Food Biodeterioration and Preservation

EDITED BY GARY S. TUCKER
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Gary S. Tucker
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Biodeterioration can be defined as the breakdown of food by agents of microbiological origin, either directly or indirectly by products of their metabolism. This book examines how the agents of food biodeterioration operate and the commercial methods available to counteract these agents and produce safe, wholesome foods. Contamination of foods can arise from microbiological, chemical and physical sources, but it is the microbiological sources – micro-organisms and the enzymes they produce as part of their metabolic processes – that are the focus of this book.

Food preservation aims to extend the shelf life of foods. In most cases, it is the growth of either spoilage or disease-causing micro-organisms that limits the length of time a food can be kept, and most preservation techniques are primarily based on reducing or preventing this growth. However, other factors limit shelf life such as the action of naturally-occurring enzymes within the food, or natural chemical reactions that occur between the constituents of the food. These must also be taken into consideration.

The introductory chapter, which sets the scene for the more detailed chapters to follow, describes the many types of enzymes and micro-organisms responsible for biodeterioration of foods. Food preservation originated with traditional methods such as curing, salting and sugaring, all of which are still important commercial methods. Major advances in preservation technology were the introduction of the canning and freezing processes, and these methods still form a substantial part of the food preservation business.

Even the most effective food preservation treatments cannot ensure the consistent manufacture of foods with a guarantee of absolute safety. For this reason, food companies use Hazard Analysis Critical Control Point (HACCP) systems to control their manufacturing processes, and the effective implementation of an HACCP plan is the surest way of delivering safe food. Any book on controlling food biodeterioration or food preservation would be incomplete without the inclusion of an HACCP chapter. This describes how a food company should
approach HACCP as the means of ensuring that food is manufactured with the
greatest probability of being free from biological, chemical or physical hazards.

There are many methods that can be used to preserve foods, and the remaining
chapters of the book are dedicated to the most widely used commercial methods:
thermal processing, chilling, freezing, drying and controlling the atmosphere
around a food. Each method approaches microbiological control in foods in a
different way, which results in food products of quite different organoleptic and
keeping properties. Choice of the appropriate preservation method depends on a
number of factors.

It is becoming increasingly common for preservation methods to be used in
combination in order to reduce the severity of any individual method. This is
referred to as ‘hurdle’ technology and there is a chapter dedicated to this subject.
For example, thermal processing is often used as part of a combination process
designed to present ‘hurdles’ to microbial growth. One of the traditional
preservation hurdles is acidity, used in the manufacture of fruits, jams and
preserves. The low pH in the fruit prevents Clostridium botulinum spores from
germinating, and so the thermal process needs to be effective only upon less heat-
resistant organisms. The main advantage of hurdle technologies is that the milder
treatments can lead to the production of better quality foods.

There is a growing interest in using new or novel technologies for food
preservation where a quality improvement or economic benefit can be made. The
final chapter deals with those new technologies that have attained some
commercial application, including ohmic and microwave heating, irradiation and
high-pressure treatment. These technologies may have benefits in allowing foods
to be more minimally processed, thus retaining more of their inherent attributes
such as texture, colour and nutritional content.

Gary S. Tucker
1 Control of Biodeterioration in Food
Susan Featherstone

1.1 OVERVIEW

All food undergoes deterioration to some degree once harvested or slaughtered. The deterioration may include loss of nutritional value, organoleptic and colour changes, and most importantly, safety may become compromised. It is the challenge of the food industry to control this deterioration and maintain the safety of the food, while making sure that the food is as convenient, nutritious and available as it can possibly be.

Biodeterioration is defined as any undesirable change in the property of a material caused by the vital activities of organisms. It is applicable to many materials e.g. food, wood, paper, leather, fuels, cosmetics, building materials and building structures. Biodeterioration may be as a result of the metabolic processes of one of many micro-organisms or it can be caused by insect, rodent or bird damage. An incredibly broad and diverse field, all biodeterioration has as a common theme that it affects materials and substances that we need and value, and that it can largely be controlled by proper understanding of the materials and the possible spoilage organisms and mechanisms.

Biodeterioration is also specifically different from biodegradation in that the changes are ‘undesirable’. Biodegradation occurs when complex materials are broken down by micro-organisms to form simple end-products. Within a biological ecosystem, there are micro-organisms that produce a host of enzymes that can biodegrade natural as well as some synthetic products; this is very important for maintaining the stability of the ecosystem and is extremely important for water purification and sewage treatment, and is widely used in the food industry. The main differences between biodeterioration and biodegradation are the undesirability and uncontrollability of the former.

Another important feature of biodeterioration is that it is caused by organisms. According to the definition, it is not the degradation that occurs
naturally in some organic materials or foods caused by intrinsic enzymes, i.e. those enzymes present in the product that cause degradation or decay after death. For example, loss of food quality by intrinsic enzymes is an important topic as it can cause quality deterioration and render food unacceptable. Reactions due to these enzymes will not be considered in this text, but are important to bear in mind as their activities can make nutrients from the product available and accessible to micro-organisms so that biodeterioration reactions can follow.2,3

1.2 A SUMMARY OF THE DIFFERENT KINDS OF BIODETERIORATION

1.2.1 Chemical biodeterioration

There are two modes of chemical biodeterioration. Both have a similar result, i.e. the material becomes spoilt, damaged or unsafe, but the cause or biochemistry of the two is quite different:2,4

- Biochemical assimilatory biodeterioration – the organism uses the material as food i.e. an energy source.
- Biochemical dissimilatory biodeterioration – the chemical change in the food is as a result of waste products from the organisms in question.

1.2.2 Physical biodeterioration

- Mechanical biodeterioration – this occurs when the material is physically disrupted/damaged by the growth or activities of the organisms.
- Soiling/fouling – with this kind of biodeterioration the material or product is not necessarily unsafe, but as its appearance has been compromised, it is rendered unacceptable. The building up of biofilms on the surface of a material can affect the performance of that material.

See Table 1.1 and Fig. 1.1.

Living organisms can be divided on the basis of their nutritional requirements into autotrophs and heterotrophs (see Table 1.2). Autotrophic organisms see all inorganic materials as a potential source of nutrients, while heterotrophic organisms can only use organic matter. The organisms responsible for biodeterioration of food are usually chemoheterotrophs, however it is important to realize that even the packaging that the food is stored in and the warehouses themselves, can be a source of nutrients for some micro-organisms, and it is therefore important to control the humidity, temperature and duration of storage of food, as far as possible.4,6
### Table 1.1 | Examples of the diversity of biodeterioration.

<table>
<thead>
<tr>
<th>Affected material</th>
<th>Example</th>
<th>Type of biodeterioration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone, marble, concrete</td>
<td>Deterioration of stone monuments</td>
<td>Chemical assimilatory: where calcium and other minerals are used as a food source</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical dissimilatory: where acid by-products dissolve the surfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical: where root damage can undermine and weaken structures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fouling: where biofilms can affect the aesthetics of the structure</td>
</tr>
<tr>
<td>Wood</td>
<td>Rotting of wooden floorboards and timber structures</td>
<td>Chemical assimilatory: where the cellulose and lignin in the wood are used as food by fungi and other organisms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dissimilatory: where acid and other by-products result in breakdown of the structure</td>
</tr>
<tr>
<td>Leather</td>
<td>Loss of strength and structure of leather objects</td>
<td>Chemical assimilatory: by proteolytic bacteria, which break down the proteins</td>
</tr>
<tr>
<td>Paper</td>
<td>Degradation of books</td>
<td>Chemical assimilatory: most commonly by fungi</td>
</tr>
<tr>
<td>Paint</td>
<td>Water-based paints</td>
<td>Chemical assimilatory: by bacteria and fungi, results in thinning of the paint and production of off odours</td>
</tr>
<tr>
<td>Museum artefacts</td>
<td>Discoloration and degradation of valuable relics</td>
<td>Chemical assimilatory and chemical dissimilatory: by bacteria and mould, resulting in weakening of structures and discoloration of the objects</td>
</tr>
<tr>
<td>Food</td>
<td>All foods: animal matter and vegetable based</td>
<td>The most important is chemical assimilatory: the food is used as a food source as it is nutritionally compromised and can have toxins associated with it as by-products of the microbial activity</td>
</tr>
<tr>
<td>Metal</td>
<td>Biodeterioration of the wreck of the RMS Titanic</td>
<td>Chemical assimilatory: attack on the steel by communities of bacteria and fungi</td>
</tr>
<tr>
<td>Fuels</td>
<td>Fuels in tanks</td>
<td>Chemical assimilatory: most commonly the C-10 to C-18 hydrocarbons are broken down to form shorter chain hydrocarbons that, together with the biofilms, can clog fuel lines</td>
</tr>
<tr>
<td>Lubricants</td>
<td>Lubricants in metal working lines</td>
<td>Chemical assimilatory: resulting in the loss of lubricating properties and therefore functionality</td>
</tr>
<tr>
<td>Teeth</td>
<td>Tooth decay</td>
<td>Chemical dissimilatory: waste products from oral acidogenic bacterial growth cause tooth decay</td>
</tr>
<tr>
<td>Glass</td>
<td>Leaching, staining of stained glass windows</td>
<td>Chemical dissimilatory: by waste products from growth of fungi and Cyanobacteria Mechanical: filamentous organisms can cause stress cracking</td>
</tr>
</tbody>
</table>
1.3 KINDS OF LIVING ORGANISMS INVOLVED IN BIODETERIORATION

Living organisms that can cause biodeterioration are referred to as **biodeteriogens**.\(^2\) Animals, insects and higher plants can be easily identified by visual observation and by examining their morphological and physiological characteristics. Organisms like bacteria, fungi and algae are less easy to identify and need to be isolated to be examined. Growth of these organisms under laboratory conditions is often difficult and specialized methods using fluorescent dyes and antibodies or examination using a scanning electron microscope must be used. In some instances, identification can only be made using DNA techniques.

### 1.3.1 Bacteria

Bacteria are a large diverse group of microscopic, prokaryotic, unicellular organisms. They can be of various shapes (spherical, rod-like or spiral) and may be motile or non-motile. They include both autotrophic and
heterotrophic species, and can be aerobic or anaerobic, and many species can thrive under either condition. They have relatively simple nutritional needs, and are easily adaptable and can readily change to suit their environment.

1.3.2 Fungi

Fungi are a large group of small chemoheterotrophic organisms. They do not contain chlorophyll and therefore cannot make their own food by using sunlight. They are, however extremely adaptable and can utilize almost any organic material. Their growth is characterized by unicellular or multicellular filamentous hyphae, which can often be the cause of physical biodeterioration.

1.3.3 Algae, mosses and liverworts

Algae, mosses and liverworts are eukaryotic unicellular or multicellular organisms. They are photoautotrophic and need moisture, light and inorganic nutrients to grow.
1.3.4 Higher plants

Higher plants are photoautotrophic organisms with specialized tissues and organs that show functional specialization.

1.3.5 Insects

Insects include a large group of aerobic heterotrophic organisms. They need to feed on organic matter, but as a group are diverse in what they can consume. They can feed off all processed and unprocessed foods, as well as non-food items like binding materials and adhesives. Since some insects are attracted to the tight, dark places that abound in storage areas, and since stored foods and materials are handled infrequently, insects may do significant damage before they are discovered. Some examples of insect pests are silverfish, psocids, cockroaches, borer beetles, weevils and moths. Insects can be infected by disease-causing organisms such as bacteria, viruses and fungi. Besides causing significant biodeterioration themselves, insects can contaminate food or other organic matter.

1.3.6 Birds, mammals and reptiles

Birds, mammals and reptiles are aerobic heterotrophic organisms that have fairly sophisticated food requirements. They can be very resourceful in their acquiring of food and can cause extensive physical damage. Their waste products can also serve as a source of nutrients for other biodeteriorogens and can also be corrosive.

1.4 FOOD BIODETERIORATION

From Man’s earliest history, control of biodeterioration of food has been a concern. The basic principles for control that were applied thousands of years ago are still applicable today:

- Eat food as soon after harvesting as possible.
- Physically protect food from pests by storing in sealed containers.
- Preserve by drying, salting or adding spices.

In our modern, urbanized world we find it impractical to eat food immediately after harvesting and there are times that it must travel thousands of kilometres to get to our plate. Therefore other appropriate methods of food preservation have been developed.

Food is made up from water, proteins, fats, carbohydrates and a host of vitamins and minerals. Each of these can be a target for micro-organisms
and pests, and as a result each must be considered in the method of food preservation and of storage used.

Some micro-organisms are better adapted to food spoilage than others and hence knowing and understanding food and the organisms that can cause biodeterioration will certainly help in ensuring that they do not get an opportunity to thrive and cause any spoilage of the food. All of the issues mentioned above will be considered in this text.

In addition to the microbiological aspects of food biodeterioration it is important to ensure that food is not degraded, spoiled or rendered susceptible to further or unnecessary spoilage owing to poor procedures and hygiene in farming, harvesting, storage and distribution. The impact of insects and mammals on the damage to cereals and other dry staples and on fruit and vegetables is enormous. These infestations are also initiation points in that their action renders the food susceptible to microbial attack. This is particularly relevant to developing economies in less well resourced parts of the world where dependence on primary staples is critical.

Some general examples of this sort of biodeterioration include borers, worms, pecking, gnawing, physical bruising, etc. Some examples include:

- flies that carry pathogenic bacteria, but which can also cause damage because they lay eggs, the larvae of which then invade the meat or foodstuff causing further deterioration
- snails on salad leaves
- aphids on various crops.

1.4.1 The composition of food

Food can be of animal or plant origin. It is made up mainly from varying proportions of carbohydrates, fats and proteins which provide energy and are the building blocks for growth and are essential for maintaining a healthy body. There are also small amounts of vitamins and minerals that are also essential for the body to function properly. Water is also an important component of food and is vital for cellular functions (Table 1.3).

1.4.1.1 Water

Water is essential for life and is abundant in all food products (unless there have been steps taken to remove it or formulate it without water). As micro-organisms cannot grow without water, the presence or absence of water is very important to the status of food and its potential for
biodeterioration. Many food processing techniques use the modification of water as the basis for preservation – by making it unavailable to the micro-organisms so that they cannot grow, e.g. drying, salting, freezing, emulsification, making pectin gels, etc.\(^7,8\)

The chemical formula for water is \(\text{H}_2\text{O}\). Each molecule of water is made up from two hydrogen atoms and one oxygen atom. A strong covalent bond holds the hydrogen atoms to the oxygen atom, but as the oxygen atom attracts the electrons more strongly than the hydrogen, the bond is slightly ionic, with the hydrogen being slightly positively charged and the oxygen being slightly negatively charged. As a result of this, the water molecule is polar and there are weak bonds (hydrogen bonds) between the negative and positive charges between molecules. The hydrogen bond, although weak, is very important as it is what causes water to be a liquid

### Table 1.3 The composition of some common foods.

<table>
<thead>
<tr>
<th>Food</th>
<th>% Water</th>
<th>% Protein</th>
<th>% Fat</th>
<th>% Carbohydrate</th>
<th>% Sugar</th>
<th>% Starch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fruit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple (fresh)</td>
<td>87.7</td>
<td>0.3</td>
<td>0.1</td>
<td>8.9</td>
<td>8.9</td>
<td>trace</td>
</tr>
<tr>
<td>Banana, flesh only</td>
<td>75.1</td>
<td>1.2</td>
<td>0.3</td>
<td>23.2</td>
<td>20.9</td>
<td>2.3</td>
</tr>
<tr>
<td>(ripe, fresh)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grapes (fresh)</td>
<td>81.8</td>
<td>0.4</td>
<td>0.1</td>
<td>15.4</td>
<td>15.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Cherries (fresh)</td>
<td>82.8</td>
<td>0.9</td>
<td>0.1</td>
<td>11.5</td>
<td>11.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Cherries (glace)</td>
<td>23.6</td>
<td>0.4</td>
<td>trace</td>
<td>66.4</td>
<td>66.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Peaches (fresh)</td>
<td>88.9</td>
<td>1.0</td>
<td>0.1</td>
<td>7.6</td>
<td>7.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Raisins</td>
<td>13.2</td>
<td>2.1</td>
<td>0.4</td>
<td>69.3</td>
<td>69.3</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Vegetables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baked beans (canned in tomato sauce)</td>
<td>71.5</td>
<td>5.2</td>
<td>0.6</td>
<td>15.3</td>
<td>5.9</td>
<td>9.4</td>
</tr>
<tr>
<td>Carrots (raw, young)</td>
<td>88.8</td>
<td>0.7</td>
<td>0.5</td>
<td>6.0</td>
<td>5.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Potato (raw)</td>
<td>81.7</td>
<td>1.7</td>
<td>0.3</td>
<td>16.1</td>
<td>1.3</td>
<td>14.8</td>
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<tr>
<td>Pumpkin (raw)</td>
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<td>15.6</td>
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<tr>
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<td>14.6</td>
<td>39.5</td>
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<tr>
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<tr>
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<td>18.8</td>
<td>5.4</td>
<td>0.7</td>
<td>0.6</td>
<td>0.1</td>
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<td>81.7</td>
<td>Trace</td>
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</tr>
<tr>
<td>Cheese, Cheddar</td>
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<td>34.4</td>
<td>0.1</td>
<td>0.1</td>
<td>trace</td>
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<td>Eggs (chicken)</td>
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at room temperature and influences much of its chemistry and allows it to bond with sugars, pectins, starches and proteins.

Another important characteristic of water, as far as food science is concerned, is that frozen water is less dense than liquid water. (In liquid water the molecules are free to pack together closely and ‘slide’ past each other, whereas in ice the molecules form more-or-less rigid bonds with their neighbours, which creates the solid structure but also holds them further apart.) This means that ice floats on liquid water, but more importantly, when food is frozen, the volume increases by about 9%.

1.4.1.2 Carbohydrates
Carbohydrates are organic compounds that contain carbon, oxygen and hydrogen. They can be simple sugars or complex molecules. They have the general formula $C_nH_{2n}O_n$. Food carbohydrates include monosaccharides (e.g. glucose), disaccharides (e.g. lactose, sucrose) and polysaccharides (e.g. dextrins, starches, celluloses, pectins).

Monosaccharides and disaccharides are also referred to as sugars. They are readily digested and metabolized by the human body to supply energy, but can also be easily metabolized (fermented) by micro-organisms.

1.4.1.3 Fats
Fats are the second most important source of energy in the diet, after carbohydrates. The yield of energy from fats is greater than that of carbohydrates, with fats yielding more than double the amount of energy as an equivalent weight of carbohydrate. They are also an essential part of the diet, and are utilized in membrane, cell, tissue and organ structures. Fats or oils (triglycerides) are a group of naturally occurring organic compounds – esters comprised of three molecules of fatty acid covalently bonded to one molecule of glycerol. The properties of a fat are determined by the type and length of fatty acids that are bonded to the glycerol molecule.

Fats are designated as saturated or unsaturated, depending on whether the fatty acid moieties contain all the hydrogen atoms they are capable of holding (saturated) or whether they have capacity for additional hydrogen atoms (unsaturated). To put it another way, all the carbon–carbon bonds are single bonds in saturated fats, but unsaturated fats/oils have at least one carbon–carbon double bond. Saturated fats are generally solid at room temperature; unsaturated and polyunsaturated fats are liquids. Unsaturated fats may be converted to saturated fats by the chemical addition of hydrogen atoms (hydrogenation).
1.4.1.4 Proteins

Proteins are the most abundant molecules in cells, making up about 50% of the dry mass. Protein molecules range from soluble globules that can pass through cell membranes and set off metabolic reactions (e.g. enzymes and hormones) to the long, insoluble fibres that make up connective tissue and hair. Proteins are made up from amino acids, of which 20 are used by living organisms. Each amino acid has specific properties, depending on its structure, and when they combine together to form a protein, a unique complex molecule is formed. All proteins have unique shapes that allow them to carry out a particular function in the cell. All amino acids are organic compounds that contain both an amino (NH$_2$) and a carboxyl (COOH) group.

Proteins are very important foods, both nutritionally and as functional ingredients. They serve primarily to build and maintain cells, but their chemical breakdown also provides energy, yielding almost the same amount of energy as carbohydrates on a weight-for-weight basis.

1.4.1.5 Minerals and trace elements

Living organisms need countless numbers of minerals and trace elements for them to be able to function adequately. Among these are calcium, iodine, iron, magnesium, manganese, phosphorus, selenium and zinc.

1.5 A DESCRIPTION OF THE MECHANISMS OF FOOD BIODETERIORATION

1.5.1 Fermentation

Many different types of fermented foods are consumed worldwide (See Fig. 1.2). Many countries have their own unique types of fermented food, representing the staple diet and the (raw) ingredients available in that particular place. Some of the more obvious fermented fruit and vegetable products are the alcoholic beverages: beer and wine. However, several fermented fruit and vegetable products arise from lactic acid fermentation and are extremely important in meeting the nutritional requirements of a large proportion of the global population.

Food fermentation can be brought about by bacteria, yeasts or moulds. When micro-organisms metabolize and grow, they release by-products. In food fermentation some of the by-products have a preserving effect in the food by lowering the pH and/or producing alcohols. Most food spoilage organisms cannot survive in either alcoholic or acidic environments,
therefore the production of these by-products can prevent a food from spoilage and extend the shelf life. The fermentation by-products also change the texture and flavour of the food substrate, e.g. in the case of milk, the acid causes the precipitation of milk proteins to solid curd.\textsuperscript{11,12,13,14}

The most important bacteria in desirable food fermentation are the \textit{Lactobacillaceae}, which have the ability to produce lactic acid from carbohydrates, and the acetic acid producing \textit{Acetobacter} species. Yeasts play an important role in the food industry, e.g. in the leavening of bread and the production of alcohol and invert sugar. The most beneficial yeasts in terms of desirable food fermentation are from the \textit{Saccharomyces} family, especially \textit{S. cerevisiae}. Moulds do not play a significant role in the desirable fermentation of fruit and vegetable products, however, some do impart characteristic flavours to foods and others produce enzymes, e.g. moulds from the genus \textit{Penicillium} are associated with the ripening and flavour of cheeses. Moulds are aerobic and therefore require oxygen for growth. They produce a large variety of enzymes, and can colonize and grow on most types of food.

Many of the changes that occur during fermentation of foods are the result of enzymes produced by micro-organisms. Enzymes are complex proteins produced by living cells to carry out specific biochemical reactions. They initiate and control reactions, rather than being used as part of a reaction. They are sensitive to temperature, pH, moisture content, nutrient concentration and the concentration of any inhibitors. Enzymes each have specific requirements for optimum performance. Extremes of temperature and pH will denature the protein and destroy enzyme activity. In food fermentation enzymes have several roles: the breakdown of starch, the conversion of sugars and the modification of proteins.
Most food fermentation is the result of more than one micro-organism, either working together or in a sequence. There are very few pure culture fermentations. Different species of bacteria, yeasts and moulds all have their own optimum growing conditions. An organism that initiates fermentation will grow until the by-products that it produces inhibit further growth and activity. During this initial growth period, other organisms develop that are ready to take over when the conditions become favourable for them. Generally, growth is initiated by bacteria, followed by yeasts and then moulds.

Fermentation usually results in the breakdown of complex organic substances into simpler ones. Food fermentation includes many important chemical reactions, e.g. the enzyme lactase, produced by bacteria, causes the lactose in milk to be converted into lactic acid, in alcoholic fermentation. Similarly zymase, secreted by yeast, converts simple sugars (e.g. glucose and fructose) into ethyl alcohol and carbon dioxide. Some fermentation reactions are desirable, but others are not, e.g. the formation of butanoic acid when butter becomes rancid and that of acetic acid when wine turns sour.

Fermentation is generally desirable in food as:
- Many desirable flavours and odours are generated as part of the fermentation reactions.
- It makes the nutrients more available.
- Micro-organisms are anabolic as well as catabolic, i.e. they also synthesise nutrients like riboflavin and other vitamins.

