into account, a separate study is necessary.

Moreover, codes of practice imply acceptance of some level of probability of the hazard materializing. This level will be unacceptably high in relation to some major hazards.

In some cases it may be necessary to carry out special tests to quantify aspects of particular hazards.

Where there is no generally accepted code of practice and where the problem cannot be resolved by testing, but where it is reasonably practicable to show quantitatively that the risk has been reduced to a minimal level, this should be done. In some cases this cannot be done because of lack of data or of a suitable model to describe the system. In these cases judgement will have to be used.
Examples of hazards which may not be covered by recognized codes of practice and which, if they produce major effects, would have to be individually assessed, are:

(a) Runaway reactions (e.g. decomposition and polymerization reactions).
(b) Impact of moving objects (e.g. cranes, vehicles, missiles from explosions).
(c) Failure of instrumental protective systems.
(d) Failure of services (e.g. electricity, water, compressed air).

These can be described as events leading to possible loss of containment.

The hazard quantification will normally consist of three stages in which probability and consequence must both be considered; sometimes it will be necessary to consider a number of possible outcomes differing in probability and consequence. An event which has the potential to kill many people may not cause great concern if the probability of it occurring is sufficiently small. We do not prohibit football matches because there is a small chance that an aeroplane may crash on the crowd. On the other hand we would not build a new football ground at the end of a busy runway.

(a) The first stage is the estimation of the probable consequence of the hazard. This may be based on past experience or it may be estimated from a theoretical study of the problem. The consequences may be expressed as the probability that an employee or a member of the public will be killed or injured or as the probability that extensive damage will be caused to the property of others or both.
(b) The second stage is the estimation of the probability that the hazard will occur. Again this estimate may be based on past experience, or it may be synthesized from data on the failure rates of individual components or pieces of equipment.

In estimating the probability that the hazard will occur it is necessary to assume that certain standards are followed in the operation of the equipment, for example, that relief valves are tested regularly. If these standards are not followed the conclusions of the hazard quantification are no longer valid.

(c) The third stage is comparison of (a) and (b) with the other hazards to which people are exposed in order to ensure that the risk under consideration is minimal.

This implies the use of a criterion against which risks can be judged. It is not intended that any single criterion should cover all cases.

If it is not possible to carry out a complete study as indicated (i.e. stages (a), (b) and (c)), it may be possible to carry out a partial study and, if so, this should be done, as it helps to identify those aspects of the problem which have most effect on the probability and consequences.

Where a new feature is used in place of one of proven reliability then it should be shown that the new feature is at least as safe as, and preferably safer than, the original. For example, if an instrumented protective system is used in place of a relief valve it should be shown to fail no more often, and preferably less often, than a relief valve.

In other cases it may be appropriate to show that the risk to an employee is no greater than that for employees in the industry as a whole or to show that the risk to a member of the public is comparable with the other risks to which the public are exposed without their consent.

It may be noted that it is difficult to find examples of instances in which members of the public have been killed as a result of accidents on major hazard installations. In most cases, if the risk to employees is minimal the risk to the public will also be minimal; although a lower level of risk is required, the public are usually further away.

It is necessary that the use of quantitative methods, whenever meaningful, should be a requirement of the management system. This should specify the recording and documentation required.

In some cases a detailed study may be required taking many days or even weeks, but in other cases relatively simple calculations may be sufficient.

The organization should show that it has access to, and uses as necessary, people competent to assess hazards, but these people need not be in its full-time employment; they may be consultants.

Quantitative methods provide a means to assist management to choose those measures which are 'reasonably practicable' for providing a safe plant and system of work.


The organization should show that it has a formal and well-understood management system for controlling and monitoring the design, fabrication, commissioning, operation, inspection and testing of pipework, vessels and other equipment together forming the constituents of a pressure system which may give rise to a serious hazard.

The term 'pressure system' refers to a linked series of equipment items operating at a pressure either above atmospheric or under vacuum, together with all the interconnecting pipework. Such systems commonly form processing units, but the definition includes also storage and handling installations.

The management system of control should be in two parts, and should be effected through two recognized channels of authorization, related to Design and to Operation.

The management design authority should identify and state the design parameters within which the pressure system is to operate and the conditions for which each component part of the pressure system shall be designed. It should also define the code under which the individual components shall be designed, or where no design code exists should sufficient work to be undertaken to satisfy themselves, either by experiment or by the use of specialist advisers, that the design is at least as safe under all foreseeable circumstances as the standard demanded by recognized codes.

The design authority should also define the standards to be used for the pressure system during the fabrication and construction stages. Wheneve possible the standards specified should be those quoted in recognized codes applicable to the particular pressure system.
Management should ensure that an appropriate inspection system is operated during fabrication and construction work to check that the standards set by the management design authority are being met. This inspection system may be in the same management organization as the design authority, or it may be appropriate to use one of the engineering insurance companies or other approved inspection agency. The inspection system should not be part of the operating authority. The design authority should also specify the written evidence required to demonstrate that the plant has been fabricated, constructed and proof-tested, in accordance with the design requirements. Copies of documentation forming this written evidence should be verified, preferably by the inspection agency before the pressure system enters service. Copies of all documentation relating to the design parameters, and to the verification by the inspection system, should be retained by the design authority and should also be available on the works on which the pressure system is operated.

The operating authority should prepare a comprehensive set of instructions based on information issued by the design authority and upon an analysis of hazards involved. These instructions should set out clearly the way in which the pressure system shall be operated in both normal and abnormal circumstances, and the way in which the pressure system is to be protected from the effect of conditions more extreme than those permitted by the design authority. These instructions, which should be readily available to all those responsible for operation, inspection and repair of the pressure system, should set the limits within which the system is to be operated. Any variation in these limits or with the parameters set by the design authority should be referred to the design authority or other independent qualified body for approval before fresh instructions are issued. Such submission and approval should be made in writing and copies retained in the works for future reference.

The operating authority is responsible for ensuring that any repairs and modifications are designed, fabricated and tested to a standard not less than that used by the design authority for the original system. The operating authority should have a system of documentation which controls the repair and modification procedures, so that modification to the pressure system cannot be made without written authority from an authorized person.

Thus instructions prepared by the operating authority should include formal procedures for identifying and making process modifications, for identifying and making plant modifications and for restarting the plant after discovery of a serious defect.

The operating authority should also provide and enforce the use of a code which ensures the continuing safety of the pressure system by a regular inspection of the equipment and the safety devices which are provided to protect that equipment. Such an inspection code should meet the following criteria. First, that a register is held on each works in which each item of equipment is given a unique designation and an engineering description which adequately describes the design and fabrication details and also details of operating conditions, both normal and maximum. Secondly, that the code should specify the frequency of inspection for the various classes of equipment and should also specify rules concerning the selection and training of inspectors. There should also be rules by which inspection frequencies may be increased or reduced, decisions being based upon the result of inspection records which should be held in the register. The code should specify rules which guarantee the independence of the inspecting system from the operating authority, either by appointing external inspection authorities, or by making satisfactory arrangements for the in-house inspection authority to be responsible to a senior member of the organization who has the design authority within his charge.

The organization should show that it has people competent to execute the control and monitoring functions described above in both the design authority and operating authority areas. It should also show that the inspection service is truly independent of the operating authority.

**Background**

The control of design and operation of pressure systems is a cardinal feature for ensuring safe operation of major hazard plants.

The separation of management control into the areas of a design authority and an operating authority has been made in order to bring out clearly the separate responsibilities of these two parts of the total organization which designs, builds and operates a major hazard plant. The areas of authority interlock, and in small organizations there may be sharing of some specialist personnel. It is important, however, that the design concept and subsequent modifications to that concept should be controlled by an authority separate from the operating authority. In cases of contractor design the organization will have to show that the contractor can carry out the duties of a design authority, particularly in the matter of documentation concerning the design parameters for the pressure system and the fabrication details, and in the provision of competent people for authorization.

The use of a regular inspection is an essential feature of the safe continued operation of a pressure system. The register of equipment and inspection reports is the linchpin around which this inspection system is built. Decisions on the frequency of inspection and the nature of satisfactory inspection procedures should be taken by the inspecting authority with advice from the design authority. An essential feature of the integrity of the system is that the inspectors and their management are not under the technical control of the operating authority. In small organizations considerable use can be made of external inspection agencies and other specialist help. In large organizations such facilities are likely to be provided in-house. In those cases the organization should take particular care to show the independence of the inspection agency.

It is important that safety devices such as relief valves, non-return valves and vents are included in the register of pressure systems and are subject to the same type of inspection and testing arrangements as are specified for the pressure equipment. Details of testing and frequency of examination may well be different from arrangements made for pressure equipment, but the principle of inclusion in a register, together with test and inspection notes, is essential.
A system for registering and inspecting pressure vessels and other equipment and for the keeping of verification documentation which satisfies many of these criteria is described in BS 5500:1976 Unfired fusion welded pressure vessels, in the Pressure Vessel Inspection Code and in the draft Piping Systems Inspection Code of the Institute of Petroleum.

7. Licence Condition: The Arrangement for Minimization of Exposure of Personnel

The organization should show that it has assessed the hazards to personnel involved in the installation and that where necessary it has taken steps to reduce these hazards to a minimal level. In particular, measures should be taken to limit the number of people at any one time in areas of high hazard to a minimum consistent with safe and efficient operation and to afford protection to exposed personnel, who may include operating personnel, maintenance personnel, investigation teams, construction workers and visitors.

Background
This matter is fully dealt with in Chapter 7 of this report.

8. Licence Condition: The Arrangements for the Administration of Emergencies

The organization should show that it has assessed the hazards involved in the installation in relation to major emergencies and has maintained emergency plans.

Emergency planning should include identification and assessment of possible major emergencies; nomination of persons responsible for administering an emergency; development of procedures for declaring, communicating and controlling the emergency and for evacuation; provision of buildings such as a control centre or refuge rooms and of equipment such as an alarm system; designation of works emergency teams and definition of duties of other workers; liaison with external services including police, fire and medical services; training and exercises for emergencies.

Background
A guide Recommended Procedures for Handling Major Emergencies is published by the Chemical Industries Association (second edition, 1976). This covers primarily the administration of emergencies within the works.

The guide also deals briefly with the planning of action, such as evacuation, which may be required outside the works. This is particularly important for certain major hazards. It should be emphasized in this connection that for toxic gas hazards the value of the time bought by any distance separating the factory and the public may be wasted if there is no evacuation plan.

9. Licence Condition: The Arrangements for Reporting of and Learning from Incidents

The organization should show that it has prepared a schedule of signals to be recorded and that the relevant instruments are housed in such a way that an accident on the plant is unlikely to prevent recovery of the records.

The organization should show that it has a system for the reporting of incidents which might endanger the installation or lead to loss of containment and that it uses the information obtained from this reporting system to learn how to reduce these hazards.

These requirements for the reporting of hazardous incidents are additional to the existing statutory requirements. They have two main objectives. One is to ensure the reporting within the company of the 'near miss' type of incidents which often precede an accident. The other is to obtain data at national level on incidents related to serious hazards. HSE may request that certain types of incident be included.

Background
There already exist certain statutory requirements for the reporting of incidents. These include:

The Petroleum (Consolidation) Act 1928
The Factories Act 1961
The Dangerous Occurrences (Notification) Regulations 1947

as well as those specific to explosives factories, mines and quarries, and nuclear installations.

These requirements are mainly concerned with accidents causing plant downtime, lost-time accidents and fatalities.

It is well known, however, that for every serious accident there are numerous incidents, including 'near-misses'. Since they are more numerous, these incidents offer greater scope for learning and improvement.

It is therefore proposed that the organization should have its own reporting system covering the type of incident significant in relation to its particular hazards.

We have deliberately not specified the incidents which should be reported but we have in mind incidents relating to such matters as:

Incidents involving serious operator error
Incidents involving trip system malfunction or disarming
Malfunctions of valves, e.g. pressure relief, non-return
Leaks of flammable materials
Leaks of toxic materials
Leaks and fires at pumps
Fires and explosions in furnaces
Storage tank collapse

The important point is that the reporting system should be tailored to the needs of the organization.

There may also be certain types of incident on which HSE wish to collect information nationally. In this case it may request their inclusion in the reporting scheme. Again we have not specified these incidents but an obvious one is the unconfined vapour cloud explosion.

These reporting requirements should be seen in relation to the fact that we have not recommended that all major hazard installations have a 'black box' recording instrument system. We consider that the arrangements proposed here are a more efficient way of learning both at company and national level.

The reporting system is intended primarily to assist the organization to learn from incidents and it should show that it has formal arrangements to do this.
10. Licence Condition: the Design and Operating Documentation

The organization should provide full documentation on the design and operation of the installation. The documentation required is as follows:

Part 1 Documentation
(For Part 1(a) The System Documentation see Introductory Section of this Appendix.)

Part 1(b) Preliminary Design Document
This should contain:

(1) A brief description of the process and should include the nature of any chemical reaction involved and the various operations to which the material in process is subjected. In addition, any other exothermic reactions which may arise if operating conditions fall outside the design values, should be specified.

(2) A comprehensive description of the nature of the hazards in the materials handled (toxic, flammable, explosive materials), of the objectives to be achieved in order to limit these hazards and of the methods in plant design and operation necessary to achieve these objectives.

(3) A statement of any less hazardous process which could have been used and the reasons for selecting the particular process in question. This might include outstanding economic advantages, factors relating to the availability of raw materials, the avoidance of particularly difficult engineering operations or the necessity of making a product of a particular purity.

(4) A process flow sheet, indicating quantities, the temperatures and pressures of materials at each stage and the vessel inventories, and the flow-rates in each of the principal flowlines. The reasons why such pressures and temperatures must be used should be given. Mass and heat balance diagrams should be given where appropriate.

(5) A list of the main plant items, specifying the capacity, design pressure, temperature limits for safe operation (upper and lower), and any special features of construction, together with the actual operating conditions. Details of services should be given.

(6) Details of the principal standards and codes to be used in the design.

(7) A statement of the inventory of all hazardous materials in process and of the steps taken to keep this at the lowest level consistent with safe and efficient operation.

(8) A statement of the method whereby the process will be controlled. Abnormal features, with particular reference to hazards, should be highlighted and references made to any special features, including trip systems.

(9) A list of all hazardous materials in bulk storage which may be endangered by a process incident and the steps to be taken to minimize the risk of their involvement.

(10) A statement of all materials and services needed to maintain safe operation of the plant and of the steps taken to ensure their continuous availability.


(12) A site layout showing the proposed plant and control room, and their position relative to other installations and buildings in the works, to loading bays at tanker terminals, to plants in neighbouring works and to the public area.

(13) A statement of the location and construction of the control room.

(14) The routing for all vehicles needing access to the plant, whether for the supply of materials and removal of products, or for maintenance or emergency purposes.

(15) An account of the procedures for maintaining effective liaison between the company and any outside organizations involved in the design or construction of the plant.

(16) Details of actual experience of the company, or of availability of experience from external sources, in operation of pilot and production scale plants, for the same or a similar process.

(17) Manning levels on the plant.

(18) Proposals for dealing with emergency situations.

Part 2 Documentation
(For Part 2(a) The Background Documentation see Introductory Section of this Appendix.)

Part 2(b) The Design Document
This should contain:

(1) An updated and detailed statement of all materials submitted in the Preliminary Design Document, including the process flowsheet, quantities and flow-rates of all materials in process and storage areas, heat and material balances, instrument diagrams and plant layout diagrams.

(2) Details of all principal plant items, as in item 5 of Part 1(b), giving codes used, materials of construction and any special features.

(3) Installation drawings and pipe layouts.

(4) Documentation on hazard assessments and reliability studies.

Part 2(c) The Operating Document
This should contain:

(1) A statement of the technical staff structure, including names of the Responsible Persons, together with details of standby arrangements for absence such as sickness or holidays, and of call-in arrangements.

(2) A statement of the numbers of operating personnel and of their training with particular reference to emergency procedures.

(3) The Operating Manual. This should include details of the startup, normal shutdown and emergency shutdown procedures.
Appendix 25

HSE Guidelines on Developments near Major Hazards

The Siting of Developments in the Vicinities of Major Hazards: HSE's Draft Guidelines to Planning Authorities

The full text, which is reproduced by courtesy of the HM Stationery Office, is as follows:

**The Siting of Developments in the Vicinities of Major Hazards: HSE’s Draft Guidelines to Planning Authorities** (by the Health and Safety Executive—Major Hazards Assessment Unit)

**Introduction**

The control of risks from major hazards may be achieved in various ways, e.g.:

(a) limit the amount of hazardous material present;
(b) reduce the likelihood of an accidental release of material;
(c) plan for emergencies; and
(d) reduce the number of people exposed to risk.

Some of these measures may be taken within the installation, particularly at the project planning stage.

In many cases the situation in the installations is already fixed and the scope for improvement under the HSW Act is fully utilized. Even so, there may remain some residual risk. It is unlikely that the residual risk could justify the removal of existing populations by the termination of viable land uses. However, it is possible to inhibit an increase in the population at risk by control of new developments under planning legislation.

It is the purpose of HSE’s advice to facilitate planning control where appropriate. Planning authorities are expected to include the factor of risk in their consideration of a planning decision. Thus the types of development near major hazards should be deliberately chosen to minimize the population at risk.

HSE takes as a starting point the assumption that the major hazard installation complies with the requirements of HSW Act. It is then necessary to assess the level of residual risk to a proposed development in the vicinity, and to judge whether this might be a significant factor in the planning decision. HSE’s assessment takes account of the consequences and likelihoods of various accident scenarios, and the implications of variations in vulnerability between different types of development. In some cases the assumption of compliance with HSW Act implies a precise standard.

In other cases the standards are not precisely defined, or it may be possible to comply in a variety of ways. The individual characteristics of installations are taken into account where possible, but there are limits to the amount of detail which can be considered. It may be necessary to assume average performance in the absence of obvious individual variations, or for cases which are being assessed on paper.

This note deals only with the provision of advice on proposals for new developments in the vicinity of existing major hazard. The assessment techniques are used in a similar way when considering the siting of new major hazards in relation to existing buildings, but the judgement of the significance of the risks may be different. For example, the siting of a new major hazard may be constrained by the need to integrate it with existing plant. The application of a simple ‘reciprocal rule’ for the siting of new major hazards would neglect the differences in availability of sites for the two situations. There is also the possibility of seeking special safety standards on a new plant to facilitate its siting.

**Assessment: likelihood and consequences of an accident**

The first part of the assessment is objective in the sense that it does not include social or political judgements, but it does include estimates of various factors where data is more or less unavailable. Thus it includes technical judgement by professional risk assessors. There is inevitably some uncertainty introduced by this judgement process and by lack of precision in basic data. This does not prevent the derivation of reasonable conclusions but it does imply that some caution is necessary. The technical judgements may tend to lead to an over-estimate of the risk level. If a planning decision is finely balanced, a more detailed review of assumptions may be worthwhile.

Assessments of risk from different materials differ in detail but they have many features in common. The basic sequence of events for LPG and chlorine are:

**LPG:** Plant failure
release
vaporization
mixture with air
ignition
explosion and/or fire
blast and/or heat propagation
impact (either directly on people, or on buildings which collapse or burn).

**Chlorine:** Plant failure
release
vaporization
mixture with air
travel downwind
dilution
inhalation
injury.

The risks from such sequences can be evaluated in two main ways, namely historical and analytical. In the historical approach, information from past incidents is used to predict the risks. The **Second Report of the Advisory Committee** contains information on some past incidents, and it derives a 'Mortality Index' to indicate the average number of fatalities per tonne of material released. This approach may be useful to devise a hazard rating for a material, but it is noticeable that the average index conceals a wide variation between cases and it is thus of questionable value for predicting individual situations. Other problems with the historical approach are the small number of cases and the incompleteness of information on cases, so it may therefore provide a rather poor statistical basis. This approach might be difficult to adapt for prediction in situations different from those already included by the accidents.

The alternative, analytical approach attempts to synthesize the risk on the basis of sequences outlined above. This approach is complex and requires assumptions to be made in the absence of data. Also, it may be difficult to select appropriate scenarios to include. It is, of course,
possible to combine the approaches, and in practice this is what is done. The historical approach is used to provide information on the likelihoods of releases, while the analytical approach is used to predict consequences.

To illustrate the approach, the example of bulk pressurized LPG is used. Installations of this type comprise the majority of the major hazards in Britain, and the risks from them are relatively straightforward to assess. The assessment may begin by listing the various possible releases, either by quantity (short release, e.g. tank burst) or by rate (long release, e.g. uncontrolled pipe-split). There is a continuous range of possible release, but this can usually be simplified by identifying obvious sub-divisions. For the LPG case we might have:

<table>
<thead>
<tr>
<th>Event</th>
<th>Probability</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor flange or gland weeping</td>
<td>Quite likely</td>
<td>Not felt off-site</td>
</tr>
<tr>
<td>Pipework break</td>
<td>Rather unlikely, especially for major cases</td>
<td>Localized, but could extend off-site from major cases</td>
</tr>
<tr>
<td>Tank burst: BLEVE</td>
<td>Very unlikely</td>
<td>May be harmful at considerable distances off-site</td>
</tr>
<tr>
<td>Tank burst: UVCE (delayed ignition)</td>
<td>Extremely unlikely</td>
<td>May be harmful at considerable distances off-site</td>
</tr>
<tr>
<td>Tank burst: drifting gas clouds</td>
<td>Extremely unlikely</td>
<td>May be harmful at considerable distances off-site</td>
</tr>
</tbody>
</table>

It is now necessary to determine more precisely what are the probabilities and consequences of these events. Obviously there could be wide variations between individual plants and between events in each sub-division. For example, the effects from pipe-break might depend on: size of hole; duration before shut-off; whether liquid gaseous or two-phase; wind-speed; delay before ignition; dispersion to below flammable limits; type of combustion, and specific site features. To simplify the problem, assumptions are made to give an indication of the realistic outcome from the most severe event within a sub-division.

The consequences in terms of likelihood of injury are derived by first calculating the impact intensity of the heat or blast at a particular distance, then relating this to the vulnerability of the population at that distance. The possibility is noted that different types of building, having different populations, might give different degrees of protection from any given intensity.

The result of this process is a list of events and risks. A decision can then be made on which events are trivial in that no injury could result. For remaining events, the consequences are considered in conjunction with the likelihood, to determine the combined risk of release and injury. This completes the objective assessment.

It should be noted that this approach does not automatically rule out from consideration any type of source event, however unlikely. Even the largest, most unlikely events are included, so there is not necessarily any cut-off corresponding to a ‘maximum credible accident’. However, attention is paid to the combined risks, which may be very small from an unlikely event, so that the largest events are not necessarily significant determinants of the overall risk. In practice, assessments may be based on one or two events which may thus appear to correspond to ‘maximum credible accidents’; this implies that lesser events may be more damaging but they are so unlikely as to present negligible extra risk. For the LPG example, separation distance guidelines for the siting of the first category of development near existing installations tend to be based on the provision of substantial protection from BLEVE and UVCE; this automatically gives a very high degree of protection from pipe-break and lesser events.

**Assessment: types of development**

It was indicated earlier that different types of building may have associated with them populations whose vulnerabilities differ. This may be of great importance in a siting judgement. HSE feels that it would be inappropriate to advise against all forms of new development near major hazards nor need new major hazards to be sited away from all existing buildings. Types of developments may be distinguished by various factors which relate to the risks, e.g.:

(a) whether residential, workplace, recreational, shopping, etc.;
(b) length of time any individual may be present;
(c) number of people who may be present and duration of occupancy;
(d) ease of evacuation;
(e) inherent vulnerability of people, e.g. elderly, disabled, children; and
(f) physical factors, e.g. building height, materials of construction, etc.