Undesirable reactions that render the food inedible or unsafe can also take place. Some examples of specific fermentations and examples when they change from being useful to being biodegradation reactions are as follows:

1.5.1.1 Pickles

Pickling (corning) is the process of preparing a food by soaking it in brine containing salt and acid, resulting in a product that would otherwise be perishable being stable for months. The resulting food is called a pickle. The preservation of food by lactic acid bacteria fermentation has been one of the most important methods of food conservation for thousands of years. Pickled products are made from many different fruits and vegetables (e.g. cucumbers, olives, cabbages, peppers, green tomatoes, okra, carrots, mangoes, etc). If the food contains sufficient moisture, a pickling brine may be produced simply by adding dry salt to the vegetables to draw out excess water, then allowing natural fermentation to create an acidic
brine solution containing lactic acid (e.g. sauerkraut). Other pickles are made by placing the vegetable in a brine solution (e.g. cucumbers) and allowing enough time for the subsequent fermentation reactions to take place.

The salinity of the brine solution, the temperature of fermentation, the exclusion of oxygen and the acidity of the brine all determine which micro-organisms dominate, as well as the flavour of the end product. For example when the salt concentration and temperature are low, *Leuconostoc mesenteroides* dominates, producing a mix of acids, alcohol, and aroma compounds. When the temperature is higher, *Lactobacillus plantarum* dominates, which produces primarily lactic acid. Many commercial pickles have starter cultures added and start with *Leuconostoc*, and change to *Lactobacillus* with higher acidity.

**The manufacture of cucumber pickles**

The cucumber is one of the oldest vegetables cultivated by man and is thought to have had its origin in Asia more than 3000 years ago. Pickled cucumbers are sold commercially worldwide. While many different recipes are popular, the basic method of manufacture from traditional fermentation is as follows. Immature cucumbers are picked and care is taken not to bruise or damage them. The washed cucumbers are placed in large tanks and 4.0–5.3% salt brine (15–20° by salometer) is added. The cucumbers are submerged in the brine, ensuring that none float on the surface. The strong brine draws sugars and water out of the cucumbers. This reduces the salinity of the solution, which must be monitored daily, and more salt should be added when necessary (the concentration of salt must be maintained above 3.1% (12° by salometer) or spoilage will occur through putrefaction and softening). Shortly after the cucumbers have been placed in the brine the fermentation process, which generates heat and acids, begins. During fermentation visible changes take place that are important in judging the progress of the process. The colour of the surface of the cucumbers changes from bright green to a dark olive green as acids interact with the chlorophyll. The interior of the cucumber changes from white to a waxy translucent shade as air is forced out of the cells. The specific gravity of the cucumbers also increases as a result of the gradual absorption of salt and they begin to sink in the brine rather than floating on the surface.

In the primary stage of fermentation there are many micro-organisms, but after a few days Gram-positive cocci, e.g. *Leuconostoc mesenteroides*, predominate. This species is more resistant to temperature changes and tolerates higher salt concentration than the competitor and subsequent species. As fermentation proceeds and the acidity increases, *Lactobacilli*
and *Pediococcus* take over from the *Leuconostoc*. After about 10–14 days all extraneous and undesirable micro-organisms should have disappeared. A complete fermentation lasts for between 10 and 30 days, depending upon the temperature of the fermentation. The optimum temperature for *Lactobacilli cucumeris* is 29–32°C. During the fermentative period, the acidity increases to about 1% (as lactic acid) and the pH can go as low as 3.3. If sugar or acetic acid is added to the fermenting mixture during this time it increases the production of acid.

Some problems encountered in the production of pickled cucumbers

**Softening:** Soft texture can result from many conditions such as excessive aeration, poor salting procedure and varying temperatures. When the normal sequence of bacterial growth is altered or disturbed, it can result in a soft product. There are three main pectolytic enzymes responsible for softening: polygalacturonase, pectin methyl esterase and polygalacturonic acid trans-eliminase. These can be produced by a host of bacteria and sometimes fungi, including various species of *Bacillus* and *Achromobacter, Aerobacter* and *Escherichia*. Factors that have been found to contribute to the softening of cucumbers include unusually high numbers of pectinolytic bacteria in the initial microbiological population, pH of brine above 5.5, delay in lactic acid fermentation and brine concentrations of 5–8%.

**Floaters/bloaters:** Gas producing micro-organisms (yeasts and bacteria) can grow inside the cucumbers causing internal cavities, loss of structure and texture.

**Shriveling:** Excessive amounts of acid during the fermentation, causing the pickles to shrivel.

### 1.5.1.2 Yogurt

Yogurt is made when bacteria ferment milk sugar (lactose) to lactic acid, which lowers the pH and causes the characteristic curd to form. The acid also restricts the growth of food-poisoning bacteria. During the fermentation of yogurt flavours are produced that give it its characteristic taste. To be named yoghurt, the product should at least contain the bacteria *Streptococcus salivarius ssp. thermophilus* and *Lactobacillus delbrueckii ssp. bulgaricus*. Often these are co-cultured with other lactic acid bacteria (*L. acidophilus, Lactobacillus casei* and *Bifidobacterium* species) for either taste or health effects (probiotics).

It is thought that yogurt fermentation was discovered – probably by accident – by Balkan tribes several thousands of years ago. Yogurt remained
mainly a food of eastern Europe until the 1900s, when the biologist Mechnikov postulated the theory that *Lactobacilli* bacteria in yogurt are responsible for the longevity of Bulgarian people.

Many types of yogurt are manufactured commercially and each type and manufacturing company have their own recipes. A basic method of manufacture is as follows. A mixture of pasteurized fat-free, low-fat or full-cream milk, usually with some milk solids added and, depending on the type of yogurt, with sweeteners and stabilizers, is inoculated with a starter culture of *Streptococcus thermophilus* and *Lactobacillus bulgaricus*. The mixture is held at 30–43°C for 3–16 hours.

Typical problems that can be found with yogurt are flavour related (i.e. the lack of flavour development, or too intense or unnatural flavours), slimy texture or lack of body.

1.5.1.3 Bread

Bread is one of the oldest prepared foods. Part of the manufacture of bread is called leavening, which is the process of adding gas to the dough before baking, to produce a bread that is lighter in texture. Leavening can be done chemically or by yeast. The development of leavened bread possibly began in prehistoric times, however the earliest archaeological evidence is from ancient Egypt, where scientists using scanning electron microscopy have detected yeast cells in some ancient Egyptian loaves. The yeast used for leavening bread is *Saccharomyces cerevisiae*, which ferments carbohydrates in the flour, producing carbon dioxide.

Flour (made from grain that has been ground into a powdery consistency) is the main ingredient, wheat flour being the most common. Some other common grains are rye, barley and maize. Besides starch flour contains three water-soluble protein groups – albumin, globulin, proteoses – and two non-water soluble protein groups – glutenin and gliadin. When flour is mixed with water the water-soluble proteins dissolve, leaving the glutenin and gliadin to form the gluten and the structure of the resulting dough.

There is a large variety of breads made from many different ingredients. A basic method of bread manufacture is as follows. Firstly flour, salt and fat are mixed with yeast and warm liquid to form an elastic dough. This is then kneaded to develop the gluten. In the fermentation stage the dough is left to ‘prove’ in a warm environment, which allows the carbon dioxide gas to permeate and stretch it, giving the dough structure and shape. The dough is kneaded again to ensure that the bubbles of carbon
dioxide are of uniform shape, and then it is left to prove again, usually to double its size. Finally, the bread is baked at a high temperature (about 220°C).

Microbiological spoilage that is possible in bread includes surface mould growth usually promoted by *Rhizopus*. Ropiness in bread is cause by *Bacillus subtilis* and is characterized by stringiness in the dough.

1.5.1.4 Wine

Wine is an alcoholic beverage produced by the fermentation of the sugar in fruit, typically grapes, though a number of other fruits are also quite popular. A brief description of how wine is made (in a modern winery) is as follows:

- Once the grapes reach the winery, they are crushed. Inside the crusher there is a perforated, rotating drum. The holes in the drum allow the juice and the skins of the grapes to pass through, but keep the stems inside the drum. The crushed grapes and juice are called ‘must’.
- Red-grape must is sent directly to the fermentation tanks. White-grape must is sent first to a wine press, where the juice is separated from the skins.
- Fermentation tanks are large, airtight, stainless steel vessels. They are cooled to about 4°C. The winemaker adds sugar and yeast to start the process of fermentation. The type of yeast and the amount of sugar added depend on the type of grape.
- When the yeast gets mixed into the must, the concentration of glucose (C₆H₁₂O₆) is very high. The yeast breaks down the glucose via a metabolic process called glycolysis. The products of glycolysis are two three-carbon sugars, called pyruvates, and some ATP (adenosine triphosphate). ATP supplies energy to the yeast and allows it to multiply. The pyruvates are then converted by the yeast into carbon dioxide (CO₂) and ethanol (CH₃CH₂OH), which is the alcohol in wine.
- The fermentation process takes about two to four weeks. During this time, the winemaker samples the fermenting must and measures the pH or acid levels to determine whether the fermentation process is proceeding as it should.
- Once the fermentation process is completed, red wines are sent to the press to separate the skins from the wine and are then filtered to remove the yeast. White wines are allowed to settle and are filtered to remove the yeast. Once the yeast has been removed, the wines are stored in either stainless steel storage tanks or oak barrels (oak gives many wines a characteristic flavour) depending on the type of wine. In some red wines, a second type of fermentation, called malolactic fermentation, is
undertaken while in storage. In malolactic fermentation, the winemaker adds a bacterium to the wine that breaks down malic acid, a byproduct of aerobic metabolism, into lactic acid, a byproduct of anaerobic metabolism. Lactic acid is a milder acid than malic acid. The ageing process can be anywhere from three months to three years.

- After the wine has aged sufficiently, as determined by the winemaker, it is time to bottle and package it for sale.

A wine fault or defect is an unpleasant characteristic of a wine often resulting from poor winemaking practices or storage conditions. Some examples are listed below:

- **Acetaldehyde** production is associated with the presence of surface film-forming yeasts and bacteria, such as acetic acid bacteria, which form the compound by the decarboxylation of pyruvate. Acetaldehyde is an intermediate product of yeast fermentation; however, it is more commonly associated with ethanol oxidation catalysed by the enzyme ethanol dehydrogenase. Wine with levels above 100–125 ppm can be described as ‘green apple’, sour and metallic.

- **Acetic acid** in wine, often referred to as volatile acidity or vinegar taint, can be contributed by many wine spoilage yeasts and bacteria. This can be from either a by-product of fermentation, or due to the spoilage of finished wine. Acetic acid bacteria, such as those from the genera *Acetobacter* and *Gluconobacter*, produce high levels of acetic acid.

- **Ethyl acetate** is formed in wine by the esterification of ethanol with acetic acid. Therefore wines with high acetic acid levels are more likely to see ethyl acetate formation, but the compound does not contribute to the volatile acidity. It is a common microbial fault produced by wine spoilage yeasts, particularly *Pichia anomala*, *Kloeckera apiculata* and *Hanseniaspora uvarum*. High levels of ethyl acetate are also produced by lactic acid bacteria and acetic acid bacteria. Low levels of ethyl acetate can give an added richness and sweetness to the wine, but above about 150–200 ppm an aroma characteristic of nail polish remover, glue, or varnish can be detected.

- **Hydrogen sulphide** (*H₂S*) is generally thought to be a metabolic by-product of yeast fermentation in nitrogen-limited environments. It is formed when yeast ferments via the sulphate reduction pathway. Hydrogen sulphide can further react with wine compounds to form mercaptans and disulphides.

- **Geosmin** is a compound with a very distinct earthy, musty, beetroot, even turnip flavour and aroma and has an extremely low sensory threshold of down to 10 ppt. Its presence in wine is usually derived as a metabolite from the growth of filamentous actinomycetes such as
Streptomyces, and moulds such as Botritis cinerea and Penicillium expansum, on grapes. Geosmin is also thought to be a contributing factor to cork taint.

- **Lactic acid bacteria** have a useful role to play in winemaking by converting malic acid to lactic acid in malolactic fermentation. However after this function has been completed the bacteria may still be present within the wine, where they can metabolize other compounds and produce wine faults. Wines that have not undergone malolactic fermentation may be contaminated with lactic acid bacteria, leading to refermentation of the wine and its becoming turbid, ‘swampy’ and slightly effervescent. Lactic acid bacteria can also be responsible for wine taints.

- **Ropiness** is manifested as an increase in viscosity and a slimy or fatty mouth-feel of a wine. It is caused by the production of dextrans and polysaccharides by certain lactic acid bacteria, particularly of the genera Leuconostoc and Pediococcus.

- **Mousiness** is a wine fault most often attributed to Brettanomyces, but it can also originate from the lactic acid bacteria Lactobacillus brevis, Lactobacillus fermentum and Lactobacillus hilgardii. The compounds responsible are lysine derivatives, and the taints are not volatile at the pH of wine, and therefore not obvious as an aroma. However, when mixed with the neutral pH of saliva they can become very apparent on the palate especially at the back of the mouth, as ‘mouse cage’ or ‘mouse urine’ flavour.

- **Refermentation/secondary fermentation** is caused by yeasts refermenting the residual sugar present within bottled wine. It occurs when sweet wines are bottled in non-sterile conditions, allowing the presence of micro-organisms. The most common yeast to referment wine is the standard wine fermentation yeast Saccharomyces cerevisiae, but has also been attributed to Schizosaccharomyces pombe and Zygosaccharomyces bailii. The main issues associated with the fault include turbidity, excess ethanol production, carbonation and some coarse odours.

### 1.5.1.5 Beer

Beer is one of the oldest beverages humans have produced, dating back to at least the 5th millennium BC, and recorded in the written history of Ancient Egypt and Mesopotamia. It is most likely that beer-like beverages were independently developed among various cultures throughout the world. Beer is produced by the fermentation of many starch-based materials, though commonly barley, cassava, millet, sorghum, potato and agave are used. Because the ingredients and processes used to make beer differ dramatically, characteristics such as taste and colour also vary.
Beer manufacturing methods vary depending on the type of raw material used. A method for commercial beers with the basic ingredients water, malted barley, yeast (*Saccharomyces cerevisiae* or *Saccharomyces uvarum*) and hops is as follows:

- **Malt** is formed from barley by soaking it in water, allowing it to start to germinate, and then drying the germinated grain in a kiln. Malting the barley produces the enzymes that will eventually convert the starches into fermentable sugars.
- **Mashing**: The first phase of brewing, in which the malted grains are crushed and soaked in warm water in order to create a malt extract. The mash is held at a constant temperature for long enough for enzymes to convert starches into fermentable sugars.
- **Lautering** is the separation of the extracts formed during mashing from the spent grain. It is achieved in either a Lauter tun, a wide vessel with a false bottom, or a mash filter, a plate-and-frame filter designed for this kind of separation. It has two stages: first wort run-off, during which the extract is separated in an undiluted state from the spent grains, and sparging, in which extract which remains with the grains is rinsed off with hot water.
- **Boiling**: The wort is boiled along with any remaining ingredients (excluding yeast), to remove excess water and kill any micro-organisms. The hops are added at some stage during the boil.
- **Fermentation**: The yeast is added and the beer is left to ferment. After primary fermentation, the beer may be allowed a second fermentation, which allows further settling of yeast and other particulate matter that may have been introduced earlier in the process. Some brewers may skip the secondary fermentation and simply filter off the yeast.
- **Packaging**: At this point, the beer contains alcohol, but not much carbon dioxide. The brewer has a few options to increase carbon dioxide levels. The most common approach by large-scale brewers is force carbonation, via the direct addition of CO₂ gas to the keg or bottle. Smaller-scale or more classically-minded brewers will add extra sugar or a small amount of newly fermenting wort to the final vessel, resulting in a short refermentation known as 'cask-' or 'bottle conditioning'.
- **After brewing**, the beer is usually a finished product. At this point the beer is kegged, casked, bottled, or canned.

Lager is the English name for bottom-fermented beers. Lager yeast is a bottom-fermenting yeast, and typically undergoes primary fermentation at 7–12°C (the ‘fermentation phase’), and then is given a long secondary fermentation at 0–4°C (the ‘lagering phase’). During the secondary stage, the lager clears and mellows. The cooler conditions also inhibit the natural production of esters and other byproducts, resulting in a ‘crisper’ tasting beer.
Ales are brewed with top-fermenting yeasts. Ale is typically fermented at temperatures between 15°C and 24°C, at which temperatures yeast produces significant amounts of esters and other secondary flavour and aroma products, and the result is often a beer with slightly ‘fruity’ compounds resembling, but not limited to, apple, pear, pineapple, banana, plum, or prune. Typical ales have a sweeter, fuller body than lagers. The important distinction for ales is that they are fermented at higher temperatures and thus ferment more quickly than lagers.

Problems encountered in beer making
A stuck fermentation is a fermentation of wine or beer that has stopped before completion, i.e., before the anticipated percentage of sugars has been converted by yeast into alcohol. It may be caused by: (1) insufficient or incomplete nutrients required to allow the yeast to complete fermentation; (2) low temperatures, or temperature changes which have caused the yeast to stop working early; or (3) an alcohol content too high for the particular yeast chosen for the fermentation. Conditions like ropiness (beer becomes viscous and pours as an oily steam), sourness (caused by elevated levels of acetic acid) and turbidity are just some of the conditions caused by undesirable microbiological activity.

1.5.1.6 Cheese
Cheese is an ancient food, the origins of which are debated; estimates range from around 8000 BC (when sheep were domesticated) to around 3000 BC. It was probably discovered in Central Asia or the Middle East and taken from there to Europe. The earliest cheeses would probably have been quite sour and salty, similar in texture to feta. When basic cheese-making found its way into Europe, the cooler climates meant less aggressive salting was needed for preservation. With moderate salt and acidity, cheese became a suitable environment for a variety of beneficial microbes and moulds, which are what give aged cheeses their pronounced and interesting flavours.

Cheese is a solid food made from the milk of cows, goats, sheep, buffalo or other mammals. Their milk is curdled using some combination of bacterial acidification and the enzyme rennet (or a rennet substitute). Bacteria that turn milk sugars into lactic acid acidify the milk and play a role in defining the texture and flavour of most cheeses. Some cheeses also feature moulds, either on the outer rind or throughout (See Fig. 1.3).

Cheese making
- Curdling: This is the only strictly required step in making any sort of cheese and results in separating the milk into solid curds (protein) and
liquid whey. This is done by acidifying the milk (usually by starter bacteria from the *Lactococci*, *Lactobacilli*, or *Streptococci* families) and adding the enzyme rennet. The starter bacterium converts milk sugars into lactic acid and the enzymes that they produce play a large role in the eventual flavour of aged cheeses. Some fresh cheeses are curdled only by acidity, but rennet is also used in most cheeses. Rennet sets the cheese into a strong and rubbery gel (compared to the fragile curds produced by acidic coagulation alone).

- **Curd processing:** At this point, the cheese has set into a very moist gel. Some soft cheeses are now essentially complete: they are drained, salted, and packaged. For most of the rest, the curd is cut into small cubes. This allows water to drain from the individual pieces of curd. Salt has a number of roles in cheese besides adding a salty flavour. It preserves cheese from spoiling, draws moisture from the curd, and firms up a cheese’s texture in an interaction with its proteins. Some cheeses are salted from the outside with dry salt or brine washes. Most cheeses have the salt mixed directly into the curds.

- **Ageing/ripening:** A new cheese usually has a salty bland flavour, and the harder varieties are rubbery in texture. Cheeses are usually left to rest under carefully controlled conditions. This ageing period can last from a few days to several years. As cheese ages, micro-organisms and enzymes transform its texture and intensify its flavour. This transformation is largely a result of the breakdown of casein proteins and milk fat into a complex mix of amino acids, amines, and fatty acids.

There are many potential problems associated with cheese making, as for each cheese type there are many very specific parameters that have to be complied with, e.g. pH control in the initial fermentation is significant in the control of curdling. At many stages there can be the development of off or uncharacteristic flavours as well as uncharacteristic textures.
Flavour defects include:

- *Sourness/acidity* caused by excessive fermentation and/or inadequate washing of the curds.
- *Bitterness* caused by abnormal protein degradation.
- *Fruity and fermented flavour* caused by anaerobic spore-formers. This occurs when the pH is high and the salt content is low.

Texture defects include:

- *Corky*, caused by inadequate acid development of and/or excessive washing of the curds.
- *Weak/pasty*, caused by too much moisture or too little salt.
- *Gassiness*, caused by the growth of various bacteria and yeasts.
- *Openness*, caused when whey is trapped between curds (and the opening remains after draining).

### 1.5.2 Fermentation biochemistry

Prokaryotic and eukaryotic cells share a major metabolic pathway in which glucose is catalysed to pyruvate through several enzymatic pathways. The pyruvate is further broken down to compounds like ethanol and lactic acid. This requires no oxygen and produces energy in the form of adenosine triphosphate (ATP). Although this is not a very efficient way of producing energy, it is fast.\textsuperscript{16,17}

Metabolically fermentation is a process that is important for an organism in anaerobic conditions when there is no oxidative phosphorylation to maintain the production of ATP by glycolysis. During fermentation pyruvate is metabolized to various different compounds. Homolactic fermentation is the production of lactic acid from pyruvate; alcoholic fermentation is the conversion of pyruvate into ethanol and carbon dioxide; and heterolactic fermentation is the production of lactic acid as well as other acids and alcohols (see Fig. 1.4).\textsuperscript{16}

Biochemically, fermentation is the anaerobic metabolic breakdown of carbohydrate nutrients, like glucose, without net oxidation (see Fig. 1.5).\textsuperscript{16} Fermentation does not release all the available energy in a molecule; it merely allows glycolysis to continue by replenishing reduced coenzymes. Depending on where it is taking place, fermentation may yield lactate, acetic acid, ethanol, butyric acid, acetone and other reduced metabolites. Food fermentation uses the term more broadly, and fermentation refers to the anaerobic or aerobic growth (see Fig. 1.6) of micro-organisms on a substrate. It refers to the chemical changes in
organic substances produced by the action of specific enzymes, produced by micro-organisms such as moulds, bacteria, and yeasts.

1.5.3 Putrefaction

Putrefaction is the breakdown of proteins by microbial enzymes, usually produced by anaerobic spoilage micro-organisms. It results in 'off' odours
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1.5.4 Lypolysis

Lypolysis is the breakdown of fat into glycerol and free fatty acids. Lipolysed fat has a rancid taste and smell. The lypolysis reaction is controlled by enzymes called lipases, which are produced by microorganisms. As with many enzymatic reactions, high storage temperatures encourage lypolysis. In foods like fatty fish, the fish oils are largely composed of glycerol combined with fatty acids to form glycerides. Splitting of the glycerides of the oil and formation of free fatty acids (FFA) result in reduced quality of the oil with serious economic consequences. In dairy products, where the fat component is a significant part of the whole product, much effort has to be taken in processing, storage and distribution to ensure that lypolysis is minimized.

1.6 MICRO-ORGANISMS INVOLVED IN BIODETERIORATION REACTIONS

1.6.1 Factors that affect microbial growth

There are many complex reactions and conditions that either inhibit or encourage microbial growth. The availability of oxygen, the temperature (hot or cold), light and other radiation, moisture and dryness, the activity of natural enzymes and the amount of spoilage micro-organisms that are present will all affect the growth of spoilage organisms. A few of the basic physical properties of the food or the storage environment are discussed briefly below.\textsuperscript{14,15}
1.6.1.1 pH

pH refers to the hydrogen ion concentration of a solution, a measure of the solution’s acidity. It is defined as the negative logarithm of the concentration of $H^+$ ions.

$$\text{pH} = -\log_{10}[H^+] \quad \text{(Eqn. 1.1)}$$

where $[H^+]$ is the concentration of $H^+$ ions in moles per litre.

Most micro-organisms grow best at neutral pH and only a few are able to grow at a pH lower than 4.0. Bacteria are more fastidious about their pH requirements than are yeasts and moulds. The fact that pH can limit microbial growth is a basic principle of food preservation and has been used for thousands of years. Fermentation and pickling extend the shelf-life of food products by lowering the pH. The fact that no known spore-forming pathogenic bacteria can grow at pH $< 4.6$ is the basis for the food sterilization principle for low acid and acid foods. See Fig. 1.9 for examples of pH growth ranges of various micro-organisms.

The pH of some food is inherently low and therefore the kinds of organisms that can cause biodegradation of that food is limited. Some foods are

![Fig. 1.9 pH growth ranges for selected micro-organisms.](image-url)
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To preserve them, or as one of the food preservation hurdles. See Table 1.4 for some examples of the pH of foods.

Table 1.4 The pH of selected foods.

<table>
<thead>
<tr>
<th>Food</th>
<th>pH</th>
<th>Food</th>
<th>pH</th>
<th>Food</th>
<th>pH</th>
<th>Food</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit</td>
<td></td>
<td>Vegetables</td>
<td></td>
<td>Miscellaneous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple</td>
<td>3.3–4.0</td>
<td>Asparagus</td>
<td>6.0–6.7</td>
<td>Bread, white</td>
<td>5.0–6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banana</td>
<td>5.0–5.3</td>
<td>Avocado</td>
<td>6.3–6.6</td>
<td>Bread, whole</td>
<td>5.5–5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherries</td>
<td>3.3–3.6</td>
<td>Beans (soy)</td>
<td>6.0–6.6</td>
<td>wheat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grapes</td>
<td>3.5–3.8</td>
<td>Beans in</td>
<td>5.3</td>
<td>Cheddar cheese</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grapefruit</td>
<td>3.0–3.8</td>
<td>tomato sauce</td>
<td></td>
<td>Cottage cheese</td>
<td>4.7–5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lemon</td>
<td>2.0–2.6</td>
<td>Carrots</td>
<td>5.9–6.4</td>
<td>Eggs</td>
<td>6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peaches</td>
<td>3.3–4.1</td>
<td>Mushrooms</td>
<td>6.0–6.7</td>
<td>Egg, white</td>
<td>7.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pineapple</td>
<td>3.2–4.0</td>
<td>Olives</td>
<td>6.0–7.5</td>
<td>Egg, yolk</td>
<td>6.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish and meat</td>
<td></td>
<td>Olives, fermented</td>
<td>3.6–4.6</td>
<td>Honey</td>
<td>3.7–4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish</td>
<td>5.8–6.8</td>
<td>Peas</td>
<td>6.2–6.8</td>
<td>Ketchup</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beef</td>
<td>5.1–6.2</td>
<td>Sweet</td>
<td>5.3–5.6</td>
<td>Milk, cow’s</td>
<td>6.4–6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pork</td>
<td>5.3–6.9</td>
<td>Sweet</td>
<td>5.3–5.6</td>
<td>Marmalade</td>
<td>3.0–3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamb</td>
<td>5.4–6.7</td>
<td>potatoes</td>
<td></td>
<td>Peanut butter</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chicken</td>
<td>6.2–6.4</td>
<td>Tomatoes</td>
<td>4.0–4.9</td>
<td>Tea</td>
<td>7.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.6.1.2 Moisture content of the food

Micro-organisms cannot grow in a water-free environment, as enzyme activity is absent, and most chemical reactions are greatly slowed down. Fresh vegetables, fruit, meat, fish and some other foods naturally have a high moisture content, which averages about 80%. Drying is one of the oldest methods of food preservation. Drying reduces the availability of moisture, thereby limiting the number and types of micro-organisms that can grow and reducing the rate at which they can do so. A measure of this parameter is called water activity and is defined by the ratio of the water vapour pressure in the food substrate to the vapour pressure of pure water at the same temperature, and is denoted by $a_w$.

$$a_w = \frac{p}{p_o} \quad \text{(Eqn. 1.2)}$$

Where $p =$ vapour pressure of solution
$p_o =$ vapour pressure of solvent (usually water)

Water activity is a measure of the water that is available to micro-organisms. Pure water has a water activity of 1.0 while most fresh foods have a water activity of about 0.99. In general bacteria require a higher $a_w$ than yeasts and moulds. Most spoilage bacteria cannot grow at $a_w < 0.91$, with *Clostridium botulinum* having a minimum growth level of 0.94. *Staphylococcus aureus*, has, however, been found to grow at $a_w$ as low as
0.84. The lowest reported $a_w$ value for a bacterial growth is 0.75. Most spoilage moulds cannot grow at $a_w < 0.80$. The lowest reported $a_w$ for any mould growth is 0.65, and for yeasts it is 0.61.

1.6.1.3 Humidity of the environment

The humidity of the environment is important as it affects the $a_w$ of the food as well as the moisture on its surface. Food can pick up moisture from the atmosphere. Under conditions of high relative humidity storage (e.g. in a refrigerator), surface spoilage can take place, unless food is adequately protected by packaging.

1.6.1.4 Temperature

Storage temperature can be considered the most important factor that affects biodeterioration of food; however, the relative humidity and availability of oxygen must also be controlled. Micro-organisms have been reported to grow over a wide temperature range; the lowest reported is $-34^\circ$C and the highest is $90^\circ$C. All micro-organisms do, however, have an optimum temperature as well as a range in which they will grow. This preference for temperature forms the basis of dividing micro-organisms into groups.

- Psychrotrophs have an optimum from 20 to $30^\circ$C, but can grow at or below $7^\circ$C.
- Mesophiles have an optimum of 30–$40^\circ$C, but can grow between 20 and $45^\circ$C.
- Thermophiles grow optimally between 55 and $65^\circ$C, but can grow at a temperature as low as $45^\circ$C.

Just as moulds are able to grow over a wide range of pH values and moisture conditions, they can also tolerate a wider temperature range than bacteria. Many moulds can grow in the refrigerator. Yeasts are not usually found growing in the thermophilic temperature range, but prefer psychrotrophic and mesophilic temperatures.

While lower storage temperature generally slows down microbial growth, it is not suitable to store all foods in the freezer ($-18^\circ$C) or even the refrigerator ($<8^\circ$C), as they loose texture and other desirable features.

1.6.1.5 Availability of oxygen

Controlling the availability of free oxygen is one means of controlling microbial activity within a food. Although oxygen is essential for carrying out metabolic activities that support all forms of life, some
micro-organisms use free atmospheric oxygen, while others metabolize the oxygen (reduced form) which is bound to other compounds such as carbohydrates.

Micro-organisms can be broadly classified into two groups – aerobic and anaerobic. Aerobes grow in the presence of atmospheric oxygen, while anaerobes grow in the absence of atmospheric oxygen. In between these two extremes are the facultative anaerobes, which can adapt and grow in either the absence or presence of atmospheric oxygen, and micro-aerophilic organisms, which grow in the presence of reduced amounts of atmospheric oxygen. In aerobic fermentation the amount of oxygen present is one of the limiting factors. It determines the type and amount of biological product obtained, the amount of substrate consumed and the energy released from the reaction.

1.6.2 Bacteria

There is a vast number of different bacteria involved with biodeterioration reactions. Below a few examples are discussed. In some instances biodeterioration has dire consequences, as it can cause food poisoning and in some instances death.12,14,18

1.6.2.1 Clostridium botulinum

Food-poisoning incidents that result in fatalities are relatively rare. One bacterium that can cause death is *Clostridium botulinum*. The botulinum toxin is one of the most potent neurotoxins known. It has been considered a real threat for use in biological warfare. Only one gram of crystalline toxin, could, if evenly dispersed over a city and then inhaled by its inhabitants, kill more than a million people. Food contaminated with only a few nano grams ($10^{-9}$ g) can be toxic. For this reason, while fairly uncommon, the risk is taken very seriously by all producers of products packed in an anaerobic environment and stored for an extended period of time, e.g. canned and vacuum-packed foods. All food processes are designed with organisms like *Clostridium botulinum* in mind. The canning process is specifically designed to ensure that the food is safe with regard to its being eliminated. Heat processing is one way of ensuring food safety, but the integrity of the can has to be maintained right up until the contents are consumed, as pathogenic bacteria can ‘leak’ into the can if given the opportunity.

*Clostridium botulinum* is a Gram-positive, obligate anaerobe, spore-forming bacterium. It is commonly found in soils throughout the world. Since it is found in the soil, it might contaminate vegetables cultivated in...
or on the soil and will colonize the gastrointestinal tract of fish, birds and mammals. *Clostridium botulinum* is classified as a single species of bacterium but includes at least three genetically distinguishable groups of organisms that have been found to be toxic to humans (*Clostridium botulinum*, *Clostridium baratii* and *Clostridium butyricum*). These organisms share the ability to produce the neurotoxins. The toxin types are classified as A, B, C, D, E, F and G. Human botulism has been described with the strains of *Clostridium botulinum* that produce toxin types A, B and E.

*Clostridium botulinum* bacteria produce spores that are fairly heat resistant and cannot be killed simply by boiling. Canned food sterilization processes are specifically designed so as to eliminate the possibility of any spores surviving. The toxin is, however, fairly heat sensitive and heating at 80°C for 30 minutes or 100°C for 10 minutes will destroy the active toxin. If canned food like meat, fish or vegetables is under-processed or becomes contaminated after processing with *Clostridium botulinum* the sealed can provides an ideal, anaerobic environment for the bacterium to grow. The factors which limit the growth of *Clostridium botulinum* include: (1) low pH: Clostridia will not produce toxin in acid or acidified foods (i.e. below pH 4.5); (2) low water activity: a minimum of 0.94 is needed to support bacterial growth and toxin production. This water activity corresponds to a 10% salt (NaCl) solution, which is why salting is sometimes used as a method of preservation; (3) temperature: most strains grow optimally at 40°C, but some can grow at temperatures as low as 3°C; (4) food preservatives: many preservatives (nitrite, sorbic acid, phenolic antioxidants, polyphosphates, etc.) inhibit *Clostridium botulinum* growth; (5) competing micro-organisms.

Botulism is a paralytic illness caused by a neuro- (nerve) toxin that is produced by the bacterium *Clostridium botulinum*. There are five types of botulism:

1) Food-borne botulism: an intoxication most commonly found in home-preserved foods, usually because of under-processing.
2) Wound botulism: caused when the bacterium manages to grow inside a wound (usually a puncture wound or gun-shot wound or with drug abusers).
3) Infant botulism: caused when the intestine of the infant (less than one year of age) is colonized by the bacterium, which then produces toxin. Honey is known to be a source of *Clostridium botulinum* spores and is therefore not recommended for babies less than one year old.
4) Adult infectious botulism: this is similar to infant botulism, but is usually found in patients with intestinal diseases or after bowel surgery.
5) Inadvertent botulism: following treatment with botulinum toxin injection, used to treat various muscular problems.

### 1.6.2.2 Salmonella

*Salmonella* is a Gram-negative, rod shaped, motile bacterium, that does not form spores. It is widespread in occurrence, being found in, for example, fresh and salt water, soil and animal faeces. Various foods have been found to be associated with salmonellosis, the illness caused by *Salmonella* spp., including raw meat, poultry and seafood, raw eggs and foods made from raw eggs, dried gelatine, cocoa, chocolate, peanut butter, yeast and coconut. Salmonellosis is caused by infection with the organism and extremely low doses (as low as 15 cells) can cause disease.

### 1.6.2.3 Listeria monocytogenes

*Listeria* are Gram-positive, motile bacteria. They do not form spores, but are quite resistant to desiccation and heat. They are found in the soil and associated with birds and animals. Infection with these bacteria causes a disease called listeriosis, which can result in septicaemia, meningitis encephalitis and spontaneous abortions in pregnant females. *Listeria monocytogenes* has been associated with raw milk, soft cheeses, raw vegetables, raw meat, fish and poultry. It can grow at temperature as low as 3°C, which allows growth during refrigeration.

### 1.6.2.4 Staphylococcus aureus

*S. aureus* is a Gram-positive, small round bacterium (coccus), that can produce a heat-stable toxin. Less than 1µg of toxin can cause illness. *S. aureus* is found all over, but the most common source of contamination of food is via humans, i.e. food handlers. Staphylococci are found in the nasal passages, throat, on the skin and in the hair of more than half of healthy people. Intoxication is caused by contaminated food being kept either not hot enough (i.e. at <60°C) or not cold enough (i.e. at >8°C), which allows the organism to grow and produce its toxin. The symptoms (nausea, vomiting, cramping) of staphylococcal food poisoning come on very rapidly (within a few hours) and are usually acute.

### 1.6.2.5 Clostridium perfringens

*Clostridium perfringens* is a Gram-positive spore-forming anaerobic rod-shaped bacterium. It is widely distributed in nature and is also found associated with the intestines of animals and humans. *Clostridium perfringens* produces a toxin that causes intense abdominal cramps and diarrhoea.
Food poisoning from this organism is usually associated with cooked foods that have been inadequately cooled and held for several hours before consumption.

### 1.6.2.6 Bacillus cereus

*Bacillus cereus* is a Gram-positive, facultatively aerobic, spore-forming rod-shaped bacterium. The presence of this organism in large numbers can result in two types of food poisoning illness. A protein toxin causes diarrhoeal symptoms, similar to those caused by *Clostridium perfringens*, and a heat-stable peptide causes vomiting symptoms, similar to those caused by *Staphylococcus aureus*. The diarrhoeal type of illness has been diagnosed after consumption of a variety of foods, e.g. milk, meat, fish and vegetables, while the vomiting-type is associated with the consumption of rice products and other starchy foods like potatoes and pasta. Puddings, soups, casseroles, pastries and salads have all been implicated in food poisoning by this bacterium.

### 1.6.2.7 Escherichia coli

*Escherichia coli* are Gram-negative bacteria that are found in the intestines of all mammals, including humans. *E. coli* produce toxins that can cause four different classes of illnesses that are of concern to the food industry. The first class is enterovirulent (EEC) that causes gastroenteritis. This class includes *E. coli* 0157:H7 (EHEC), which is enterohaemorrhagic. The second type is referred to as enterotoxigenic (ETEC), the third is enteropathogenic (EPEC) and the fourth is enteroinvasive (EIEC). Outbreaks of food poisoning due to *E. coli* are usually associated with faecal contamination of water by food handlers, or are due to unprocessed or under-processed foods.

### 1.6.2.8 Campylobacter jejuni

*Campylobacter jejuni* are Gram-negative, microaerophilic, motile, rod-shaped bacteria. They are found on raw chickens, in raw milk, and are often carried in the intestines of healthy cattle. They can contaminate food via flies on farms and are also found in non-chlorinated water. Consumption of contaminated food results in diarrhoea caused by a heat-labile toxin and by the invasive organism.

### 1.6.2.9 Lactic acid bacteria

Lactic acid bacteria form a large, diverse group comprising bacteria from *Lactobacillus, Lactococcus, Leuconostoc, Pediococcus, Streptococcus*, etc.
These bacteria are commonly involved with fermentation reactions that are desirable, but can also cause spoilage by acid and gas formation in some products (see Fig. 1.10).

1.6.2.10 Pseudomonas

*Pseudomonas* spp. are a large group of Gram-negative rod-shaped bacteria that are responsible for spoilage of many refrigerated proteinaceous products (e.g. meat, fish, eggs). Some strains produce blue-green pigments. They are implicated in many food spoilage conditions, e.g. green rot, black rot, pink rot and red rot. They have very varied nutritional requirements and can even cause spoilage of bottled water.

1.6.2.11 Toxins formed by bacterial action – scombrotoksin

Scombroid poisoning is caused by consuming foods that contain high levels of histamine. Histamine and other amines are formed by the growth of a variety of bacteria and the subsequent action of their decarboxylase enzymes on the amino acid histidine.

Any food product that contains high levels of this amino acid can be susceptible to this sort of spoilage, but it occurs most commonly with tuna, mackerel, pilchards and some other fish. Once present, the levels of histamine cannot be reduced by cooking or freezing. The symptoms of scombroid poisoning can be immediate to about 30 minutes and may include tingling or a burning sensation in the mouth, development of a rash, itching, headache, drop in blood pressure, nausea and vomiting.
1.6.3 Moulds

Moulds are filamentous fungi that rapidly grow in a mass that may cover several centimetres in a day (see Fig. 1.11).

Moulds multiply by means of ascospores, zygospores or conidia. The ascospores of some moulds are particularly significant in food spoilage as they are heat resistant. Some moulds found associated with food spoilage are:

- **Botrytis** moulds, which cause grey mould rot: this condition affects many fruit and vegetable crops and products (e.g. grapes, strawberries, tomatoes, cauliflowers, pumpkins, cucumbers, sweet potatoes and many more). The fungus grows, causing the decay of the fruit or vegetable, and appears as a prominent grey mould.
- **Rhizopus stolonifer** moulds, which produce pectinases that cause soft rot, which makes vegetables soft and mushy.
- **Aspergillus** moulds, which have been implicated in the spoilage of a large number of foods including bacon, bread, peanuts, fish, etc. They produce mycotoxins.
- **Byssochlamys** moulds, which can cause spoilage in canned fruit as a result of their heat-resistant ascospores and the pectinases that they produce. They produce mycotoxins.
- **Fusarium** moulds, which have extensive mycelium that have tinges of brown, red, purple and pink. They cause brown rot in citrus fruit and on pineapples and can grow on cereal crops. They produce mycotoxins.
- **Penicillium** moulds, which typically spoil fruits causing blue and blue-green coloration. They produce many different mycotoxins.

1.6.3.1 Mycotoxins

Mycotoxins are secondary metabolites produced by moulds. The name mycotoxin comes from the Greek words mykes (mould) and toxicum
(poison). There are many known types of mycotoxins and they can contami-
nate a wide variety of food and animal feeds. Examples of common
mycotoxins include Aflatoxin, Ocratoxin A, Patulin, Fusarin, Fumonis,
deoxynivalenol (DON) and Zearalenone. Mycotoxins are not essential to
maintaining the life of the mould in a primary way (i.e. obtaining energy
or synthesizing structural components, etc.). They are chemical com-
ounds that give the mould a competitive advantage over other mould
or bacteria species in their environment. They are almost all cytotoxic,
disrupting various cellular structures like membranes and interfering with
vital cellular processes like RNA and DNA synthesis.

The consumption of food contaminated with mycotoxin is related to sev-
eral acute and chronic diseases in humans and animals, examples of which
are listed below.

- In 1960, 100,000 turkey poults died after eating peanut meal that was
  contaminated with aflatoxins. Aflatoxins are a group of toxins pro-
  duced by *Apergillus* spp. that have a similar structure and form highly
  oxygenated heterocyclic compounds. There are four major aflatoxins:
  B1, B2, G1 and G2. Aflatoxins have a potent carcinogenic effect.
  Aflatoxins occur in crops (most commonly corn, peanuts and cotton-
  seed) post-harvesting if the moisture level in the foodstuff is allowed to
  exceed the critical values for mould growth. They can also be found in
  milk, cheese and eggs if the animals are fed contaminated feed.

- Patulin is produced by certain species of *Penicillium*, *Apergillus*, and
  *Byssochlamys* moulds. The moulds that produce patulin grow on a
  variety of foods, including fruit (e.g. apples, grapes and pears), veget-
  ables, grains (e.g. flour and malt) and cheese. However, owing to the
  nature of the food (e.g. pH, protein amino acid composition, etc.), the
  manufacturing processes, or consumption practices for many foods,
  patulin does not appear to pose a public safety concern, except in the
  case of apple juice. Patulin is relatively stable in acid solutions, but is
  susceptible to alkaline hydrolysis. It is destroyed by fermentation,
  which means that it is not found in either alcoholic fruit beverages or
  vinegar produced by fruit juices, but will survive pasteurization.

- Ocratoxin A is a mycotoxin produced by *Apergillus ochraceus* and a
  few other moulds e.g. *Penicillium viridicatum* and *Penicillium verru-
  cosum*. It has both antibiotic and toxic (carcinogenic, teratogenic and
  nephrotoxic) properties. The moulds that produce Ocratoxin A can be
  found on wheat sorghum, raisins and coffee amongst other foodstuffs.

### 1.6.4 Yeasts

Yeasts may be generally viewed as unicellular fungi and are much larger
than bacteria. They are widely distributed in nature, and are present in
orchards and vineyards, in the air and in the soil as well as in the intestinal tracts of animals. There are many very beneficial fermentation reactions initiated by yeasts, but some can cause spoilage. Some examples of yeasts that can cause food spoilage include:12,14,15

- **Rhodotorula** is a diverse organism that can grow in high sugar concentrations and is implicated in the spoilage of jams, jellies and candies. It can grow well at refrigerator temperatures as well as on the surface of butter.
- **Zygosaccharomyces** can grow in high sugar concentrations and can cause spoilage of jams and jellies. *Z. rouxii* can grow at a pH as low as 1.8 and water activity as low as 0.62.
- **Brettanomyces** produces acetic acid from glucose under aerobic conditions and can cause spoilage in beer, wine and other fermented products.
- **Debaryomyces** can grow in 25% NaCl and at water activities as low as 0.65. It has been found to cause a slimy growth on salted meats, cheeses and in brines. It is also one of the causes of spoilage of yogurt.
- **Candida** can cause spoilage of refrigerated meat.
- **Saccharomyces bailii** is a spoilage yeast causing spoilage in mayonnaise, tomato sauce, fruit drinks and wine. It is resistant to benzoate and sorbate preservatives.

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2 Principles of HACCP: The Importance of HACCP Systems in Food Manufacturing

Sara Mortimore and Sue Emond

2.1 INTRODUCTION AND HISTORICAL PERSPECTIVE

When the Hazard Analysis Critical Control Point (HACCP) concept was introduced in the 1970s, it changed the way that food manufacturers managed food safety. Consequently, it has become a significant and important element in the history of food manufacturing. Much has been written about HACCP in the last 20 or more years, and its initial conception is also well documented. Discussion and debate about its implementation have continued and continue to occur, which is somewhat surprising for such a logical and straightforward food safety management tool.

It is widely acknowledged that, although absolute safety in food production is unattainable, the effective implementation of HACCP is the surest way of delivering safe food. The HACCP concept was endorsed by the World Health Organization and the Food and Agriculture Organization (WHO/FAO) as an effective means of ensuring control of food-borne illness as long ago as 1983 when the Joint FAO/WHO expert committee on food safety advised that HACCP should replace traditional end-product testing. Many guidance documents followed shortly afterwards, but the most notable was not published until Codex Alimentarius Commission (CAC) alongside the United States National Advisory Committee on the Microbiological Criteria for Foods (NACMCF) published theirs. The current documents are regarded as the reference documents worldwide and have been instrumental in harmonizing the approach.

As well as being a systematic approach, HACCP is important in that its successful use relies on the application and interpretation of a wide body of scientific and technical knowledge, such as:

- consideration of the risk and consequences of all known likely hazards
- complete understanding of what is making food safe (i.e. formulation and other factors such as processing and storage).
This is critically important both for day-to-day manufacturing control and for change management, such as recipe/process change or relocation to another production facility.

The real value of HACCP systems in food manufacturing lies in the fact that HACCP, as a concept, is a way of thinking and working and is not something that is done as an add-on to the day job or, even worse, becomes a ‘burden’ for the Quality Manager. Food safety remains a topic of interest in the popular press, and discussion about HACCP continues, stimulated by too many examples of food-borne illness that continue to occur as a result of a failure in control during manufacture.

This chapter will consider factors that are required in order for manufacturers to fully reap the benefits of HACCP as well as focusing on the importance of HACCP in developing a ‘preventative’ mindset, in product design as well as in food processing. This is a mindset that includes the ability to anticipate, observe, and gain control 24/7. While the chapter will not focus on the details of the HACCP principles themselves, nor the process by which they are implemented, these will be covered in brief to ensure the completeness and to set a context for the discussions that follow.