On the basis of these factors, HSE identifies three main categories of development. The first consists of developments where users would be present for most of the time, or where large numbers could be present at any one time, or where people are particularly vulnerable. Examples include housing, shopping centres or very large retail outlets, multi-storey office blocks, etc. The second category consists of less sensitive developments and includes industrial developments with low employment density, warehouses, etc. HSE also identifies a third category containing special cases such as hospitals, schools and other particularly vulnerable developments, to which particular attention should be paid in siting judgements.
It is normally advised that planning control is only necessary in respect of the first and third categories of developments near major hazard installations. There are various mitigating factors associated with the second category, such that it would be difficult to argue that the risks to users justify inhibition of this type of land-use. These factors could include ease of evacuation, low occupancy-time, fitness of population (e.g. adult workforce), small number of people, building protection or building not hazardous to occupants, etc.

**Summary of MHAU’s advice**

For LPG and similar flammable liquid gases, HSE recommends separation distance limits such that the consequences of minor releases at the limit would not be injurious, while the consequences of major releases (BLEVE, UVCE) would be unlikely to seriously injure more than a small fraction of the exposed population. In principle, unignited vapour clouds could travel to the limit, or even beyond it in unfavourable weather conditions, and people enveloped in a cloud would probably be seriously injured, but the risk to an individual from such a scenario is very low.

For chlorine, HSE recommends separation distance limits such that the consequences of major pipework failures would be unlikely to seriously injure more than a small fraction of the population downwind, in typical prevailing weather conditions. In unfavourable weather, or with larger releases from tank failure, people at greater distances could be injured, but the risk to an individual from such a scenario is very low.

**Presentation of advice**

In presenting its advice, HSE attempts to give planning authorities clear guidance on the weight to be attached to the factor of safety. HSE tends to use one of three graded responses as follows:

- **Situation 1 (negligible risk):** No significant reasons for refusing planning permission.

- **Situation 2 (marginal risk):** The risks are very small and are not in themselves sufficient grounds for refusing planning permission, but they could be a factor against the development to add to any other adverse factors. This would apply near the outer limit of separation distance, or with small developments.

- **Situation 3 (substantial risk):** While the probability of a serious incident is low, the consequences at the proposed development site could be serious. The safety issue should be a major factor and the planning authority is advised not to grant planning permission. If there were other factors which weighed strongly in favour of the application, HSE would seek to explain the technical assessment and level of risk in more detail before the planning authority’s decision was made. (In exceptional cases of Situation 3, where the planning authority was minded to grant permission contrary to the HSE’s advice, HSE might consider whether to request a planning inquiry where the issues could be examined in detail in a public forum.)

It often happens that an initial unfavourable response from HSE leads to discussions of the scope for modifications to reduce the risk. Significant reduction may enable HSE to advise favourably. In other cases, HSE may give a conditional response, with advice on the use of planning conditions to ensure that the risk is reduced.
Appendix 26

Public Planning Inquiries

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A26.1 Mossmorran  A26/2
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A26.3 Canvey  A26/3
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A26.5 Expert Evidence  A26/5
In a limited number of cases a planning proposal involving a major hazard goes to a public inquiry. The inquiry will then normally hear technical evidence, which is likely to centre around the hazard assessments carried out by the parties. Experience shows that there are a number of problems associated with expert testimony at public inquiries.

A study of large public inquiries is given in *The Big Public Inquiry* by Sieghart (1979).

Accounts have been given of the public inquiries at Mossmorran by McGill (1981, 1982, 1983), Pheasant Wood by Petts (1985b) and at Canvey by Petts (1985a). A comparative review of the problems of expert evidence at public inquiries and proposals for their mitigation has been given by Petts, Withers and Lees (1986).

Public accident inquiries are discussed on Chapter 27.

**A26.1 Mossmorran**

It is usual in Scotland for planning applications for major oil related developments to be called in for review by the Secretary of State. In the case of the application of Shell Expro to build a gas plant and of Esso Chem to build an ethylene cracker at Mossmorran together with associated facilities at Braefoot Bay, the minister decided on a public inquiry, which was held in 1977. The local planning authority (LPA) retained the consultants Cremer and Warner to produce an assessment of the hazards. The HSE also gave its own assessment. These were the two main sources of technical evidence and neither opposed the development. Opposition came from local interest groups at Aberdour, Braefoot Bay and Dalgety Bay, who mistrusted their own assessments. There was a delay of some 18 months after the inquiry closed until 1979 before the minister gave his approval. The delay was apparently caused in part at least by the issue of ignition of ‘radio sparks’, which was raised after the inquiry had ended.

The Mossmorran inquiry, which has been studied by McGill (1981, 1982, 1983), illustrated the difficulties of public inquiries on hazardous installations, particularly with regard to expert testimony. The amount of information on the plant limited the contribution of the HSE and severely restricted that of the objectors. The latter considered that the statutory authorities had not made available a sufficiently full hazard assessment and they were not satisfied that the objections made to the assessments presented received sufficient weight or that either the LPA or the HSE were sufficiently independent of government and industry. The LPA were clearly in favour of the proposals before they commissioned the consultant’s report.

A planning application is concerned with the development of land. The extent to which a planning inquiry should cover marine activities is perhaps a grey area. The hazards from marine activities at Braefoot Bay were briefly considered in the consultant’s report and the inspector did take some evidence on shipping movements in the estuary, but marine hazards were not thoroughly revealed. The objectors were not unnaturally more concerned with the level of risk than with its source and considered that insufficient attention was given to the marine hazards, which might exceed those from land-based activities.

The inquiry exemplified the problem of assessing the risk from a plant for which the completed design is not yet available. The first stage of planning permission is outline planning permission. At this point the design of the plant is generally available as a feasibility study only. It is outline planning permission, however, which is the important stage and it is difficult thereafter to revoke permission. In this case since the detailed design of the plant had not been done when planning permission was applied for, the assessments which could be made were that much less detailed and the uncertainties in the risks assessed that much greater. The objectors evidently thought that an adequate estimate of the risks could not be made without a hazard study, although this cannot be done until a detailed design is available.

The inquiry did demonstrate, however, the effectiveness of a planning condition. Condition 24 of the planning permission eventually given required the companies to carry out hazard studies and major studies were carried out.

The consultant’s report reviewed the various hazard scenarios and graded their likelihood in qualitative terms such as ‘low’, ‘very low’ and ‘extremely low’, but did not give a full assessment of individual and societal risks. The HSE evidence was qualitative. The lack of any full quantitative assessment was criticized by the interest groups, who emphasized that the Canvey study, a quantitative assessment and public report, was regarded by the HSE as a major step forward in hazard control, yet such an exercise was not done for Mossmorran. These groups were also critical of various apparent inconsistencies in the HSE approach. It was alleged that the HSE estimate of the maximum credible spill at Braefoot Bay was not consistent with that given for Canvey and that the HSE was recommending a *cordon sanitaire* at the gas plant but not at the marine terminal, where many of the hazards were. Some of the HSE’s assessments of physical phenomena were challenged and the opposition was able to call expert witnesses of some academic standing. The safety distances acceptable to the HSE were said to be less than those required in certain other countries. The opposition groups produced some risk estimates which indicated that the likelihood of a multiple fatality accident at Aberdour/Dalgety Bay marine terminal was $10^{-6}$/year as opposed to the estimate of $10^{-6}$/year given by the consultants.

The consultant’s report, despite the absence of a quantitative assessment, gave advice on risk criteria. This raised the question whether it is the expert’s job not only to do the risk estimates but also to evaluate them. On the other hand there did appear to be some opposition groups would not have been too unhappy with an annual risk of ‘one in a million’ ($10^{-6}$/year).

After the inquiry had ended the question was raised of the possible hazard of ignition of a release of flammables by radio transmissions from the nearby naval transmitter at Crimond. The HSE undertook extensive work on this ‘radio spark’ hazard.

The inquiry also illustrates another very basic problem, that if the company makes no modifications to its proposals as a result of objections posed, it appears to ride roughshod over the opposition, while if it does, it appears to be incompetent.

The inquiry and its aftermath give an impression of imbalance in the treatment of the hazards. In particular,
the question of hazards associated with radio sparks received a disproportionate amount of attention relative to the hazards at the marine terminal. Despite this concession to the opposition groups, they were clearly dissatisfied with the inquiry.

**A26.2 Pheasant Wood**

The Pheasant Wood inquiry, which has been studied by Petts (1985b), on proposed housing development near to ICI chlorine and phosgene storages arose when the HSE asked the Secretary of State to call in the proposal for review after the LPA had indicated its intention to grant planning permission. The HSE gave its hazard assessment. The developer retained Cremer and Warner to present an alternative assessment, while ICI, although not directly involved, chose to offer its own assessment. All these parties presented technical evidence. The HSE’s assessment included estimates of both frequencies and consequences of events, but did not combine these together to give individual and societal risks. They were criticized by the inquiry assessor and by ICI for this limitation. On the other hand the other parties, although they did estimate these risks, did not always give the full basis of their estimates. Another point at issue between the HSE and the ICI evidence was some of the data used for the frequency of release. Whereas the HSE had to rely on generic data, the company was able to use data from its own installations which, depending on the viewpoint, were less pessimistic or more optimistic. The appropriateness of the gas dispersion models used was also an issue between the parties. The inspector found against the HSE’s case and in favour of granting planning permission. A feature of the Pheasant Wood inquiry which distinguishes it from those at Mossmorran and at Canvey was the low level of public interest.

**A26.3 Canvey**

The Canvey complex of oil refineries, chemical works, etc., has been the subject of several inquiries and hazard assessments, which have been described by Petts (1985a). The period 1965–73 saw a spate of planning applications and three public inquiries for oil refinery development. The economic pressures were clearly strong. The inquiry inspector’s recommendations were twice overruled by the minister in favour of development. At the same time the level of local concern over the hazards and environmental impact of the Canvey complex was rising and led to the opening, in 1975, of an inquiry into the possibility of revoking the planning permission granted to United Refineries Ltd (URL) in 1971. The technical assessor’s report discussed the hazards in qualitative terms. No quantitative hazard assessments were presented.

One of the assessor’s recommendations was a study of the possible hazardous interaction between the various installations at Canvey. Acting on this, the minister asked the HSC to look into the matter and the HSE commissioned a study from SRD, the First Canvey Report.

With the publication of this report the minister was in a position to reopen the inquiry on the revocation of planning permission for URL. The inquiry was held in 1980 and considered both the bearing of the Canvey Report on the URL project and also the validity of the report itself, the parties being essentially the HSE and the objectors. The only full hazard assessment presented was that of the HSE in the form of the report. The report had not been commissioned specifically for the inquiry, but nevertheless there was for the first time available to an inquiry in Britain a full assessment of individual and societal risks.

One of the main hazards considered was a marine spill of LNG or LPG at the British Gas methane terminal. Disagreements arose over the estimates both of the frequency and the magnitude of this hazard. While the Port of London Authority (PLA) considered that the report overestimated the frequency of ship collision, the objectors presented graphic qualitative evidence of the problems of tanker handling. Estimates of the distance travelled by the flammable gas cloud before it fell to its lower flammability limit varied widely from 1 km to 28 miles.

Doubt was cast on some of the HSE’s proposals for mitigating the hazards. The practicality and effectiveness of the water spray barrier against an ammonia cloud was challenged. PLA witnesses stated that the 8 knot speed limit proposed in the Scheduled Area was not practical.

The estimated risks were also matter for debate. The risk values were relatively high. For example, the calculated fatality risk attributed to the URL extension was comparable with the national fatality risk at work. The inspector considered the risks in some areas unacceptable.

Although the Canvey Report received praise and its overall approach was not challenged, it had certain deficiencies which detracted from it. The text was very disjointed, there were discrepancies between text and tables and there were some inaccuracies.

The inspector recommended that the URL planning permission should not be revoked, but only if the risk from the British Gas methane terminal were reduced by installing a ring of igniters at the periphery or by closure.

In 1981 the Second Canvey Report appeared. In this reassessment, which used revised failure data, more refined hazard models and more accurate population profiles and which took into account changes made on the installations, the assessed risks were less, some by an order of magnitude.

In 1982 another public inquiry was held, this time on the possible discontinuance of the British Gas methane terminal. British Gas produced a full hazard assessment, while the two Canvey Reports formed the basis of the HSE’s evidence. The British Gas assessment used by intent broadly realistic estimates, the HSE conservative ones. The risks estimated by British Gas were lower, in some cases by two orders of magnitude. Realism rather than conservatism was not the only reason for this. The British Gas estimates of failure rates were lower and its gas dispersion estimates gave lower travel distances. The inspector stated that he found HSE’s evidence much easier to understand and that he preferred their conservative approach, and he put some value on the independence of the HSE.

A number of expert witnesses were called by the objectors, notably the Castle Point District Council and the Castle Point Refineries Resistance Group. In many
cases their evidence failed to stand up to cross-examina-
tion due to weak hypotheses on accident scenarios,
oversimplified assumptions, incorrect hazard models,
misunderstanding of the work of others, especially the
Second Canvey Report, and numerical errors. The
technical assessor played an active role in this inquiry
both in advising the inspector and in producing the
report.

The inspector recommended against closing the British
Gas terminal or requiring igniters.

A26.4 Sizewell

The inquiry on the proposal to construct a PWR at
Sizewell B began in January 1983 and ended in February
1985. This is by any standards a ‘big’ public inquiry and
the hazards of a nuclear reactor are one of the topics on
which much expert testimony has been heard. In the
present context the inquiry is of interest for its influence
on the development of the form of such inquiries; for its
influence on the formulation of risk criteria; and for the
evidence given on some of the technical safety issues,
particularly on rare events.

An important feature of the inquiry was the use of
counsel to the inquiry. The inquiry also saw the
increased use of informal ‘side’ meetings between
experts at which issues can be clarified and misunder-
standings removed.

Another feature of the inquiry is that a preconstruction
safety report was available before the inquiry from the
CEGB, although many design aspects remained unre-
solved.

With regard to risk, the Inspector suggested that
where risks of the kind considered are accepted they are
better described as ‘tolerable’ rather than ‘acceptable’ and
encouraged the HSE to develop risk criteria. Such
criteria have subsequently been published by the HSE

Among the many issues on hazards which the inquiry
illustrates is that of the very rare event. A crucial
accident scenario for a PWR is failure of the reactor
pressure vessel (RPV). Such a failure is generally agreed
to be a very rare event, but it may have very serious
consequences. Estimation of the frequency of an event
which has a high hazard potential but is very infrequent,
perhaps scarcely credible, is one of the most intractable-
problems in hazard assessment. The inquiry is instructive
not only because there were differences between experts
in the methodology of estimation of the RPV failure
frequency but also because there was scope for
differences of perception of what was eventually estab-
lished.

Evidence on the estimation of the RPV failure
frequency was given for the CEGB by Dr B. Edmundson,
for the Greater London Council by Technica Ltd and for
the Suffolk Local Authorities by Professor Kussmaul from Germany. Another expert,
Professor T.A. Kletz, gave evidence at the invitation of
the inspector. On the basis of historical pressure vessel
failure data Technica estimated the RPV failure rate at 1
× 10⁻⁶/year. This figure was derived from the crude
figure of 3.2 × 10⁻⁶/year obtained from the historical
data, and was intended to give credit for improved
technology embodied in the RPV, but to be nevertheless
a realistic rather than a conservative estimate, as the
witnesses were at pains to point out. The CEGB derived
their estimate of RPV failure rate using engineering
principles, such as fracture mechanics, to determine the
frequency of the failure modes which they considered
credible, and obtained for catastrophic vessel rupture
with generation of missiles an estimate of 2.4 × 10⁻³/year.
Professor Kussmaul preferred the CEGB’s approach
to that of Technica but advocated an alternative method
of pressure vessel construction so as to minimize the
risk of weld failure. This construction was not accepted
by the CEGB and after further discussion between the
parties Professor Kussmaul accepted the CEGB’s
approach subject to certain procedures which he speci-
fied and to which they agreed. As a result the Suffolk
Local Authorities withdrew their objections on grounds of
safety, since they accepted Professor Kussmaul’s advice
that the risks were ‘so low as to be incredible’.

There were nearly two orders of magnitude between
the CEGB and Technica estimates of the RPV failure
rate. The Technica estimate was in fact based on a single
historical pressure vessel failure, which the CEGB
regarded as so unusual as to be inconceivable on their
vessel. However, even if no failure has occurred
historically, it is still possible to make a statistical
estimate by using the number of failure-free years and
assuming that a failure is just about to occur. It therefore
makes little difference to the number obtained whether
the number of failures is one or zero. More important
was the difference between the parties on whether the
estimate should be based on historical statistics or
engineering principles. Technica argued that even if the
single historical failure was a bizarre one, such events
cannot be completely discounted, that this stood in for
the whole set of bizarre events which might occur, and
that the method based on the historical data was the
appropriate one to use.

In his cross-examination counsel for the CEGB sought
to identify assumptions in the Technica estimate. For
Technica Dr R.A. Cox stated clearly that the figure of
1 × 10⁻³/year was a ‘best estimate’, intended as
realistic rather than conservative. However, counsel
drew attention to the fact that in its written evidence
Technica had at one point referred to this figure as an
‘upper bound’. Dr P.J. Kayes for Technica then explained
that what was meant by this was that the figure was an
‘upper bound on the type of studies that would claim
RPV failure to be incredible’. Counsel then asked: ‘Is it
intended to provide an upper bound to the likelihood of
RPV failure?’ and the witness replied: ‘Yes, it is, as a best
estimate’. Thus Technica were liable to believe that their
figure was accepted as a realistic estimate, the CEGB
that it had been conceded to be conservative.

In cross-examination Professor Kletz commented that
the two methods should not be seen as necessarily in
conflict. A difference between the two by orders of
magnitude was understandable. He did say, however,
that while a large improvement in the reliability of
the CEGB vessel over historic vessels could be expected,
had some personal scepticism whether any man-made
artefact could provide such a low figure as the CEGB
was claiming. In the case of the RPV the failure
frequency was so low that he felt there was some
justification for making allowance as Technica proposed
for bizarre events and referred to possible failure due to
previously unknown metallurgical phenomena. When
cross-examined by one of the assessors, he agreed that his scepticism regarding very low numbers applied to a very low figure for a single event rather than one obtained as the product of the figures for a chain of events.

Thus while the differences of opinion over points raised by Professor Kussmaul were largely settled by discussion outside the formal proceedings and the main findings reported back to the inquiry, the differences arising from the Technica evidence were not resolved at the side meetings and the parties were liable to interpret the evidence given in the inquiry cross-examination as supporting their particular positions.

A26.5 Expert Evidence

The foregoing account of some of the principal inquiries which have been held on hazardous installations indicates that there are a number of problem areas. These problems have been reviewed and proposals made for mitigating them by Petts, Withers and Lees (1986).

A26.5.1 Problems of adversarial forum

A view commonly expressed by technical experts is that the adversarial situation of a public inquiry is not an appropriate means of examining technical issues. Many experts find the adversarial process unfamiliar and intimidating and regard it as an inappropriate means of arriving at the truth on technical matters. The adversarial process tends to lead to adoption of rigid, defensive positions.

For interest groups opposed to a development the adversarial forum of an inquiry has the advantage that they can examine the developer's case, but can be intimidating to them also and it presents considerable difficulties for groups with few resources.

A26.5.2 Problems with hazard assessments

Many of the problems of expert testimony at public inquiries on process installations centre round hazard assessment. Most of these difficulties can be grouped under one or other of the following heads:

1. obscurity,
2. incompleteness, and
3. inconsistency.

Obscurity

There may be inherent difficulties in the subject matter or in its presentation.

Thus at the Sizewell inquiry the debate on engineering features of the pressure vessel was difficult to follow without engineering drawings. At the Canvey inquiry the inspector himself had difficulties with the hazard assessment by British Gas and felt that the mode of presentation was more appropriate to a learned society than an inquiry.

Fundamentally difficult matters are typified by the arguments at Sizewell over the frequency of rare events and over probabilistic risk analyses.

Incompleteness

Information may be incomplete for many reasons. The engineering design may not be complete by the time of the inquiry, there may be deliberate selectivity in the hazards examined and there may be simple failure to identify all the hazards.

Thus at the Mossmorran and Sizewell inquiries much plant-specific information was unavailable because the projects were still in the feasibility stage. Estimates were therefore conceptual and based on generic data. This is likely to be a common situation.

Selectivity is exemplified by Mossmorran, where the objectors expressed concern about hazards at the port which seemed to have received less attention than the gas plant itself. Again at Mossmorran, there were objections to the exclusion of aircraft crashes. Later the possible hazard of ignition from radio sparks was raised and led to a separate investigation.

Inconsistencies

Some inconsistencies appear at an inquiry simply because of the lack of an agreed structure and methodology for the hazard assessment. There are also differences in the particular models used and in the basic approach to probability estimation.

Examples of differing structures and methodologies appeared at Pheasant Wood, where the assessment by the HSE did not provide any estimates of individual or societal risk, while those of the consultants and of ICI did. The HSE case was based on generic data, while the ICI case was based on plant-specific data.

At Canvey there were wide differences in the results obtained from different gas dispersion models. There have also been wide differences in the relations describing injury and damage. This is illustrated by the Rimmer Report, which, although not a document presented to an inquiry, represents the type of hazard assessment which might be submitted. The report revealed ten-fold differences in estimates of the lethal concentrations of chlorine.

Such differences and uncertainties usually result in judgements being made about the likely margin of error. These judgements may occur at a number of points in the chain of calculations which make up the assessment. They may be optimistic or pessimistic.

In general, industry is anxious that the risks should not be exaggerated and presses for realistic assessments wherever possible. It may seek to avoid the use of numerical estimates of risk altogether where the confidence bounds are very wide. The HSE, on the other hand, is bound in the public interest to take a fairly cautious view and may be expected to incline towards the use of values which are to some degree conservative.

In the risks assessed for the methane terminal at Canvey, the HSE and British Gas sometimes differed by a factor of a hundred, partly due to the difference between realism and conservatism.

Examples of the use of differences in approach to probability estimation were demonstrated at Sizewell, where the objectors based their estimate of pressure vessel failure rate on historical data and the CEBG its estimate on engineering considerations, the latter thereby obtaining for the event in question a frequency lower by some two orders of magnitude.

It should be recognized that public opposition to an industrial development may in some cases be so strong as to influence the character of the presentation and examination of the hazard assessments. At Pheasant
Wood there was little public interest, whereas at Mossmorran this interest was strong and organized.

A26.5.3 Availability of information
An essential requirement of the parties to an inquiry is the availability of information. This information needs to be of the appropriate kind and to be provided at the right time. This requirement would in large part be met if the company makes available at the outset of the inquiry a form of open conceptual safety case.

The LPA may wish to commission an independent report from a consultant, as well as seeking advice from the HSE.

The use of open safety cases presented in a uniform style would greatly assist the LPAs to become familiar with the problems posed by hazardous installations and to instruct consultants.

The HSE may also provide for the inquiry inspector an independent hazard assessment by which he can evaluate the evidence of the other parties.

Twenty-eight days before the inquiry the LPA is required to produce a written statement. It is only the LPA which has this obligation.

A26.5.4 Parties to inquiry
The LPA will always be a party to a planning inquiry. There is no general requirement that staff from other government bodies (such as the HSE) should appear in person. In practice they often do.

The parties will often be represented by legal counsel at the inquiry. An innovation at Sizewell was the appointment of counsel to the inquiry itself. This appears to have been of great assistance to the inspector and to have helped other parties to clarify issues. In an adversarial process the investigatory role of such counsel appears of great value, particularly for technically complex projects.

The part played by the HSE at an inquiry needs to be seen in the context of its wider and ongoing role in the control of hazards. In order to safeguard this role, it is desirable that as far as possible the HSE should appear as an adviser rather than a protagonist and the situation where the HSE is the instigator of an inquiry is to be avoided as far as possible.

It is appropriate that at the outset of an inquiry the HSE be invited to state its role, the legislation under which it operates and the limits of its powers, that it define the set of principles by which it judges the nature of the risk and the relevant safety criteria required by the HSWA as enforced by the HSE. It may also indicate its expectations of the ability of the developer to meet these standards, while leaving it to the inquiry to balance these expectations with those of others, and with other relevant factors.

Many experts are called by objectors. The problems experienced at past inquiries have often centred around disagreements between these experts and others. It is desirable that these experts play their full part in the formal and informal meetings described below. In this way issues can be clarified and difficulties which have arisen in the past avoided. Another class of witness is those called by the inspector, but these appear to present fewer problems.

A26.5.5 Arrangements at inquiry
A large inquiry usually has a formal preliminary meeting presided over by the inspector at which a detailed set of objectives, procedures and timetable are developed from the terms of reference. Such a meeting, which largely determines the subsequent course of the inquiry, is essential for large, technically complex projects.

The normal procedure in a public inquiry is to hear evidence by party rather than by issue, with the project's proposer having the final right of reply. This results in safety evidence being interspersed with other evidence on other topics, and not taken in its logical order. An exception tends to be made in big inquiries such as Sizewell, where hearing may be by issue. In general, hearing by issue suits the large organizations, who have little difficulty in making experts available on each issue as it arises. It may, however, create problems for smaller bodies with limited resources.

As described above, there has been some criticism of the adversarial approach inherent in public inquiries. In eyes of the public, however, it remains a safeguard, albeit imperfect, against concealment and is an important factor in legitimizing the inquiry process.

The problem of dealing with expert evidence in an adversarial forum may be mitigated by the use of non-adversarial side meetings between experts. Some of these may be formal meetings with minutes kept which are part of the inquiry record.
Standards and codes of practice are one of the principal means by which experience of problems and of solutions is transmitted and are fundamental to good industrial practice.

The production of a code is normally undertaken by a group of experienced practitioners under the aegis of the appropriate organization. The code represents the consensus of this group on what constitutes good practice. There is usually some degree of consultation with the parties who will use the code.

There are a large number of codes produced by a variety of bodies and the status of a code depends on that of the body which promulgates it.

Inevitably a code becomes out of date as technology changes, so that a process of continuous revision is necessary. The philosophy commonly adopted in writing a new code is to define limited objectives and to get the code finished, recognizing that further revision will be necessary in due course, rather than to seek to produce a definitive work.

Leading standards institutions are the British Standards Institution (BSI), the American National Standards Institute (ANSI), the Deutsches Institut für Normung (DIN), the Verein Deutscher Ingenieure (VDI), the Association Française de Normalisation (AFNOR), the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), the Comité de Normalisation Européen (CEN) and the Comité de Normalisation Européen Electrotechnique (CENELEC).

Some of the principal sets of standards are listed in the following collections:

- British Standards Catalogue
- Catalog of American National Standards
- Annual Book of ASTM Standards
- DIN Katalog für Technische Regeln (English translation = English Translations of German Standards (Berlin: Beuth Verlag)). This catalogue contains the VDI Richtlinien
- AFNOR Catalogue
- ISO Catalogue

Standards and codes of practice normally use a specialized and defined terminology. For British Standards this is described in BS 0: 1974 A Standard for Standards. BS 0 states

Mandatory requirements i.e. those that it is essential to satisfy, are expressed by the use of the auxiliary ‘shall’. Non-mandatory requirements i.e. those that are recommended or desirable are usually expressed by the use of the auxiliary ‘should’.

The word ‘must’ should not be used to state a requirement with a British Standard, but this does not preclude its use when an absolute imperative arises, for example when safety considerations apply.

The CIA codes of practice also have a defined terminology. The Code of Practice for Chemicals with Major Hazards: Ethylene Dichloride (CIA, 1975 PA13) gives the following usage:

(i) Should implies a recommendation based upon the judgement of experienced people but recognises that some discretion is appropriate in special circumstances
(ii) Shall implies a strong recommendation based upon experience or upon the position adopted by recognized authorities.

(iii) Must is a definite requirement, but is normally limited to procedures essential to adequate design or sound operation.

The limited degree of discretion expressed in the first two definitions is usually permitted in actual technical matters.

A further discussion of standards and codes, and in particular of Approved Codes of Practice (ACOPs), is given in Chapter 3.

Some principal standards and codes of practice relevant to safety and loss prevention are listed below.

Addresses of the organizations mentioned are given in Appendix 29.

**American National Standards**

(American National Standards Institute, New York)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Construction</td>
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<tr>
<td>A10</td>
<td>Construction and Demolition</td>
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<td>A21.14–1989</td>
<td>Ductile Iron Fittings, 3 inch through 24 inch, for Gas</td>
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<td>A21.52–1991</td>
<td>Ductile-Iron Pipe, Centrifugally Cast, for Gas</td>
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<td>B</td>
<td>Mechanical</td>
</tr>
<tr>
<td>B1</td>
<td>Screw Threads</td>
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<tr>
<td>B7.1–1988</td>
<td>The Use, Care and Protection of Abrasive Wheels</td>
</tr>
<tr>
<td>B16</td>
<td>Fittings, Flanges and Valves</td>
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<td>B18</td>
<td>Fasteners</td>
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<td>B93</td>
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<td>B109</td>
<td>Meters and Metering</td>
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<td>B133</td>
<td>Gas Turbines</td>
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<tr>
<td>C</td>
<td>Electrical and Electronic</td>
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<tr>
<td>C37</td>
<td>Switchgear, High Voltage Circuit Breakers, etc.</td>
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<tr>
<td>C50</td>
<td>Rotating Electrical Machinery</td>
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<tr>
<td>C57</td>
<td>Transformers</td>
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<td>C62</td>
<td>Surge Arresters, etc</td>
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<td>Highway Traffic Safety</td>
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<td>H</td>
<td>Non-Ferrous Materials and Metallurgy</td>
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<td>Aluminum Alloys</td>
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<td>K</td>
<td>Chemicals</td>
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<td>K61.1–1989</td>
<td>Safety Requirements for the Storage and Handling of Anhydrous Ammonia</td>
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<td>MC</td>
<td>Measurement and Automatic Control</td>
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<td>MC96.1–1982</td>
<td>Temperature Measurement Thermocouples</td>
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<td>MH</td>
<td>Materials Handling</td>
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<tr>
<td>MH5.1M–1982</td>
<td>Requirements for Tank Containers for Liquids and Gases</td>
</tr>
<tr>
<td>MH15.1–1979</td>
<td>Glossary of Packing Terms</td>
</tr>
<tr>
<td>MH16.2–1984</td>
<td>Safe Practices for the Use of Industrial and Commercial Steel Storage Racks</td>
</tr>
<tr>
<td>MH26.1–1991</td>
<td>Specifications for Industrial Metal Containers</td>
</tr>
</tbody>
</table>
MH27.1–1981 Specification for Underhung Cranes and Monorail Systems

N Nuclear

S Acoustics, Vibration, Mechanical Shock and Sound Recording Acoustics, etc.

S1 Specification for Sound Level Meters

S1.4–1983 Methods for the Measurement of Sound Pressure Levels

S2 Shock and Vibration


S2.5–1962 (1990) Recommendations for Specifying the Performance of Vibration Machines

S2.7–1982 (1986) Balancing Terminology


X Information Systems

Y Drawing, Symbols and Abbreviations

Y14 Drafting Manual

Y32 Graphic Symbols


Z Miscellaneous

Z9 Ventilation


Z9.2–1979 Fundamentals Governing the Design and Operation of Local Exhaust Systems

Z16 Injury Statistics

Z21 Gas Burning Appliances

Z41–1991 Personal Protection – Protective Footwear

Z49.1–1988 Safety in Welding and Cutting

Z83 Gas Equipment Installation

Z87.1–1989 Practice for Occupational and Educational Eye and Face Protection

Z88 Standards for Respiratory Protection

Z89 Standards for Head Protection


Z244.1–1982 Safety Requirements for Lock Out/Tag Out of Energy Sources

See also the following, which are to be found under the second acronym:

ANSI/AIHA; ANSI/API; ANSI/ASME; ANSI/ASHRAE;

ANSI/ASQC; ANSI/ASTM; ANSI/AWS;

ANSI/IEEE; ANSI/ISA; ANSI/NFPA; ANSI/UL

American Industrial Hygiene Association

(Fairfax, VA)

AIHA Z9.5–1993 Standard for Laboratory Ventilation

American Petroleum Institute

(Washington, DC)

Standards

Std 510 Pressure vessel inspection code: maintenance inspection, rating, repair, and alteration, 7th ed., 1992

Std 526 Flanged steel safety relief valves, 3rd ed., 1984


Std 541 Form-wound squirrel-cage induction motors, 250 horsepower and larger, 2nd ed., 1987

Std 560 Fired heaters for general refinery services, 1986

Std 589 Fire test for evaluation of valve stem packing, 1993

Std 598 Valve inspection and testing, 6th ed., 1990

Std 599 Steel and ductile iron plug valves, 3rd ed., 1988

Std 600 Steel gate valves – flanged and buttwelding ends, 9th ed., 1991

Std 607 Fire test for soft-seated quarter-turn valves, 4th ed., 1993

Std 608 Metal ball valves – flanged and butt-welding ends, 1989

Std 610 Centrifugal pumps for general refinery service, 7th ed., 1989


Std 612 Special-purpose steam turbines for refinery services, 3rd ed., 1987


Std 614 Lubrication, shaft-sealing, and control oil systems for special purpose applications, 3rd ed., 1992

Std 615 Sound control of mechanical equipment for refinery services, 1973 (1987)

Std 616 Gas turbines for refinery services, 3rd ed., 1992

Std 617 Centrifugal compressors for general refinery service, 5th ed., 1988

Std 618 Reciprocating compressors for general refinery service, 3rd ed., 1986

Std 619 Rotary type positive displacement compressors for general refinery services, 2nd ed., 1985 (1991)

Std 620 Design and construction of large, welded, low-pressure storage tanks, 8th ed., 1990

Std 650 Welded steel tanks for oil storage, 9th ed., 1993

Std 653 Tank inspection, repair, alteration and reconstruction, 1991


Std 661 Air-cooled heat exchangers for general refinery services, 3rd ed., 1992

Std 670 Vibration, axial position and bearing-temperature monitoring systems, 2nd ed., 1986


Std 677 General-purpose gear units for refinery service, 1989


Std 1104 Welding of pipelines and related facilities, 17th ed., 1988

Std 2000 Venting atmospheric and low-pressure storage
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tanks (non-refrigerated and refrigerated), 4th ed., 1992
Std 2015  Safe entry and cleaning of petroleum storage tanks, 5th ed., 1993
Std 2508  Design and construction of ethane and ethylene installations at marine and pipeline terminals, natural gas processing plants, refineries, petrochemical plants, and tank farms, 2nd ed., 1985
Std 2510  Design and construction of LP-gas installations at marine and pipeline terminals, natural gas processing plants, refineries, petrochemical plants, and tank farms, 6th ed., 1989

Specification
Spec. 6A  Specification for valves and wellhead equipment, 16th ed., 1989
Spec. 6D  Specification for pipeline valves (steel gate, plug, ball, and check valves), 20th ed., 1991
Spec. 6FA  Specification for fire test for valves, 2nd ed., 1994
Spec. 6FB  Fire test for end connections, 2nd ed., 1992

Recommended Practices
RP 14B  Recommended practice for design, installation, repair and operation of subsurface safety valve systems, 3rd ed., 1990
RP 14C  Recommended practice for analysis, design, installation and testing of basic surface safety systems on offshore production platforms, 4th ed., 1986
RP 14E  Recommended practice for design and installation of offshore production platform piping systems, 5th ed., 1991
RP 14F  Recommended practice for design and installation of electrical systems for offshore production platforms, 3rd ed., 1991
RP 14G  Recommended practice for fire prevention and control on open type offshore production platforms, 2nd ed., 1986
RP 17A  Recommended practice for design and operation of subsea production systems, 1987
RP 17B  Recommended practice for flexible pipe, 1988
RP 17C  Recommended practice on TFL (through flowline) systems, 1991
RP 53  Recommended practice for blowout prevention equipment systems for drilling wells, 2nd ed., 1984
RP 500  Recommended practice for classification of locations for electrical installations at petroleum facilities, 1991 (replaces 500A, 500B, 500C)
RP 510  Pressure vessel inspection code – maintenance, inspection, rating repair and alteration, 7th ed., 1992
RP 530  Calculation of heater tube thickness in petroleum refineries, 3rd ed., 1988
RP 531M  Measurement of noise from fired process heaters (metric only), 1980 (1985)
RP 540  Electrical installations in petroleum processing plants, 3rd ed., 1991
RP 551  Process measurement instrumentation, 1993
RP 572  Inspection of pressure vessels, 1992
RP 573  Inspection of fired boilers and heaters, 1991
RP 574  Inspection of piping, tubing, valves, and fittings, 1990
RP 575  Inspection of pressure relieving devices, 1992
RP 591  User acceptance of refinery valves, 1990
RP 651  Cathodic protection of aboveground petroleum storage tanks, 1991
RP 652  Lining of aboveground petroleum storage tank bottoms, 1991
RP 750  Management of process hazards, 1990
RP 1102  Steel pipelines crossing railroads and highways, 6th ed., 1993
RP 1104  Welding of pipelines and related facilities, 17th ed., 1988
RP 1107  Pipeline maintenance welding practices, 3rd ed., 1991
RP 1109  Marking liquid petroleum pipeline facilities, 2nd ed., 1993
RP 1110  Pressure testing of liquid petroleum pipelines, 3rd ed., 1991
RP 1111  Design, construction, operation and maintenance of offshore hydrocarbon pipelines, 2nd ed., 1993
RP 1112  Developing a highway emergency response plan for incidents involving hazardous materials, 2nd ed., 1992
RP 1113  Developing a pipeline supervisory control center, 2nd ed., 1993
RP 1118  Training and qualification of liquid pipeline controllers, 1991
RP 1119  Training and qualification of liquid pipeline operators, 1991
RP 1120  Training and qualification of liquid pipeline maintenance personnel, 1991
RP 1122  Emergency preparedness and response for hazardous liquids pipelines, 1991
RP 1124  Ship, barge and terminal hydrocarbon vapor collection manifolds, 1991
RP 1125  Overfill control systems for tank barges, 1991
RP 1139  Training guidelines for tank ship personnel, 2nd ed., 1993
RP 1140  Guidelines for developing bridge management teams, 1991
RP 2003  Protection against ignitions arising out of static, lightning, and stray currents, 5th ed., 1991
RP 2200  Repairing crude oil, liquefied petroleum gas and product pipelines, 3rd ed., 1993
RP 2350  Overfill protection for petroleum storage tanks, 1987
The following do not appear in the current list:

*Manual on Disposal of Refinery Wastes*
Liquid wastes, 1969 (not current, under revision)
Liquid wastes, ch.21 – Handling stormwater runoff, 1980
Atmospheric emissions, 1977
Solid wastes, 1980

*Guide for Inspection of Refinery Equipment*
Ch. 1 Introduction, 2nd ed., 1976
2 Conditions causing deterioration or failure, 2nd ed., 1973
3 General preliminary or preparatory work, 2nd ed., 1976
5 Preparation of equipment for safe entry and work, 3rd ed., 1978
6 Pressure vessels (towers, drums and reactors), 4th ed., 1982
7 Heat exchangers, condensers, and cooler boxes, 2nd ed., 1967 (reaffirmed 1973)
8 Direct-fired boilers and auxiliary equipment, 2nd ed., 1974
10 Pumps, compressors, and blowers, and their drivers, 2nd ed., 1976
11 Pipe, valves and fittings, 2nd ed., 1974
12 Foundations, structures and buildings, 2nd ed., 1975
13 Atmospheric and low-pressure storage tanks, 4th ed., 1981
14 Electrical systems, 3rd ed., 1982
16 Pressure-relieving devices, 2nd ed., 1974
17 Auxiliary and miscellaneous equipment, 2nd ed., 1978
18 Protection of idle equipment, 3rd ed., 1982
19 Inspection for accident prevention, 2nd ed., 1971
20 Inspection for fire protection, 2nd ed., 1971

Appendix Inspection for welding, 3rd ed., 1978
Std 601 Metallic gaskets for piping, double-jacketed and spiral wound, 5th ed., 1982
605 Large diameter carbon steel flanges (nominal pipe sizes 26 through 60, 75, 150, 300, 400, 600, and 900), 3rd ed., 1980
RP 50 Recommended gas plant good operating practices for protection of the environment, 1975 (reissued 1982)
55 Recommended practices for conducting oil and gas production operations involving hydrogen sulfide, 1981 (1983)
500A Classification of areas for electrical installations in petroleum refineries, 4th ed., 1982
500B Recommended practice for classification of areas for electrical installations at drilling rigs and production facilities on land and on marine fixed and mobile platforms, 2nd ed., 1973
500C Classification of areas for electrical installations at petroleum and gas pipeline transportation facilities, 2nd ed., 1984
525 Testing procedure for pressure relieving devices discharging against back pressure, 1960

550 Manual on installation of refinery instruments and control systems, 1974–75
631M Measurement of noise from air-cooled heat exchangers (metric only), 1981
942 Controlling weld hardness of carbon steel refinery equipment to prevent environmental cracking, 2nd ed., 1982
2001 Fire protection in refineries, 1984

American Society of Civil Engineers
(New York)
ASCE 1–82 N-725 Guideline for Design and Analysis of Nuclear Safety Related Earth Structures
ASCE 7–88 Minimum Design Loads for Buildings and Other Structures (formerly ANSI 58.1)

American Society of Heating, Refrigerating and Air-Conditioning Engineers
(Atlanta, GA)
ASHRAE 34–1992 Number Designation and Safety Classification of Refrigerants
ASHRAE 55–1981 Thermal Environmental Conditions for Human Occupancy
ASHRAE 62–1989 Ventilation for Acceptable Indoor Air Quality

American Society of Mechanical Engineers
(New York)
ASME Boiler and Pressure Vessel Code
ASME Boiler and Pressure Vessel Code: 1992
Section I Power Boilers
II Material Specification
III Nuclear Power Plant Components
IV Heating Boilers
V Non-Destructive Examination
VI Recommended Rules for Care and Operation of Boilers
VII Recommended Rules for Care of Power Boilers
VIII Pressure Vessels
Division 1
Division 2 – Alternative Rules
IX Welding and Brazing Qualifications
X Fiberglass-Reinforced Plastic Pressure Vessels
XI Rules for In-Service Inspection of Nuclear Power Plant Components

Code Case Books:
Boiler and Pressure Vessels Nuclear Components

ASME Code for Pressure Piping
ASME B31 Guide for Piping and Piping Systems
ASME B31.1–1992 Power Piping
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ASME B31.3–1990 Chemical Plant and Petroleum Refinery Piping
ASME B31.4–1979 Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia, and Alcohol
ASME B31.5–1987 Refrigeration Piping
ASME B31.8–1989 Gas Transmission and Distribution Piping Systems
ASME B31.9–1988 Building Services Piping

Performance Test Codes
This series gives performance test codes for a wide range of equipment, including:
ASME PTC 1–1991 Performance Test Codes – General Instructions
ASME PTC 25.3–1988 Performance Test Code – Safety and Relief Valves
ASME PTC 36–1985 Measurement of Industrial Sound

General and Safety Standards
ASME A112.26M–1984 Water Hammer Arresters
ASME B16.6–1988 Non-Metallic Flat Gaskets for Pipe Flanges
ASME B16.21–1992 Large Diameter Steel Flanges
ASME B16.47–1990 Air Compressor Systems
ASME 20.1–1990 Manual for Determining the Remaining Strength of Corroded Equipment
ASME B31G–1991 Welded and Seamless Wrought Steel Pipe
ASME B36.1M–1985 Stainless Steel Pipe
ASME B36.19M–1985 Specifications for Horizontal End Suction Centrifugal Pumps for Chemical Processes
ASME B73.1M–1991 Specifications for Vertical In-Line Centrifugal Pumps for Chemical Processes
ASME B73.2M–1991 Welded Aluminum – Alloy Storage Tanks
ASME B96.1–1989 Design of Transmission Shafting
ASME B106.1M–1985 Hand Torque Tools

ASME CSD-1–1992 Controls and Safety Devices for Automatically Fired Boilers
ASME MFC-1M–1991 Glossary of Terms Used in the Measurement of Flow
ASME NQA-1–1989 Quality Assurance Program Requirements for Nuclear Facilities
ASME OM-1990 Operation and Maintenance of Nuclear Power Plants
ASME Y14.24M–1989 Types and Applications of Engineering Drawings
ASME Y14.34M–1989 Parts Lists, Data Lists and Index Lists
ASME Y32.2.3–1949 (1988) Graphic Symbols for Pipe Fittings, Valves and Piping

American Society for Quality Control
(Milwaukee, MI)
ASQC A3–1987 Quality Systems Terminology
ASQC C1–1985 General Requirements for a Quality Program
ASQC E1–1988 Quality Program Guidelines for Project Phase of Non-Nuclear Power Station Generation Facilities
ASQC Q1–1986 General Guidelines for Auditing of Quality Systems

American Society for Testing and Materials
(Philadelphia, PA)
ASTM A106–91 Standard specification for seamless carbon steel pipe for high temperature service
ASTM A515/515M–90 Standard specification for pressure vessel plates, carbon steel, for intermediate and higher-temperature service
ASTM A516/516M–90 Standard specification for pressure vessel plates, carbon steel, for moderate and lower-temperature service
ASTM D92–90 Standard test method for flash and fire point by Cleveland open cup
ASTM D93–90 Standard test method for flash point by Pensky–Martens closed cup
ASTM D3517–91 Standard specification for ‘Fiberglass’ (glass-fiber-reinforced thermosetting resin) plastic pipe
ASTM D4021–86 Standard specification for contact molded glass-fiber-reinforced thermosetting resin
underground petroleum storage tanks

ASTM D4097–88 Standard specification for contact molded glass-fiber-reinforced thermosetting resin chemical resistant tanks

ASTM E 399–90 Standard test method for plane-strain fracture toughness testing of metallic materials

ASTM E502–84(89) Standard test method for selection and use of ASTM standards for the determination of flash point of chemicals by closed cup methods

ASTM E 569–91E1 Standard practice for acoustic emission monitoring of structures during controlled simulation

ASTM E 610–89A Standard definition of terms relating to acoustic emissions

ASTM E 1002–86 Standard method of testing for leaks using ultrasonics

ASTM E 1067–89 Standard practice for acoustic emission examination of (91E1) fiberglass reinforced plastic resin (FRP) tanks/vessels

ASTM E 1211–87 Standard practice for leak detection and location using surface-mounted acoustic emission sensors

ASTM E 681–85(91) Standard test method for concentration limits of flammability of chemicals

ASTM F 1129–88 Standard guide for using aqueous foam to control the vapor hazard from immiscible volatile liquids

ASTM E 1290–90 Standard test method for crack tip opening displacement (CTOD) fracture toughness measurement

American Welding Society (Miami, FL)

AWS A2.4–91 Symbols for Welding, Brazing and Non-Destructive Testing

AWS A3.0–89 Welding Terms and Definitions


AWS B1.10–86 Guide for the Nondestructive Inspection of Welds

AWS B1.11–88 Guide for the Visual Inspection of Welds

AWS B4.0–92 Methods for Mechanical Testing of Welds

AWS C3.8–90 Recommended Practices for Ultrasonic Inspection

AWS D10.4–86 Recommended Practices for Welding Austenitic Chromium-Nickel Stainless Steel Piping and Tubing

AWS D10.10–90 Recommended Practices for Local Heating of Welds at Piping and Tubing


AWS F1.1–92 Method for Sampling Airborne Particulates Generated by Welding and Allied Processes

AWS F1.3–90 A Sample Strategy Guide for Evaluating Contaminants in the Welding Environment

AWS F4.1–88 Recommended Safe Practices for the Preparation of Welding and Cutting of Containers that have Held Hazardous Substances

British Chemical Industry Safety Council (see Chemical Industries Association)