2.2 THE HACCP PRINCIPLES AND CODEX (CAC 1997)

To many, the HACCP principles provide guidance on what is simply a logical way of working, particularly in a food industry where a preventative approach would seem highly appropriate. HACCP is sometimes seen as being difficult to implement, but being science-based, it requires scientific knowledge and experience to adopt effectively. In small businesses or developing countries, that technical depth is not always available. That said, the concept itself is fairly easy to communicate, providing those charged with doing the communication have a proper understanding themselves, together with effective communication skills.

The seven principles of the HACCP system are:

Principle 1 Conduct a hazard analysis, describe appropriate control measures, i.e. if there is a biological, chemical or physical agent, or the condition of the food itself has the potential to cause an adverse health effect, then it must be controlled so as to prevent it.

Principle 2 Determine the critical control points (CCPs). These are the controls that are essential to prevent or eliminate a hazard
Principles of HACCP: The Importance of HACCP Systems in Food Manufacturing

Principle 3 Establish critical limits, i.e. the criteria that separate acceptability (in terms of food safety) from unacceptability.

Principle 4 Establish a system to monitor control of the CCPs, i.e. observations or tests that will assess whether the CCP is under control.

Principle 5 Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control.

Principle 6 Establish procedures for verification to confirm that the HACCP system is working effectively. To do this, there needs to be a validation that the likely hazards have been identified and that the control measures will control the hazards of concern. Validation of critical limits is also necessary to ensure that the system will be effective, as is verification that the HACCP system is operating as designed – i.e. that control of the CCPs is being maintained and that all the appropriate monitoring procedures are being adhered to.

Principle 7 Establish documentation concerning all procedures and records appropriate to these principles and their application. As indicated earlier this principle is sometimes contentious in relation to small businesses; however, if the true CCPs have been correctly identified, it is reasonable to want to record the results of monitoring to demonstrate (provide evidence) that the process is under control.

These seven principles are really just the minimum practical steps needed in order to evaluate and control food safety hazards in a systematic way. Guidelines for their use are outlined by Codex as 12 logical tasks that need to occur (Table 2.1).

Codex does not specifically describe an ‘HACCP plan’, which is the term commonly used for the document that captures the outcome of the study including the monitoring and corrective action requirements. Codex refers to this as an HACCP worksheet, which includes the product description, process flow diagram, control chart, and verification procedures. Whatever terminology is used, documenting the thought processes, discussion points and outcomes is important not just as evidence during a regulatory authority’s inspection but for the business team itself as people change roles and the system evolves. Appendix 5 gives some examples of typical HACCP control charts that may be seen.
Table 2.1 Guidelines for the application of the HACCP system.

<table>
<thead>
<tr>
<th>Task</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assemble the HACCP team: the size and composition of the team will vary according to the size and complexity of the business. The key point is that it should include a range of expertise, covering the design, manufacture and use of the product. (See Appendix 1.)</td>
</tr>
<tr>
<td>2</td>
<td>Describe the product: this is a very important step and, without a thorough understanding of the product composition, factors such as $a_w$, pH, major process steps, packaging, storage and distribution requirements, consumer use instructions and shelf life, it will be difficult if not impossible to conduct a hazard analysis. (See Appendix 2.)</td>
</tr>
<tr>
<td>3</td>
<td>Identify intended use: consider not just intended use, but how else might consumers use it. For example, might they eat a raw product, such as cookie dough, without cooking it?</td>
</tr>
<tr>
<td>4</td>
<td>Construct a flow diagram: this is an excellent way for the HACCP team to understand how the food is manufactured. The diagram should include all process steps within the operation and can be broken down into unit operations if this is easier to manage. Consideration of potential cross-contamination routes should be a high priority, e.g. floor layout, rework routing, personnel routing, equipment design, waste disposal, high/low risk segregation, sanitation procedures. (See Appendix 3.)</td>
</tr>
<tr>
<td>5</td>
<td>On-site verification of flow diagram – to make sure that it is accurate.</td>
</tr>
<tr>
<td>6</td>
<td>List all potential hazards, conduct a hazard analysis, and determine control measures. The HACCP team will typically brainstorm all likely hazards. Raw material specifications and literature references are very useful in considering what may be of concern. Likely occurrence decisions are based on product history – either within the company or external, the severity of the hazard [e.g. life threatening, chronic, mild illness or injury]. Appendix 4 highlights typical tools that may be used by the HACCP team for the analysis of hazards. Process conditions that might lead to an increase in likely occurrence or severity, e.g. production of toxins, or survival or increase of pathogens, also need to be considered. The team is then able to determine what control measures should be in place for each identified hazard (bearing in mind that one control measure may control more than one identified hazard).</td>
</tr>
<tr>
<td>7</td>
<td>Determine CCPs: many teams use tools such as CCP logic sequence decision trees [see Fig. 2.1, later in this chapter] to help with this process, but experience and judgement coupled with scientific knowledge are needed in order to do this effectively. This will be discussed further later on.</td>
</tr>
<tr>
<td>8</td>
<td>Establish critical limits for each CCP: this is the limit that separates acceptability from unacceptability in terms of food safety. They are observable, measurable parameters and are used to demonstrate that the CCP is under control. Most HACCP systems will also set an operating limit that is more stringent than the critical limit, and this is used as an indicator that the system is out of control before it becomes a food safety concern.</td>
</tr>
<tr>
<td>9</td>
<td>Establish a monitoring system for each CCP: this is done to ensure that loss of control at a CCP is detected in a timely manner and that a food safety incident is prevented. Monitoring systems are ideally on line and in real time, i.e. close to the process operation. Microbiological testing is not used for monitoring as it cannot be representative of the whole batch and analysis occurs too late to change the process and regain control.</td>
</tr>
<tr>
<td>10</td>
<td>Establish corrective action for deviations that may occur: a plan is needed to determine what to do if the CCP goes out of control; it is not sufficient to simply state ‘contact the Quality Manager’. The real benefit will come from the team being able to clearly anticipate likely failures and to determine disposition ahead of time.</td>
</tr>
<tr>
<td>11</td>
<td>Establish verification procedures: this will include as a first step validation that the HACCP plan will be effective, i.e. that all significant hazards have been identified and that the control measures will control them effectively. Validation needs to occur ahead of implementation of the HACCP system. It is basically a one-off activity, but it will need to be carried out any time there is a change to the HACCP plan. Verification is an ongoing activity, which will include activities such as audit, records and consumer complaints review and could include microbiological testing. Verification confirms that the plant is correctly following the requirements of the HACCP plan and it also confirms that the plan remains effective.</td>
</tr>
<tr>
<td>12</td>
<td>Establish record keeping and documentation, as evidence that an HACCP study has been carried out and that the business is being run under an HACCP system, also to confirm that the HACCP plan is effective [i.e. the validation and verification records].</td>
</tr>
</tbody>
</table>
2.3 HACCP IMPLEMENTATION: IMPORTANT CONSIDERATIONS

2.3.1 Prerequisite programmes

HACCP alone will not give sufficient assurance of food safety. It needs to be supported by prerequisite programmes and be a part of a broader food safety management system. The World Health Organization has published a definition for prerequisites – ‘Practices and conditions needed prior to and during the implementation of HACCP and which are essential for food safety’ – and mentions that these are described in Codex Alimentarius Commission’s *General Principles of Food Hygiene and other Codes of Practice*. Basically, when thinking about the foundations of HACCP, we tend to think of them generally as the good manufacturing practices (GMPs) that need to be in place in any food company in order to ensure wholesome food. This is not a new concept, but it has been well understood by responsible food manufacturers for many years. What is new, perhaps, is the formalizing of those programmes alongside HACCP to ensure that HACCP can focus on the real CCPs.

The scope of prerequisite programmes covers a range of general measures across both primary production and secondary processing. The Codex (1997a) principles include guidance on:

- establishment – design and facilities
- hygiene training, equipment and procedures for personnel
- cleaning and disinfection programmes for plant and equipment
- pest and waste management systems
- water and air control
- process control – including temperature
- equipment maintenance
- raw materials: purchasing and supplier quality assurance requirements
- transportation
- product information: labelling and traceability systems
- product rework, withdrawal and recall systems.

Elements of a prerequisite programme are usually not CCPs in the HACCP sense, and whether certain specific prerequisite controls are included in or excluded from the HACCP plan should be based on a risk assessment rather than making a blanket decision. A good example of this is incoming ingredient inspection. There may be a CCP at this step but only if specific ingredients have been identified as being potential sources of significant hazards. However, many ingredients are harmless and if inspected at all, it is for quality purposes only. Being specific about which ingredients are of concern and for what type of hazard is much more in
2.3.2 Application of the HACCP principles and the importance of training

As previously stated, HACCP is logical and straightforward as a concept. Most people can understand it, but many struggle with effective implementation. The possible reasons for this are important to try to understand in order to consider how to improve in the future. There are likely to be many opinions, but from a personal perspective the list would include:

- Lack of technical depth of knowledge: The following chapters are written by experts in their field and serve to illustrate the depth of knowledge needed to be able to make risk assessments that are science-based. Not many companies have that level of expertise in house. Knowing ‘what you don’t know’ is probably one of the best solutions, i.e. knowing when to seek advice from an expert rather than continuing in ignorance. That said, basic microbiology can be taught and applied. Rather than considering ‘pathogens’ as a hazard, spore formers, toxin producers and vegetative cells should be considered, i.e. the use of pathogen profiles to determine appropriate preventive measures.

- Ineffective training: Understanding of the basic principles of HACCP is fairly easily grasped, but learning enough to apply them requires more than an introductory course to be successful. Effective HACCP training is a key element of a successful HACCP system. HACCP will not play an important role in the manufacturing plant unless this is understood. Effective training will require a holistic approach. For example:
  - preparation and planning, which might require some pre-reading
  - the training intervention itself:
    - short introductory course or on-line distance learning
    - in-depth course, typically 2–3 days
  - practical case studies

The understanding that clearly defining what constitutes a prerequisite programme will enable us to develop much more focused and effective HACCP plans is still fairly new thinking. There are many companies where this is not yet understood. Yet it is a simple approach and, as stated, totally in line with the HACCP principles.
implementation of learning including follow-up coaching and support from technical experts and plant management
– review of results.

Ineffective training is a root driver of many of the following causes of failure to implement a valid and sustainable HACCP programme:

● Lack of real management commitment: vocal support not always supported by action in terms of funding for training, head-count, access to expertise.
● Misunderstanding of CPs versus CCPs and the role of prerequisite programmes in HACCP systems.
● Intrinsic product safety not understood nor taken into consideration when writing the HACCP plan.
● Incomplete HACCP plans:
  – flow diagrams incomplete, i.e. not all process steps included, or inaccurate
  – out of date, e.g. might not include all products produced, all ingredients used, incorrect process steps owing to changes, lack of consideration of recent hazard information
  – inconsistencies in content.
● HACCP seen as a one-off activity (with an end-point) rather than 24/7 continuous activity.
● Inadequate or no validation, i.e. failure to confirm that the CCPs and critical limits will control the hazards of concern.
● Verification:
  – thought of as just an audit
  – records/data not used to confirm compliance or to monitor trends.
● Target or operational limits versus critical limits not understood or not used to manage food safety at the plant.
● HACCP not properly transferred into work areas, e.g. a copy of the HACCP plan is taped to the wall rather than being transferred into meaningful work instructions and monitoring sheets.
● Monitoring not taken seriously. Missed checks or out-of-specification results noted but no action taken.
● HACCP done by just one individual rather than a team (though sometimes this is necessary in a small business).
● Corrective actions: Lack of forethought is often observed with the HACCP plan simply stating ‘inform Quality Manager’ if a CCP goes out of control. Many plants not only do not think about back-up, but also do not think to brainstorm probable failures and therefore possible corrective action ahead of time. This makes a real difference in terms of the HACCP system being useful and seen as important by the business.
This list could probably be even longer but it provides insight into some of the reasons why we still have breakdowns in food safety control systems, despite having HACCP systems. HACCP is extremely important in food manufacture and it is of utmost importance to implement a real programme in order to realize the true benefits. A root cause for the poor application of HACCP is a lack of insight and understanding of how to use HACCP and a resulting lack of belief in the necessity or importance of the approach.

HACCP requires a conceptual leap on the part of the trainer as well as the trainee. Current HACCP training often falls short of meeting the need. Too many ‘trained’ people still do not properly understand the concept itself or the relationship between HACCP and pre-requisite programmes (PRPs), and that is one of the main causes of failure, but not the only one. This may be owing to the quality of the trainers (who do not fully grasp the concept themselves) or the approach that we typically take to training – usually a one-off course with limited support afterwards. This can sometimes be mitigated in larger organizations where there is a body of corporate expertise and knowledge to give support and to advise.

That said, how can we make HACCP easier to understand? Perhaps by referring back to Codex. A CCP is clearly defined as a step (i.e. it is not a programme) at which control can be applied and is essential to prevent or eliminate a food safety hazard or reduce such a hazard to an acceptable level. In HACCP training the trainees should be reminded to use their common sense – if the CCP was not there would the plant continue to run without it? If the answer is ‘yes’, then we have to question whether it is essential for food safety. The Codex definition of ‘hazard analysis’ is also helpful . . . ‘the Process of collecting and evaluating information on hazards and conditions leading to their presence to decide which are significant for food safety and therefore should be addressed in the HACCP plan’. We should be including only the significant hazards, i.e. those that both have the potential to cause harm and are reasonably likely to occur.

The Codex decision tree (Fig. 2.1) also helps to guide us, question 2 in particular: ‘Is the step specifically designed to eliminate or reduce the likely occurrence of the hazard to an acceptable level?’ Consider prerequisite programmes – they are often general activities rather than a single step, e.g. keeping lids on containers, washing hands, having a pest-control programme, good ventilation, etc. These are things that we know are sometimes not followed as a result of human nature or, for instance, sporadic instances of pest activity. Yet the plant continues to operate. In contrast, if a true CCP fails, e.g. thermal process failure or allergen bar
Acceptable standards of prerequisite hygiene/GMPs continue to differ around the world; however, process-related CCPs for similar products are often the same whatever country the product is manufactured in. This does not mean that a specific element of a prerequisite programme is never a CCP. The HACCP team always needs to consider product risk on a case-by-case basis and the local operating environment. For example, having a potable water supply for the washing of fresh produce may be difficult to control, particularly in countries where the water supply is unreliable.

It is much easier to develop and implement a really good HACCP programme now that we have a clearer understanding. In the past (10 years...
ago) it was common to see HACCP plans with literally hundreds of ‘CCPs’ – most of which were really managed by prerequisite programmes. Those same HACCP plans probably now have less than 10 true CCPs supported by a good prerequisite programme and all managed within a food safety and quality management system. HACCP is important as it can truly focus attention on the real critical control points both by aiding the design of safe products and also by providing clarity within the process environment.

2.4 THE IMPORTANCE OF HACCP IN FOOD MANUFACTURING: THE PREVENTATIVE MINDSET

The importance of HACCP lies in its ability to manage risk and to foster a preventative mindset. However, that can only be achieved if those charged with designing and manufacturing food understand this.

2.4.1 Food design

The most effective use of HACCP in food safety assurance is to design safe products, but we cannot live on biscuits and dry breakfast cereal alone. Food obviously comes not only in many shapes and sizes, but also in many forms in terms of moisture, acidity, packaging, etc., etc. We have to understand what factors make food intrinsically safe – such as low pH, low $a_w$, chemical preservatives – together with processes that involve, for example, a thermal kill step or conditions that prohibit the growth of harmful micro-organisms, such as freezing. Including safe product design within a HACCP system is sometimes overlooked, but early in the conceptual stage of a product’s life cycle hazards and control measures can and should be considered. Mortimore and Wallace\(^9\) describe one way of doing this systematically that is in line with HACCP philosophy. This involves consideration of:

- the target market, i.e. likely consumers
- ingredients, e.g. are they microbiologically sensitive, are they allergenic?
- intrinsic factors such as $a_w$, pH, chemical preservatives, organic acids
- major process steps, e.g. is there a kill step in the process?
- storage and distribution.

What a HACCP system cannot do is to make safe a product that is inherently unsafe. HACCP is a structured, logical way of thinking that involves several steps (Table 2.2), the first three of which can be done during the design stage. Product developers should know what the critical factors are with any product they are working on in terms of formulation and processing. That information needs to be captured in product specifications
so that operators and quality personnel can use this information and work together on the final HACCP study and its implementation in the plant.

### 2.4.2 Food manufacturing

In the real world, nothing is guaranteed so much as change, so we have to accept and live with that. In food safety terms, conducting an initial HACCP study, developing an HACCP plan and implementing it in the manufacturing plant comprise only the beginning. There is no end-point when implementing HACCP; however, the continuous improvement and 24/7 state of readiness implied by the concept are two of the major benefits that are lost to many users. In a food plant likely changes may include:

- increased production output
- new raw material suppliers
- building work
- changing workforce
- process conditions varying from specified range
- ingredient exception requests from suppliers.

All of these will require anticipation and thoughtful evaluation of increased risk. When HACCP is used effectively, this becomes routine such that users apply the principles of hazard analysis almost without consciously realizing it – it becomes their way of working. This is a preventative approach, and there are countless examples of failures that could have been avoided if HACCP had been applied.9

Change, of course, occurs on a wider scale and continues to impact on the health of the world’s population and cause reduced economic productivity. Motarjemi *et al.*10 cite a number of reasons for this, including:

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Looking at how the product is made – from start to finish and step-by-step, identifying possible hazards, deciding at what stage in the process they are likely to occur and putting in controls to prevent these hazards from occurring</td>
</tr>
<tr>
<td>2</td>
<td>Deciding which of these controls are absolutely critical to food safety</td>
</tr>
<tr>
<td>3</td>
<td>Setting a limit for safety for the operation of these critical controls</td>
</tr>
<tr>
<td>4</td>
<td>Monitoring these controls to make sure that they do not exceed the safety limit</td>
</tr>
<tr>
<td>5</td>
<td>Identifying the likely corrective action should something go wrong</td>
</tr>
<tr>
<td>6</td>
<td>Documenting the requirements and recording all findings as the products are produced</td>
</tr>
<tr>
<td>7</td>
<td>Ensuring that the system works effectively through regular reviewing of performance and auditing</td>
</tr>
</tbody>
</table>
1) The proportion of the population that has increased susceptibility to food-borne illness is increasing, for example, the elderly, the immuno-compromised and the malnourished.

2) Changing lifestyles have resulted in a number of changes to our eating habits:
   a) More people now eat out, which has led to an increased demand for catering establishments of varying type;
   b) Many more women work outside the home and rely on processed foods for fast meal preparation. This has meant that knowledge of how to handle and prepare foods has decreased in recent years;
   c) Increased mass production of foods has increased the potential for larger numbers of consumers to be affected in the event of an outbreak of food-borne disease;
   d) Increased tourism has meant that people are exposed to food-borne hazards from other parts of the world.

3) Emerging pathogens, such as verocytoxin-producing *E. coli*.

4) New technologies and processing methods.

### 2.4.3 Globalization and trade

Increased globalization of the food supply has meant that we look for equivalency in standards across countries. Some countries, including China, actually require an HACCP certification as a prerequisite to food exporting. HACCP therefore is very important for the world trade in food. This was recognized back in 1995 when the General Agreement on Tariffs and Trade (GATT) Uruguay Round was completed and the World Trade Organization (WTO) was established. However, while Codex\(^3\) took us a long way towards harmonization of the principles, we remain a long way from consistency in interpretation at the detailed level. ISO22000\(^11\) may in time assist with this, but given the fact that current HACCP training often falls short of meeting the need\(^12\), it is unlikely to happen quickly.

### 2.5 THE LEGAL POSITION

Since the early days of HACCP, many governments have adopted it on either a voluntary or a mandatory basis. Where voluntary HACCP was the legislative stance, many companies still had it in place as they sought to improve or satisfy a customer requirement.

Up to 1st January 2006, the legal position throughout Europe was to follow Council Directive on the Hygiene of Foodstuffs 93/43/EEC, which laid out the general guidance across the food industry. The legal requirement was that food business operators had to identify any step in their
activities critical to ensuring food safety and ensure that adequate safety procedures were identified, implemented, maintained and reviewed on the basis of the following principles, used to develop the system of HACCP:

- analysing the potential food hazards in a food business operation
- identifying the points in those operations where food hazards may occur
- deciding which of the points identified are critical to food safety – the ‘critical points’
- identifying and implementing effective control and monitoring procedures at those critical points
- reviewing the analysis of food hazards, the critical control points and the control and monitoring procedures periodically and whenever the food business operations change.

The legislation also required that competent authorities should be reviewing the companies’ identified critical points to see whether appropriate monitoring and verification activities were being carried out.

The problem with the legislation was that there was no requirement for documentation for the majority of the food industry, unless the company was covered by the vertical directives that looked at products of animal origin (meat, fish, dairy and eggs) that did require ‘own checks’ and documentation. From an enforcement viewpoint, this was a nightmare scenario as many assessments had to be made on systems that required no documented evidence.

A new suite of hygiene regulations came into force on 1st January 2006. Regulation 852/2004 covers the general principles for the hygiene of foodstuffs throughout the food chain, with the primary aim of ensuring a high level of consumer protection with regard to food safety. The legislation states: ‘The HACCP system is an instrument to help food business operators attain a higher standard of food safety’ and ‘The HACCP requirements should take account of the principles contained in the Codex Alimentarius. They should provide sufficient flexibility to be applicable in all situations, including in small businesses’.

The legislative requirement is that food business operators shall put in place, implement and maintain a permanent procedure or procedures based on the HACCP principles together with the application of good hygiene practices. This stops short of requiring a full-blown HACCP system as it demands a system that is ‘based on’ HACCP. A company can put its own food safety management system in place. It must be based on HACCP principles, but does not have to be called HACCP. Examples of this can be seen in the England and Wales Food Standards Agency
document *Safer Food Better Business*\(^{13}\) and the Scottish equivalent, *CookSafe*.\(^{14}\) Also, the requirement of an HACCP-based system by law only applies to companies after primary production. There still is no requirement for farmers, growers, etc., to have an HACCP-based system in place, although they still are required by law to control hazards. The legislative requirement for documentation is that evidence of the HACCP-based system should be available commensurate with the nature and size of the business.

The main benefit and drawback of the new hygiene package is its ‘flexibility’. For certain business it has been highlighted that a full HACCP system may be too complex and that a well-controlled prerequisite programme may be sufficient.\(^{15}\) This is a benefit to the businesses, but makes it difficult to assess for the competent authorities.

The legislative requirements throughout the rest of the world are gradually becoming more prescriptive. Mandatory HACCP is in place for fish and seafood in the USA, Canada, Cuba, Thailand and Mexico. The USA and Australia also have mandatory HACCP for meat and poultry products. In New Zealand, HACCP is mandatory for all products. It can be seen that HACCP is now incorporated more and more into legislative requirements throughout the world and is likely to continue in this vein for all food products, including eventually primary products.

### 2.6 CLOSING THOUGHTS

HACCP has been in the public domain for many years. Food scientists, regulators and academics continue to work hard to ensure a safe food supply, and yet there are still many examples of failure in the system resulting in illness (or worse), and high costs. Most recently Cadbury withdrew 10 million chocolate bars as a result of *Salmonella montivideo* contamination. News reports\(^{16}\) suggest that the company was reliant on end-product testing. These days end-product testing is mostly used for verification that the HACCP system is working, with companies relying more on ingredient and process control, together with environmental monitoring for *Listeria* and *Salmonella*. Another example is the series of US *E. coli* contaminations in salad crops such as spinach, suggesting that an HACCP approach needs to be applied not just at process plants but also in the agricultural sector.

HACCP is being recognized as the most effective way of preventing food-borne illness, but the benefit of this preventative approach will not be realized if implementation is ineffective. As a closing thought and point
of emphasis, one of the most critical success factors – if not the most critical – for successful HACCP use is effective training. Training needs to be seen as more than a single course and recognized as an ongoing educational process that starts before the course and continues way after, with continuing support from managers and experts. This can then lead the way for the business to have a successful HACCP system and understand that developing the system was only the beginning of a new approach to food safety management. HACCP is important in food manufacturing because it can add real value ... if applied properly and continuously.