1975 Codes of Practice for Chemicals with Major Hazards: Chlorine
1975 Codes of Practice for Chemicals with Major Hazards: Hydrogen Chloride (Anhydrous)
See also Chemical Industries Association

British Compressed Gases Association (London)

Codes of Practice

CP 3 The Safe Disposal of Gas Containers, 1987

CP 4 Industrial Gas Cylinder Manifolds and Distribution Pipelines (excluding Acetylene), 1986

CP 5 The Design and Construction of Manifolds using Acetylene Gas to a Maximum Working Pressure of 25 bar (362 lb/in²), 1986

CP 8 The Safe Storage of Gaseous Hydrogen in Seamless Cylinders and Similar Containers, 1986

CP 13 Guide to Labelling Gas Containers (Cylinders) – Classification, Packaging and Labelling of Dangerous Substances Regulations SI 1984 1244, 1985

CP 19 Bulk Liquid Oxygen Storage at Users’ Premises, rev. 1, 1992

CP 20 Bulk Liquid Oxygen Storage at Production Sites, 1990

CP 21 Bulk Liquid Argon or Nitrogen Storage at Users’ Premises, 1992

CP 23 Application of the Pressure Systems and Transportable Gas Containers Regulations 1989 to Industrial and Medical Pressure Systems Installed at Consumer Premises, 1992

CP 24 Application of the Pressure Systems and Transportable Gas Containers Regulations 1989 to Operational Process Plant, 1992
APPENDIX 27/8 STANDARDS AND CODES

British Gas
(London)

Corrosion Control (Cathodic Protection)
GBE/EC1 Code of Practice for Corrosion Control of Buried Steel and Ductile Iron Pipe, 1992

Commissioning and On-Line Inspection
BGC/PS/FC2 Notes for Guidance on the Use of Pigs in Gas Transmission Pipelines, 1982
BGC/PS/OLI2 Recommendations for On Line Piggging Operations on Gas Transmission Pipelines, 1983
BGC/PS/OLI4 Code of Practice for Monitoring the Condition of High Pressure Gas Transmission Pipelines Externally, 1989

Electrical
BGC/PS/EES1 Code of Practice for the Installation and Testing of Earths and Earthing Systems, 1984
GBE/EL2 Notes for Guidance on the Standards Available for the Certification of Electrical Apparatus for Potentially Explosive Atmospheres, 1993
GBE/EL3 Requirements for the Selection, Protection, Maintenance and Operation of Electrically-Operated Portable and Transportable Tools and Equipment, 1994
GBE/EL4 Procedures for Inspection and Testing of Fixed Electrical Equipment and Systems, 1994
BGES/EL7 Notes for Guidance on the Electricity at Work Regulations 1989, 1994

Equipment
BGC/PS/E4 Specification for Inflatable, Self-Centring Bag-Stoppers for Use on Operating Mains up to and including 300 mm Nominal Size, 1977
GBE/E1 Technical Specification for Combined Drilling, Tapping and Service Fitting Insertion Machines for Use up to 2 bar, 1993
GBE/E10 Technical Specification for Pig Traps, 1993
GBE/E21 Technical Specification for Pigs for Use in Gas Transmission Pipelines, 1994

Graphical Symbols
GBE/CD01 Graphical Symbols Manual, 1989–

Instrumentation
BGC/PS/INP3 Specification for Bourdon Tube Pressure Gauges for Plant Mounting in

Distribution and Transmission Installations, 1981
BGC/PS/INP2 Specification for Pressure Switches for Use with Natural or Manufactured Gas in Zone 1 Hazardous Areas, 1984
BGC/PS/INP1 Specification for High Accuracy Electrical Differential Pressure Transmitters for Natural Gas, 1985

Leakage Control

Line Pipe
GBE/PL Technical Specification for Steel Pipe 15 mm to 450 mm Inclusive Nominal Size for Operating Pressures up to 7 bar, 1992
GBE/L1 Technical Specification for Seamless Line Pipe 40 mm to 100 mm Inclusive Nominal Size for Operating Pressures greater than 7 bar, 1993
GBE/LX4 Technical Specification for Seamless Pipe 150 mm to 450 mm Inclusive Nominal Size for Operating Pressures greater than 7 bar, 1993
GBE/LX5 Technical Specification for Electric Welded Pipe 150 mm to 450 mm Inclusive Nominal Size for Operating Pressures greater than 7 bar, 1993

Noise
BGC/PS/N1 Notes for Guidance on the Evaluation of Environmental Noise, 1984

Pipework
BGC/PS/PW8 Specification for Pipework for Steam Tracing, 1983
BGC/PS/PW3 Code of Practice for Pipework and Associated Equipment for High Pressure Gas Storage Installations, 1984
GGE/PWC1 Technical Specification for Acoustic Cladding, 1993

Plastics
BGC/PS/PL2 Technical Specification for Polyethylene Pipes and Fittings for Natural Gas and Suitable Manufactured Gas, 1986

Pressure Vessels
BGC/PS/CP/PV6 Code of Practice for the Siting, Installation, Operation and
Maintenance of High Pressure Gas Receivers, 1976

GBE/PV3

Technical Specification for Pressure Vessels Manufactured to BS 5500 in Carbon, Ferritic Alloy and Austenitic Stainless Steels, 1993

GBE/V6

Procedures for the Assessment of Defects Using Fracture Mechanics Techniques for In-Service Pressure Vessels, 1993

Quality Assurance Procedures

BG/PS/Q4 Specification for Qualifications and Recommendations for Duties of Pipeline Inspectors, 1988

GBG/Q8

BG/PS/Q9 Specification for Identification System for Pipes and Associated Fittings Differing from their Specified Requirements, 1989

Safety

GBG/PS/CP/SND1 Code of Practice (Safety) for Non-Destructive Testing of Isolated and Purged High Pressure Gas Receivers, 1979

BG/PS/SFP1


BG/PS/SSW2

Code of Practice for Safe Working in the Vicinity of British Gas Transmission Pipelines and Associated Installations Operating at Pressures in Excess of 7 bar, 1984

BG/PS/SHA1

Code of Practice for Hazardous Area Classification for Natural Gas, 1986; Suppl., 1986

Testing

BG/PS/PT3 Procedure for Pressure Testing High Pressure Pipework, 1980

BG/PS/PT4

Code of Practice for Pressure Testing Above Ground Austenitic Stainless Steel Pipework (up to 300 mm Nominal Size) for Operation at Temperatures in the Range –196°C to 50°C, 1980

BG/PS/PT2

Procedure for Pre-Installation Testing of Pipes and Fittings, 1981

BG/PS/PT1

Procedure for Pressure Testing Pipework Installations, 1984

BGEC/PS/PT5

Procedures for Pressure Testing Small Bore Pipework, 1994

Transmission

BG/PS/TR2 Notes for Guidance on Monitoring the Condition of High Pressure Gas Transmission Pipelines, 1988

Valves


GBG/V6

Technical Specification for Steel Valves for Use with Natural Gas at Normal Operating Pressure above 7 bar, 1993

Welding

BG/PS/P5 Specification for Welding and Inspection of Austenitic Steel Pipework, 1976

BG/PS/P6

Specification for Welding and Inspection of Aluminium Alloy Pipework, 1976

BG/PS/CP/P12

Code of Practice for the Installation of Epoxy Resin Gruated End Seals on Steel Shaives on Operational Pipelines, 1977

BG/PS/P10


BG/PS/P11

Procedures for Inspection and Repair of Damaged Steel Pipelines Designed to Operate at Pressure above 7 bar, 1983

BG/PS/P9

Specification for the Welding of Fittings to Gas Pipelines under Pressure and having a Wall Thickness not less than 5 mm, 1984

BG/PS/P13

Specification for the Partial Penetration Butt Welding, Socket and Fillet Welding of Steel Pipe and Fittings for Operating Pressures up to 7 bar, 1984

BGES/P2

Technical Specification for Welding of Land Pipelines and Installations Designed to Operate at Pressures greater than 7 bar (incorporating BS 4515), 1994

BGS/PS

Standard Data Sheets

BG/PS/DAT11 Zinc Embrittlement of Austenitic Stainless Steel, 1983

BG/PS/DAT12

Aluminium Based Light Metals and Paints in Potentially Hazardous Areas, 1983

BG/PS/DAT24 Standards and Other Documentation Relating to Liquefied Petroleum Gas Plant, 1983

BG/PS/DAT1

Recommended Layout and Dimensions for New Fig Traps for On Line Inspection, 1990

GEB/PS/DAT29

Hard Stamping of Components and Pipes, 1991

DAT43

Magnetic Particle Inspection of Ferritic Components, 1992

GEB/PS/DAT30

Insulation Joints Using Insulated Flanges, 1992

GEB/PS/DAT31

Typical Requirements for Radio Telephones for In-Pipe Communications, 1992

GEB/PS/DAT15

Materials for Bolting and Jointing for Use with Carbon Steel Flanges, 1993

GEB/PS/DAT27

Propane Storage Vessels, 1994
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| BGES/DAT44 | Safety Valves to BS 6759: Part 3, 1984 | 5343: 1986–
| | | Pt 1: 1986 Specification for short term gas detector tubes  
| TIN1 | Bellows Expansion Joints, 1977 | Flashpoint of petroleum and related products  
| TIN10 | Recommended Bolting Procedures for Low Alloy Steel Studbolts, 1979 | Pt 5: 1990 Method for determination of flashpoint by Pensky–Martens closed tester  
| TIN16 | Liquid Metal Attack and its Significance for British Gas Plants, 1982 |  
| TIN19 | Recommendations for the Construction and Testing of Civil, Building, Mechanical and Electrical Works on Transmission Pipeline Installations, 1984 |  
| TIN20 | The Use of Bursting Discs on Pressure Systems and their Influence on Design Pressure and Working Pressure, 1984 |  
| TIN25 | Atmospheric Monitoring for Operational Safety, 1987 |  
| TIN26 | Materials and Impact Requirements to Avoid Brittle Fracture in Pipework at Temperatures down to –50°C, 1990 |  
| British Standards (London) |  |  
| Analytical Methods |  |  
| BS 1427: 1962 (1989) | Routine control methods of testing water used in industry |  
| 1747: 1969– | Methods for the measurement of air pollution |  
| 2000: 1982– | Methods of test for petroleum and its products  
| | Pt 0: 1982 General introduction  
| | Pt 35: 1993 Determination of open flash and fire point – Pensky–Martens method  
| | Pt 69: 1982 (1985) Reid vapour pressure of petroleum products  
| | Methods of testing water used in industry |  
| 2690: 1964– | Analysis of fuel gases |  
| 3156: 1969– | Method for the determination of vapour pressure of liquefied petroleum gases (LPG method) |  
| 3406: 1963– | Specification for liquid chlorine  
| | Liquefied petroleum gas  
| | Pt 1: 1987 Specification for commercial butane and propane  
<p>| | Pt 2: 1987 Specification for automotive LPG |<br />
| 3947: 1976 | Methods of sampling and test for liquefied anhydrous ammonia |<br />
| 4250: 1987 | Methods for sampling chemical products |<br />
| 4431: 1989 |  |<br />
| 5309: 1976– |  |<br />
| Buildings |  |<br />
| BS 1722: 1978– | Fences |<br />
| 5628: 1985– | Code of practice for use of masonry |<br />
| 5925: 1991 | Code of practice for ventilation principles and designing for natural ventilation |<br />
| 6651: 1992 | Code of practice for protection of structures against lightning |<br />
| 8313: 1989 | Code of practice for accommodation of building services in ducts |<br />
| Burners |  |<br />
| BS 799: 1981– | Oil burning equipment |<br />
| Centrifuges |  |<br />
| Chimneys |  |<br />
| BS 4076: 1989 | Specification for steel chimneys |<br />
| Civil Engineering |  |<br />
| BS 5930: 1981 | Code of practice for site investigations (replaces CP 2001) |<br />
| Gas detector tubes |  |<br />
| Pt 1: 1986 Specification for short term gas detector tubes |<br />
| Flashpoint of petroleum and related products |<br />
| Pt 2: 1986 Method for determination of flashpoint (closed cup equilibrium method) |<br />
| Pt 5: 1990 Method for determination of flashpoint by Pensky–Martens closed tester |<br />
| Boilers |  |<br />
| BS 759: 1984– | Valves, gauges and other safety fittings for application to boilers and to piping installations for and in connection with boilers |<br />
|  | Pt 1: 1984 Specification for valves, mountings and fittings |<br />
| | Specification for design and manufacture of water-tube steam generating plant (including super-heaters, reheaters and steel tube economizers) |<br />
| 1113: 1992 |  |<br />
| Buildings |  |<br />
| BS 1722: 1978– | Fences |<br />
| 5628: 1985– | Code of practice for use of masonry |<br />
| 5925: 1991 | Code of practice for ventilation principles and designing for natural ventilation |<br />
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| BS 799: 1981– | Oil burning equipment |<br />
| Centrifuges |  |<br />
| Chimneys |  |<br />
| BS 4076: 1989 | Specification for steel chimneys |<br />
| Civil Engineering |  |<br />
| BS 5930: 1981 | Code of practice for site investigations (replaces CP 2001) |<br />
| 5343: 1986– | Gas detector tubes |<br />
| 6664: 1986– | Flashpoint of petroleum and related products |<br />
| 1113: 1992 | Valves, gauges and other safety fittings for application to boilers and to piping installations for and in connection with boilers |<br />
| | Specification for design and manufacture of water-tube steam generating plant (including super-heaters, reheaters and steel tube economizers) |</p>
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<tr>
<td>6187</td>
<td>1982</td>
<td>Code of practice for demolition and repair of beams, columns, and concrete structures</td>
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<td>8004</td>
<td>1986</td>
<td>Code of practice for foundations and building materials</td>
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<td>8005</td>
<td>1987–</td>
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<td><strong>Cranes</strong></td>
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<td>BS 327: 1964 Specification for power-driven derrick cranes (obsolescent)</td>
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<td>466: 1984 Specification for power driven overhead travelling cranes, semi-goliath and goliath cranes for general use</td>
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<td>1757: 1986 Specification for power-driven mobile cranes</td>
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<td>2573: 1980–1986 Rules for the design of cranes</td>
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<td>2799: 1974 Specification for power-driven tower cranes for building and engineering construction (obsolescent)</td>
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<td>142: 1982–1986 Electrical protection relays</td>
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<td>775: 1974–- Specification for contactors</td>
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<td>951: 1986 Specification for clamps for earthing and bonding purposes</td>
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<td>2769: 1984– Low voltage switchgear and controlgear assemblies (obsolescent)</td>
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<td>2771: 1986– Electrical equipment for industrial machines</td>
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<td>5000: 1973– Rotating electrical machines of particular types or for particular applications</td>
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<td>5227: 1992 Specification for a.c. metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV</td>
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<td>6351: 1983 Code of practice for maintenance of electrical switchgear and controlgear for voltages up to and including 1 kV</td>
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<td>6626: 1985 (1993) Code of practice for maintenance of electrical switchgear and controlgear for voltages above 1 kV and up to and including 36 kV</td>
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<td>BS 12: 1991 Specification for Portland cements</td>
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<td>915: 1972– Specification for high alumina cement</td>
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<td>8110: 1985– Structural use of concrete</td>
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<td><strong>Condition Monitoring</strong></td>
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<td>BS 4675: 1976– Mechanical vibration in rotating machinery</td>
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<td>Pt 1: 1976 (1986) Basis for specifying evaluation standards for rotating machines with operating speeds from 10 to 200 revolutions per second</td>
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<td><strong>Construction</strong></td>
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<td>BS 5973: 1990 Code of practice for access and working scaffolds and special scaffold structures in steel</td>
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<td>7430: 1991 Code of practice for earthing and protection against lightning</td>
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<td>9000: 1989 General requirements for a system for electronic components of assessed quality</td>
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<td><strong>Conveyors</strong></td>
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<td>BS 490: 1975– Conveyors and conveyor belts</td>
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<td>2890: 1989 Specification for troughed belt conveyors</td>
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<td><strong>Environmental Management</strong></td>
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<td>BS 7750: 1992 Specification for environmental management systems</td>
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<td>BS 6713: 1986 Explosion protection systems</td>
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<td>Pt 1: 1986 Method for determination of explosion indices of combustible dusts in air</td>
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Fire Protection
BS 336: 1989

476: 1970– Specification for fire hose couplings and ancillary equipment
Fire tests on building materials and structures
Pt 5: 1979 Method of test for ignitability (not in current list)
Pt 6: 1989 Method of test for fire propagation of products
Pt 7: 1987 Method for classification of the surface spread of flame of products (not in current list)
Pt 8: 1972 Test methods and criteria for the fire resistance of elements of building construction
Pt 13: 1987 Method of measuring the ignitability of products subjected to thermal irradiance
Pt 20: 1987 Method for determination of the fire resistance of elements of construction (general principles)
Pt 21: 1987 Methods for determination of the fire resistance of load bearing elements of construction
Pt 22: 1987 Methods for determination of the fire resistance of non-load bearing elements of construction
Pt 24: 1987 Method for determination of the fire resistance of ventilation ducts
Pt 31: 1983– Methods of measuring smoke penetration through doorsets and shutter assemblies

750: 1984 Specification for underground fire hydrants and surface box frames and covers

2050: 1978 Specification for electrical resistance of conducting and anti-static products made from flexible polymeric material

3165: 1986 Specification for rubber and plastics suction hoses and hose assemblies for fire-fighting purposes
Specfication for first aid reel hoses for firefighting purposes
Specification for electrically conducting rubber flooring
Tests on electric cables under fire conditions
Fire hydrant systems equipment
Specification for lined industrial Vulcanized rubber boots
Specification for fire hose reels (water) for fixed installations
Fire extinguishing installations and equipment on premises
Pt 0: 1986 Guide for the selection of installed systems and other fire equipment
Pt 2: 1990 Specification for sprinkler systems
Pt 3: 1985 Code of practice for selection, installation and maintenance of portable fire extinguishers
Pt 4: 1986 Specification for carbon dioxide systems
Pt 5: 1982– Halon systems
Pt 6: 1988– Foam systems
Pt 6.1: 1988 Specification for low expansion foam systems
Pt 6.2: 1989 Specification for medium and high expansion foam systems
Pt 7: 1988 Specification for powder systems
Specification for portable fire extinguishers
Components of automatic fire detection systems
Specification for electrically conducting and anti-static rubber footwear (withdrawn—replaced by BS 5145 and BS 7193)
Fire safety signs, notices and graphic symbols
Fire precautions in the design and construction of buildings
Pt 4: 1978 Code of practice for smoke control in protected escape routes using pressurization
Pt 5: 1991 Code of practice for firefighting stairways and lifts
Pt 9: 1989 Code of practice for ventilation and air conditioning ductwork
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<td>5908: 1990</td>
<td>Code of practice for fire precautions in chemical plant (replaces CP 3013)</td>
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<td>6020: 1981–</td>
<td>Instruments for the detection of combustible gases (replaced by BS EN 50054–50058)</td>
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<td>6266: 1982</td>
<td>Code of practice for fire protection for electronic data processing installations</td>
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<td>6643: 1985–</td>
<td>Recharging fire extinguishers</td>
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<td>6651: 1992</td>
<td>Code of practice for protection of structures against lightning</td>
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<td>7193: 1989</td>
<td>Specification for lined light-weight rubber overshoes and overboots</td>
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<td>7273:</td>
<td>Code of practice for the operation of fire protection measures Pt 1: 1990 Electrical actuation of gaseous total flooding extinguishing systems</td>
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**Flame Arresters**

BS 7244: 1990 Specification for flame arresters for general use

**Glossaries**


- Welding terms and symbols
- Glossary of terms used in automatic controlling and regulating systems

1846: 1968–

- Glossary of terms relating to solid fuel burning equipment

2474: 1983

- Recommendations for names for chemicals used in industry

2737: 1956 (1985)

- Terminology of internal defects in castings as revealed by radiography

3015: 1991

- Glossary of terms relating to mechanical vibration and shock

3138: 1992

- Glossary of terms used in management services

3455: 1973

- Glossary of terms used in nuclear science and technology

3533: 1981

- Glossary of thermal insulation terms

3683: 1965–

- Glossary of terms used in non-destructive testing

3810: 1964–

- Glossary of terms used in materials handling

3811: 1984

- Glossary of maintenance management terms in terotechnology

3851: 1990

- Glossary of terms used in the mechanical balancing of rotating machinery

4200: 1967–

- Guide on the reliability of electronic components and parts used therein (all parts withdrawn – see BS 4778)

4422: 1975–

- Glossary of terms associated with fire

4547: 1972

- Classification of fires (withdrawn)

4727: 1971–

- Electrotechnical, power, tele-communications, electronics, lighting and colour terms

4778: 1987–

- Quality vocabulary Pt 3 1991– Availability, reliability and maintainability terms

5233: 1986

- Glossary of terms used in metrology (incorporating BS 2843)

5643: 1984

- Glossary of refrigeration, heating, ventilating and air-conditioning terms

6100: 1984–

- Glossary of building and civil engineering terms

6562: 1985–

- Terms used in the iron and steel industry Pt 1: 1985 Glossary of heat treatment terms

6927: 1988

- Glossary of terms for respiratory protective devices (replaced by BS EN 132: 1991)

**Hazardous Area Classification, Flameproofing, Intrinsic Safety**

BS 229: 1957

- Specification. Flameproof enclosure of electrical apparatus (obsolescent)


- Specification for flameproof electric light fittings (withdrawn)

1259: 1958

- Intrinsically safe electrical apparatus and circuits for use in explosive atmospheres (obsolescent)

3101: 1986

- Specification for control and interlock circuits primarily associated with flameproof restrained plugs and sockets for use in coal mines

4137: 1967

- Guide to the selection of electrical equipment for use in Division 2 areas (obsolescent)

4683: 1971–

### Appendix 27/14 Standards and Codes

**5308: 1986-5345: 1977-**

- **Instrumentation cables**
  - Code of practice for the selection, installation and maintenance of electrical equipment for use in potentially explosive atmospheres (other than mining applications or explosive processing and manufacture)
- **Heat Exchangers**
  - BS 3274: 1960 Specification for tubular heat exchangers for general purposes
- **Hoses and Hose Couplings**
  - BS 1102: 1991 Specification for rubber hose for water suction and discharge hose with smooth or corrugated exterior
  - 1435: 1987- Rubber hose assemblies for oil suction and discharge services
  - 2952: 1958 Rubber hose for i.c. engine cooling systems
  - 3158: 1985 Specification for rubber hoses and hose assemblies for aircraft ground fuelling and defuelling
  - 3169: 1986 Specification for first aid reel hoses for fire fighting purposes
  - 3212: 1991 Specification for flexible rubber tubing and rubber hose assemblies for use in LPG vapour phase and LPG/air installations
  - 3395: 1989 Specification for electrically bonded hose and hose assemblies for dispensing petroleum based fuels
  - 3492: 1987 Specification for road and rail tanker hoses and hose assemblies for petroleum products, including aviation fuels
  - 4089: 1989 Specification for rubber hose and hose assemblies for liquefied petroleum gas lines
  - 4586: 1992 Specification for spiral wire reinforced rubber covered hydraulic hoses and hose assemblies
- **6182: 1982-**
  - Intrinsic safety power supplies for use in coal mines
  - 6941: 1988 Specification for electrical apparatus for explosive atmospheres with type of protection N

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**5501: 1977-**

- **Electrical apparatus for potentially explosive atmospheres**
  - Pt 1: 1977 General requirements (not in current list)
  - Pt 2: 1977 Oil immersion ‘o’
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  - 5120: 1987 Rubber hose for gas welding and allied processes
  - 5122: 1986 Specification for rubber hoses for low-pressure and medium-pressure saturated steam
  - 5173: 1985- Methods of test for rubber and plastics hoses and hose assemblies
5244: 1986 (1991) Recommendations for application, storage and life expiry of hydraulic rubber hoses and assemblies

5274: 1985 Specification for fire hose reels (water) for fixed installations

5306: 1976– Fire extinguishing installations and equipment on premises

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BS 381C: 1988 Specification for colours for identification, coding and special purposes

822: 1964– Terminal markings for electrical machinery and apparatus


2770: 1986 Specification for pictorial marking of handling instructions for goods in transit

3510: 1968 Specification for a basic symbol to denote the actual or potential presence of ionizing radiation

5378: 1980– Safety signs and colours


Instrumentation

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1042: 1983– Methods of measurement of fluid flow in closed conduits


3693: 1992 Recommendations for the design of scales and indexes on analogue indicating instruments

4509: 1985 Methods for evaluating the performance of transmitters for use in industrial-process control systems

5793: 1979– Industrial-process control valves

5863: 1980– Analogue signals for process control systems

6739: 1986 Code of practice for instrumentation in process control systems: installation design and practice

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BS 3958: 1972– Thermal insulating materials

5422: 1990 Method for specifying thermal insulating materials on pipes, ductwork and equipment in the temperature range −40°C to +700°C

5970: 1992 Code of practice for thermal insulation of pipework and equipment (in the temperature range −100°C to +870°C)

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BS 4402: 1982 Specification for safety requirements for laboratory centrifuges

BS 7258: 1990– Laboratory fume cupboards

Lasers

BS 7192: 1989 Specification for radiation safety of laser products (replaced by BS EN 60825)

Lifting Equipment

BS 302: 1987– Stranded steel wire ropes

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3113: 1959 (1985) Specification for alloy steel chain, grade 60. Short link for lifting purposes


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437: 1978 Specification for cast iron spigot and socket drain pipes and fittings
778: 1966 Steel pipes and joints for hydraulic purposes (obsolescent)
806: 1990 Specification for design and construction of ferrous piping installations for and in connection with land boilers
1471: 1972 Specification for wrought aluminium and aluminium alloys for engineering purposes – drawn tube

4504: 1989– Circular flanges for pipes, valves and fittings (FN designated)
4772: 1988 Specification for ductile iron pipes and fittings
4882: 1990 Specification for bolting for flanges and pressure containing purposes
5222: 1975– Specification for aluminium piping systems (withdrawn)
5292: 1980 Specification for jointing materials and compounds for installations using water, low pressure steam or 1st, 2nd and 3rd family gases
5480: 1990 Specification for glass reinforced plastics (GRP) pipes, joints and fittings for use for water supply or sewerage

1560: 1989– Circular flanges for pipes, valves and fittings (Class designated)
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1782: 1951 Specification for couplings for suction and delivery hose (1/4 in. to 8 in. nominal sizes) other than fire hose couplings (obsolescent)

1832: 1992 Specification for compressed asbestos fibre jointing
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2464: 1968– Hose couplings for petrol, oil and lubricants
2815: 1973 Specification for compressed asbestos fibre jointing (replaced by BS 1832)
3063: 1965 Specification for dimensions of gaskets for pipe flanges (obsolescent)

3293: 1960 (1990) Specification for carbon steel pipe flanges (over 24 in. nominal size) for the petroleum industry

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Pt 10: 1993– Guide to reliability testing

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<td>BS CP 3: 1950–</td>
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<td>Electrical Engineering</td>
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Pt 1: 1964 Choice, installation and maintenance of flameproof and intrinsically-safe equipment (obsolescent)

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**Mechanical Engineering**

BS CP 3009: 1970 Thermally insulated underground piping systems

3010: 1972 Code of practice for safe use of cranes (mobile cranes, tower cranes, and derrick cranes)

**British Standards Handbooks**


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BS PD 2379: 1982 Register of colours of manufacturers’ identification threads for electric cables and cords

3542: 1988 The operation of standards in a company

6433: 1969 Guide to the application of stress analysis to design

6437: 1969 A review of design methods given in present standards and codes and design proposals for nozzles and openings in pressure vessels

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50054: 1991 Electrical apparatus for the detection and measurement of combustible gases. General requirements and test methods

50055: 1991 Electrical apparatus for the detection and measurement of combustible gases. Performance requirements for Group I apparatus indicating up to 5% (v/v) methane in air

50056: 1991 Electrical apparatus for the detection and measurement of combustible gases. Performance requirements for Group I apparatus indicating up to 100% methane

50057: 1991 Specification for electrical apparatus for the detection and measurement of combustible gases. Performance requirements for Group II apparatus indicating up to 100% lower explosive limit

50058: 1991 Electrical apparatus for the detection and measurement of combustible gases. Performance requirements for Group I apparatus indicating up to 100% gas

60825: 1992 Radiation safety of laser products, equipment classification and user’s guide

**Chemical Industry Safety and Health Council (London)**

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1975 Codes of Practice for Chemicals with Major Hazards: Ethylene Dichloride

1975 Codes of Practice for Chemicals with Major Hazards: Ethylene Oxide

1975 Codes of Practice for Chemicals with Major Hazards: Phosgene

1978 Codes of Practice for Chemicals with Major Hazards: Acrylonitrile

**Det Norske Veritas (Stavanger, Norway)**

**Recommended Practices**


RP C202 Relief, Depressuring and Disposal Systems, 1987
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<td>Imperial Chemical Industries plc (publication – Birmingham: Roy. Soc. Prevention of Accidents)</td>
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IEEE 841–1986  Recommended Practice for Chemical Industry Severe Duty Squirrel-Cage Induction Motors – 600 Volts or Below


IEEE 944–1986  Recommended Practice for the Application and Testing of Uninterruptible Power Supplies for Power Generating Stations


IEEE 982.1–1988  Standard Dictionary of Measures to Produce Reliable Software

IEEE 1012–1987  Software Verification and Validation Plans

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IEEE 1028–1988  Software Reviews and Audits


IEEE 1058.1–1987  Software Project Management Plans

IEEE 1063–1989  Software User Documentation

IEEE 1202–1991  Flame Testing of Cables for Use in Cable Trays in Industrial and Commercial Occupancies

Guides

IEEE 518 1982  Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources

1990 Measuring Electrical Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

Institute of Petroleum (publication – Barking, Essex: Applied Science Publishers)

IP Model Code of Safe Practice in the Petroleum Industry (earlier editions)

Pt 1  Electrical Safety Code, 5th ed., 1966

Electrical Code Instrumentation supplement

2  Marketing Safety Code, 2nd ed., 1965

3  Refining Safety Code, 2nd ed., 1965


12  Pressure Vessel Inspection Safety Code, 1976

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9  Liquefied Petroleum Gas Safety code Vol.1 Large Bulk Pressure Storage and Refrigerated LPG, 2nd ed., 1987


14  Inspection and Testing of Protective Instrumentation Systems, 1980

15  Area Classification Code for Petroleum Installations, 1990

16  Tank Cleaning Safety Code, 1989

17  Well Control during the Drilling and Testing of High Pressure Offshore Wells, 1992

18  Occupational Health, 1993

19  Fire Precautions at Petroleum Refineries and Bulk Storage Installations, 1995

European Model Code of Safe Practice in the Petroleum Industry

Storage and Handling of Petroleum Products.

Pt 1  Operations, 1973 (not in current list)

2  Design, Layout and Construction, 1980

Other codes

Code of practice for the development of a response plan for serious incidents involving petroleum product road tankers, 1989  1

Code of practice for the investigation and mitigation of possible petroleum-based land contamination, 1993  2

Code of practice for occupational hygiene audits, 1993  3

Code of practice for compatibility in design and operation of road tank vehicles equipped for bottom loading, vapour collection and overfill prevention, 1994  4

Code of practice for on-board computer systems for petroleum road tankers, 1994  5
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<th>Instrument Society of America (Research Triangle Park, NC)</th>
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<td>ISA RP7.7–1984 Producing Quality Instrument Air</td>
<td>Safety in Chemical Tankers, 1977 Item 1</td>
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<td>ISA S5.5–1985 Graphic Symbols for Process Displays</td>
<td>Contingency Planning and Crew Response Guide for Gas Carrier Damage at Sea and in Port Approaches, 1989 7</td>
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<td>ISA S67.01–1979 (1987) Transducer and Transmitter Installation for Nuclear Safety Applications</td>
<td>Some of the above items are joint publications with the Oil Companies International Marine Forum (OCIMF) and/or the Society of International Gas Tanker and Terminal Operators (SIGTTO). See separate entries for publications solely by these latter bodies.</td>
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<td>ISA S67.02–1980 Nuclear Safety-Related Instrument Sensing Line Piping and Tubing Standards</td>
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<td>ISA S67.03–1982 Light Water Reactor Coolant Pressure Boundary Leak Detection</td>
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<td>ISA S75.01–1985 Flow Equations for Sizing Control Valves</td>
<td>IEC SC65A WG9 1991 Software for computers in the application of industrial-safety related systems</td>
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<td>ISA S75.05–1983 Control Valve Terminology</td>
<td>1987 Software for computers in the safety systems of nuclear power stations</td>
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<td>ISA S75.15–1986 Face-to-Face Dimensions for Buttweld-End Globe-Style Control Valves (ANSI Classes 150, 300, 600, 900, 1500 and 2500)</td>
<td>IEC Std 1025 Fault tree analysis</td>
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<td>ISA S75.15–1987 Face-to-Face Dimensions for Flanged Globe-Style Control Valve Bodies (ANSI Classes 800, 1500 and 2500)</td>
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<td>ISA S82.01–1988 Electric and Electronic Test, Measuring, Controlling and Related Equipment General Requirements</td>
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International Standards Organisation
(Geneva)

ISO 1940: 1986  Mechanical vibration – balance qual-
ity requirements for rigid rotors
Part 1 Determination of permissible residual imbalance
ISO 2371: 1974  Field balancing equipment: descrip-
tion and evaluation
ISO 2953: 1985  Balancing machines: description and evaluation
ISO 3945: 1985  Mechanical vibration of large rotat-
ing machines with speed range from 10 to 200 r/s: measure-
ment and evaluation of vibration severity in situ
ISO 4126: 1991  Safety valves
ISO 6718: 1991  Bursting discs and disc devices
ISO 9000: 1987  Quality management and quality assurance standards – guidelines for selection and use
ISO 9000-3: 1987  Quality management and quality assurance standards – guidelines for the application of ISO 9000 to the development, supply and maintenance of software
ISO 9001: 1987  Quality systems – model for quality assurance in design/development, production, installation and servicing
ISO 9002: 1987  Quality systems – model for quality assurance in production and instal-
lation
ISO 9003: 1987  Quality systems – model for quality assurance in final inspection and test
ISO 9004: 1987  Quality management and quality system elements – guidelines
ISO 10011: 1990– Guidelines for auditing quality systems

Liquefied Petroleum Gas Industry Technical Association
(London)

LPG Codes of Practice
1  Installation and Maintenance of Fixed Bulk LPG Storage at Consumers’ Premises
   Part 1 Design and Installation, 1991
   Part 3 Periodic Inspection and Testing, 1986
2  Safe Handling and Transport of LPG by Road, 1974
3  Prevention and Control of Fire Involving LPG, 1972
7  Storage of Full and Empty LPG Cylinders and Cartridges, 1986
9  LPG–Air Plants, 1979
12  Filling of LPG Cylinders at Depots, 1989
14  Hoses for the Transfer of LPG in Bulk – Installation, Operation, Inspection, Testing and Maintenance, 1984
15  Safety Valves for LPG Cylinders
   Part 1 Valves for LPG Cylinder, 1979
   Part 2 Outlet Valves for Butane Cylinders – Quick Coupling Types, 1992
17  Purging LPG Vessels and Systems, 1980
19  Liquid Measuring Systems for LPG, 1982
22  LPG Piping System Design and Installation, 1990
26  The Carriage by Road of Static LPG Vessels, 1991

National Fire Protection Association
(Quincy, MA)

NFPA 1 1992  Fire Prevention Code
10 1990  Portable Fire Extinguishers
11 1988  Low Expansion Foam and Combined Agent Systems
11A 1988  Medium and High Expansion Foam Systems
11C 1990  Mobile Foam Apparatus
12 1993  Carbon Dioxide Extinguishing Systems
12A 1992  Halon 1301 Fire Extinguishing Systems
12B 1990  Halon 1211 Fire Extinguishing Systems
13 1991  Installation of Sprinkler Systems
13A 1987  Inspection, Testing and Maintenance of Sprinkler Systems
14 1993  Standpipe and Hose Systems
14A 1989  Inspection, Testing and Maintenance of Standpipe and Hose Systems
15 1990  Water Spray Fixed Systems
16 1991  Deluge Foam-Water Sprinkler and Spray Systems
16A 1988  Installation of Closed-Head Foam-Water Sprinkler Systems
17 1990  Dry Chemical Extinguishing Systems
17A
18 1990  Wetting Agents
20 1990  Installation of Centrifugal Fire Pumps
22 1993  Water Tanks for Fire Protection
30 1990  Flammable and Combustible Liquids Code
31 1992  Installation of Oil Burning Equipment
37 1990  Stationary Combustion Engines and Gas Turbines
43A 1990  Storage of Liquid and Solid Oxidizers
43B 1993 Storage of Organic Peroxide Formulations
43C 1986 Storage of Gaseous Oxidizing Materials
45 1991 Fire Protection for Laboratories Using Chemicals
49 1991 Hazardous Chemical Data
50 1990 Bulk Oxygen Systems at Consumer Sites
50A 1989 Gaseous Hydrogen Systems at Consumer Sites
50B 1989 Liquefied Hydrogen Systems at Consumer Sites
51B 1989 Cutting and Welding Processes
53M 1990 Fire Hazards in Oxygen-Enriched Atmospheres
54 1992 National Fuel Gas Code
55 1993 Storage, Use and Handling of Compressed and Liquefied Gases in Portable Containers
58 1992 Storage and Handling of Liquefied Petroleum Gases
59 1992 Storage and Handling of Liquefied Petroleum Gases at Utility Gas Plants
59A 1990 Production, Storage and Handling of Liquefied Natural Gas
61A 1989 Fires and Dust Explosions in Facilities Manufacturing and Handling Starch
61B 1989 Fires and Explosions in Grain Elevators and Facilities Handling Bulk Raw Agricultural Commodities
68 1994 Deflagration Venting
69 1992 Explosion Prevention Systems
70 1993 National Electrical Code
70B 1990 Electrical Equipment Maintenance
72E 1990 Automatic Fire Detectors
75 1992 Protection of Electronic Computer/Data Processing Equipment
77 1988 Static Electricity
79 1991 Electrical Standard for Industrial Machinery
80 1990 Fire Doors and Windows
80A 1992 Exterior Fire Exposures
85H 1989 Combustion Hazards in Atmospheric Fluidized Bed Combustion System Boilers
86 1990 Ovens and Furnaces
86C 1991 Industrial Furnaces Using Special Processing Atmosphere
90A 1993 Installation of Air Conditioning and Ventilation Systems
91 1992 Blower and Exhaust Systems for Dust, Stock and Vapor Removal or Conveying
92A 1988 Smoke Control Systems
92B 1991 Smoke Management Systems
99C 1993 Gas and Vacuum Systems
101M 1992 Alternative Approaches to Life Safety
110 1993 Emergency and Standby Power Systems
111 1993 Stored Energy Emergency and Standby Power Systems
214 1992 Water-Cooling Towers
220 1992 Standard Types of Building Construction
231 1990 General Storage
231C 1991 Rack Storage of Materials
232 1991 Protection of Records
241 1989 Safeguarding Building Construction and Demolition Operations
251 1990 Fire Tests of Building Construction and Materials
258 1989 Research Test Method of Determining Smoke Generation of Solid Materials
262 1990 Method of Test for Fire and Smoke Characteristics of Wires and Cables
291 1988 Fire Flow Testing and Marking of Hydrants
306 1993 Control of Gas Hazards on Vessels
307 1990 Marine Terminals, Piers and Wharves
321 1991 Basic Classification of Flammable and Combustible Liquids
325M 1991 Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids
326 1993 Safe Entry of Underground Storage Tanks
327 1993 Cleaning or Safeguarding Small Tanks and Containers
328 1992 Flammable and Combustible Liquids and Gases in Manholes, Sewers and Similar Underground Structures
329 1992 Underground Leakage of Flammable and Combustible Liquids
385 1990 Tank Vehicles for Flammable and Combustible Liquids
386 1990 Portable Shipping Tanks for Flammable and Combustible Liquids
471 1992 Responding to Hazardous Materials Incidents
472 1992 Professional Competence of Responders to Hazardous Materials Incidents
490 1993 Storage of Ammonium Nitrate
491M 1991 Hazardous Chemical Reactions
495 1992 Explosive Materials Code
496 1993 Purged and Pressurised Enclosures for Electrical Equipment
497A 1992 Classification of Class I Hazardous Locations for Electrical Installations in Chemical Plants
497B 1991 Recommended Practice for the Classification of Class II Hazardous (Classified) Locations for Electrical Installations in Chemical Plants
497M 1991 Classification of Gases, Vapors and Dusts for Electrical Equipment in Hazardous (Classified) Locations
498 1992 Explosives Motor Vehicle Terminals
505  1992  Powered Industrial Trucks, Including
     Type Designations, Areas of Use,
     Maintenance and Operation
512  1990  Truck Fire Protection
513  1990  Motor Freight Terminals
550  1986  Fire Safety Concepts Tree
601  1992  Guard Service in Fire Loss Prevention
650  1990  Pneumatic Conveying Systems for
     Handling Combustible Materials
651  1987  Manufacture of Aluminum and
     Magnesium Powder
654  1988  Prevention of Fire and Dust
     Explosions in the Chemical, Dye,
     Pharmaceutical and Plastics Industries
655  1988  Sulfur Fires and Explosions
704  1990  Identification of the Fire Hazards of
     Materials
801  1991  Facilities Handling Radioactive
     Materials
803  1993  Light Water Nuclear Power Plants
820  1992  Fire Protection in Wastewater
     Treatment Plants
850  1992  Fossil Fueled Steam and Combustion
     Turbine Electric Generating Plants
901  1990  Uniform Coding for Fire Protection
902M  1990  Fire Reporting Field Incident Manual
1404 1989  Fire Department Self-Contained
     Breathing Apparatus Program
1405 1990  Guide for Land-Based Fire Fighters
     Who Respond to Marine Vessel Fires
1410 1988  Training Standard on Initial Fire
     Attack
1561 1990  Standard on Fire Department Incident
     Management System
1661 1992  Fire Hose
1662 1993  Care, Use, and Maintenance of Fire
     Hose Including Connections and
     Nozzles
1664 1993  Spray Nozzles (Shut Off and Tip)
1991 1990  Standard on Vapor-Protective Suits for
     Hazardous Chemicals Emergencies
1992 1990  Standard on Liquid Splash-Protective
     Suit for Hazardous Chemicals
     Emergencies
1993 1990  Standard on Support Function
     Protective Garments for Hazardous
     Chemicals
2001 1994  Clean Agent Fire Extinguishing
     Systems

The following codes do not appear in the current list:
NFPA 78  1989  Lightning Protection Code
85A  1987  Prevention of Furnace Explosions in
     Fuel-Oil and Natural Gas-Fired Single
     Burner Boiler-Furnaces
85B  1989  Prevention of Furnace Explosions in
     Natural Gas-Fired Multiple Burner
     Boiler-Furnaces
85D  1989  Prevention of Furnace Explosions in
     Oil-Fired Multiple Burner Boiler-
     Furnaces
85E  1985  Prevention of Furnace Explosions in
     Pulverized Coal-Fired Multiple Burner
     Boiler-Furnaces

85F  1988  Installation and Operation of
     Pulverized Fuel Systems
85G  1987  Furnace Implosions in Multiple Burner
     Boiler-Furnaces
110A 1989  Stored Energy Emergency and
     Standby Power Systems (see NFPA 111)
602  1986  Guard Operations in Fire Loss
     Prevention

Oil Companies International Marine Forum
     (London)

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Disabled Tankers – Report of Studies on Ship
     Drift and Towing, 1981  1
Drift Characteristics of 50000 to 70000 DWT
     Tankers, 1982  2
Safety Guide for Terminals Handling Ships
     Carrying Liquefied Gases in Bulk, 1982  3
Marine and Terminal Operations Survey
     Guidelines, 1983  4
Design and Construction Specification of Marine
     Loading Arms, 2nd ed., 1987  5
Guide on Marine Terminal Fire Protection and
     Emergency Evacuation, 1987  6
Recommendations for Manifolds for
     Refrigerated Liquefied Gas Carriers for Cargoes
     from 0°C to minus 104°C, 2nd ed., 1987  7
Inspection Guidelines for Bulk Carriers, 1989  8
Guidelines for the Preparation of Shipboard
     Oil Spill Contingency Plans, 1990  9
Inspection Guidelines for Ships Carrying
     Liquefied Gases in Bulk, 1990  10
Guide to Purchasing, Manufacturing and
     Testing of Loading and Discharge Hoses
     for Offshore Moorings, 4th ed. (formerly the
     Hose Standards), 1991  11
Recommendations for Oil Tanker
     Manifolds and Associated Equipment, 4th
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These publications are available from the International
     Chamber of Shipping (q.v.)