APPENDICES

The appendices provide a simple example of the output of an HACCP study in a salad manufacturing plant, detailing:

- Example of the make-up of an HACCP team (Appendix 1)
- Example of a product description (rice salad with vinaigrette dressing) (Appendix 2)
- Examples of process flow diagrams (for rice salad and vinaigrette) (Appendix 3)
- Hazard analysis tool as an example guide as to how significant hazards can be identified. The knowledge and experience of the HACCP team should always prevail but tools can be a helpful discussion framework (Appendix 4)
- A sample of the hazard analysis and CCP determination of a few ingredients and processes used in product preparation (Appendix 5)
- An example of the HACCP control chart (Appendix 6)

**Appendix 1: Example of the make-up of an HACCP team**

Codex states that the development of an HACCP plan should optimally be done by a multidisciplinary team. Typically a team make-up would comprise:

- Team leader: typically technical manager or quality manager
- Team members:
  - R&D technologist
  - engineer or maintenance manager
  - production staff (manager/line leader)
  - quality engineer
- Specialists:
  - microbiologist
  - packaging technologist
- Scribe: technical secretary (typically a technical writer)
Appendix 2: Example of a product description

The product to be manufactured is rice salad (Table A1).

Table A1  Product description – rice salad.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>The product will be stored, distributed and displayed at a maximum of 5°C</td>
</tr>
<tr>
<td>Formulation/preservation</td>
<td>The product is made up of cooked cooled rice, vinaigrette dressing, sweetcorn kernels, spring onions and diced red pepper. The product contains no preservatives</td>
</tr>
<tr>
<td>Packaging</td>
<td>The product is packed into PVC–PET trays with snap-on lids. There is no atmosphere modification. The pack is labelled with a stick-on paper label containing ingredient information and shelf life (2 days from packing). The label also contains allergen information (contains gluten)</td>
</tr>
<tr>
<td>Principal hazards of concern and control measures</td>
<td>The principal biological hazards are the potential presence of pathogens in incoming ingredients and cross contamination during processing. Control measures include thermal process and pH control together with segregation of the cooked product into a high-care process area</td>
</tr>
<tr>
<td>Consumer practices</td>
<td>The product is ready to eat and should be eaten within 2 days of packing and kept chilled for that period</td>
</tr>
<tr>
<td>Intended use</td>
<td>The product is aimed at the general population</td>
</tr>
</tbody>
</table>
Appendix 3: Examples of process flow diagrams

1. Rice salad process flow diagram

- Incoming ingredients
  - Water
  - Ingredients storage
  - Water

- Rice
  - Debag
  - Cook
  - Cool
  - Drain
  - Hold <5°C

- Sweetcorn kernels (Canned)
  - Debox
  - Open cans
  - Decant into tote bin
  - Hold <5°C

- Fresh vegetables (Red Peppers / Spring onions)
  - Debox
  - Wash
  - Drain
  - Trim and Chop
  - Hold <5°C

- Vinaigrette (see flow diagram 2)

- Trays
  - Labels

- Outercases

- Blend
  - Check pH <4.5
  - Fill holding tanks
  - Storage <5°C
  - Pack into trays
  - Lidding
  - Labelling
  - (Metal detection)
  - Outercasing

- Warehouse storage <5°C

- Distribution (chilled)

- Consumer
2. Vinaigrette process flow diagram

- Incoming ingredients
- Ingredients storage
  - Ground nutmeg
  - Vegetable oil
  - Olive oil
  - Red wine vinegar
  - Salt

Weigh all ingredients into mixer
Mix to uniformity
Hold
(Check pH = 3.4 ± 0.2)
(Check viscosity for ‘clingability’)
Mix before adding to salad

See flow diagram 1
Appendix 4: Hazard analysis tool as an example guide

Tool to assess significance of hazard – Logic table

Anything to the right of the bold line is included in the HACCP study as a significant hazard. Anything to the left of the line is typically controlled by the prerequisite programme.

This is an example only. A four-point scale is used for each axis but it could be any number of points. It is a company decision as to how they lay out a logic table and also a company decision as to where the cut-off point will be for hazards that are classed as either significant or not significant.

On this basis the likelihood of vegetative pathogens not being destroyed during rice cooking could be classed as ‘impossible’, given that rice needs to be cooked to develop the required sensory (texture) changes, and that requires a much longer heat treatment than is needed for the destruction of *Salmonella.*
Appendix 5: Examples of hazard analysis and CCP decision logic: fresh vegetables, rice, vinaigrette, salad blending and assembly

1) Fresh vegetable preparation

<table>
<thead>
<tr>
<th>PROCESS STEP</th>
<th>HAZARD</th>
<th>CONTROL MEASURES</th>
<th>Q1</th>
<th>Q1a</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>CCP</th>
<th>CP</th>
<th>RATIONALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredient receipt</td>
<td>General contamination (soil, micro)</td>
<td>SQA audit and agreed specifications. Handle in a low risk area. Decontamination through later washing</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Washing will reduce contamination. Low pH will inhibit micro growth Govt. surveillance with sporadic verification testing</td>
</tr>
<tr>
<td>Ingredient receipt</td>
<td>Pesticides residues</td>
<td>Pesticide residue programme</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>N</td>
<td></td>
<td>Y</td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Ingredient storage</td>
<td>No significant hazard</td>
<td>Clean and hygienic storage area. Controlled time/temp of storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Debox</td>
<td>No significant hazard</td>
<td>Inspection and good handling practices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Washing/dip</td>
<td>Failure to reduce microbial load</td>
<td>Control the dip strength and time (e.g. 300 ppm hypochlorite for 40 minutes). Sterilant action may be temperature dependent</td>
<td>Y</td>
<td>–</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Field grown produce which could be heavily contaminated. Later low pH reduces this risk but this is seen as a critical step</td>
</tr>
<tr>
<td>Drain</td>
<td>No significant hazard</td>
<td>Drain in sanitized lidded containers in high-risk area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Trim and chop</td>
<td>Cross contamination from environment, equipment (e.g. metal) and people</td>
<td>Sanitized equipment and hygiene training. Metal detection of finished product</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Prerequisite GMPs in place. Later metal detection</td>
</tr>
<tr>
<td>Hold</td>
<td>Cross contamination from equipment and environment.</td>
<td>Hold in sanitized lidded containers</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td></td>
<td>Growth of pathogens, mould</td>
<td>Hold at &lt;5°C. Use within 24 hours. Record keeping and traceability (quality system)</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place. Later pH control</td>
</tr>
</tbody>
</table>
### 2) Rice preparation

<table>
<thead>
<tr>
<th>PROCESS STEP</th>
<th>HAZARD</th>
<th>CONTROL MEASURES</th>
<th>Q1</th>
<th>Q1a</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>CCP</th>
<th>CP</th>
<th>RATIONALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredient receipt</td>
<td>Contaminated ingredient (B. cereus)</td>
<td>Later cooking and cooling steps</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td></td>
<td></td>
<td>Contamination would not increase at this step</td>
</tr>
<tr>
<td>Ingredient storage</td>
<td>No significant hazard.</td>
<td>Clean and dry storage area. Sealed containers</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Debag</td>
<td>Foreign material</td>
<td>Sieve; inspect; flotation (Process Step 4); metal detection at a later step</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place and later metal detection</td>
</tr>
<tr>
<td>Cook in water</td>
<td>Survival of vegetative pathogens</td>
<td>Defined cooking time and temperature (e.g. boil for 15 minutes)</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td></td>
<td></td>
<td>The cooking step is designed for sensory, not food safety. At the temperature and time needed to hydrate the rice, there would be an extremely low likelihood of survival of the vegetative pathogens</td>
</tr>
<tr>
<td>Cool in water</td>
<td>Pathogen spore outgrowth (B. cereus), and potential toxin production</td>
<td>Cool rapidly in chilled water at &lt;5°C. Rice must reach &lt;5°C within 1 hour. Chilled water with &gt;3 ppm available chlorine. Potable water micro checks. (Managed as an ingredient)</td>
<td>Y</td>
<td>–</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td>Scientific evidence shows that if cooked rice is not cooled rapidly outgrowth of B. cereus spores is highly likely</td>
<td></td>
</tr>
<tr>
<td>Drain</td>
<td>No significant hazard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hold</td>
<td>Pathogen spore outgrowth (as above)</td>
<td>Hold at &lt;5°C. Use within 4 hours. Record keeping and traceability (quality system)</td>
<td>Y</td>
<td>–</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td></td>
<td>In this case, storage below 5°C is essential to control the identified hazard</td>
</tr>
</tbody>
</table>
3) Vinaigrette processing

<table>
<thead>
<tr>
<th>PROCESS STEP</th>
<th>HAZARD</th>
<th>CONTROL MEASURES</th>
<th>Q1</th>
<th>Q1a</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>CCP</th>
<th>CP</th>
<th>RATIONALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredient receipt</td>
<td>Contaminated nutmeg (Salmonella)</td>
<td>SQA; pathogen clearance; non ETO treated (e.g. steam sterilization method)</td>
<td>Y</td>
<td></td>
<td></td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Salmonella in a ready to eat product is a concern but at a pH of &lt;4.5</td>
</tr>
<tr>
<td>Ingredient storage</td>
<td>No significant hazard. Micro concern if it gets wet in storage</td>
<td>Dry storage in intact packaging</td>
<td>Y</td>
<td></td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Ingredient weighing</td>
<td>No significant hazard</td>
<td>Sterilized equipment. Hygiene training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prerequisite GMPs in place</td>
</tr>
<tr>
<td>Mixing</td>
<td>Inconsistent pH and salt level allowing pathogen growth in end product</td>
<td>Correct mixing (speed and time). Thorough pH checking and monitoring</td>
<td>Y</td>
<td></td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>This step is a control point as although a later step will monitor pH level, economic waste can be prevented</td>
</tr>
<tr>
<td>Storage</td>
<td>No significant hazard</td>
<td>Sealed and sterilized vessels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4) Salad blending and product assembly

<table>
<thead>
<tr>
<th>PROCESS STEP</th>
<th>HAZARD</th>
<th>CONTROL MEASURES</th>
<th>Q1</th>
<th>Q1a</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>CCP</th>
<th>CP</th>
<th>RATIONALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix vinaigrette</td>
<td>Inconsistent pH and salt level allowing pathogen growth at a later step</td>
<td>Correct mixing (speed and time)</td>
<td>Y</td>
<td></td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>This step is a control point as it contributes to ensuring even distribution of salt and acetic acid intrinsic control factors</td>
<td></td>
</tr>
<tr>
<td>Blending of all</td>
<td>Pathogen growth as a result of uneven blending, i.e. pH and salt unevenly distributed</td>
<td>Time limit/high risk area, pH check &lt;= 4.5</td>
<td>Y</td>
<td></td>
<td>Y</td>
<td></td>
<td></td>
<td>Y</td>
<td>This is the final control point and is therefore critical</td>
<td></td>
</tr>
<tr>
<td>High Care</td>
<td>No significant hazard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holding</td>
<td>No pathogen hazard if pH &lt;= 4.5, temperature &lt;= 5°C and time limit</td>
<td>Time and temperature control</td>
<td>Y</td>
<td></td>
<td>N</td>
<td>N</td>
<td></td>
<td>Y</td>
<td>Spoilage might be a concern</td>
<td></td>
</tr>
<tr>
<td>Fill tanks</td>
<td>No significant hazard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill pots</td>
<td>Foreign material (metal) not detected</td>
<td>Invert pots and air-blow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assemble product</td>
<td></td>
<td>Seal testing of lids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lidding and labelling</td>
<td></td>
<td>Metal detection</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>Final metal detector is a CCP</td>
<td></td>
</tr>
<tr>
<td>Coding</td>
<td>Incorrect shelf life (micro spoilage)</td>
<td>Coding check to ensure accuracy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>Spoilage is not a food safety hazard</td>
<td></td>
</tr>
<tr>
<td>Storage and distribution</td>
<td>Spoilage due to temperature abuse</td>
<td>Store below 5°C, Stock rotation</td>
<td>Y</td>
<td></td>
<td>N</td>
<td>N</td>
<td></td>
<td>Y</td>
<td>Spoilage is not a food safety hazard, Prerequisite GMPs in place</td>
<td></td>
</tr>
</tbody>
</table>
## Appendix 6: Example of the HACCP control chart (for rice salad)

<table>
<thead>
<tr>
<th>Process step</th>
<th>CCP No.</th>
<th>Hazard to be controlled</th>
<th>Control measures</th>
<th>Critical limits</th>
<th>Actions to be taken if deviation occurs</th>
<th>Procedure</th>
<th>Frequency</th>
<th>Responsible person(s)</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice cooling</td>
<td>1</td>
<td>Pathogen spore outgrowth during cooling (B. cereus); toxin formation</td>
<td>Rapid cooling, &lt;5° in 1 hour</td>
<td>≤7°C</td>
<td>Destroy</td>
<td>Record time and temperature</td>
<td>Each batch</td>
<td>Cooker operator</td>
<td>CCP records review by QA prior to dispatch. Calibrated thermometers</td>
</tr>
<tr>
<td>Cooked rice holding</td>
<td>2</td>
<td>Pathogen spore outgrowth during inadequate storage conditions (B. cereus); toxin formation</td>
<td>Store at &lt;5°C</td>
<td>7°C</td>
<td>Destroy</td>
<td>Record storage temperature</td>
<td>Continuous – via chart recorder</td>
<td>Warehouse supervisor</td>
<td>CCP records review by QA prior to use. Calibrated thermometers</td>
</tr>
<tr>
<td>Salad blending</td>
<td>3</td>
<td>Pathogen growth</td>
<td>pH control, &lt;4.5</td>
<td>&lt;4.5</td>
<td>Hold batch and inform QA. Addition of additional red wine vinegar under QA supervision</td>
<td>Test and record pH</td>
<td>Each batch</td>
<td>Blender operator</td>
<td>CCP records review by QA prior to dispatch. pH meter daily calibration</td>
</tr>
<tr>
<td>Packaging</td>
<td>4</td>
<td>Metal</td>
<td>Metal detection</td>
<td>No metal is detected in product</td>
<td>1. Stop line and inform QA 2. Determine root cause and assess risk 3. Reject, rework or release 4. If calibration fails to detect then hold product until last good check 5. Recalibrate metal detector</td>
<td>Pass product through metal detector</td>
<td>Continuous</td>
<td>Line supervisor</td>
<td>Verify calibration to detect and reject 1.5 mm carbon steel and 2.4 mm 316 stainless steel spheres. Test at start up, every 2 hours minimum, and at end of run. Daily record review by QA prior to dispatch</td>
</tr>
</tbody>
</table>
REFERENCES

3 Thermal Processing
Ian J. Britt

3.1 INTRODUCTION

The purpose of thermal processing or canning technology is to produce shelf-stable food products packaged in hermetic containers. Generally, this is accomplished in one of two ways: aseptic processing, where product and package are sterilized separately, after which filling and sealing are completed in an aseptic zone; or in-container sterilization, where an hermetic container is filled with the product and sealed, and the product and container are then heated as a unit to achieve a shelf-stable product. This chapter will focus on the latter.

The origin of in-container sterilization may be credited to Nicolas Appert who, in 1810, patented a process whereby glass bottles were filled with foods, closed with a wired cork and heated in a water bath for extended periods of time. The result of this empirically designed process was the production of a variety of shelf-stable products. However, the causes underlying food spoilage were not discovered until 50 years later when Louis Pasteur published his theories on food spoilage. Then near the turn of the century Samuel Prescott and William Underwood outlined the canning principles that, in a basic sense, we still use today. Their work showed the need to achieve certain time/temperature conditions in the food to kill harmful bacteria, as well as the importance of cooling to minimize post-processing spoilage due to thermophilic bacteria. This was followed by significant work in the 1920s by a number of researchers. Notably, Bigelow and co-workers\textsuperscript{1,2} published methods for evaluating the heat resistance of bacterial spores, ‘logarithmic spore death’, and the effects of pH on processing requirements. Esty and Meyer\textsuperscript{3} published a landmark manuscript on the heat resistance of \textit{Clostridium botulinum} spores, which is still being used today to define product safety, and Ball\textsuperscript{4} developed process evaluation methodologies. Through the remainder of the last century, a greater understanding of the underlying principles of food preservation was gained, and sophisticated processing equipment was developed.
3.2 PRODUCT CLASSIFICATION

Processing requirements for canned foods are dictated by product pH and water activity (a_w). As shown in Fig. 3.1, foods with an a_w < 0.85 are classified as shelf stable and do not require heat treatment; these foods include nuts, raisins, jams, honey and cheese spreads. Foods with an a_w > 0.85 may have a wide range of pH, as shown in Fig. 3.2. For these foods a critical pH of 4.6 is used to classify foods as acid (pH ≤ 4.6) or low-acid (pH > 4.6). The acidity of the former prevents the growth of C. botulinum and other spore-forming bacteria.

Acid products only require heat treatment at pasteurization temperatures (typically 80 to 100°C) to destroy vegetative cells present in the food. In contrast, low-acid foods require a more severe heat process (115–125°C) to destroy C. botulinum spores to protect public health, and to destroy other spore-forming bacteria to minimize economic losses due to spoiled products. It is noteworthy that some researchers make a further distinction by classifying foods with pH 4.0 to 4.6 as acid foods, and those below pH 4.0 as high-acid foods.5

![Fig. 3.1 Product classification based on pH and water activity (a_w).](image-url)

![Fig. 3.2 Representative pH values for canned foods.](image-url)
3.3 MICROBIAL DESTRUCTION

In 1921 Bigelow reported that the thermal death of micro-organisms is logarithmic in nature. Over a period of time this finding led to the organization of thermal death behaviour data in a number of graphical forms, including end-point thermal death time curves, survivor curves, and thermal resistance curves.

3.3.1 End-point thermal death time curve

End-point thermal death time experiments use small cans or tubes containing a known initial population of bacterial spores suspended in a product of interest. Once filled, these small containers are quickly heated in an oil bath or mini-retort, held at a constant temperature for different periods of time, and then quenched in an ice bath. Samples are then incubated and tested for microbial growth. The objective is to determine the time required at each experimental temperature to destroy the spores present in the container.

The logarithms of these thermal death times (tdt) are then plotted against exposure temperature (Fig. 3.3). The resulting curve is defined by a slope index, z, and the tdt, F, corresponding to a processing temperature of 121.1°C. The z-value is the temperature difference required to decrease the tdt by one log cycle, and mathematically it is the negative reciprocal slope of the curve. The equation of the line may be expressed as:

\[
\log \text{tdt} - \log F = -\frac{1}{z}(T - 121.1) = \frac{1}{z}(121.1 - T) \quad (\text{Eqn. 3.1})
\]

The results of this approach define the time required at a specified temperature to destroy a known population of spores in a specific product. Note that the F-value derived from the curve is dependent on the initial

![Diagram of thermal death time curve](Fig. 3.3 Thermal death time curve.)
population of spores, $N_0$, used in the thermal death time experiments. If $N_0$ increases, $F$ will increase, and if $N_0$ decreases, $F$ will decrease.

### 3.3.2 Survivor curve

The procedures used to collect survivor curve data are similar to the end-point thermal death time experiments. Small containers containing a known number of spores in a medium of interest are heated at a constant temperature for varying exposure times. The spore load present after each exposure time is then determined and the logarithm of that number is plotted as a function of time, as shown in Fig. 3.4. The equation of the line may be expressed as:

$$t = D_T (\log N_0 - \log N)$$  \hspace{1cm} (Eqn. 3.2)

where $D_T$, the decimal reduction time, is the time required at a constant temperature, $T$, to reduce a population of spores by 90% or one log cycle.

### 3.3.3 Thermal resistance curve

The end-point thermal death time curve shows that the time required to destroy a given population of spores decreases as the exposure temperature increases. It follows that in experiments to define a survivor curve, higher exposure temperatures will result in smaller $D$-values. When $D$-values for a range of exposure temperatures are plotted against the exposure temperature on a semi-logarithmic plot, they form a linear relationship (Fig. 3.5).

As in the end-point tdt curve, the slope index or the temperature difference needed to reduce the $D$-value by one log cycle is the $z$-value. The line may be defined by the $z$-value and $D_{121.1^\circ C}$, the $D$-value associated with the
reference temperature of 121.1°C. The equation of the line may then be expressed as:

$$\log D_T - \log D_{121.1\degree C} = -\frac{1}{z(T - 121.1)},$$
or

$$D_T = D_{121.1\degree C}10^{(121.1-T)/z} \quad \text{(Eqn. 3.3)}$$

### 3.4 COLD-SPOT TEMPERATURE HISTORIES

Ultimately, the objective of a thermal process is to destroy spores present in a product to a level that provides an acceptable probability of spoilage. To achieve that goal a thermal process is designed to deliver heat energy to the cold spot, or slowest heating point, of a product packaged in a specific container. This requires knowledge of the temperature response at that slowest heating point, and that is achieved by direct measurement using thermocouples or similar temperature-measuring devices.

Canned food products may be heated by conduction, convection, mixed convection/conduction, or induced convection, as shown schematically in Fig. 3.6 for cylindrical containers. Important to our application is how the mode of heating influences the location of the cold spot in the container, since this is the point that will receive the least amount of microbial kill during heating. For products heated by conduction, such as pumpkin, the cold spot will be near the geometric centre of the container. In vertically oriented cans, the cold spot for products heated by convection, such as chicken broth, will shift from the geometric centre to a location on the axis near the bottom of the can. Convection/conduction heating may be seen in products such as carrots in brine, where the liquid phase is heated by convection while the slower heating solids are heated by conduction. When liquid products are agitated during a process the
temperature may become nearly uniform throughout the container, with no specific cold spot.

The temperature response at the cold spot combines the effects of the container size and geometry, the properties of the food and the temperature profile of the heating medium. Fig. 3.7 shows an example of the retort and product temperature histories attained in a batch retort process. For batch retort systems it takes a period of time, \( t_c \), for the retort to reach the desired processing temperature (as shown in the retort temperature profile). After that time, the temperature is held constant for a specified period of time, \( t_p \), which is required for the process to deliver the lethality or microbial kill necessary to attain commercial sterility; the retort is then cooled.

![Conduction and Convection](image)

**Fig. 3.6** Heating modes of canned foods.

![Retort and Product Temperature Curves](image)

**Fig. 3.7** Retort temperature and product temperature (heat penetration) curves.
3.5 LETHALITY CALCULATIONS

3.5.1 The general method

In the sterilization of low-acid foods, process lethality is expressed as equivalent minutes at a reference temperature of 121.1°C, and is commonly expressed as an $F_o$-value. For example, a particular $F_o$-value of 6 minutes (Fig. 3.8) would assume a step-change temperature response where the cold-spot temperature would rise instantaneously to the reference temperature, be held there for 6 minutes and then cool instantaneously. This response, of course, is not possible for an in-container sterilization process. However, in early work, Bigelow determined that lethalities attained at different temperatures are additive and thus may be accumulated as the temperature at the cold spot changes through a process. Thus, knowing the cold-spot temperature history one can determine the rate of lethality at each time increment, plot the resulting data as a function of time, and integrate under the curve to obtain the equivalent lethality at the reference temperature.

From the work of Esty and Meyer, it is widely recognized that $C.\ botulinum$ spores may be characterized by a $z$-value of 10 Celsius degrees (18 Fahrenheit degrees) and a $D_{121.1°C}$ of 0.21 minutes. Also, since tdt data were frequently not available for a specific product formulation, Ball proposed that a unit thermal death time curve should be applied in calculations where the $F$-value is 1 minute. Recognizing that $\log 1 = 0$ and combining this with the death kinetics for $C.\ botulinum$, Eqn. 3.1 for the end-point tdt curve may be expressed as:

$$\log tdt = (1/10)(121.1 - T). \quad (\text{Eqn. 3.4})$$

Note that the tdt is now the time at a specified product temperature equivalent to $F_o$ minutes at a reference temperature of 121.1°C. The units of
the tdt are minutes at T per minute at 121.1°C. It follows that the lethal rate then is 1/tdt, with units of minutes at 121.1°C per minute at the product temperature T. Thus the lethal rate, L, is expressed as:

\[ L = \frac{1}{tdt} = \frac{10(T-121.1)}{10} \]  
(Eqn. 3.5)

where the units are minutes at the reference temperature per minute at the product temperature. The process lethality is calculated by integrating L over the time of the process:

\[ F_0 = \int L \, dt = \Delta t \sum L \]  
(Eqn. 3.6)

and in general:

\[ L = 10^{T-T_x/z} \]  
(Eqn. 3.7)

Thus, a reference temperature and z-value may be assigned to suit the process being evaluated. For example, when pasteurizing beer, processes are commonly calculated using a z-value of 10 Celsius degrees and a reference temperature of 60°C.6

### 3.5.2 Other calculation methods

General method calculations remain the benchmark when determining the lethality delivered by a specific thermal process. However, there are many mathematical models reported in the literature that predict process lethality based on the heating and cooling characteristics of the product, and processing time and temperature data. While beyond the scope of this introductory chapter, readers are directed to Holdsworth’s *Thermal Processing of Packaged Foods*7 for a comprehensive summary of mathematical models used in the industry.

Finite difference analysis can be applied to determine both delivered lethality and quality loss during processing.8 These techniques were published as early as 1969,9 but the software and computer capacity to complete these calculations have only recently become more widely available.

### 3.6 QUALITY ATTRIBUTES

The objective in thermal processing is to ensure public safety while minimizing quality loss. The concepts described to evaluate microbial death and process lethality may also be applied to product quality attributes. D- and z-values describing quality loss may be determined experimentally or taken from the literature. A comprehensive summary of kinetic factors has been reported by Holdsworth.7 Using the general method, a value for quality degradation may be calculated based on the z-value of the
attribute of interest, and the effects of using different heat profiles may be compared. It should be noted that the value calculated with this approach represents the degradation at the slowest heating (and cooling) location in the container. A mass average value would more accurately describe degradative losses and may be calculated readily using finite difference calculation programs.

3.7 RETORT SYSTEMS

Retort is the term commonly used in the food industry for sterilizers or autoclaves used to process canned foods. These systems may be classified according to the heating medium, and then as batch or continuous, and as static or agitated. Agitation of fluid and semi-fluid foods during thermal processing operations can increase the effective heat transfer rate throughout a product and reduce the time required to achieve a safe thermal process. Furthermore, with a shorter time of exposure to sterilizing temperatures, heat-labile quality attributes will degrade to a lesser extent and thereby result in improved product quality. Most of the early retorts utilizing axial agitation of foods in cans were continuous steam processing systems designed such that every container experienced the same rotational and temperature history during a process. These retorts provided an efficient means of processing large production runs of commodity products, such as brine-packed vegetables in metal cans. Today, as the canned food industry attempts to produce higher-value entrée items in microwaveable containers to meet the demands of the marketplace, there has been a move towards the use of overpressure batch rotary retorts to commercially sterilize foods in the new packaging forms. These versatile batch retort systems achieve forced convection heating of foods within packages by rotating entire product cars filled with food containers while providing overpressure conditions necessary to maintain the integrity of retortable plastic containers.

3.7.1 Steam retorts

Steam retorts have historically been the industry workhorse for processing foods packaged in metal cans. These retorts are vented at start-up to eliminate air pockets that may result in reduced heat transfer and potentially under-processing. Heating is accomplished by condensing steam. At a specific pressure this is an isothermal process; thus, these retorts, after proper venting, have stable and uniform temperature distribution through the constant temperature heat portion of the cycle. Moreover, the very high surface heat transfer coefficients associated with the condensing steam ensure uniform heating throughout the vessel.
3.7.1.1 Batch systems

Batch steam retorts may be configured in a number of geometries, the most common being vertical or horizontal cylindrical vessels. Fig. 3.9 is a schematic representation of a vertical steam retort.

During operation, baskets containing the product to be processed are loaded into the vessel and the door is secured. At the start of the process, the vent valve is opened and a high flow of steam enters the vessel through a distribution spreader located at the bottom of the retort. This condition is maintained for a minimum time interval and until the retort reaches a minimum temperature; these factors are determined by experimental data to ensure that air present in the retort has been purged. At that point the vent is closed and the retort is brought to the desired processing temperature. At the end of the heating period, cooling water floods the retort and
at the same time the retort is pressurized with compressed air to maintain a stable pressure as the steam present condenses.

### 3.7.1.2 Semi-continuous systems

Crate-less retort systems consist of a single can conveyor and a bank of batch processing vessels (Fig. 3.10). At the start of an individual process the retort is filled with water to cushion filled cans as they enter the retort directly from the conveyor. When an individual retort is full, as determined by a can counter, the conveyor diverts the continuous flow of cans to the next retort in the bank. Simultaneously, the door of the filled retort is closed, a bottom vent is opened, and steam enters the vessel through a circular distribution spreader at the top of the retort, rapidly evacuating the remaining cushion of water together with any air present in the retort. Cans are then heated in condensing steam for the design process time. At the end of heating, the retort is flooded with cooling water, and the product is pressure cooled for a specified length of time. At the end of the pressure cooling step, a door located in the bottom of the vessel is opened and the cans are discharged onto a conveyor located in a cooling canal. The processed cans move through the cooling canal to a descrambler and then on to the labelling area.

### 3.7.1.3 Continuous systems

Hydrostatic retorts and spiral cookers are the most common continuous systems used in the food industry. Hydrostatic retorts (Fig. 3.11) use the pressure generated by the height of water in the entry and exit legs to
create a pressure in the heating dome equal to the saturated steam pressure at the processing temperature. During processing, containers undergo a pre-heat treatment as they move through the entry leg, are exposed to condensing steam in the heating dome, are cooled as they move through the exit leg – through a cooling water spray – and are then discharged. The processing time is determined by the length and speed of the conveyor or chain carrying the containers. Because of their large size, venting of these retorts is time and energy intensive. That combined with a high capital investment, means that these retorts generally run 24 hours per day, 7 days per week.

The other major continuous system is the spiral cooker (see Fig. 3.12). In these systems cans enter and exit the processing vessel through mechanical pressure locks. Once in the vessel, cans move through a spiral track mounted on a reel that rotates inside a horizontal cylindrical shell. In one revolution, cans roll along the bottom part of the arc approximately 120 degrees, which provides product mixing within the can, and the cans
are essentially still as they pass through the remainder approximately 240 degrees of the arc. Process times are determined by the rotational speed of the reel and the length of the vessel. Systems are usually configured as a number of vessels with different functions connected in series. For example, a pre-heat shell, heating shell, and cooling shell could make up a complete system.

3.7.2 Overpressure retorts

Thermal processes for foods in glass and plastic-based packages generally require pressures in the retort to be above the saturated steam pressure associated with sterilizing temperatures. Overpressure serves to counteract expansion of gases inside flexible and semi-rigid packages so that heat transfer may be optimal and predictable, as well as to minimize the likelihood of package rupture. Plastics become soft and pliable at retort temperatures; thus, the differential pressure between the inside and outside of the package must be minimized to prevent package distortion and stress on the hermetic seal. For glass packaging, the differential pressure must be great enough to keep the lid in contact with the container; this maintains the hermetic seal as internal pressures increase owing to product and gas expansion during heating.
Suitable overpressure conditions can be provided by water immersion, cascade or spray with air or steam overpressure and by steam/air mixtures. In each case, heat transfer to food packages during processing in these rotary retort systems involves complex mechanisms, and all these processes exhibit reduced surface heat transfer properties compared to the heat transfer from ‘pure’ condensing steam. This leads to the need for mechanical circulation of the heating medium to ensure uniform heating conditions throughout the product load during processing.

### 3.7.2.1 Water immersion

Many still-cook, water-immersion retorts – where the processing water is heated in the retort either before or after the product is loaded – are used in the industry, particularly for processing glass containers. However, in most modern retorts the processing water is preheated externally to minimize the come-up time in a process. Furthermore, most of these retorts are designed for end-over-end product rotation during processing to enhance the quality of flowable products. Typical of these retorts is the Stock Rotomat water immersion retort (Fig. 3.13).

During a retort cycle processing water is preheated in the upper storage tank and then released at the start of the process to fill the processing

![Fig. 3.13 Stock Rotomat water immersion retort. See also Colour plate 3.](image)
vessel. When the product load is fully immersed, water is pumped from the bottom of the vessel through an external steam injection heat exchanger and back into the top of the vessel. In this fashion the processing water is reheated to be slightly above the nominal processing temperature while at the same time providing circulation past the containers in the processing vessel. Following the constant temperature process time, cold water is injected into the top of the processing vessel while hot water is pumped from the bottom of the vessel back into the upper storage tank to be reheated and used in the next cycle. Overpressure is established by introducing steam or compressed air to the retort during processing.

3.7.2.2 Water spray and cascade

The operating principle of these retorts is to circulate water from the bottom of the retort through an external heat exchanger and then distribute it inside the retort, either through spray nozzles (see Fig. 3.14) or as a cascade generated by flow through a perforated plate located near the top of the retort shell. The resulting spray or cascade of heated water is then directed through the load to heat individual containers. Overpressure is established by introducing steam or compressed air to the retort during processing.

3.7.2.3 Steam/air

Steam/air retorts (see Fig. 3.15) utilize condensing steam to supply the heat energy for product heating and compressed air for overpressure. Since pockets of air would result in reduced heat transfer and underprocessing, these retorts are equipped with high-speed fans to maintain a uniform mixture of steam and air in the retort.

![Fig. 3.14 Surdry spray retort (1. water circulation pump, 2. water spray manifold, 3. water inlet, 4. water level sight glass, 5. air inlet, 6. temperature measuring device, 7. heat exchanger for cooling, 8. steam inlet). See also Colour plate 3.](image-url)
Processes start with a short vent cycle to provide a large initial flow of steam into the retort to rapidly heat the shell, rotational cage (if present) and transfer cars. After venting, steam and air are added independently to obtain the desired operating conditions. The amount of overpressure is simply the total retort pressure minus the saturated steam pressure at the operating temperature. After steam-on, a high-speed circulation fan pulls the steam/air mixture through the load and then forces it to the back along the length of the retort, either through an annular space between the rotating cage and the retort shell, or through side plenums in a still-cook system.

Retort control is maintained by injecting steam between the retort baskets by means of a steam spreader when the retort temperature drops below the set-point. This replenishes the steam/air mixture just prior to its passing through each basket. In conditions where the retort pressure exceeds the set-point, a vent valve opens to release pressure, while an air inlet valve opens to let air into the retort if the pressure falls below the set-point. The result is constant temperature and pressure throughout the heating period. At steam-off, the cooling cycle commences with a pre-cool, when cooling water is sprayed slowly into the circulating steam/air mixture to collapse the steam in a controlled manner; air is added concurrently to maintain the retort pressure and ensure package integrity. After the pre-cool cycle, the circulation fan is stopped and water that accumulated in the bottom of the retort is pumped from the bottom of the retort through an external heat exchanger. Here the water is cooled to a programmed temperature before it flows back into the processing vessel via a row of spray nozzles mounted longitudinally in a manifold located at the top inside surface of the retort. In rotary processes, rotation commences with steam-on and continues through the completion of the cooling cycle.
REFERENCES


4 Food Chilling
Steve James and Christian James

4.1 THEORY

Chilling is often preferred over other food preservation methods, such as smoking, drying, salting or canning, because it produces no significant changes in the texture, taste, smell or appearance of the food and maintains the original ‘fresh’ quality characteristics of the food. There is no strict definition of what constitutes a chilled food. In general, it covers any food whose temperature is reduced to, and maintained at, a temperature below ambient but above the temperature at which any of its water content will begin to freeze. With fish and meat the maximum chilled shelf life will be achieved at a temperature close to the initial freezing point. However, for some foods, such as bananas and other tropical fruit, the optimum temperature can be as high as +14°C.

The removal of heat from a material reduces the kinetic energy of that material, thus decreasing the rate of motion of the molecules or atoms within it. The rate at which molecules and atoms move within a material determines the rate at which they react with one another. In food products many important reactions and processes are controlled by temperature:

- the growth of micro-organisms
- chemical and enzymatic reactions, such as browning reactions, lipid oxidation, cold-shortening, vitamin degradation and pigment degradation
- physical processes, such as moisture loss
- physiological processes, such as ripening, senescence and respiration.

In almost all cases reducing the temperature reduces the rate at which these changes take place in foods and thus extends their preservation. There are, however, instances where excessively rapid chilling rates, or too low a chilling temperature, can cause quality problems in foods. For example a serious defect known as ‘woolly texture’ can be produced in rapidly cooled peaches. Substantial textural problems due to a phenomenon known as ‘cold shortening’ can occur in rapidly chilled lamb, beef and pork. While rapid chilling in a few cases may affect
product quality, where it does not there are a number of clear advantages in production economics if faster cooling can be achieved. Most foods are of high value and any increase in rate of product throughput will improve cash flow and utilize expensive plant more efficiently.

### 4.1.1 Effect of chilling on micro-organisms

In general, chilling does not stop all microbial growth, but in many cases it severely reduces the rate of growth. Reducing the temperature below the optimum growth range of a micro-organism increases its generation time. The main group of micro-organisms of concern in chilled foods are psychrophiles. These organisms can grow at temperatures below 0°C, and some reportedly have an optimum growth temperature as low as 10°C. The optimum temperature growth range of mesophiles is 25–30°C and for many the minimum growth temperature is about 10°C. Since most chilled food is kept below this temperature, mesophiles are not usually of concern in chilled distribution. However, some mesophilic micro-organisms are psychrotrophic and can grow on refrigerated foods.

Although psychrophilic and psychrotrophic micro-organisms can grow at low temperatures, they grow more slowly as the temperature is reduced. Thus the generation time for a pseudomonad (a common form of spoilage organism) might be 1 hour at 20°C, 2.5 hours at 10°C, 5 hours at 5°C, 8 hours at 2°C or 11 hours at 0°C. As temperatures are reduced below 10°C, fewer strains can grow and cause spoilage. In general, food will spoil about four times as fast at 10°C and twice as fast at 5°C, as at 0°C. Chill temperatures also have a marked effect on the type of spoilage microflora present on food by altering the balance of activities of the microbial community. For example, raw milk stored at temperatures close to 0°C tends to putrefy because of the activity of pseudomonads, rather than to sour due to the activity of lactic acid bacteria.

Pathogenic bacteria such as *Salmonella*, *Listeria* and *Yersinia* are of particular concern in chilled foods because they are capable of growth at low temperatures. Many of the organisms that compete with pathogens at ambient temperatures will not grow at low temperatures, thus low temperatures may preferentially favour the growth of pathogenic organisms. However, most will not grow, or produce toxins, below 4°C, with the exception of *Yersinia*.

### 4.1.2 Effect of chilling on enzymes and biochemical reactions

Many different enzymic and biochemical reactions within the food itself can contribute to perishability. Enzymic reactions are influenced by two
opposite factors. Although a rise in temperature tends to increase reaction rates there is also decreased action owing to the thermal denaturation of proteins in their structure. At low temperatures (below 45°C) thermal inactivation is negligible, while high temperatures (45–100°C, depending on the enzyme and substrate) have a marked effect on reactivity. Among the most thermally resistant enzymes are catalases and peroxidases. Low temperatures reduce the rate of biochemical reactions, however enzymes will remain active.

Different foodstuffs exhibit particular quality advantages as a result of chilling and in some cases the rate of chilling is also important. In meat the pH starts to fall immediately after slaughter and protein denaturation begins. The result of this denaturation is a pink proteinaceous fluid, commonly called ‘drip’ often seen in pre-packaged joints. The rate of denaturation is directly related to temperature and it therefore follows that the faster the chilling rate the less the drip. Investigations using pork⁸ and beef⁹ muscles have shown that rapid rates of chilling can halve the amount of drip loss. Fish passing through rigor mortis above 17°C are largely unusable because the fillets shrink and become tough.¹⁰ A relatively short delay of an hour or two before chilling can demonstrably reduce shelf life.

Fig. 4.1 shows the relationship between sugar loss and temperature in freshly harvested sweetcorn.¹¹ Prompt cooling is clearly required if this vegetable is to retain its desirable sweetness.

Many fruits and vegetables are susceptible to injury if stored below a critical temperature, and some examples are given in Table 4.1. Similar
injuries may result from using too cold a chilling medium to achieve rapid cooling. Not all fruits and vegetables are so susceptible, for example there would seem to be no evidence that grapes can be cooled too rapidly.\textsuperscript{12}

4.1.3 Effect of chilling on physical processes

Since many foods are sold by weight, any water loss from the food during processing and storage can have a substantial influence on the profitability of the operation. In many cases appearance changes due to desiccation also decrease the market value of the product. The vapour pressure at the surface of a food governs the rate of moisture migration and is a function of temperature. Vapour pressure increases with temperature and thus any reduction in the surface temperature will reduce the rate of evaporation.\textsuperscript{15} The use of very rapid chilling systems for pork carcasses has been shown to reduce weight by at least 1\% when compared with conventional systems.\textsuperscript{4} In fruits and vegetables excessive dehydration in unrefrigerated stores can lead to a total loss owing to wilting and shrivelling of the product.\textsuperscript{16} For example, failure to rapidly cool dessert grapes to 0.5°C may result in ‘unattractive brown, shrivelled and fragile stalks, berries shed from the stalk, soft, dull or even shrivelled berries, slack packs which are susceptible to vibration during handling and transport’.\textsuperscript{12}

\begin{table}[h]
\centering
\caption{Fruits and vegetables susceptible to chilling damage.\textsuperscript{6,13,14}}
\begin{tabular}{lll}
\hline
Commodity & Lowest safe temperature (°C) & Damage \\
\hline
Apples, certain varieties & 1.1–2.2 & Internal browning, brown core \\
Avocados, West Indian & 11 & Pitting, internal browning \\
other varieties & 5–7 & Pitting, internal browning \\
Bananas & 12–13 & Dull colour, blackening of skin \\
Beans & 7.2–10 & Pitting and russeting \\
Cucumbers & 7.2 & Pitting, water soaked spots, decay \\
Grapefruit & 7.2 & Scald, pitting, watery breakdown, internal browning \\
Lemons & 12.8–14.4 & Internal discoloration, pitting \\
Mangoes & 5–10 & Internal discoloration, abnormal ripening \\
Melons cantaloupe & 7.2 & Pitting, surface decay \\
honeydew & 4.4–10 & Pitting, surface decay \\
watermelons & 2.2 & Pitting, objectionable flavour \\
Oranges & 3 & Pitting, brown stains \\
Papaya & 6 & Pitting, water soaking of flesh, abnormal ripening \\
Potatoes & 3 & Mahogany browning, sweetening \\
Tomatoes & 7–10 & Water soaking and softening \\
\hline
\end{tabular}
\end{table}
4.1.4 Effect of chilling on physiological processes

Fruits and vegetables differ from other foods in that they remain alive and continue to respire. Reducing the temperature reduces the rate of respiration, transpiration and other metabolic processes. Respiration uses oxygen and produces carbon dioxide, heat, water and volatile substances. The heat generated by respiration must be accounted for during storage. A high rate of respiration is, in general, an indication of short storage life. Similarly, the ripening of fruit can be controlled by rapid cooling, the rate of ripening declining as temperature is reduced and ceasing below about 4°C. The relationship between respiration and ripening is different for climacteric and non-climacteric fruits. Climacteric fruits, e.g. bananas, show a very rapid rise in respiration rate (carbon dioxide production) and ethylene evolution when they ripen. For non-climacteric fruits, e.g. citrus fruit, there is very little change in respiration rate and ethylene production during ripening. Like all living materials, fruits and vegetables vary greatly from one species to another, and from one cultivar to another.

4.2 CHILLING OPERATIONS

Chilling systems for foodstuffs will contain many, if not all, of the following unit operations:

- preparatory treatment – conditioning, waxing, cooking, pasteurising, blanching, etc.
- chilling; primary or secondary
- chilled storage
- transportation
- retail display.

During the preparatory treatment there can be a range of temperature responses, from a large gain to a small decrease in the temperature of the product. In chilling there is, of course, a substantial decrease in the mean temperature of the product, but in a correctly designed cold chain there should be no significant change in mean product temperature during storage, transport or retail display.

4.3 CHILLING EQUIPMENT

4.3.1 Refrigeration systems

Mechanical refrigeration systems operate using the same basic refrigeration cycle. A low-pressure liquid refrigerant is allowed to evaporate to a
gas within a coil. This process requires heat, which is extracted from the coil’s surroundings, thus cooling the medium surrounding the ‘evaporator’ coil. The gas from the evaporator is compressed in the compressor to a high-pressure hot gas. This high-pressure hot gas is then passed through another coil where it condenses, releasing heat into the medium surrounding the ‘condenser’ coil. This high-pressure cold liquid refrigerant then passes through a valve, the ‘expansion valve’, back to the evaporator.

In a direct expansion system, the evaporator coil is either in direct contact with the food to be refrigerated, or the media (i.e. air, brine, etc.) surrounding the food. In a secondary refrigeration system, a liquid (i.e. water, brine, etc.) is cooled by passing it over the evaporator coil. This cooled liquid is pumped through cooling coils to areas of the food plant where it is used to cool air that is subsequently used to cool the food.

4.3.2 Moving air

Air is by far the most widely used method of chilling food as it is economical, hygienic and relatively non-corrosive to equipment. Systems range from the most basic, in which a fan draws air through a refrigerated coil and blows the cooled air around an insulated room (see Fig. 4.2), to purpose-built conveyerized blast chilling tunnels or spirals. Relatively low rates of heat transfer are attained from product surfaces in air-cooled systems. The big advantage of air systems is their versatility, especially when there is a requirement to cool a variety of irregularly shaped products or individual products.
In practice air distribution is a major problem, often overlooked by the system designer and the operator. The cooling time of the product is reduced as the air speed is increased. An optimum value exists between the decrease in cooling time and the increasing power required to drive the fans to produce higher air speeds. This optimum value can be as low as \(1.0 \text{ ms}^{-1}\) when cooling large meat carcasses to more than \(15 \text{ ms}^{-1}\) plus for thin products.

As with liquid foodstuffs solid/liquid mixtures are commonly cooked in large steam-heated vats either open or under pressure. In many of the smaller commercial operations the mixture is transferred into large bins or trays and either left in ambient air or placed in chill rooms. Unless shallow trays are used the mixture cools very slowly and the texture and quality of the product deteriorate. In simple or small-scale processes, containers of hot liquids, soups, sauces or gravy are allowed to cool in ambient air or placed inside chill rooms. Temperatures as high as \(65^\circ\text{C}\) have been recorded in the centre of storage bins after 16 hours of ‘cooling’, and during this period the product continues to cook with a consequent deterioration in flavour.\(^{18}\) However, better batch or continuous cooling systems are available.

### 4.3.2.1 Batch air coolers

Placing warm food items in large refrigerated rooms is the most common method of cooling. Large individual items such as meat carcasses, tuna, or bunches of bananas are hung from overhead rails, smaller products are placed either unwrapped or in cartons on racks or pallets, and bulk fruits and vegetables in large bins.

In simple single-stage batch chilling systems the risk of surface freezing limits the lowest air temperature that can be used. This problem is further complicated if products with different thermal properties and/or sizes are cooled at the same time. For example, two-compartment ready meal consumer packs typically contain rice or pasta in one compartment, and a meat- or fish-based product in the second. The components have very different thermal properties and may be filled to different depths. Investigations have shown that using air at \(-10^\circ\text{C}\) and a high velocity of \(5 \text{ ms}^{-1}\) resulted in a cooling time of 34 minutes but substantial quantities of the product in both compartments were frozen (see Table 4.2). Reducing the air velocity to \(0.5 \text{ ms}^{-1}\) more than doubled the cooling time but produced a situation where only a small area of the rice was frozen. With higher air temperatures the extent of freezing was reduced. At \(-5^\circ\text{C}\) only a small amount of freezing occurred at \(5.0 \text{ ms}^{-1}\) and a cooling time of approximately 0.75 h was achieved.
The relative effect of changes in air velocity depends on the size of the product being chilled. Increasing the air velocity during chilling of beef sides substantially reduces chilling times at low air velocities but the effect is smaller at higher velocities (see Table 4.3). The power required by the fans to move the air within a chill room increases with the cube of the velocity. For example, a four-fold increase in air velocity from 0.5 to 2 m·s⁻¹ results in a 4.4 h (18%) reduction in chilling time for a 140-kg side of beef, but requires a sixty-four-fold increase in fan power. Increasing the air velocity to 3 m·s⁻¹ only achieves an extra 6% reduction in chilling time.