Society of International Gas Tanker and Terminal
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Hydrates in LPG Cargoes, 1984  1
Cargo Firefighting on Liquefied Gas
     Carriers, 1986  2
Liquefied Gas Handling Principles on
     Ships and in Terminals, 1986  3
Guidelines for the Alleviation of
     Excessive Surge Pressure in ESD, 1987  4
Recommendations and Guidelines for
     Linked Ship/Shore Emergency Shutdown
     of Liquefied Gas Cargo Transfer, 1987  5

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Tubular Exchangers Manufacturers Association

TEMA B78.1–1982 Tubular Heat Exchangers in Chemical
     Process Service
| UL 1 1985 | Flexible Metal Conduit | US Armed Forces |
| UL 21 1986 | LP-Gas Hose | MIL-HDBK-189 Reliability Growth Management |
| UL 96 1988 | Lightning Protection Components | MIL-HDBK-472 Maintainability Prediction |
| UL 130 1990 | Electrical Heating Pads | MIL-STD-470 Maintainability Program Requirements (for Systems and Equipment) |
| UL 142 1987 | Steel Aboveground Tanks for Flammable and Combustible Liquids | MIL-STD-471 Maintainability Demonstration Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety |
| UL 144 1985 | Pressure Regulating Valves for LP Gas | MIL-STD-756 Reliability Prediction |
| UL 217 1985 | Single and Multiple Station Smoke Detectors | MIL-STD-781A Reliability Tests: Exponential Distributions Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors and Safety |
| UL 268A 1985 | Protective Signaling Systems Smoke Detectors for Duct Applications | MIL-STD-1388-1A Logistic Support Analysis Human Engineering Design |
| UL 467 1984 | Grounding and Bonding Equipment | MIL-STD-1629A Procedures for Performing a Failure Modes, Effects and Criticality Analysis |
| UL 555 1989 | Fire Dampers | MIL-STD-1472 Human Engineering Design |
| UL 723 1086 | Test for Surface Burning Characteristics of Building Materials | MIL-STD-1629A Procedures for Performing a Failure Modes, Effects and Criticality Analysis |
| UL 781 1992 | Portable Electric Lighting Units for Use in Hazardous (Classified) Locations | MIL-STD-38130 Design of safe equipment and machinery |
| UL 844 1990 | Electric Lighting Fixtures for Use in Hazardous (Classified) Locations | | |
| UL 924 1990 | Emergency Lighting and Power Equipment | | |
| UL 1004 1988 | Electric Motors | | |
| UL 1012 1988 | Power Supplies | | |
| UL 1247 1991 | Diesel Engines for Driving Centrifugal Fire Pumps | | |
| UL 1316 1986 | Glass-Fiber-Reinforced Plastic Underground Storage Tanks for Petroleum Products | | |
| UL 1478 1988 | Fire Pump Relief Valves | | |
| UL 1709 1991 | Rapid Rise Fire Tests for Protection Materials for Structural Steel | | |
| UL 1778 1991 | Uninterruptible Power Supply Equipment | | |
| There are a number of UL standards for equipment for use in hazardous areas, including UL 674, UL 698, UL 823, UL 844, and UL 1002 | | |
VDI 2263: Dust fires and explosions: hazards, assessment, protective measures
Pt 1: 1990 Test methods for the determination of the safety characteristic of dusts
Pt 2: 1992 Inerting
Pt 3: 1990 Pressure shock resistant vessels and apparatus: calculation, construction and tests
Pt 4: 1992 Suppression of dust explosions

VDI 3673: 1979 The pressure relief of dust explosions
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(VDI 2263 and 3673 are part of VDI Handbuch Reinhaltung der Luft, vol.6)
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<tr>
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<td>Documentation for the Biological Exposure Indices (BEIs)</td>
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<td>Documentation for the Physical Agents Threshold Limit Values</td>
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<td>Documentation of Threshold Limit Values and Biological Exposure Indices, 6th ed.</td>
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PM 23 Photo-electric safety systems, 1981  
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PM 27 Construction hoists, 1981 (not in current list)  
PM 28 Working platforms on fork lift trucks, 1981  
PM 29 Electrical hazards from steam/water pressure cleaners, rev., 1988  
PM 30 Suspended access equipment, 1983  
PM 32 Safe use of portable electrical apparatus, 1990  
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PM 53 Emergency private generation: electrical safety, 1985  
PM 54 Lifting gear standards, 1985  
PM 56 Noise from pneumatic systems, 1985  

PM 58 Diesel engined lift trucks in hazardous areas, 1986  
PM 60 Steam boiler blowdown systems, 1987  
PM 64 Electrical safety in arc welding, 1986  
PM 65 Worker protection at crocodile (alligator) shears, 1986  
PM 73 Safety at autoclaves, 1990  
PM 75 Glass reinforced plastic vessels and tanks: advice to users, 1991  

**Guidance Booklets**  
HS(G) 3 Highly flammable materials on construction sites, 1978  
HS(G) 5 Hot work: welding and cutting on plant containing flammable materials, 1979  
HS(G) 6 Safety in working with lift trucks, 1979  
HS(G) 7 Container terminals: safe working practice, 1980  
HS(G) 11 Flame arresters and explosion reliefs, 1980  
HS(G) 12 Offshore construction: health, safety and welfare, 1980  
HS(G) 13 Electrical testing: safety in electrical testing, 1980 (not in current list)  
HS(G) 15 Storage of liquefied petroleum gas at factories, 1981 (not in current list)  
HS(G) 16 Evaporating and other ovens, 1981  
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HS(G) 20 Guidelines for occupational health services, 1982  
HS(G) 22 Electrical apparatus for use in potentially explosive atmospheres, 1984  
HS(G) 25 Control of Industrial Major Accident Hazards Regulations 1984 (CIMAHR): further guidance on emergency plans, 1985  
HS(G) 26 Transport of dangerous substances in tank containers, 1986  
HS(G) 27 Substances for use to work: provision of information, 1985  
HS(G) 28 Safety advice for bulk chlorine installations, 1986  
HS(G) 30 Storage of anhydrous ammonia under pressure in the United Kingdom: spherical and cylindrical vessels  
HS(G) 34 Storage of LPG at fixed installations, 1987  
HS(G) 37 Introduction to local exhaust ventilation, 1987  
HS(G) 38 Lighting at work, 1987  
HS(G) 39 Compressed air safety, 1990  
HS(G) 40 Chlorine from drums and cylinders, 1987  
HS(G) 43 Industrial robot safety, 1988  
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HS(G) 52 The storage of flammable liquids in fixed tanks (exceeding 10,000 m³ total capacity), 1991  
HS(G) 53 Respiratory protective equipment: a practical guide for users, 1990  
HS(G) 54 The maintenance, examination and testing of local exhaust ventilation, 1990  
HS(G) 56 Noise at work. Noise assessment, information and control, 1990
HS(G) 61 Surveillance of people exposed to health risk at work, 1990
HS(G) 64 Assessment of fire hazards from solid materials and the precautions required for their safe storage and use, 1991
HS(G) 65 Successful health and safety management, 1991
HS(G) 71 Storage of packed dangerous substances, 1992
HS(G) 78 Container packing, 1992
HS(G) 96 The costs of accidents at work, 1993

Regulations Booklets
HS(R) 1 Packaging and Labelling of Dangerous Substances – Regulations and Guidance Notes, 1978
HS(R) 3 Guide to tanker marking regulations, 1979
HS(R) 6 Guide to the HSW Act, 1983
HS(R) 8 Guide to the Diving Operations at Work Regulations 1981, 1981
HS(R) 11 First-aid at work, 1981
HS(R) 13 Guide to the Dangerous Substances (Conveyance by Road in Road Tankers) Regulations 1981, 1981
HS(R) 14 Guide to the Notification of New Substances Regulations 1982, 1982
HS(R) 15 Administrative guidance on the implementation of the European Community ‘Explosive Atmospheres’ Directive (76/117/EEC and 79/196/EEC), 1983
HS(R) 16 Guide to the Notification of Installations Handling Hazardous Substances Regulations 1982, 1983
HS(R) 17 Guide to the Classification and Labelling of Explosives Regulations 1983, 1983
HS(R) 18 Administrative guidance on the application of the European Community ‘Low Voltage’ Directive (73/23/EEC) to electrical equipment for use at work in the United Kingdom, 1984
HS(R) 19 Guide to the Asbestos (Licensing) Regulations 1983, 1984
HS(R) 21 Guide to the Control of Industrial Major Accident Hazards Regulations 1984, 1985
HS(R) 22 Guide to the Classification, Packaging and Labelling of Dangerous Substances Regulations 1984, 1985
HS(R) 23 Guide to the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1985, 1986
HS(R) 24 Guide to the Road Transport (Carriage of Dangerous Substances in Packages, etc.) Regulations 1986, 1987
HS(R) 25 Memorandum of guidance on the Electricity at Work Regulations 1989, 1989
HS(R) 27 A Guide to Dangerous Substances in Harbour Regulations 1987, 1988
HS(R) 29 Notification and marking of sites. The Dangerous Substances (Notification and Marking of Sites) Regulations, 1990


Hazard Analysis Reports
HA 3 Sizewell B: A Review by HM Nuclear Installations Inspectorate of the Preconstruction Safety Report, 1982
HA 4 PWR: A Report by the Health and Safety Executive to the Secretary of State for Energy on a Review of the Generic Safety Issues of Pressurised Water Reactors, 1979
HA 5 Nuclear Safety: Safety Assessment Principles for Nuclear Power Reactors, 1979

Health and Safety at Work Booklets (not in current list)
1 Lifting and Carrying
3 Safety Devices for Hand and Foot Operated Presses, 1971
4 Safety in the Use of Abrasive Wheels
6 Safety in Construction Work: General Site Safety Practice
6B Safety in Construction Work: Roofing
6C Safety in Construction Work: Excavations
6D Safety in Construction Work: Scaffolding
6E Safety in Construction Work: Demolition
6F Safety in Construction Work: System Building
10 Fire Fighting in Factories, 1970
13 Ionizing Radiations: Precautions for Industrial Users, 1970
14 Safety in the Use of Mechanical Power Presses
18 Industrial Dermatitis: Precautionary Measures
20 Drilling Machines: Guarding of Spindles and Attachments
22 Dust Explosions in Factories, 1970
24 Electrical Limit Switches and Their Applications, 1970
25 Noise and the Worker, 1971
27 Precautions in the Use of Nitrate Salt Baths, 1971
28 Plant and Machinery Maintenance, 1970
29 Carbon Monoxide Poisoning: Causes and Prevention
30 Storage of Liquefied Petroleum Gas at Factories, 1973
31 Safety In Electrical Testing
32 Repair of Drums and Small Tanks
33 Safety in the Use of Guillotines and Shears
34 Guide to the Use of Flame Arresters and Explosion Reliefs, 1965
35 Basic Rules for Safety and Health at Work, 1975
36 First Aid in Factories
37 Liquid Chlorine
38 Electric Arc Welding, 1970
40 Means of Escape in Case of Fire in Offices, Shops and Railway Premises
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| IAC/L1 | Guidance on the implementation of safety policies, 1982 |

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**Medical Advice (not in current list)**

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<th>MDHS 70</th>
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<td>ACSNI Study Group on Human Factors. Third report: Organizing for safety, 1993</td>
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**Sizewell B**

| 19   | Sizewell B, 1982 |
| 20   | Appraisal of the current situation on large LOCA calculations in the context of Sizewell B, 1984 |

**Sizewell B public inquiry**

| NII/P/1 | Sizewell B public inquiry; proof of evidence on the work and responsibilities of HM Nuclear Installations Inspectorate, 1983 (plus additional material denoted ADD1, ADD2, etc.) |
| NII/P/2 | Sizewell B public inquiry; proof of evidence on HM Nuclear Installations Inspectorate’s view of the Central Electricity Generating Board’s safety case, 1983 (plus additional material denoted ADD1, ADD2, etc.) |
| NII/S/2 | Sizewell B inquiry: the Inspectorate’s approach to the assessment of code validation submissions, 1983 |
| NII/S/4 | Sizewell B inquiry: schedule of NII reservations and issues all of which require to be resolved to the Inspectorate’s satisfaction prior to licensing, 1983 |
| NII/S/5 | Sizewell B power station public inquiry: safety case computer codes – categorisation and validation assessment, 1983 |

**NII/S/83** Sizewell B power station inquiry: relationship between the NII’s assessment principles and levels of risk, 1984

**NII 01** Sizewell B: a review by HM Nuclear Installation Inspectorate

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**HA 3** Sizewell B: a review by HM Nuclear Installations Inspectorate of the preconstruction safety report, 1982

**Occasional Papers**

| OP 1 | Problem drinker at work, 1981 |
| OP 2 | Microprocessors in industry: safety implications of the use of programmable electronic systems in factories, 1981 |
| OP 3 | Managing safety, 1981 |
| OP 5 | Electrostatic ignition: hazards of insulating materials, 1982 |
| OP 9 | Monitoring safety |
| OP 10 | Safety of electrical distribution systems in factories, 1985 |
| OP 11 | Measuring the effectiveness of HSE’s field activities, 1985 |

**Offshore Technology Reports**

| OTH 91 337 | Pipeline and riser loss of containment study, 1990 (PARLOC 90) |
| OTH 92 389 | Human factors, shift work and alertness in the offshore industry, 1993 |
| OTH 92 585 | Generic foundation data to be used in the assessment of blast and fire scenarios and typical structural details for primary, secondary and supporting structures and components, 1992 |
| OTH 92 586 | Representative range of blast and fire scenarios, 1992 |
| OTH 92 587 | The prediction of single and two-phase release rates, 1992 |
| OTH 92 588 | Legislation, codes of practice and certification requirements, 1992 |
| OTH 92 589 | Experimental facilities suitable for use in studies of fire and explosion hazards in offshore structures, 1992 |
| OTH 92 590 | The use of alternative materials in the design and construction of blast and fire resistant structures, 1992 |
| OTH 92 591 | Gas/vapour build up on offshore structures, 1992 |
| OTH 92 592 | Confined vented explosions, 1992 |
| OTH 92 593 | Explosions in highly congested volumes, 1992 |
OTI 92 594 The prediction of the pressure loading on structures resulting from an explosion, 1992
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OTI 92 596 Oil and gas fires: characteristics and impact, 1992
OTI 92 597 Behaviour of oil and gas fires in the presence of confinement and obstacles, 1992
OTI 92 598 Current fire research: experimental, theoretical and productive modelling resources, 1993
OTI 92 599 The effects of simplifications of the explosion pressure–time history, 1988
OTI 92 601 Computerised analysis tools for assessing the response of structures subjected to blast loading, 1992
OTI 92 602 The effects of high strain rate on material properties, 1992
OTI 92 603 Analysis of projectiles, 1992
OTI 92 604 Experimental data relating to the performance of steel components at elevated temperatures, 1992
OTI 92 605 Methodologies and available tools for the design/analysis of steel components at elevated temperatures, 1992
OTI 92 606 Passive fire protection: performance requirements and test methods, 1992
OTI 92 607 Availability and properties of passive and active fire protection systems, 1992
OTI 92 608 Existing fire design criteria for secondary, support and system steelwork, 1992
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Oil Industry

A guide to the principles and operation of permit-to-work procedures as applied to the petroleum industry, 1986
Guidelines for occupational health services in the oil industry, 1987
Guidance on health and safety monitoring in the petroleum industry, 1992
Guidance on multiskilling in the petroleum industry, 1992
Guidance on permit-to-work systems in the petroleum industry, 1991

Promotional Leaflets

PML 6 New regulations on packaging and labels for dangerous substances: Classification, Packaging and Labelling of Dangerous Substances Regulations 1984, 1985
PML 7 Deadly maintenance: a study of fatal accidents at work, 1985
PML 10 Monitoring safety, 1986

Research Papers

RP 1 Examination of entrained air-flow rate data for large-scale water spray installations by J. McQuaid, 1978
RP 7 Decay of spherical detonations and shocks by H. Phillips, 1980
RP 8 Dispersion of heavier-than-air gases in the atmosphere: review of research, and progress report on HSE activities by J. McQuaid, 1978
RP 11 Comparative risks of electricity production systems: a critical survey of the literature by A.V. Cohen and D.K. Fitchard, 1980
RP 18 Reproducibility of asbestos counts by T.L. Ogden, 1982
RP 24 Dispersion of heavier-than-air gases in the atmosphere: a review of the organization and management of the HSE field trials 1982/84 by D.G. Wilde, 1984
RP 32 First aid retention of knowledge survey by M.C. Cullen, 1992

Research Reviews

Item
Shift work and health by J.M. Harrington, 1978  1
Manual handling and lifting by J.D.G. Troup and F.C. Edwards, 1985  2
Alternatives to asbestos products: a review, 1986  3

Safety Health and Welfare Leaflets

SHW 29 Phenol poisoning (cautionary notice), 1984
SHW 367 Dermatitis (cautionary notice), 1975
SHW 385 Cyanide poisoning (cautionary notice), 1983
SHW 395 Gassing and chemical burns (cautionary notice), 1984
SHW 397 Effects of mineral oil on the skin (cautionary notice), 1982
SHW 830 Dust explosions in factories, 1975
SHW 849 Nitrate salt baths (cautionary notice), 1975
SHW 932 Dangers from carbon monoxide (cautionary notice), 1981
SHW 2125 Danger and explosion in oil storage tanks fitted with immersed heaters (cautionary notice), 1981

Sector Guidance

See Asbestos, Dangerous Substances, Major Hazards, Nuclear Installations, Oil Industry

Specialist Inspectors Reports

SIR 5 Avoiding water hammer in steam systems by S. Mortimer and D.C. Edwards, 1988
SIR 9 The fire and explosion hazards of hydraulic accumulators by D.B. Pratt
SIR 16 Low volume, high velocity extraction systems by B. Fletcher
SIR 19 Fire and explosion hazards associated with the storage and handling of hydrogen peroxide by R. Merrifield
SIR 21 Assessment of the toxicity of major hazard substances by R.M. Turner and S. Fairhurst

Technical Data Notes (not in current list)

1 Dust control – the low volume, high velocity system, 2nd rev., 1976
2/73  Threshold limit values for 1975, 1976  
3  Occupational cancer of the renal tract, rev., 1973  
4  Stibine – health and safety precautions, 1976  
5  Antimony – health and safety precautions, 1975  
6  Arsenic – health and safety precautions, 1975  
7  Phosphine – health and safety precautions, 1975  
8  Chromium – health and safety precautions, 1973  
9  Arsenic – health and safety precautions  
10  Aniline – health and safety precautions  
11  Cadmium – health and safety precautions, rev., 1975  
12  Notes for the guidance of designers on the reduction of machinery noise, 1975  
13  Standards for asbestos dust concentration for use with Asbestos Regulations 1969, rev., 1974  
14  Health – dust in industry  
15  Methyl bromide – health and safety precautions  
16  Prevention of industrial lead poisoning  
17  Trichloroethylene, rev., 1973  
18  The safe cleaning repair and demolition of large tanks for storing flammable liquids, rev., 1975  
19  Ventilation of buildings: fresh air requirements, rev., 1975  
20  Anthrax  
21  Mercury, rev., 1975  
25  Safe operation of automatically controlled steam and hot water boilers, 1975  
26  Erection and dismantling of tower cranes, 1973  
27  Access to tower cranes, 1974  
29  Fire risk in the storage and industrial use of cellular plastics, rev., 1975  
32  Guiding of portable pipe threading machines  
33  Power press mechanisms: overrun and fall-back devices  
35  Control of asbestos dust, 1975  
36  Safety in the use of cartridge operated fixing tools  
38  Tripping device for radial and heavy vertical drilling machines  
40  Standards for chromic acid concentration in air for use with the chromium plating regulations  
41  Isocyanates – toxic hazard and precautions, 1975  
42  Probable asbestos dust concentration at construction processes  
43  Technical level training: code of practice for reducing the exposure of employed persons to noise, 1976  
44  Road transport in factories, 1973  
45  Industrial use of flammable gas detectors, 1973  
46  Safety at quick opening and other doors of autoclaves, 1974  
47  Entry into confined spaces: hazards and precautions, 1973  
48  Permissible opening in fixed guards  
53/1  Zinc embrittlement of austenitic stainless steel, 1976  
53/2  Nitrate stress corrosion of mild steel, 1976  
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World Health Organisation
(Geneva)

Environmental Health Criteria
EHC1 Mercury
EHC2 Polychlorinated Biphenyls and Terphenyls
EHC3 Lead
EHC4 Oxides of Nitrogen
EHC5 Nitrates, Nitriles and N-Nitroso Compounds
EHC6 Principles and Methods for Evaluating the Toxicity of Chemicals, Pt 1
EHC7 Photochemical Oxidants
EHC8 Sulphur Oxides and Suspended Particulate Matter
EHC9 DDT and its Derivatives
EHC10 Carbon Disulphide
EHC12 Noise
EHC13 Carbon Monoxide
EHC14 Ultraviolet Radiation
EHC19 Hydrogen Sulfide, 1983
EHC20 Selected Petroleum Products
EHC21 Chlorine and Hydrogen Chloride
EHC28 Acrylonitrile
EHC53 Asbestos
ECH54 Ammonia

Note:
Some of the series in this appendix which are shown with a closed range of dates are continuing series, e.g. the AIChE series on Ammonia Plant Safety

B Nuclear Regulatory Commission

Periodic Reports

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NUREG-1144:1985 Nuclear plant aging research (NPAR) program plan
NUREG-3819:1985 Survey of aged power plant facilities
NUREG-4144:1985 Importance ranking based on aging considerations of components included in probabilistic risk assessments
NUREG-4156:1985 Operating experience and aging-seismic assessment of electric motors
NUREG-4234:1985 Aging and service wear of electric motor-operated valves used in engineered safety-featured systems of nuclear power plants

Acoustic Emission Monitoring

NUREG/CR-3825:1985 Acoustic emission/flaw relationship for in-service monitoring of nuclear pressure vessels
NUREG/CR-5645:1991 Acoustic emission/flaw relationships for in-service monitoring of LWRs

Aerosols

NUREG/CR-1367:1981 AEROSOL user's manual
NUREG/CR-2139:1981 Aerosols generated by free fall of powders and solutions in static air

NUREG/CR-2299:1982 Aerosol release and transport program
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NUREG/CR-4501:1986 Modeling of vapor generation in flashing flow
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<td>NUREG/CR-4715:1987</td>
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US Nuclear Regulatory Commission human factors program plan

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**Nuclear Power Plant Maintenance Personnel Performance Simulation (MAPPS):**

**Management and Organizational Assessments**

- Assessment of selected organizations
- Literature review relevant to organization and administration of nuclear power plants

**Objective Indicators of Organizational Performance**

- Evaluation of welding and repair-welding practices in nuclear power plants
- Influence of organizational factors on performance reliability

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**Evaluation of Welded and Repair-Welded Stainless Steel**

- Evaluation for Light Water Reactor (LWR) service

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**Nuclear Power Plant Maintenance**

- Status of maintenance across the US nuclear power industry
- Trends and patterns in maintenance performance

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**Programmatic Analysis**

- Programmatic root cause analysis of maintenance personnel performance

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**Nuclear Regulatory Commission**

- Staff computer programs for use with meteorological data
- Variations in planetary boundary layer dispersion properties

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**Local Meteorology**

- Method to characterize local meteorology at nuclear facilities for application to emergency response needs

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**Mitigation Systems**

- Survey of the state of the art in mitigation systems
- Experimental results pertaining to thermal igniters
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- NUREG/CR-3804:1985  Physics of reactor safety
- NUREG/CR-4240:1985  Physics of reactor safety

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- NUREG/CR-2801:1983  Piping reliability mode validation and potential use for licensing regulation development
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- NUREG/CR-3996:1984  Response margins of the dynamic analysis of piping systems
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- NUREG/CR-4263:1985  Reliability analysis of stiff versus flexible piping. Final project report
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NUREG/CR-4082:1986  Degraded piping program

NUREG/CR-4290:1986  Probability of pipe failure in the reactor coolant loops of Babcock and Wilcox PWR plants

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Plant Operation


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NUREG/CR-3226:1983  Station blackout accident analyses

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NUREG-5032:1988  Modeling time to recovery and initiating event frequency for loss of offsite power incidents at nuclear power plants

Precursors to Potential Accidents


NUREG/CR-3591:1984  Precursors to potential severe core damage accidents


Pressure Systems

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NUREG/CR-3853:1984  Preloading of bolted connections in nuclear reactor component supports

NUREG/CR-3228:1985  Structural integrity of water reactor pressure boundary components

Pressure Vessels

NUREG/CR-2308:1982  Design criteria for the spacing of nozzles and reinforced openings in cylindrical nuclear pressure vessels and pipe

NUREG/CR-4267:1985  Vessel integrity (VISA) simulation code sensitivity study

NUREG/CR-4486:1986  VISA II: a computer code for predicting the probability of reactor pressure vessel failure
NUREG/CR-4614:1986 VISA II sensitivity study of code calculations input and analytical model parameters

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NUREG/CR-2300:1983 PRA procedures guide
NUREG/CR-2815:1984 Probabilistic safety analysis procedure
NUREG-1093:1984 Reliability and risk analysis methods research plan
NUREG/CR-3440:1984 Identification of severe accident uncertainties
NUREG/CR-3852:1984 Insight into PRA methodologies
NUREG/CR-2815:1985 Probabilistic safety analysis procedures guide
NUREG/CR-3485:1985 PRA review manual
NUREG/CR-3887:1985 Human factors review for severe accident sequence analysis
NUREG/CR-3904:1985 A comparison of uncertainty and sensitivity analysis techniques for computer models
NUREG/CR-4229:1985 Evaluation of current methodology employed in probabilistic risk assessment (PRA) of fire events at nuclear power plants
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NUREG/CR-4377:1985 Evaluations and utilizations of risk importances
NUREG/CR-3969:1986 Independent code assessment: Sandia-proposed accuracy quantification methodology
NUREG/CR-4372:1986 Probabilistic risk assessment (PRA) applications
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NUREG/CR-5050:1988 Annotated bibliography of reliability and risk data sources
NUREG/CR-5425:1989 Evaluation of allowed outage times (AOTs) from a risk and reliability standpoint
NUREG/CR-5262:1990 PRAMIS: probability risk assessment model integration system

**Quality Assurance**

NUREG-1055:1984

**Reactor Safety Research**

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NUREG/CR-2716:1982 Reactor safety research programs: quarterly report
NUREG/CR-2531:1983 Introductory user's manual for the US Nuclear Regulatory Commission reactor safety research data bank

NUREG/CR-5477:1990 An evaluation of the reliability and usefulness of external initiator PRA methodologies
NUREG/CR-5520:1991 Procedures guide for extracting and loading probabilistic risk assessment data into MAR-D using IRRAS 2.5