Much higher air speeds can be justified with small products. Using air at −1.5°C, the minimum air temperature that would avoid surface freezing, a small increase in air velocity from 0.5 to 1.0 m·s⁻¹ reduced the cooling time of individual pork pies by 85 minutes (almost 30%) (see Fig. 4.3). In a high throughput baking line (>1000 items per h) the 7% increase in throughput that would be achieved by raising the air velocity from 6 to 10 m·s⁻¹ (reducing the cooling time by 10 minutes), could justify the higher capital and running costs of larger fans.

Even when a system has been designed to distribute air through the product, poor management and/or poor understanding of the requirements of the plant commonly leads to uneven cooling. Products stacked or racked irregularly will leave channels around the stacks that are larger in

<table>
<thead>
<tr>
<th>Air temperature (°C)</th>
<th>Velocity, (m·s⁻¹)</th>
<th>Time, 80 to 4°C (min)</th>
<th>Minimum temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−10</td>
<td>5.0</td>
<td>34</td>
<td>−4.2</td>
</tr>
<tr>
<td>−10</td>
<td>1.0</td>
<td>58</td>
<td>−1.4</td>
</tr>
<tr>
<td>−10</td>
<td>0.5</td>
<td>78</td>
<td>−0.2</td>
</tr>
<tr>
<td>−5</td>
<td>5.0</td>
<td>42</td>
<td>−2.2</td>
</tr>
</tbody>
</table>

Table 4.3  Chilling time (hours) to maximum temperature of 10°C in beef side.

<table>
<thead>
<tr>
<th>Side weight (kg)</th>
<th>Air velocity (m·s⁻¹)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>105</td>
<td>19.5</td>
</tr>
<tr>
<td>140</td>
<td>24.1</td>
</tr>
</tbody>
</table>

* Air temperature 0°C.
cross-sectional area than those within the stacks and channels of differing area through the stacks. Air leaving and returning to the refrigeration coil will take the path of least resistance through the largest gaps, instead of passing evenly through or over the product. Similar problems occur where cooled air under pressure is passed through large silos of grain or fruit.

4.3.2.2 Continuous air coolers

Conveying the product through the cooling system overcomes the problem of uneven air distribution since each item is subjected to the same velocity–time profile. In the simplest continuous air chilling systems the food is suspended from an overhead conveyor and moved through a refrigerated room. This process is often used in air chilling of poultry or in pre-chilling of pork carcasses.

In more sophisticated plants the product is conveyed through a chilling tunnel. The main advantage of this method is that the refrigeration capacity and air conditions can be varied throughout the length of the tunnel. Large capacity evaporators can be installed in the initial stage to cater for the high rates of heat release encountered at the start of a cooling process. Higher air temperatures can be used in the latter stages to avoid surface freezing.

Fig. 4.3 Effect of air speed on the cooling time of pork pies.
Some small cooked products are continuously cooled on racks of trays (8 to 16 high) that are pulled or pushed through a chilling, or freezing, tunnel using a simple mechanical system. However, this process often involves double handling and it is difficult to achieve an even air distribution through the different layers. In larger operations it is more satisfactory to convey the cooked products through a linear tunnel or spiral chiller/freezer. Linear tunnels are far simpler constructions than spirals but their use is often ruled out owing to constraints on floor area. Even if a high packing density of 20 kg m\(^{-2}\) can be achieved, processing 1 tonne per hour of a small product, with a cooling time of 0.5 h, requires a 1 m wide belt 25 m long. Much lower packing densities (<14 kg m\(^{-2}\)) and longer cooling times (1 to 1.5 h) are often required, which results in belt lengths that are too long to be accommodated in most factories. Belts of this length are most economically used in a spiral configuration where the belt is designed to collapse on its inner edge, enabling it to be wound round a drum in an ascending or descending orientation.

Advantages are claimed for both horizontal and vertical systems of air distribution. In horizontal systems a lower pressure drop and smaller temperature difference across the products and coil result in less weight loss from unwrapped products, while in vertical systems increased turbulence and higher, and more uniform, heat transfer coefficients lead to reduced chilling times.\(^{21,22}\)

4.3.2.3 Wet air/ice bank cooling

One of the principal disadvantages of air-cooling systems is their tendency to dehydrate the product. A way around this problem is to saturate the air with water. Wet air-cooling systems recirculate air over ice cold water so that air leaving the cooler is cold (0 to 1°C) and virtually saturated with water vapour (100% RH). An ice bank chiller uses a refrigeration plant with an evaporator (plate or coil) immersed in a tank of water that chills the water to 0°C. During times of low load and overnight use of off-peak electricity a store of ice is built up on the evaporator that subsequently melts to maintain temperatures during times of high load. As well as the economic advantage of reduced weight loss, the operation of ice bank chillers offers the following economic savings over conventional air chillers:

- The size of refrigeration plant required for an ice-bank chiller is smaller since peak heat loads are met by the reserve of ice, the plant therefore runs for longer periods at full capacity.
- Running a refrigeration plant at full load (as ice-bank systems operate) is more efficient than running at part load, therefore the overall efficiency of the chilling operation is greater.
- A smaller plant consumes less power.
Part of the cooling capacity is used to build up a reserve of ice during the period between midnight and 7.00 am. During this time electrical power is approximately 1/3 of the cost during the daytime.

The principal disadvantage of ice-bank coolers is the space required. For example a chiller holding 800 pigs of average weight 45 kg would require 2000 kg of ice occupying approximately 4.0 m³.

Wet air cooling has been used commercially for some 25 to 30 years, principally for the pre-cooling and storage of vegetables and fruit. Ice-bank refrigeration systems have a proven role in providing chilled water for milk cooling. Other applications remain to be exploited.

4.3.3 Direct contact

Contact refrigeration methods are based on heat transfer by contact between products and metal surfaces, which in turn are cooled by either primary or secondary refrigerants. Contact chilling offers two advantages over air cooling, i.e. much better heat transfer and significant energy savings.

4.3.3.1 Plate heat exchangers

Modern plate cooling systems differ little in principle from the first contact freezer patented in 1929 by Clarence Birdseye. Though generally designed for freezing, these systems can be readily modified to operate at higher temperatures for chilling operations. Essentially the product is pressed between hollow metal plates containing a circulating refrigerant (see Fig. 4.4). A hydraulic cylinder is used to bring the refrigerated plates,

![Diagram of a horizontal plate cooler](image-url)
which can be either horizontal or vertical, into pressure contact with the product. They tend to be expensive, especially if automatic loading and unloading is required, but have low running costs.

Good heat transfer is dependent on product thickness, good contact and the conductivity of the product, thus the need for regularly shaped products with large flat surfaces is a major hindrance. Air spaces in packaging and fouling of the plates can have a significant effect on cooling time. With thin materials a plate chilling system has the potential to halve the cooling time required in an air blast system (see Table 4.4). Plate chillers are often limited to a maximum thickness of 50 to 70 mm.7,25

### 4.3.4 Jacketed heat exchangers

Batch coolers for liquid foods can range in capacity from 100 to 10,000 litres with the foodstuff usually contained in a stainless steel vessel. The cooling medium may circulate through the jacket of the vessel, through a coil immersed in the liquid, or both. Most vessels are provided with agitators to improve the rate of convective heat transfer and stop temperature stratification. Jacketed vessels have a lower heat transfer efficiency, but they are easier to clean and are often preferred for that reason.

When a direct expansion refrigeration system is used, the refrigeration surface is usually built into the stainless steel lining of the tank. Direct expansion coils are sometimes placed in the base and a reservoir of ice built up before the hot foodstuff is introduced into the vat. Alternatively, ambient or iced water is used as the cooling liquid with jacketed vessels. The water may be simply circulated or sprayed around the top of the outer surface of the vat, from where it flows down to a collector at the base. Investigations have shown that direct expansion only requires about half the energy of ice-water chilling but requires a condensing unit two to four times as large.26

<table>
<thead>
<tr>
<th>Cooling method (operating at −1°C)</th>
<th>Meat thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Air (still)</td>
<td>5.0 h</td>
</tr>
<tr>
<td>Air (5 ms⁻¹)</td>
<td>1.2 h</td>
</tr>
<tr>
<td>Plate</td>
<td>0.7 h</td>
</tr>
<tr>
<td>Immersion</td>
<td>0.4 h</td>
</tr>
</tbody>
</table>
Burfoot et al.\textsuperscript{27} found that cooling times from 90 to 20°C of quite small quantities of liquids (250 litres) in a jacketed vessel with cooling water are over 120 minutes (Fig. 4.5).

One common method used to decrease cooling times of liquid products in a closed vessel is to apply a vacuum to produce evaporative cooling. Applying a vacuum of 0.006 bar to such a vessel reduces the cooling time of water from 130 to 11 minutes. In larger operations water and vacuum cooling systems similar to those described for liquids are used. However, cooling rates are always lower than those achieved in liquids because the cooling of solid particles, which may be as large as 25 mm cubes, will be controlled by conduction.\textsuperscript{27} Temperature stratification is a problem in unstirred vats while in agitated vessels the design and operation of stirrers are critical if breakdown of delicate solid product is to be avoided.

4.3.4.1 Belt heat exchangers

Belt systems consist of an endless steel belt (around 1 mm thick), the underside of which is cooled either directly with water, brine or glycol sprays or by sliding over a stationary cold surface. Since only one side of the product is in contact with the cooling surface relatively thin products are required, such as hamburgers, fish fillets, or liquid and semi-liquid products such as purées and sauces. A cooler of this type using a 1 m wide belt, 10 m long, would cool 8 tonnes of 2 cm thick meat per day from 40°C to 2°C. The main advantages of belt systems are: (i) continuous processing; (ii) easy continuous cleaning and sanitation; (iii) reduced evaporative losses, in comparison with air systems; and (iv) the possibility of operating with several temperature zones.
4.3.4.2 Continuous heat exchangers

The majority of liquid foodstuffs require cooling after a heat processing operation such as cooking of sauces and soups, and pasteurization or sterilization of fruit juices, milk and other dairy products. Milk is also cooled at the point of collection to maintain its quality. Unpasteurized ‘freshly squeezed’ fruit juices are cooled immediately after production. Fermented beverages are often cooled during primary and secondary fermentation, and before storage.

Falling film or surface coolers (also known as Baudelot coolers) (Fig. 4.6a), in which the hot liquid is pumped over the top of a horizontal bank of refrigerated coils and flows down over the cooled surfaces, were originally used for liquid foods such as beer wort and cream. Such coolers were easy to clean and a desirable amount of aeration occurred during cooling. However, these systems have now been replaced by totally enclosed coolers, e.g. multi-plate or multi-tube, and aeration is achieved by injecting filtered and sterilized air. Double-pipe coolers (Fig. 4.6b) have also been employed in specialized applications but have a limited heat transfer surface. Multi-plate coolers (Fig. 4.6c) are extensively used for liquid foods. They have the highest available heat transfer surface, lowest material requirements, maximum efficiency (up to 90% heat recovery in counter-current mode), are very flexible in operation and are easy to clean. In certain applications, such as beer and wine cooling, multi-tube coolers (Fig. 4.6d), which have a much higher resistance to pressure and can use primary refrigerants, have advantages over multi-plate coolers.
Scrapped surface heat exchangers can have advantages in the cooling of very viscous liquid foods and where surface fouling is a potential problem.\textsuperscript{28}

Continuous pipe heating systems for solid/liquid foods are now in commercial use. An ohmic heater can raise the average temperature of the product to 140°C in minutes, but if over-cooking is to be avoided in sensitive products a similarly rapid rate of temperature reduction is required. The simplest method of cooling the foodstuff is to pass a cooled liquid over the surface of the pipe. However, the rate of cooling that can be achieved in a mixture of solids and liquid is restricted by a number of practical limitations. The cooling of solid particles will always be conduction controlled, and as the outer layer of the liquid phase cools, its viscosity will increase to a point where it is no longer economical to pump and will limit the rate of cooling that can be achieved. Other methods of cooling, such as direct addition of liquid carbon dioxide into the pipeline, separating the solid and liquid phases and cooling them independently before recombining, or vacuum cooling, show promise.

**4.3.5 Immersion/spray**

As their names imply, these involve dipping the product into a cold liquid, or spraying a cold liquid onto the food. This produces high rates of heat transfer owing to the intimate contact between product and cooling medium. Both offer several inherent advantages over air cooling in terms of reduced dehydration and coil frosting problems.\textsuperscript{29} Clearly if the food is unwrapped the liquid has to be ‘food safe’. Any uptake of the cooling medium, whether ‘food safe’ or not, by the product may present problems both in terms of flavour changes and the requirement for periodic replacement of the medium. Such uptake can be minimized by packaging, although this may hinder heat transfer.

Hydrocooling is probably the least expensive method of achieving rapid cooling in small products. The product to be cooled is immersed in, or sprayed with, cool water, either at ambient temperature or near 0°C. This water is often treated with a mild disinfectant such as chlorine. Practical systems vary from simple stirred or unstirred tanks to plants where the product is conveyed through agitated tanks or under banks of sprays. Small weight gains are often recorded during hydrocooling. Hydrocooling is very effective for chilling fruit and vegetables, however not all crops can tolerate wetting. Fruit can be cooled from 30°C to 5°C in between 8 and 45 minutes, depending on the diameter of the fruit, without weight loss.\textsuperscript{30} Commercial hydrocoolers can treat 20–30 tonnes/hour. Such systems are typically used for celery, asparagus, peas, sweetcorn, carrots, peaches, etc.
Immersion chilling also has applications with larger products. Most frozen poultry is initially cooled by immersion in chilled water or an ice/water mixture (slush ice). The procedure is very fast and the birds gain weight during the process. The maximum weight gain is controlled by legislation and the birds have to be conveyed in the opposite direction to the water flow (counter current) to minimize the possibility of bacteria such as *Salmonella* being transferred from one carcass to another. Overhead conveyers or Archimedian screws are used to transport the birds through the immersion tank.

Investigations into immersion chilling have also been carried out with hot jointed pork primals in brine. Lower fluid temperatures and consequently faster cooling rates can be achieved and the joints are vacuum packed to minimize problems of brine uptake and cross contamination. However computer predictions show clearly (see Table 4.4) that the relative reduction in chilling time produced by immersion chilling decreases as product thickness is increased.

Spraying with chilled water or water at ambient temperature is an effective method of initially cooling cooked products that can withstand wetting, i.e. hams, sausages, chubs, etc. Spray bars are fitted either in the batch cookers or in separate cooling cabinets. Spray chilling of meat carcasses is widely practised in the USA and is used for poultry in Europe. With some products it is possible to hot fill the retail pack, in which case any of the systems previously described for cooling solid foods could be applied. However, in many cases the product is too fragile to transport or fill in the hot state.

### 4.3.6 Ice

Chilling with crushed ice or an ice/water mixture is simple, effective and commonly used for fish cooling. Cooling is more attributable to the contact between the product and the cold melt water percolating through it (i.e. hydrocooling) than with the ice itself. The individual fish are packed in boxes between layers of crushed ice, which extracts heat from the fish and consequently melts. Ice has the advantage of being able to deliver a large amount of refrigeration in a short time as well as maintaining a very constant temperature, −0.5 to 0°C where seawater is present. The biggest disadvantage of crushed-ice treatment is a considerable labour requirement, although automatic filling systems have been developed.

To cut down on the amount of ice required, refrigerated seawater (RSW) and chilled seawater (CSW) systems have been developed. Both of these methods have the disadvantage of no longer guaranteeing the maintenance
of 0°C and introducing the added expense of temperature control and recording.\textsuperscript{35} The RSW system is also expensive and installation of a compressor of suitable size to chill large catches is often impractical. CSW systems use tanks of ice and water mixes. Insufficient mixing of the ice and water caused by the tendency of the ice to float in the upper part of the tank can cause temperature control problems. Compressed air can be used to mix the fish, water and ice (the so-called ‘champagne method’).

Supplementation of the chilling and storage of fish with mechanical refrigeration has produced some unexpected drawbacks.\textsuperscript{35} Boxed fish in ice stored at room temperature causes constant thawing and subsequently the production of a constant supply of water at 0°C running over the fish. This produces very efficient heat transfer. Placing the same boxes in refrigerated rooms stops the ice thawing, and the ice instead of cooling the fish acts as an insulating layer.

Ice may also be used for cooling fruit and vegetables, but, as with immersion/hydrocooling, only vegetable and fruit produce that can tolerate wetting. In the UK ice is used by some producers to cool watercress, broccoli and some other brassicas.\textsuperscript{34} It is also frequently used to keep produce cool during transport.

### 4.3.7 Vacuum

Solid products having a large surface area to volume ratio and an ability to readily release internal water are amenable to vacuum cooling. The products are placed in a vacuum chamber (typically operating at between 530 and 670 Nm\(^{-2}\)) and the resultant evaporative cooling removes heat from the food. Evaporative cooling is quite significant, the amount of heat released through the evaporation of 1 gram of water being equivalent to that released in cooling 548 grams of water by 1°C. Suitable products, such as lettuce, can be vacuum cooled in less than 1 hour. In general terms a 5°C reduction in product temperature is achieved for every 1% of water that is evaporated. Since vacuum cooling requires the removal of water from the product, pre-wetting is commonly applied to prevent the removal of water from the tissue of the product. Pre-wetting is also useful in products that do not have a large surface area in proportion to their mass. When pre-wetting, a thin film of water must be applied to the product since coarse droplets will evaporate preferentially causing frost-burn spots on the product.

Vacuum cooling is rapid and economical to operate because of low labour costs, but the capital cost of the large vacuum vessels is very high, and this has limited their widespread use. Despite this, increasingly large amounts
of lettuce, celery, cauliflower, green peas and sweetcorn are vacuum cooled. The advantages and disadvantages of vacuum cooling are shown in Table 4.5.

In a similar way to microwave cooking vacuum cooling is selective, in that it is the moisture-containing product rather than the container that is cooled. This also means that the type of packaging has very little effect on the rate of cooling, providing the packaging is not completely closed, unlike most other refrigeration systems.

Rapid rates of temperature reduction can be achieved in trays of cooked products such as mince, baby foods and poultry portions when cooled under vacuum. Larger products, such as 10-kg cooked turkey carcasses, can be cooled from 80 to 10°C in less than 1 h, but the rate of pressure reduction has to be carefully controlled if textural quality is to be maintained.

### 4.3.8 Cryogenic

Cryogenic cooling uses refrigerants such as liquid nitrogen or solid carbon dioxide directly. The method of cooling is essentially similar to water-based evaporative cooling, cooling being brought about by boiling off the refrigerant, the essential difference being the temperature required for boiling. As well as using the latent heat absorbed by the boiling liquid, sensible heat is absorbed by the resulting cold gas. Owing to very low operating temperatures and high surface heat transfer coefficients between product and medium, cooling rates of cryogenic systems are often substantially higher than those of other refrigeration systems.

Most systems use total-loss refrigerants, i.e. the refrigerant is released to the atmosphere and not recovered. Alternatively dichlorodifluoromethane (CCl₂F₂) (otherwise known as Freon 12, R.12 or F12) may be used in a recovery and recycle system, however it is not generally accepted in all countries. Owing to environmental and economic factors total-loss refrigerants must be both readily available and harmless, which limits the choice to atmospheric air and its components. Liquid air was first used

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**Table 4.5** Advantages and disadvantages of vacuum cooling in comparison with mechanical refrigeration.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low labour costs</td>
<td>Relatively high capital investment</td>
</tr>
<tr>
<td>Rapid cooling rate</td>
<td>Not applicable to all products</td>
</tr>
<tr>
<td>Selective cooling</td>
<td>Relatively high weight losses</td>
</tr>
<tr>
<td>Close temperature control</td>
<td>Batch process</td>
</tr>
</tbody>
</table>
commercially in the 1930s. However, liquid air contains a high proportion of liquid oxygen, which is a powerful oxidising agent, and its use has been superseded by less harmful liquid nitrogen (LN) and liquid or solid carbon dioxide (CO₂). Nitrogen is the main constituent of atmospheric air and at atmospheric pressure liquefies at a temperature of −196°C, giving a refrigerating capacity of 378 kJkg⁻¹. It is usually supplied and stored at a pressure of 3 to 6 bar, with corresponding boiling points of −185°C to −177°C.³⁷,³⁸ A useful rule of thumb is that 1 ton per h of liquid nitrogen is approximately equivalent to 100 kW of mechanical refrigeration. Carbon dioxide gas is present in air at a concentration of 0.03 to 0.05%. Its physical properties are unusual, in that it does not exist in liquid form at atmospheric pressure. If stored as a pressurized liquid and released into the atmosphere, the liquid changes partly to gas and partly to a frozen solid at −78.5°C, which sublimes directly into gas without going through a liquid phase. Liquid carbon dioxide is generally supplied either at ambient temperature (e.g. 25°C and 65 bar), giving a refrigerating capacity of 199 kJkg⁻¹, or at −16°C and 22 bar, giving a refrigerating capacity of 311 kJkg⁻¹. At the point of use, spray nozzles reduce the pressure of the liquid, generating a mixture of cold vapour and solid carbon dioxide ‘snow’. Carbon dioxide may also be supplied in solid form at −78.5°C, giving a refrigerating capacity of 620 kJkg⁻¹.

The particular characteristics of total-loss refrigerants that may be regarded as advantages or disadvantages are listed in Table 4.6.

Avoiding surface freezing of the product is the main problem in using cryogens for chilling. Continuous chilling systems using liquid nitrogen have either immersed the product in the liquid, sprayed the nitrogen onto the surface or vaporized the nitrogen in a forced draught and passed it over the surface of the foodstuff.³⁹ Direct immersion in liquid nitrogen will achieve a crust freeze in a matter of seconds, thus a relatively small

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low capital investment</td>
<td>High operating cost</td>
</tr>
<tr>
<td>High refrigerating capacity</td>
<td>High weight at start of use</td>
</tr>
<tr>
<td>Low weight when out of use</td>
<td>Limited duration without filling</td>
</tr>
<tr>
<td>No residual weight (dry ice)</td>
<td>Poor temperature control</td>
</tr>
<tr>
<td>No noise</td>
<td>Reduced humidity</td>
</tr>
<tr>
<td>Advantageous storage atmosphere (N₂)</td>
<td>Suffocation hazard</td>
</tr>
<tr>
<td>Bacteriostatic effect (CO₂)</td>
<td>Limited availability</td>
</tr>
<tr>
<td>Low maintenance requirements</td>
<td>Foolproof once installed (dry ice)</td>
</tr>
</tbody>
</table>
piece of equipment may be used to process a large throughput. The two main problems are that the product is subjected to a high thermal shock and only the latent heat of vaporization is utilized in the process. Since the change in sensible heat of the cold gas is wasted efficiencies tend to be low.

Direct spraying of liquid nitrogen onto a food product while it is conveyed through an insulated tunnel is the most commonly used method of application. Surface freezing is still a problem but an extra refrigeration effect is obtained by pre-cooling the food with the cold gas that results from the vaporization. Forced gas cooling is the only method that can be employed when surface freezing has to be avoided. However, the system tends to be inefficient.