**Pumps**

NUREG/CR-1205:1982 Data summaries of Licensee Event Reports of pumps at US commercial nuclear power plants
The in-plant reliability data base for nuclear power components: interim data report – the pump component
A statistical analysis of nuclear power plant pump failure rate variability
Pump and valve qualification review guide
Reactor coolant pump shaft seal behavior during station blackout
The impact of mechanical- and maintenance-induced failures of main reactor coolant pump seals on plant safety
Reactor coolant pump seal related instrumentation and operator response
Reactor coolant pump shaft seal stability during station blackout
Technical findings related to generic issue 23: reactor coolant pump seal failure
Potential safety-related pump loss. An assessment of industry data

**Improving quality and the assurance of quality in the design and construction of commercial nuclear power plants**

**A method for using PRA to establish quality program applicability**

**Engineering and quality assurance cost factors associated with nuclear plant modification**

**Introductory user's manual for the US Nuclear Regulatory Commission reactor safety research data bank**
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**Institutional Publications Appendix 28/91**

- Report of the Committee to Review Safeguards Requirements at Power Reactors
- Technical specifications – enhancing the safety impact (prescriptive regs)
- Institutional implications of establishing safety goals for nuclear power plants
- Operating reactors licensing actions summary
- US Nuclear Regulatory Commission annual report
- SCALE, a modular code system for performing standardized computer analyses for licensing evaluation
- Standard setting standards: a systematic approach to managing public health and safety risks
- Benchmark description of current regulatory requirements and practices in nuclear safety and reliability assurance
- Regulatory analyses for severe accident issues: an example
- US Nuclear Regulatory Commission policy and planning guidance
- NRC/FEMA operational response procedures for response to a commercial nuclear reactor accident
- Guidelines and workbook for assessment of organization and administration of utilities seeking operating license for a nuclear power plant
- Nuclear power safety reporting system implementation and operational specifications
- An independent safety organization
- Applications of foreign probabilistic safety assessment experience to the US nuclear regulatory process
- Recommendations for NRC policy on shift scheduling and overtime at nuclear power plants
- Operating reactors licensing actions summary
- Nuclear regulatory legislation
- Long-range research plan
- NRC safety research in support of regulation
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Particular Nuclear Power Stations
A - Technical specifications for (name) station
B - Safety evaluation report related to the operation of (name) station

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<td>San Onofre</td>
<td>Seabrook</td>
<td>1443</td>
</tr>
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<td>1207, 1331</td>
<td>0896</td>
</tr>
<tr>
<td>Shearon Harris</td>
<td>Shoreham</td>
<td>1208, 1240</td>
</tr>
<tr>
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<td>1012, 1126</td>
<td>0420</td>
</tr>
<tr>
<td>South Texas Project</td>
<td>Susquehanna</td>
<td>1255, 1334</td>
</tr>
<tr>
<td></td>
<td>Vogtle</td>
<td>1042</td>
</tr>
<tr>
<td></td>
<td>Waterford</td>
<td>1237, 1247, 1343</td>
</tr>
<tr>
<td></td>
<td>Watts Bar</td>
<td>1117</td>
</tr>
<tr>
<td></td>
<td>Wolf Creek</td>
<td>1104, 1136</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0881</td>
</tr>
</tbody>
</table>
Appendix 29

Contents

Selected Organizations Relevant to Safety and Loss Prevention A29/2
Selected Organizations Relevant to Safety and Loss Prevention

United Kingdom
Associated Otcl Company, Ellesmere Port, Cheshire
Association of British Chemical Manufacturers – succeeded by Chemical Industries Association
Association of British Insurers, Aldermary House, Queen Street, London EC4N ITT
British Approvals Service for Electrical Equipment in Flammable Atmospheres (BASEEFA) – succeeded by Electrical Equipment Certification Service
British Chemical Engineering Contractors Association, 1–2 Regent Street, London SW1Y 4NR
British Chemical Industries Safety Council – succeeded by Chemical Industries Association
British Cryogenic Council, Department of Engineering Science, Parks Road, Oxford OX1 3PJ
British Compressed Gas Association, 21 St James Square, London SW1Y 4UJ
British Computer Society, 13 Mansfield Street, London W1M 0BP
British Engine Insurance Company, Longridge House, Manchester M60 4DT
British Fire Services Association, 86 London Road, Leicester LE2 0QR
British Hydromechanics Research Association, Cranfield, Bedfordshire MK43 0AJ
British Insurance Association – succeeded by Association of British Insurers
British Occupational Hygiene Society, Room 426, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT
British Pump Manufacturers Association, 235 Vauxhall Bridge Road, London SW1V 1EJ
British Rail, 222 Marylebone Road, London NW1
British Red Cross Society, 9 Grosvenor Crescent, London SW1X 7EJ
British Safety Council, 62–64 Chancellors Road, London W6 9RS
British Standards Institution, 2 Park Street, London W1A 2BS
British Waterways, Melbury House, Melbury Terrace, London NW1
Building Research Establishment, Garston, Watford
Chamber of Shipping of the UK, 2 Minories, London EC3N 1BJ
Chemical and Allied Product Industry Training Board – now disbanded
Chemical Industries Association, Alembic House, 93 Albert Embankment, London SE1 7TU
Chemical Industry Safety and Health Council – succeeded by Chemical Industries Association
The Chemical Society – see the Royal Society for Chemistry
Chief and Assistant Fire Officers Association, West Midland Fire Service, Fire Service HQ, Lancaster Circus, Queensway, Birmingham B4 7DE
Confederation of British Industry, 103 New Oxford Street, London WC1A 1DU
Electrical Equipment Certification Service, Sheffield
Engineering Equipment and Materials Users Association – succeeded by Engineering Equipment and Materials Users Association
Engineering Equipment and Materials Users Association, 34–15 Belgrave Square, London SW1X 8PS
The Fellowship of Engineering – now The Royal Academy of Engineering
Fire Officers Committee – see Association of British Insurers
Fire Protection Association, 140 Aldersgate Street, London EC1A 4HX
Fire Research Station, Borehamwood, Hertfordshire WD6 2BL
Fire Service Technical College, Moreton-in-the-Marsh, Gloucestershire
Friends of the Earth Ltd., 377 City Road, London EC1V 1NA
Health and Safety Commission/Executive, Baynards House, 1 Chepstow Place, London W2
Health and Safety Executive, Research and Laboratory Division, Broad Lane, Sheffield
High Pressure Technology Association, c/o Dr R.A. Duckett, Department of Physics, University of Leeds, Leeds LS2 9JT
HM Stationery Office, 49 High Holborn, London WC1V 6HB
Home Office, 50 Queen Anne’s Gate, London SW1
Imperial Chemical Industries plc, Imperial Chemical House, Millbank, London SW1
Imperial Chemicals Insurance, 1Adam Street, London WC2
Industrial Fire Protection Association of Great Britain, 140 Aldersgate Street, London EC1A 4HX
Industrial Safety (Protective Equipment) Manufacturers Association, 69 Cannon Street, London EC4N 5AB
The Industrial Society, 3 Carlton House Terrace, London SW1Y 5DG
Institute of Cancer Research, Royal Cancer Hospital, 17a Osnaburg Gardens, London SW7 3AL
Institute of Geological Sciences, CSU North, Murchison House, West Mains Road, Edinburgh EH9 3LA; CSU South, Ring Road, Halton, Leeds LS15 8TQ
Institute of Materials, 1 Carlton House Terrace, London SW1Y 5DB
Institute of Measurement and Control, 87 Gower Street, London WC1E 6AA
Institute of Metals – see Institute of Materials
Institute of Oceanographic Sciences, Wormley, Godalming, Surrey GU8 5UB
Institute of Offshore Engineering, Riccarton, Currie, Edinburgh EH14 4PS
Institute of Petroleum, 61 New Cavendish Street, London W1M 8AR
Institute of Physics, 47 Belgrave Square, London SW1X 8QX
Institution of Chemical Engineers, 165–171 Railway Terrace, Rugby CV21 3HQ
Institution of Civil Engineers, Great George Street, London SW1
Institution of Electrical Engineers, Savoy Place, London WC2R 0BL
Institution of Fire Engineers, 148 New Walk, Leicester LE1 7QB
Institution of Gas Engineers, 17 Grosvenor Crescent, London SW1X 7ES
Institution of Industrial Safety Officers – see Institution of Occupational Safety and Health
Institution of Marine Engineers, 76 Mark Lane, London EC3R 7JN
Institution of Mechanical Engineers, 3 Birdcage Walk, London SW1H 9JH
Institution of Nuclear Engineers, 1 Penerley Road, London SE6 2LQ
Institution of Occupational Safety and Health, 222 Uppingham Road, Leicester
Institution of Plant Engineers, 77 Gt Peter Street, London SW1P 2EZ
Insurance Technical Bureau – now disbanded
Joint Fire Research Organisation – see Fire Research Station
Liquefied Petroleum Gas Industry Technical Association, 17 Grosvenor Crescent, London SW1X 7EF
Loss Prevention Council, Melrose Avenue, Borehamwood and 140 Aldersgate Street, London EC1
Medical Research Council, 20 Park Crescent, London W1
Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ
Ministry of Defence, Research Establishment, Porton Down
Ministry of Defence, Tidal Branch, Hydrographic Department MOD(N), Taunton, Somerset TAI 2DN
National Engineering Laboratory, East Kilbride, Scotland
National Society for Clean Air, 136 North Street, Brighton
National Radiological Protection Board, Harwell, Didcot, Oxfordshire OX11 0RQ
National Vulcan Engineering Insurance Group, 3 St Mary Parsonage, Manchester
Oil and Chemical Plant Manufacturers Association, Suites 41–48, 87 Regent Street, London W1R 7HF
Petroleum Industry Training Board, Staines House, 158/162 High Street, Staines, Middlesex
The Royal Academy of Engineering, 2 Little Smith Street, London SW1P 3DL
The Royal Institute of Chemistry (incorporated in The Royal Society of Chemistry)
The Royal Meteorological Society, 104 Oxford Road, Reading RG1 7LJ
The Royal Society, 6 Carlton House Terrace, London SW1H 5AG
The Royal Society of Chemistry, 9 Savile Row, London W1
The Royal Society for the Prevention of Accidents, Cannon House, The Priory, Queensway, Birmingham B4 6BS
Safety in Mines Research Establishment, Sheffield
Safety and Reliability Directorate – see UK Atomic Energy Authority
Safety and Reliability Society, PO Box 25, Cambridge Arcade, Lord Street, Southport PR8 1AS
Society of Chemical Industry, 14–15 Belgrave Square, London SW1X 8BS
Society of Gas Tanker and Terminal Operators, 91 Worship Street, London EC2A 2BE
Society of Occupational Medicine, Royal College of Physicians, 11 St Andrews Place, London NW1 4LE
Trades Union Congress, 23–28 Great Russell Street, London WC1B 3LS
Transport and Road Research Laboratory, Crowthorne, Berkshire
TUC Centenary Institute of Occupational Health, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT
UK Atomic Energy Authority, 11 Charles II Street, London SW1
UK Atomic Energy Authority, Safety and Reliability Directorate, Wigshaw Lane, Culcheth, Warrington, Lancashire
The Welding Institute, Abington Hall, Cambridge, CB1 6AL

United States
Air Pollution Control Association, Pittsburgh, PA 15230
American Association for Artificial Intelligence, 445 Burgess Drive, Menlo Park, CA 94025
American Chemical Society, 1155 16th Street NW, Washington DC 20036
American Gas Association, 1515 Wilson Boulevard, Arlington VA 22209
American Industrial Hygiene Association, 2700 Prosperity Avenue, Suite 250, Fairfax, VA 22031
American Institute for Aeronautics and Astronautics, 1633 Broadway, New York, NY 10019
American Institute of Chemical Engineers, 345 East 47th Street, New York, NY 10017
American Insurance Association, 85 John Street, New York, NY 10038
American Meteorological Society, 45 Beacon Street, Boston, MA 02108
American National Standards Institute, 1430 Broadway, New York, NY 10018
American Nuclear Society, 555 N Kensington Avenue, Lagrange Park, IL 60525
American Petroleum Institute, 1220 L Street NW, Washington DC 20005
American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017
American Society of Heating, Refrigerating and Ventilating Engineers, 1791 Tullie Circle NE, Atlanta, GA 30329
American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017
American Society for Quality Control, 230 W Wells Street, Suite 7000, Milwaukee, WI 53203
American Society of Safety Engineers, 850 Busse Highway, Park Ridge, IL 60068
American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103
American Standards Association – now American National Standards Institute
American Trucking Association, 2201 Mill Road, Alexandria, VA 22304
American Welding Society, 550 Lejeune Road, Miami, FL 33135
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
Association of American Railroads, American Railroads Building, 1920 L Street NW, Washington, DC 20036
Atomic Energy Commission – now Nuclear Regulatory Commission
Ballistics Research Laboratories, Aberdeen Proving Ground, MD 21005
 Battelle Columbus Laboratory, 505 King Avenue, Columbus, OH 43201
 Battelle Northwest Laboratory, Richmond, WA 99352
Brookhaven National Laboratory, Upton, Long Island, NY 11973
Bureau of Mines, 2401 E Street NW, Washington, DC 20241
Center for Chemical Process Safety – see American Institute of Chemical Engineers
Chemical Manufacturers Association, 2501 M Street NW, Washington, DC 20037
Chemical Transport Emergency Center (CHEMTREC), 2501 M Street NW, Washington, DC 20037
Chlorine Institute, 70 W 40th Street, New York, NY 10018
Clippinghouse for Occupational Safety and Health Information, Public Health Service, 4676 Columbia Parkway, Cincinnati, OH 45226
Combustion Institute, 5001 Baum Road, Pittsburgh, PA 15213
Compressed Gas Association, 1235 Jefferson Davis Highway, Arlington, VA 22202
Department of Transportation, Materials Transportation Bureau, 400 7th Street SW, Washington, DC 20590
Department of Transportation, US Coast Guard, Office of Research and Development, 2100 Second Street SW, Washington, DC 20593
Dow Chemical Company, Bldg 566, Midland, MI 48640
Earthquake Engineering Research Institute, 47th Street and Hoffman Boulevard, Richmond, CA 94804
Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304
Environmental Protection Agency, Office of Research and Development, 401 M Street SW, Washington, DC 20460
Ethylene Oxide Industry Council, 2501 M Street NW, Washington, DC 20037
Factory Insurance Association – see Industrial Risk Insurers
Factory Mutual Research Corporation, 1151 Boston-Providence Turnpike, Norwood, MA 02062
Factory Mutual System, 1151 Boston-Providence Turnpike, Norwood, MA 02062
Federal Emergency Management Agency, 500 C Street SW, Washington, DC 20472
Federal Energy Regulatory Commission, 825 N Capitol Street NE, Washington, DC 20426
Federal Power Commission – see Federal Energy Regulatory Commission
Hartford Steam Boiler Inspection and Insurance Company, Hartford, CT
Human Factors Society, Box 1369, Santa Monica, CA 90406
Idaho National Laboratory, 550 Second Street, Idaho Falls, ID 83401
Industrial Risk Insurers, 85 Woodland Street, Hartford, CT 06102
Institute of Electrical and Electronic Engineers, 345 East 47th Street, New York, NY 10017
Institute of Gas Technology, 3424 State Street, Chicago, IL 60616
Instrument Society of America, 67 Alexander Drive, Research Triangle Park, NC 27709
Lawrence Livermore National Laboratories, Livermore, CA 94550
Los Alamos National Laboratory, Los Alamos, NM 87545
Lovelace Biomedical and Environmental Research Institute, 2425 Ridgmount Drive, Albuquerque, NM
Manufacturers Standardization Society of the Valve and Fittings Industry, 127 Park Street NE, Vienna, VA 22180
Manufacturing Chemists Association – now Chemical Manufacturers Association
National Aeronautics and Space Administration, NASA Headquarters, Washington, DC 20546
National Board of Fire Underwriters – defunct
National Bureau of Standards, Chemical Thermodynamics Data Center, Chemistry Building, Gaithersburg, MD 20899
National Center for Atmospheric Research, Box 3000, Boulder, CO 80309
National Fire Protection Association, Batterymarch Park, Quincy, MA 02269
National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, OH 45226
National LP Gas Association, 1301 W 22nd Street, Oak Brook, IL 60521
National Safety Council, 444 N Michigan Avenue, Chicago, IL 60611
National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161
National Transportation Safety Board, 800 Independence Avenue SW, Washington, DC 20594
Naval Surface Weapons Center, Silver Springs, White Oak, MD 20910
Nuclear Regulatory Commission, Washington, DC 20555
Oak Ridge National Laboratory, Oak Ridge, TN
Occupational Safety and Health Administration, Directorate of Field Operations, 200 Constitution Avenue NW, Washington, DC 20210
Oil Insurance Association – merged in Industrial Risk Insurers
Sandia National Laboratory, Albuquerque, NM 87185
Southwestern Research Institute, San Antonio, TX
Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062
Union of Concerned Scientists, 26 Church Street, Cambridge, MA 02238
USA Standards Institute – now American National Standards Institute

Europe
European Commission, Brussels
European Commission, Joint Research Centre, Ispra, Italy
European Process Safety Centre, c/o Institution of Chemical Engineers, q.v.

Other Countries
Finland
VTT, Espoo

France
Société de Chimie Industrielle, 28 rue St Dominique, F75007, Paris

Germany
Berufsgenossenschaft der Chemischen Industrie
Bundesanstalt für Materialprüfung, Berlin
DEHEMA, Theodor-Heuss Allee 25, Postfach 970146, D-6000 Frankfurt-am-Main
Deutsches Institut für Normung, Berlin and Cologne
Technische Überwachungsverien, Postfach 21 04 20, Westendstrasse 199, W-8000 München
Verein Deutscher Ingenieure, Haldener Strasse 182, 58095 Hagen

Japan
Fire Research Institute of Japan, 14-1, Nakahara 3 Chome, Mitaka

The Netherlands
Committee for Prevention of Disasters – see Ministry of Social Affairs
Ministry of Social Affairs, PO Box 90804, 2509LV, The Hague
Stichting CONCAWE, 22 President Kennedylaan, The Hague
TNO, TNO Prins Maurits Laboratory, Lange Kleiweg 137, PO Box 45, 2280 AA Rijswijk

Norway
Christian Michelsen Institute, Bergen
Norwegian Society of Chartered Engineers, Postboks 2312, Solli, 0201 Oslo 2
OREDA, c/o DnV Technica, PO Box 300, N-1322, Hovik

Switzerland
Schweizerische Chemische Gesellschaft, CH 4002, Basel

International
Intergovernmental Maritime Consultative Organisation – see International Maritime Organization
International Atomic Energy Agency, Kaertner Ring, PO Box 590, A-1011, Vienna, Austria
International Chamber of Shipping, 2 Minories, London EC3N 1BJ
International Commission on Radiological Protection, Clifton Avenue, Sutton, Surrey SM2 5PU, UK
International Federation of Chemical and General Workers Unions (ICF)
International Gas Union
International Institute for Applied Systems Analysis, Laxenburg, Austria
International Institute for Refrigeration, 177 Boulevard Malesherbes, F 75017 Paris, France
International Maritime Organization, 4 Albert Embankment, London SE1 7SR
International Labour Organisation, Geneva, Switzerland
International Occupational Safety and Health Information Centre, International Labour Office
International Standards Organization, 1 rue de Varembe, CH-1211 Geneva 20, Switzerland
Oil Companies International Maritime Forum, Esso House, Victoria Street, London SW1E 1BH
Organization for Economic Development, 2 rue Andre-Pascal, 75016, Paris
Appendix

30

Units and Unit Conversions
SI units are used in this book unless otherwise stated. These are described in BS 5555:1981 SI Units and Recommendations for the Use of their Multiples and of Certain Other Units.

Table A30.1 gives selected references on units.

**Absolute and Gauge Pressures**

It is common practice to attach to units of pressure an ‘a’ or a ‘g’, denoting ‘absolute’ or ‘gauge’, respectively (e.g. bara, psig). This is not part of the SI system, where instead the designation ‘absolute’ or ‘gauge’ or some other defining term is applied to the pressure described. In this book both practices are used.

**SI Unit Conversion**

Conversions of other units to and from SI units are given in tables compiled by Mullin (1967) and by Lees (1968). The conversion table given by the latter is reproduced in Table A30.2.

### Table A30.1  Selected references on units

Chappelar (1981); Horvath (1986); Mullin (1986)

### Table A30.2  SI unit conversion tables (Lees, 1968)

<table>
<thead>
<tr>
<th>Category</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>1 cm/s²</td>
<td>1.0000 × 10⁻² m²/s²</td>
</tr>
<tr>
<td>1 m/h²</td>
<td>7.7160 × 10⁻⁸ m²/s²</td>
</tr>
<tr>
<td>1 ft/s²</td>
<td>3.0480 × 10⁻¹ m²/s²</td>
</tr>
<tr>
<td>1 ft/h²</td>
<td>2.3519 × 10⁻⁸ m²/s²</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td></td>
</tr>
<tr>
<td>1 cm²</td>
<td>1.0000 × 10⁻⁴ m²</td>
</tr>
<tr>
<td>1 ft²</td>
<td>9.2903 × 10⁻² m²</td>
</tr>
<tr>
<td>1 in²</td>
<td>6.4516 × 10⁻⁴ m²</td>
</tr>
<tr>
<td>1 yd²</td>
<td>3.3333 × 10⁻³ m²</td>
</tr>
<tr>
<td>1 acre</td>
<td>4.0469 × 10⁻² m²</td>
</tr>
<tr>
<td>1 mile²</td>
<td>2.5900 × 10⁻² m²</td>
</tr>
<tr>
<td><strong>Calorific value (volumetric)</strong></td>
<td></td>
</tr>
<tr>
<td>1 cal/cm³</td>
<td>4.1868 × 10⁶ J/m³</td>
</tr>
<tr>
<td>1 kcal/m³</td>
<td>4.1868 × 10⁶ J/m³</td>
</tr>
<tr>
<td>1 Btu/ft³</td>
<td>3.7260 × 10⁴ J/m³</td>
</tr>
<tr>
<td>1 Chu/ft³</td>
<td>6.7067 × 10⁴ J/m³</td>
</tr>
<tr>
<td>1 therm/ft³</td>
<td>3.7260 × 10⁴ J/m³</td>
</tr>
<tr>
<td>1 kcal/ft³</td>
<td>1.4786 × 10³ J/m³</td>
</tr>
<tr>
<td><strong>Coefficient of expansion (volumetric)</strong></td>
<td></td>
</tr>
<tr>
<td>1 g/cm³°C</td>
<td>1.0000 × 10⁶ kg/m³°C</td>
</tr>
<tr>
<td>1 lb/ft³°C</td>
<td>2.8316 × 10⁴ kg/m³°C</td>
</tr>
<tr>
<td>1 lb/ft³°F</td>
<td>1.6015 × 10⁴ kg/m³°C</td>
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<tr>
<td><strong>Density</strong></td>
<td></td>
</tr>
<tr>
<td>1 g/cm³</td>
<td>1.0000 × 10³ kg/m³</td>
</tr>
<tr>
<td>1 lb/ft³</td>
<td>1.6015 × 10³ kg/m³</td>
</tr>
<tr>
<td>1 lb/UKgal</td>
<td>0.9072 × 10³ kg/m³</td>
</tr>
<tr>
<td>1 lb/US gal</td>
<td>0.9989 × 10³ kg/m³</td>
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<tr>
<td>1 kg/ft³</td>
<td>1.0000 × 10⁶ kg/m³</td>
</tr>
<tr>
<td><strong>Diffusion coefficient – see Viscosity, kinematic Energy</strong></td>
<td></td>
</tr>
<tr>
<td>1 cal</td>
<td>4.1868 J</td>
</tr>
<tr>
<td>1 kcal</td>
<td>4.1868 × 10³ J</td>
</tr>
<tr>
<td>1 Btu</td>
<td>1.0551 × 10⁴ J</td>
</tr>
<tr>
<td>1 erg</td>
<td>1.0000 × 10⁻⁷ J</td>
</tr>
</tbody>
</table>

**Other Units and Conversions**

Some other units which are used in the book are

**Volumetric flux:**

\[ 11/m³ s = 10⁻³ m³/m² s \]

\[ 11/m² min = 1.667 × 10⁻⁵ m³/m² s \]

\[ 1 UK gal/ft² min = 8.149 × 10⁻¹ m³/m² s \]

\[ 1 US gal/ft² min = 6.791 × 10⁻⁴ m³/m² s \]

**Other quantities:**

- 1 bbl (barrel) = 42 US gal
- 1 lusec = 10⁻³ torr l/s
- 1 micron = 10⁻⁶ m
- 1 mil = 10⁻³ in = 2.540 × 10⁻⁵ m
- 1 torr = 1 mm Hg = 1.333 × 10⁻⁵ N/m²
**UNITS AND UNIT CONVERSIONS**

**Appendix 30/3**

<table>
<thead>
<tr>
<th>Unit (metric)</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hp h</td>
<td>2.6477 × 10^6 J</td>
</tr>
<tr>
<td>1 kW h</td>
<td>3.6000 × 10^6 J</td>
</tr>
<tr>
<td>1 ft pdl</td>
<td>4.2139 × 10^-2 J</td>
</tr>
<tr>
<td>1 ft lbf</td>
<td>1.3558 J</td>
</tr>
<tr>
<td>1 Chu</td>
<td>1.8991 × 10^3 J</td>
</tr>
<tr>
<td>1 hp h (British)</td>
<td>2.6845 × 10^6 J</td>
</tr>
<tr>
<td>1 therm</td>
<td>1.0551 × 10^7 J</td>
</tr>
<tr>
<td>1 thermie</td>
<td>4.1855 × 10^6 J</td>
</tr>
<tr>
<td>1 ft kgf</td>
<td>2.9891 J</td>
</tr>
</tbody>
</table>

**Force**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 dyn</td>
<td>1.0000 × 10^-5 N</td>
</tr>
<tr>
<td>1 kgf</td>
<td>9.8067 N</td>
</tr>
<tr>
<td>1 pdl</td>
<td>1.3825 × 10^-1 N</td>
</tr>
<tr>
<td>1 lbf</td>
<td>4.4482 N</td>
</tr>
<tr>
<td>1 tonf</td>
<td>9.8640 × 10^3 N</td>
</tr>
</tbody>
</table>

**Heat – see Energy**

**Heat of combustion, formation, etc. – see Specific enthalpy**

**Heat capacity – see Specific heat**

**Heat flow – see Power**

<table>
<thead>
<tr>
<th>Unit (s/cm²)</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cal/s cm²</td>
<td>4.1868 × 10^6 W/m²</td>
</tr>
<tr>
<td>1 kcal/h m²</td>
<td>1.1630 W/m²</td>
</tr>
<tr>
<td>1 Btu/h ft²</td>
<td>3.1546 W/m²</td>
</tr>
<tr>
<td>1 Chu/h ft²</td>
<td>5.6784 W/m²</td>
</tr>
<tr>
<td>1 kcal/h ft²</td>
<td>1.2518 × 10^2 W/m²</td>
</tr>
</tbody>
</table>

**Heat release rate (mass)**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cal/s g</td>
<td>4.1868 × 10^3 W/kg</td>
</tr>
<tr>
<td>1 kcal/h kg</td>
<td>1.1630 W/kg</td>
</tr>
<tr>
<td>1 Btu/h lb</td>
<td>6.4612 × 10^-1 W/kg</td>
</tr>
</tbody>
</table>

**Heat release rate (volumetric)**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cal/s cm³</td>
<td>4.1868 × 10^6 W/m³</td>
</tr>
<tr>
<td>1 kcal/h m³</td>
<td>1.1630 W/m³</td>
</tr>
<tr>
<td>1 Btu/h ft³</td>
<td>1.0350 × 10^2 W/m³</td>
</tr>
<tr>
<td>1 Chu/h ft³</td>
<td>1.8630 × 10^2 W/m³</td>
</tr>
<tr>
<td>1 kcal/h ft³</td>
<td>4.1071 × 10^2 W/m³</td>
</tr>
</tbody>
</table>

**Heat transfer coefficient**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cal/s cm²°C</td>
<td>4.1868 × 10^4 W/m²°C</td>
</tr>
<tr>
<td>1 kcal/h m²°C</td>
<td>1.1630 W/m²°C</td>
</tr>
<tr>
<td>1 Btu/h ft²°F</td>
<td>5.6784 W/m²°F</td>
</tr>
<tr>
<td>1 Chu/h ft²°C</td>
<td>1.2518 × 10^2 W/m²°C</td>
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</table>

**Henry’s law constant**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1 atm/(g/cm³)</td>
<td>1.0133 × 10² (N/m²)/(kg/m³)</td>
</tr>
<tr>
<td>1 atm/(kg/m³)</td>
<td>1.0133 × 10³ (N/m²)/(kg/m³)</td>
</tr>
<tr>
<td>1 atm/(lb/ft³)</td>
<td>6.3258 × 10³ (N/m²)/(kg/m³)</td>
</tr>
<tr>
<td>1 atm/(kg/ft³)</td>
<td>2.8693 × 10³ (N/m²)/(kg/m³)</td>
</tr>
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</table>

**Latent heat – see Specific enthalpy**

<table>
<thead>
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<th>Conversion</th>
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</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>1.0000 × 10^-2 m</td>
</tr>
<tr>
<td>1 ft</td>
<td>3.0480 × 10^-1 m</td>
</tr>
<tr>
<td>1 Ångstrom</td>
<td>1.0000 × 10^-10 m</td>
</tr>
<tr>
<td>1 micron</td>
<td>1.0000 × 10^-6 m</td>
</tr>
<tr>
<td>1 in</td>
<td>2.5400 × 10^-2 m</td>
</tr>
<tr>
<td>1 yd</td>
<td>9.1440 × 10^-1 m</td>
</tr>
<tr>
<td>1 mile</td>
<td>1.6093 × 10 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 g</td>
<td>1.0000 × 10^-3 kg</td>
</tr>
<tr>
<td>1 lb</td>
<td>4.5359237 × 10^-1 kg</td>
</tr>
<tr>
<td>1 t (tonne)</td>
<td>1.0000 × 10³ kg</td>
</tr>
<tr>
<td>1 grain</td>
<td>6.4800 × 10^-3 kg</td>
</tr>
<tr>
<td>Unit</td>
<td>Equivalent</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
</tr>
<tr>
<td>1 oz</td>
<td>$2.8350 \times 10^{-2}$ kg</td>
</tr>
<tr>
<td>1 cwt</td>
<td>$5.0802 \times 10$ kg</td>
</tr>
<tr>
<td>1 ton</td>
<td>$1.0160 \times 10^4$ kg</td>
</tr>
</tbody>
</table>

### Mass per unit area

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 g/cm²</td>
<td>$1.0000 \times 10$ kg/m²</td>
</tr>
<tr>
<td>1 lb/ft²</td>
<td>$4.8824$ kg/m²</td>
</tr>
<tr>
<td>1 lb/in²</td>
<td>$7.0307 \times 10^{-3}$ kg/m²</td>
</tr>
<tr>
<td>1 ton/mile²</td>
<td>$3.9230 \times 10^{-4}$ kg/m²</td>
</tr>
<tr>
<td>1 kg/ft²</td>
<td>$1.0764 \times 10^{-5}$ kg/m²</td>
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</tbody>
</table>

### Mass flow

<table>
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<td>1 g/s</td>
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</tr>
<tr>
<td>1 kg/h</td>
<td>$2.7778 \times 10^{-4}$ kg/s</td>
</tr>
<tr>
<td>1 lb/s</td>
<td>$4.5359 \times 10^{-4}$ kg/s</td>
</tr>
<tr>
<td>1 t/h</td>
<td>$2.7778 \times 10^{-1}$ kg/s</td>
</tr>
<tr>
<td>1 lb/h</td>
<td>$1.2600 \times 10^{-4}$ kg/s</td>
</tr>
<tr>
<td>1 ton/h</td>
<td>$2.8224 \times 10^{-5}$ kg/s</td>
</tr>
</tbody>
</table>

### Mass flux, mass velocity

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 g/s cm²</td>
<td>$1.0000 \times 10^{-3}$ kg/s cm²</td>
</tr>
<tr>
<td>1 kg/m³</td>
<td>$2.7778 \times 10^{-4}$ kg/s m³</td>
</tr>
<tr>
<td>1 lb/s ft²</td>
<td>$4.8824$ kg/s m²</td>
</tr>
<tr>
<td>1 lb/h ft²</td>
<td>$1.3562 \times 10^{-3}$ kg/s m²</td>
</tr>
<tr>
<td>1 kg/h ft²</td>
<td>$2.9500 \times 10^{-3}$ kg/s m²</td>
</tr>
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</table>

### Mass release rate (volumetric)

<table>
<thead>
<tr>
<th>Unit</th>
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</tr>
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<tbody>
<tr>
<td>1 g/s cm³</td>
<td>$1.0000 \times 10^{-3}$ kg/s cm³</td>
</tr>
<tr>
<td>1 kg/m³</td>
<td>$2.7778 \times 10^{-3}$ kg/s m³</td>
</tr>
<tr>
<td>1 lb/s ft³</td>
<td>$1.6018 \times 10^{-3}$ kg/s m³</td>
</tr>
<tr>
<td>1 lb/h ft³</td>
<td>$4.4496 \times 10^{-3}$ kg/s m³</td>
</tr>
<tr>
<td>1 kg/h ft³</td>
<td>$9.8096 \times 10^{-3}$ kg/s m³</td>
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</table>

### Mass transfer coefficient, concentration driving force—see Velocity

### Mass transfer coefficient, dimensionless driving force—see Mass flux

### Momentum angular

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 g cm²/s</td>
<td>$1.0000 \times 10^{-7}$ kg cm²/s</td>
</tr>
<tr>
<td>1 lb ft²/s</td>
<td>$4.2140 \times 10^{-2}$ kg cm²/s</td>
</tr>
<tr>
<td>1 lb ft²/h</td>
<td>$1.1706 \times 10^{-5}$ kg cm²/s</td>
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</table>

### Momentum, linear

<table>
<thead>
<tr>
<th>Unit</th>
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<tbody>
<tr>
<td>1 g cm/s</td>
<td>$1.0000 \times 10^{-5}$ kg m/s</td>
</tr>
<tr>
<td>1 lb ft/s</td>
<td>$1.3825 \times 10^{-1}$ kg m/s</td>
</tr>
<tr>
<td>1 lb ft/h</td>
<td>$3.8404 \times 10^{-5}$ kg m/s</td>
</tr>
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</table>

### Moment of inertia

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 g cm²</td>
<td>$1.0000 \times 10^{-7}$ kg m²</td>
</tr>
<tr>
<td>1 lb ft²</td>
<td>$4.2140 \times 10^{-2}$ kg m²</td>
</tr>
</tbody>
</table>

### Power

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cal/s</td>
<td>$4.1868 \text{ W}$</td>
</tr>
<tr>
<td>1 kcal/h</td>
<td>$1.1630 \text{ W}$</td>
</tr>
<tr>
<td>1 Btu/s</td>
<td>$1.0551 \times 10^3 \text{ W}$</td>
</tr>
<tr>
<td>1 erg/s</td>
<td>$1.0000 \times 10^{-7} \text{ W}$</td>
</tr>
<tr>
<td>1 tonne cal/h</td>
<td>$1.1630 \times 10^7 \text{ W}$</td>
</tr>
<tr>
<td>1 hp (metric)</td>
<td>$7.3548 \times 10^2 \text{ W}$</td>
</tr>
<tr>
<td>1 ft pdl/s</td>
<td>$4.2139 \times 10^{-2} \text{ W}$</td>
</tr>
<tr>
<td>1 ft lbf/s</td>
<td>$1.3558 \text{ W}$</td>
</tr>
<tr>
<td>1 Btu/h</td>
<td>$2.9308 \times 10^{-1} \text{ W}$</td>
</tr>
<tr>
<td>1 Chu/h</td>
<td>$5.2754 \times 10^{-1} \text{ W}$</td>
</tr>
<tr>
<td>1 hp (British)</td>
<td>$7.4570 \times 10^2 \text{ W}$</td>
</tr>
<tr>
<td>1 ton refrigeration</td>
<td>$3.5169 \times 10^2 \text{ W}$</td>
</tr>
</tbody>
</table>

### Pressure

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 dyn/cm²</td>
<td>$1.0000 \times 10^{-1} \text{ N/m²}$</td>
</tr>
</tbody>
</table>
1 kgf/m² : 9.8067 N/m²
1 pdl/ft² : 1.4881 N/m²
1 standard atmosphere : 1.0133 × 10¹ N/m²
1 at (1 kgf/cm²) : 9.8067 × 10¹ N/m²
1 bar : 1.0000 × 10¹ N/m²
1 lbf/ft² : 4.7880 × 10¹ N/m²
1 lbf/in² : 6.8948 × 10¹ N/m²
1 tonf/m³ : 1.5444 × 10¹ N/m²
1 in water : 2.4909 × 10¹ N/m²
1 ft water : 2.9891 × 10¹ N/m²
1 mm Hg : 1.3333 × 10² N/m²
1 in Hg : 3.3866 × 10² N/m²

Reaction rate—see Mass release rate

Shear stress—see Pressure

Specific enthalpy

1 cal/g : 4.1868 × 10³ J/kg
1 Btu/lb : 2.3260 × 10³ J/kg
1 Cal/lb : 4.1868 × 10³ J/kg

Specific heat

1 cal/g °C : 4.1868 × 10³ J/kg °C
1 Btu/lb °F : 4.1868 × 10³ J/kg °F

Specific volume

1 cm³/g : 1.0000 × 10⁻³ m³/kg
1 ft³/lb : 6.2428 × 10⁻³ m³/kg
1 ft³/kg : 2.8317 × 10⁻³ m³/kg

Surface per unit mass

1 cm²/g : 1.0000 × 10⁻¹ m²/kg
1 ft²/lb : 2.0482 × 10⁻¹ m²/kg
1 ft²/kg : 9.2903 × 10⁻¹ m²/kg

Surface per unit volume

1 cm²/cm³ : 1.0000 × 10⁻² m²/m³
1 ft²/ft³ : 3.2808 m²/m³

Surface tension

1 dyn/cm : 1.0000 × 10⁻⁹ N/m

Temperature difference

1 degF (deg R) : 5/9 deg C (deg K)

Thermal conductivity

1 cal/s cm² (°C/cm) : 4.1868 × 10⁻² W/m² (°C/m)
1 kcal/h m² (°C/m) : 1.1630 W/m² (°C/m)
1 Btu/h ft² (°F/ft) : 1.7308 W/m² (°C/m)
1 Btu/h ft² (°F/in) : 1.4423 × 10⁻¹ W/m² (°C/m)
1 kcal/h ft² (°C/ft) : 3.8156 W/m² (°C/m)

Time

1 h : 3.600 × 10⁶ s
1 min : 6.000 × 10⁵ s
1 d (day) : 8.640 × 10⁶ s
1 yr : 3.1558 × 10⁹ s

Torque—see Energy

Velocity

1 cm/s : 1.0000 × 10⁻² m/s
1 m/h : 2.7778 × 10⁻¹ m/s
1 ft/s : 3.0480 × 10⁻¹ m/s
1 ft/h : 8.4667 × 10⁻⁵ m/s
1 mile/h : 4.4704 × 10⁻¹ m/s

Viscosity, absolute (or dynamic)

1 g/cm s (1 poise) : 1.0000 × 10⁻¹ kg/m s
1 kg/m h : 2.7778 × 10⁻¹ kg/m s
1 lb/ft s : 1.4882 kg/m s
1 lb/ft h : 4.1338 × 10⁻¹ kg/m s
1 kg/ft h : 9.1134 × 10⁻¹ kg/m s

Viscosity, kinematic

1 cm²/s (1 stokes) : 1.0000 × 10⁻⁴ m²/s
APPENDIX 30/6 UNITS AND UNIT CONVERSIONS

<table>
<thead>
<tr>
<th>Conversion</th>
<th>Equivalent</th>
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<tbody>
<tr>
<td>1 m²/h</td>
<td>2.7778 × 10⁻⁴ m²/s</td>
</tr>
<tr>
<td>1 ft²/s</td>
<td>9.2903 × 10⁻² m²/s</td>
</tr>
<tr>
<td>1 ft²/h</td>
<td>2.5806 × 10⁻⁵ m²/s</td>
</tr>
</tbody>
</table>

**Volume**

<table>
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<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm³</td>
<td>1.0000 × 10⁻⁶ m³</td>
</tr>
<tr>
<td>1 ft³</td>
<td>2.8317 × 10⁻² m³</td>
</tr>
<tr>
<td>1 l (litre)</td>
<td>1.0000 × 10⁻³ m³</td>
</tr>
<tr>
<td>1 in³</td>
<td>1.6387 × 10⁻⁵ m³</td>
</tr>
<tr>
<td>1 yd³</td>
<td>7.6455 × 10⁻¹ m³</td>
</tr>
<tr>
<td>1 UK gal</td>
<td>4.5460 × 10⁻³ m³</td>
</tr>
<tr>
<td>1 US gal</td>
<td>3.7853 × 10⁻³ m³</td>
</tr>
</tbody>
</table>

**Volumetric flow**

<table>
<thead>
<tr>
<th>Conversion</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm³/s</td>
<td>1.0000 × 10⁻⁶ m³/s</td>
</tr>
<tr>
<td>1 m³/h</td>
<td>2.7778 × 10⁻⁴ m³/s</td>
</tr>
<tr>
<td>1 ft³/s</td>
<td>2.8317 × 10⁻² m³/s</td>
</tr>
<tr>
<td>1 cm³/min</td>
<td>1.6667 × 10⁻⁵ m³/s</td>
</tr>
<tr>
<td>1 l/min</td>
<td>1.6667 × 10⁻⁵ m³/s</td>
</tr>
<tr>
<td>1 ft³/min</td>
<td>4.7195 × 10⁻⁴ m³/s</td>
</tr>
<tr>
<td>1 ft³/h</td>
<td>7.8658 × 10⁻⁶ m³/s</td>
</tr>
<tr>
<td>1 UK gal/min</td>
<td>7.5766 × 10⁻⁵ m³/s</td>
</tr>
<tr>
<td>1 US gal/min</td>
<td>6.3089 × 10⁻⁵ m³/s</td>
</tr>
<tr>
<td>1 UK gal/h</td>
<td>1.2628 × 10⁻⁶ m³/s</td>
</tr>
<tr>
<td>1 US gal/h</td>
<td>1.0515 × 10⁻⁶ m³/s</td>
</tr>
</tbody>
</table>

**Wetting rate (mass)** – see Velocity, absolute

**Wetting rate (volumetric)**

<table>
<thead>
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<th>Conversion</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 l/h in</td>
<td>1.0936 × 10⁻⁵ m³/s m</td>
</tr>
</tbody>
</table>

– see also Viscosity, kinematic

**Work** – see Energy
References
2 REFERENCES

Notes
(1) References are given in the text by surname only, except where there would be ambiguity, in which case the initials are given also.
(2) References for which no date has been established are denoted (n.d.) and head their group alphabetically. Where the approximate date is known, this is indicated, e.g. SMITH, J. (c. 1988).
(3) Anonymous entries are grouped at the start of the references and are in date order.
(4) In ranking a name alphabetically, elements such as de or von are disregarded, e.g. von Bismark is listed under B rather than V.
(5) Chinese names are given in the form used by the particular author, i.e. either in full or by surname with initials.
(6) The following abbreviated titles are used:

<table>
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<th>Abbreviated title</th>
<th>Full title</th>
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</thead>
<tbody>
<tr>
<td>Hazard Identification and Risk Analysis Hazards from Pressure</td>
<td>Int. Conf. on Hazard Identification and Risk Analysis, Human Factors and Relief and Accidental Discharge (Rugby: Inst. Chem. Engrs), 1987</td>
</tr>
<tr>
<td>LPB Loss Prevention and Safety Promotion 1–</td>
<td>Loss Prevention Bulletin (Institution of Chemical Engineers)</td>
</tr>
<tr>
<td>Major Hazards Onshore and Offshore Modelling and Mitigating the Consequences of Accidental Releases</td>
<td>Major Hazards Onshore and Offshore (Rugby: Inst. Chem. Engrs), 1992</td>
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112 1993 – STATAS: development of an HSE audit scheme for loss of containment incidents – part 1, a loss of containment model by K.B. Ratcliffe; Practical examples of safety risk assessment in BAPCO by R.K. Goyal; Use of ‘Lessons learned’ for in depth analysis by J.R. Taylor The challenge of Kozloduy by J.A. Ashurst and G. Davidson; Nitrogen near-miss, p. 20; Cumene hydroperoxide (CHP) drum explosion, p. 21; Chlorine leak during shutdown test; Letter (on Coode Island) by G. Croudace

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Acronyms
<table>
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<tr>
<th>Acronym</th>
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<td>AAE</td>
<td>Additional Accommodation East (Piper Alpha)</td>
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<td>AAM</td>
<td>accident anatomy method</td>
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<td>AAW</td>
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<td>ABC</td>
<td>general purpose dry chemical</td>
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<td>ABI</td>
<td>Association of British Insurers</td>
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<tr>
<td>ABL</td>
<td>atmospheric boundary layer</td>
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<tr>
<td>ACE</td>
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<td>Approved Code of Practice</td>
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<td>Average circle radius</td>
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<td>AQL</td>
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<td>ASM</td>
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<td>ATMS</td>
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<td>BCME</td>
<td>bis(chloromethyl)ether</td>
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<td>Beilby, Cottrell and Swinden (model)</td>
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<td>BD</td>
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<td>BLEVE</td>
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<td>BNP</td>
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<td>BOCA</td>
<td>Building Official and Code Administration</td>
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<td>BOP</td>
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Subject Index
Notes

(1) In the case where the text refers to a publication, the Author Index gives the entry for the relevant body, which may be an organization, institution or company or a commission, committee or inspectorate. Otherwise, reference to such bodies is in this index.

(2) Acronyms used in the index may be found in the Acronyms section.

(3) Free-standing entities are generally given in full but where one is used as a qualifier, its acronym may be used. A typical case is the pair of entries Trinitrotoluene and TNT equivalent model. Another pair is Institution of Chemical Engineers and IChemE Maintenance Guide.

(4) Many entries in this index are prefaced by the words Plant or Process.

(5) Cross-references are generally not given to entries which begin with the same initial word, e.g. Control algorithms, Control loops or to entries in which the words are closely related e.g. Welds, Welders, Welding.

(6) Within an entry, one form of cross-reference is use of the term see. In this case, where the following word begins with a lower case letter the cross-reference is to a subentry within the same main entry; where the word begins with an upper case letter, the cross-reference is to another main entry. Another form of cross-reference comprises the term q.v., which refers to the main entry of the same name.

(7) In a given entry, a page number in a chapter is indicated by the chapter number followed by a stroke and then the page number, e.g. 17/35, which denotes Chapter 17, page 35. Similarly, a page number in an appendix is indicated by the letter A followed by the appendix number, the stroke and the page number, e.g. A2/13 and one in the preliminary matter by the letter P, a stroke and the page number, e.g. P/7.

(8) Appendix 1 contains two series of case histories, the A and B series. In the entry Case histories and in entries where the incident is named, the reference is given in the form A7 or B13; otherwise it is given as a page number.

(9) Chemical and physical properties are generally referred to under the particular chemicals.

(10) Entries referring to case histories may include hypotheses on the causes.

(11) In the entry point probit equations use is made of the following additional abbreviations: ELB: Eisenberg, Lynch and Breeding; Fletcher: Fletcher et al.; HC: Hadjipavlou and Carr-Hill Jones: Jones et al.; PA: Perry and Articola.
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