Attempts have been made to compensate for the poor conductivity of packaging materials by introducing a quantity of liquid nitrogen into boxes of hot meat. However, substantial surface freezing occurred and nitrogen spillage produced a safety hazard in the cutting room. More success has been shown by packing hot meat in cartons and then adding carbon dioxide pellets. The meat cooled to an average of 2°C after 24 hours without any further refrigeration being required. Similarly a process using solid carbon dioxide ‘snow’ is being marketed for chilling, transport and storage of ready meals. Carbon dioxide snow is sprayed over the product and used in a similar manner to ice.

Post-harvest liquid nitrogen cooling of grapes has been developed in Brazil. In comparison with conventional cooling-room systems, liquid nitrogen cooling has been shown to significantly reduce cooling times, by between 57 and 76%, thus increasing production rates, whilst consuming significantly less energy.

Cooling of solids and solid/liquid mixtures during cutting and mixing is increasingly common to prevent heating of products due to the mechanical movement of the mixing and cutting blades. Liquid nitrogen and liquid, or solid, carbon dioxide are commonly employed for such processes. Liquid nitrogen freezing improves protein breakdown, aiding the granulation of frozen meat and bacon fat. The refrigerants are introduced directly through valves or spray bars ensuring controlled distribution and cooling. The gases provide more even and quicker chilling than the ice traditionally used.

### 4.4 CHILLED STORAGE

Most unwrapped meat, poultry, fruit and vegetables and all types of wrapped foods are stored in large rooms with circulating air. To minimize
weight loss and appearance changes associated with desiccation, air movement around the unwrapped product should be the minimum required to maintain a constant temperature. With wrapped products low air velocities are also desirable to minimize energy consumption. However, many storage rooms are designed and constructed with little regard to air distribution and localized velocities over products. Horizontal throw refrigeration coils are often mounted in the free space above the racks or rails of product, and no attempt is made to distribute the air around it. Using a false ceiling or other form of ducting to distribute the air throughout the storage room can substantially reduce variations in velocity and temperature. Using air socks an even air distribution can be maintained with localized velocities not exceeding 0.2 ms$^{-1}$. Jacketed storage rooms – where the cooling is incorporated into the walls, floor and ceiling – produce very good temperature control in the enclosed space with the minimum of air movement. They are especially suitable for controlled atmosphere storage and for unwrapped products that are very sensitive to air movement or temperature fluctuations. Although a refrigerated jacket is efficient at absorbing any heat from the surroundings, the lack of air circulation within the enclosed space means that heat removal from the product is very limited. Care must therefore be taken to: (1) attain the desired storage temperature throughout the product before storing; (2) minimize any heat loads produced during loading and unloading; and (3) provide supplementary refrigeration for any products which respire.

### 4.4.1 Controlled atmosphere storage rooms

Controlled atmosphere storage rooms were developed for specialized fruit stores, especially those for apples. In addition to the normal temperature control plant these stores also include special gas-tight seals to maintain an atmosphere that is normally lower in oxygen and higher in nitrogen and carbon dioxide than air. Additional plant is required to control the carbon dioxide concentration, generate nitrogen and consume oxygen. The optimum atmosphere must be determined experimentally for the specific product being stored. For many varieties of apples and other common fruits this information is well known, and data are becoming increasingly available for other products such as green vegetables, cauliflower, chicory, avocados and melons.

To date most commercial applications of controlled atmosphere storage have been limited to fresh fruits and vegetables that respire in storage, consuming oxygen and producing carbon dioxide. These stores have either product-generated atmospheres where the products absorb the oxygen leaking into the store and control its level or externally controlled...
atmospheres using nitrogen generators or oxygen consumers. Carbon dioxide scrubbers are required in most cases, and a number of different systems have been utilized. Carbon dioxide may be removed by passing air over dry lime, wet caustic solutions, monethanolamine or through simple water sprays. Systems are manually or automatically regenerated.

There is a growing use of controlled atmosphere and modified atmosphere retail packs to extend the chilled storage and display life of red meats,\textsuperscript{51,52} poultry\textsuperscript{53} and meat products.\textsuperscript{54} Since the packs tend to be large and insulate the products efficient pre-cooling before packaging is especially important if product quality is to be maintained.

\section*{4.5 TRANSPORTATION}

In 2002 over a million refrigerated road vehicles, 400,000 refrigerated containers and many thousands of other forms of refrigerated transport system were being used to distribute chilled and frozen foods throughout the world.\textsuperscript{55} All these transportation systems are expected to maintain the temperature of the food within close limits to ensure its optimum safety and high-quality shelf life. Developments in temperature controlled transportation systems for chilled products have led to the rapid expansion of the ‘fresh’ food market.

It is particularly important that the food is at the correct temperature before loading, since the refrigeration systems used in most transport containers are not designed to extract heat from the load but to maintain the temperature of the load. In the large containers used for long distance transportation food temperatures can be kept within \( \pm 0.5^\circ\text{C} \) of the set-point. With this degree of temperature control transportation times of 8 to 14 weeks (for vacuum packed meats stored at \(-1.5^\circ\text{C}\)) can be carried out and still retain a sufficient chilled storage life for retail display.

\subsection*{4.5.1 Overland transport}

Overland transportation systems range from 12-m refrigerated containers for long-distance road or rail movement of bulk chilled or frozen products to small uninsulated vans supplying food to local retail outlets or even directly to the consumer. Some of the first refrigerated road and rail vehicles for chilled product were cooled by air that was circulated by free or forced systems, over large containers of ice.\textsuperscript{7} Similar systems using solid carbon dioxide as the refrigerant have also been used for cooling transport vehicles. In a 1970–71 survey of vehicles used in the UK to transfer chilled meat from small abattoirs to shops, almost 70\% were
unrefrigerated and 20% had no insulation. However, the majority of current road transport vehicles for chilled foods are refrigerated using either mechanical, eutectic plates or liquid nitrogen cooling systems. The rise in supermarket home delivery services, where there are requirements for mixed loads of products that may each require different storage temperatures, is introducing a new complexity to local overland delivery.

4.5.1.1 Mechanical units

Many types of independent engine and/or electric motor driven mechanical refrigeration units are available for lorries or trailers. One of the most common is a self-contained ‘plug’ unit that mounts in an opening provided in the front wall of the vehicle. The condensing section is on the outside and the evaporator on the inside of the unit, separated by an insulated section that fits into the gap in the wall. Units have one or two compressors, depending upon their capacity, which can be belt driven from the vehicle but are usually driven direct from an auxiliary engine. Many are equipped with an additional electric motor for standby use or for quiet running, e.g. when parked or on a ferry.

Irrespective of the type of refrigeration equipment used the product will not be maintained at its desired temperature during transportation unless it is surrounded by air or surfaces at or below the maximum transportation temperature. This is usually achieved by a system that circulates moving air, either forced or by gravity, around the load. Inadequate air distribution is probably the principal cause of product deterioration and loss of shelf life during transport. Conventional forced air units usually discharge air over the stacked or suspended products either directly from the evaporator or through ducts towards the rear cargo doors. If products have been cooled to the correct temperature before loading and do not generate heat then they only have to be isolated from external heat ingress. Surrounding them with a blanket of cooled air achieves this purpose. Care has to be taken during loading to stop any product touching the inner surfaces of the vehicle because this would allow heat ingress during transport. Many trucks are now being constructed with an inner skin that forms a return air duct along the sidewalls and floor, with the refrigerated air being supplied via a ceiling duct.

Products such as fruits and vegetables that produce heat by respiration or products that have to be cooled during transit additionally require circulation through the product. This can be achieved by directing the supply of air through ducts to channels at floor level or in the floor itself. In general it is not advisable to rely on product cooling during transportation.
4.5.1.2 **Eutectic plates**

Eutectic plate cooling systems are used in refrigerated vehicles serving local distribution chains. The eutectic plate consists of a coil, through which a primary refrigerant can be passed, mounted inside a thin tank filled with a eutectic solution. Standard eutectic solutions freeze at temperatures between −3 and −50°C and some have been applied in food chilling systems. A number of these plates are mounted on the walls and ceilings or used as shelves or compartment dividers in the vehicles. To provide the required cooling capacity, the plates should be mounted so that air can circulate freely over both sides and over the product. Most systems rely on gravity circulation but some are equipped with fans, ducts and dampers for temperature control. Eutectic systems are chosen for the simplicity, low maintenance and quietness of their operation but can suffer from poor temperature control.

4.5.1.3 **Total-loss refrigerants**

In general total-loss refrigerants, such as liquid nitrogen (LN) or solid carbon dioxide (CO₂), are increasingly being replaced by mechanical refrigeration in transportation. Smith claimed many advantages for liquid nitrogen transport systems, including minimal maintenance requirements, uniform cargo temperatures, silent operation, low capital costs, environmental acceptability, rapid temperature reduction and increased shelf life owing to the modified atmosphere. The same author also states that long hauls can be carried out since vehicles are available that will maintain a chilled cargo at 3°C for 50 hours after a single charge of liquid nitrogen and that overall costs are comparable with those of mechanical systems. However, trials carried out on the distribution of milk showed that the operating costs using liquid nitrogen, per 100 l of milk transported, were 2.2 times that of a mechanically refrigerated transport system. Fixed costs of the nitrogen system were under half those of the mechanical unit but the use of nitrogen was considered to be viable only at very low throughput.

In the UK carbon dioxide is principally used for in-transit refrigeration in block or pellet form. In the US, Canada and Australia it is frequently used in liquid form, either in clip-on tanks or as dump charged ‘snow’. Though declining in use, solid carbon dioxide (dry ice) is used in the UK for road transport of dairy products. It has similar advantages to liquid nitrogen including those of low capital cost coupled with low maintenance requirements. Low maintenance is an obvious advantage for rail transport, where once loaded the cargo requires no attention. One advantage over liquid nitrogen is that the bacteriostatic effect of carbon dioxide may be useful
for some products. Dry ice is also used in airline catering where its low weight is a major advantage.

### 4.5.2 Sea transport

Recent developments in temperature control, packaging and controlled atmospheres have substantially increased the range of foods that can be transported around the world in a chilled condition. Control of the oxygen and carbon dioxide levels in shipboard containers has allowed fruits and vegetables, such as apples, pears, avocados, melons, mangoes, nectarines, blueberries and asparagus, to be shipped (typically 40 days in the container) from Australia and New Zealand to markets in the USA, Europe, Middle East and Japan. If the correct varieties are selected and rapidly cooled immediately after harvest the product arrives in good condition and has a long subsequent shelf life. With conventional vacuum packing it is difficult to achieve a shelf life in excess of 12 weeks for beef and 8 weeks for lamb. However, a shelf life of up to 23 weeks at $-2^\circ{\text{C}}$ can be achieved in cuts of lamb individually packed in evacuated bags of linear polyethylene, and then placed in gas flushed foil laminate bags filled with a volume of CO$_2$ approximately equal to that of the meat. Similar storage times are currently being achieved with beef primals transported from Australia and South Africa to the EU.

Most International Standard Organisation (ISO) containers for food transport are either 6 or 12 m long, hold up to 26 tonnes of product and can be ‘insulated’ or ‘refrigerated’. The refrigerated containers incorporate insulation and have refrigeration units built into their structure. The units operate electrically, either from an external power supply on board the ship or dock or from a generator on a road vehicle. Insulated containers either utilize the plug type refrigeration units already described or may be connected directly to an air-handling system in a ship’s hold or at the docks. Close temperature control is most easily achieved in containers that are placed in insulated holds and connected to the ship’s refrigeration system. However, suitable refrigeration facilities must be available for any overland sections of the journey. When the containers are fully loaded and the cooled air is forced uniformly through the spaces between cartons, the maximum difference between delivery and return air can be less than $0.8^\circ{\text{C}}$. The entire product in a container can be maintained to within $\pm1.0^\circ{\text{C}}$ of the set-point.

Refrigerated containers are easier to transport overland than the insulated types, but have to be carried on deck when shipped because of problems in operating the refrigeration units within closed holds. On board ship
they are therefore subjected to much higher ambient temperatures and consequently larger heat gains, which makes it far more difficult to control product temperatures.

### 4.5.3 Air transport

Air-freighting is increasingly being used for high-value perishable products such as strawberries, asparagus and live lobsters. However, foods do not necessarily have to fall into this category to make air transportation viable since it has been shown that ‘the intrinsic value of an item has little to do with whether or not it can benefit from air shipment, the deciding factor is not price but mark-up and profit’. There was a 10–12% per year increase in the volume of perishables transported by air in the 1990s. Although air-freighting of foods offers a rapid method of serving distant markets, there are many problems because the product is unprotected by refrigeration for much of its journey. Up to 80% of the total journey time is made up of waiting on the tarmac and transport to and from the airport. During flight the temperature in the hold is normally between 15 and 20°C. Perishable cargo is usually carried in standard containers, sometimes with an insulating lining and/or dry ice, but is often unprotected on aircraft pallets. Thus the product should be transported in insulated containers to reduce heat gain; it should be pre-cooled and held at the required temperature until loading; containers should be filled to capacity; and a thermograph should accompany each consignment.

### 4.6 RETAIL DISPLAY

The temperature of individual consumer packs, small individual items and, especially, thin sliced products responds very quickly to small amounts of added heat. All these products are commonly found in retail display cabinets and marketing constraints require that they have maximum visibility. Maintaining the temperature of products below set limits while they are on open display in a heated store will always be a difficult task.

Average temperatures in chill displays can varied considerably from cabinet to cabinet, with inlet and outlet values ranging from −6.7 to +6.0°C, and −0.3 to +7.8°C, respectively, in one survey. The temperature performance of an individual display cabinet does not depend only on its design. Its position within a store and the way the products are positioned within the display area significantly influence product temperatures. In non-integral (remote) cabinets (i.e. those without built-in refrigeration systems) the design and performance of the store’s central refrigeration system are also critical to effective temperature control.
The required display life and consequent environmental conditions for wrapped chilled products differ from those for unwrapped products. The desired chilled display life for wrapped meat, fish, vegetables and processed foods ranges from a few days to many weeks and is primarily limited by microbiological considerations. Retailers of unwrapped fish, meat and delicatessen products, e.g. sliced meats, pâté, cheese and prepared salads, normally require a display life of one working day.

4.6.1 Unwrapped products

Display cabinets for delicatessen products are available with gravity or forced convection coils and the glass fronts may be nearly vertical or angled up to 20°. Sections through three of the commonest types of delicatessen cabinet are shown in Fig. 4.7.

In the gravity cabinet (Fig. 4.7a) cooled air from the raised rear mounted evaporator coil descends into the display well by natural convection and the warm air rises back to the evaporator. In forced-circulation cabinets (Fig. 4.7b and c) air is drawn through an evaporator coil by a fan and then ducted into the rear of the display, returning to the coil after passing directly over the products (Fig. 4.7b), or forming an air curtain (Fig. 4.7c), via a slot in the front of the cabinet and a duct under the display shelf.

Changes in product appearance are normally the criteria that limit the display of unwrapped foods, with the consumer selecting newly loaded product in preference to that displayed for some time. Deterioration in appearance has been related to degree of dehydration in red meat (see Table 4.7) and is likely to occur similarly in other foods. Apart from any relationship to appearance, weight loss is of considerable importance in its own right. The direct cost of evaporative loss from unwrapped foods in chilled display cabinets in the UK is in excess of £5m per annum.67
A small survey carried out in the 1980s found that average relative humidity ranged from 41 to 73% and air velocity from 0.1 to 0.67 ms$^{-1}$ in delicatessen cabinets. The lowest rate of weight loss was measured in a cabinet of the type shown in Fig. 4.7c, which achieved mean conditions over the products of 0.4°C, 0.14 ms$^{-1}$ and 65% relative humidity. The same study showed that relative humidity was more important than the air temperature or velocity. Reducing the relative humidity from 95 to 40% increased weight loss over a 6-hour display period by a factor of between 14 and 18. Raising the air velocity from 0.1 to 0.5 ms$^{-1}$ had little effect on weight loss at 95% relative humidity but increased the loss by a factor of between 2 and 2.4 at 60% relative humidity. Temperature changes from 2 to 6°C had a far smaller effect on weight loss than the changes in either relative humidity or velocity used in the investigations. In further work a model developed to predict the rate of weight loss from unwrapped meat under the range of environmental conditions found in chilled retail displays showed that it was governed by the mean value of the conditions. Fluctuations in temperature or relative humidity had little effect on weight loss, and any apparent effect is caused by changes in the mean conditions.

There is a conflict between the need to make the display attractive and convenient to increase sales appeal and the optimum display conditions for the product. High lighting levels increase the heat load and the consequent temperature rise dehumidifies the refrigerated air. The introduction of humidification systems can significantly improve display life.

### 4.6.2 Wrapped products

To achieve the display life of days to weeks required for wrapped chilled foods the product should be maintained at a temperature as close to its initial freezing point as possible to prevent microbial spoilage. In some cases, e.g. particular cheeses, dairy products and tropical fruits, quality problems may limit the minimum temperature that can be used, but for the majority of meat, fish and processed foods the range $-1$ to $0°C$ is desirable.
Air movement and relative humidity have little effect on the display life of a wrapped product, but the degree of temperature control can be important, especially with transparent, controlled atmosphere packs. During any control cycle the cabinet temperature rises, heat enters the pack and the atmosphere inside the pack warms, with a consequent reduction in relative humidity and increase in the surface temperature of the product. As the surface temperature rises so does its saturation vapour pressure (a factor controlling evaporation) and more water evaporates into the sealed atmosphere of the pack. If the cabinet temperature stabilized, evaporation would continue until the atmosphere became saturated. However, in practice the cabinet air temperature cycles and as it is reduced the wrapping film is cooled. If it reaches a temperature below the dew point of the atmosphere inside the pack then water vapour will condense on the inner surface of the pack. This film of water can obscure the product and consequently reduce consumer appeal. As the cycling process continues the appearance of the product deteriorates.

Although cabinets of the type described for delicatessen products can be used for wrapped foods most are sold from multi-deck cabinets with single or twin air curtain systems (Fig. 4.8).

Twin air curtains tend to provide more constant product temperatures but are more expensive. It is important that the front edges of the cabinet shelves do not project through the air curtain since the refrigerated air will then be diverted out of the cabinet. On the other hand if narrow shelves are used the curtain may collapse and ambient air can be drawn into the display well.

Fig. 4.8 Multi-deck display cabinets (open and enclosed) for wrapped products.
To maintain product temperatures close to 0°C the air off the coil must typically be at −4°C, and any ingress of humid air from within the store will quickly cause the coil to ice up. Frequent defrost are often required and even in a well maintained unit the cabinet temperature will then rise to 10 to 12°C and the product by at least 3°C. External factors such as the ambient temperature of the store, the position of the cabinet and poor pre-treatment and placement of products substantially affect cabinet performance. Warm and humid ambient air and loading with insufficiently cooled products can also overload the refrigeration system. Even if the food is at its correct temperature, uneven loading or too much product can disturb the airflow patterns and destroy the insulating layer of cooled air surrounding the product. An in-store survey of 299 pre-packaged meat products in chilled retail displays found product temperatures in the range −8.0 to 14.0°C, with a mean of 5.3°C and 18% above 9°C. Other surveys have shown that the temperatures of packs from the top of a stack were appreciably higher than those from below owing to radiant heat picked up from store and cabinet lighting. It has also been stated that products in transparent film overwrapped packs can achieve temperatures above that of the surrounding refrigerated air owing to radiant heat trapped in the package by the ‘greenhouse effect’. However, specific investigations failed to confirm this effect.

4.7 CONCLUSIONS

In general, after initial chilling, as a chilled product moves along the chill chain it becomes increasingly difficult to control and maintain its temperature. Temperatures of bulk packs of chilled products in large storerooms are far less sensitive to small heat inputs than single consumer packs in transport or open display cases. If primary and secondary cooling operations are carried out efficiently then the food will be reduced below its required temperature before it is placed in storage. In this situation the store’s refrigeration system is only required to extract extraneous heat that enters through the walls, door openings, etc., or heat generated by the food itself.

Even when temperature controlled dispatch bays are used there is a slight heat pick-up during loading. In bulk transportation the resulting temperature rise is small and the vehicle’s refrigeration system rapidly returns the product to the required temperature. Larger problems exist in local multi-drop distribution to individual stores. There is a large heat input every time the doors are opened and product unloaded, small packs rapidly rise in temperature and the vehicle often lacks the refrigeration capacity or time to re-cool the food.
Temperature control during retail display is often poor owing to the retailer’s need to display as much product as possible in a way that is accessible to the consumer. Increasing energy costs may be the key factor that persuades retailers to reduce consumer access and hence improve temperature control.

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5 Freezing
Martin George

5.1 INTRODUCTION

The preservation of foods by freezing has a long and distinguished history. In today’s food industry, freezing is the most popular long-term preservation method, offering convenience to consumers, an excellent safety record and a means of preserving the taste, texture and nutritional value of foods better than any other long-term preservation method. The process of removing heat and maintaining food storage temperatures below that of the freezing point of the food has many beneficial effects, such as inhibiting the growth of deteriorative and pathogenic microorganisms, and retarding the biochemical and enzymic reactions that govern the deterioration of foods.

Freezing is an effective preservation technology because of two primary factors. The first is the role of temperature in biosystem stability. As temperatures are reduced, chemical, physical and biological reactions generally occur more slowly and rates of change are slowed down. The physical and biochemical reactions that govern the deterioration of foods, e.g. microbiological activity, oxidation of fats and lipids, denaturation and loss of functionality in proteins and activity of hydrolytic enzymes, are all retarded during low-temperature storage. Storage at a temperature well below the freezing point of the food should, all other factors being equal, markedly extend the storage lifetimes that can be achieved before the onset of any noticeable loss in sensory quality of the food. The second preserving factor is that during freezing water levels within the food are reduced as the available liquid water turns into solid ice. It is well established that foods with reduced moisture levels appear to be less susceptible to microbiological deterioration than similar food with higher moisture levels. The chemical and physical effects that are associated with loss of food quality even under conditions of low temperature storage, such as enzymic activity, oxidative deterioration, moisture migration and ice crystallization, are also significantly reduced under conditions of low moisture. The combined effect of reduced temperature and reduced
moisture levels in the food is that the safety and quality of frozen foods can be preserved for long periods of time, provided that appropriate low temperatures are achieved in the food during the freezing process and that these low temperatures are maintained throughout the food during its period of frozen storage.

The process of freezing involves the removal of heat from a food material accompanied by a phase change as the liquid water within the food undergoes a change of state to become solid ice. In freezing, the energy required to promote this phase change is known as the ‘latent heat of crystallization’ and for most foods this accounts for the majority of the process time needed to reduce the temperature of the food product to frozen levels. An important consideration in the manufacture of frozen foods is the rate at which heat can be removed from the product, and this is a function of both product and process factors. Product factors include size, shape and internal thermal properties, and are governed by the nature and composition of the food material. Process factors include the temperature of the freezing medium and the surface heat transfer coefficient between the material being frozen and the cooling medium. Both product and process factors dictate the nature and, ultimately, success of the freezing process.

The physical changes that occur within the food during the onset of freezing, such as the rate of formation of ice crystals (nucleation), the subsequent increase in ice crystal size (growth) and the rate of propagation of ice throughout the food, govern the quality and safety of frozen foods. Attention in recent years has focused on freezing as rapidly as possible, so that a large number of small ice crystals are formed within the food material. The formation of numerous small ice crystals contributes to a very fine and homogeneous food structure with little disruption and damage to the cellular structure of the food. This, in turn, minimizes problems such as moisture migration and drip loss. However, there is a commercially important trade-off between the speed of freezing and the economy of the freezing operation. Processing costs generally increase exponentially with speed of freezing, but improvements to product quality tend to level off beyond a certain freezing rate. It is important to note also that some products may physically crack or shatter if freezing rates are too high, downgrading the quality of the food.¹

It is important to realize that, although the process of freezing has become an important means of preserving foods from microbiological spoilage and controlling the proliferation of food-borne pathogens, freezing will also preserve micro-organisms that may already be present in the food. For some specific food applications this may, of course, be beneficial, for example frozen bread doughs and frozen yogurts require microbial
stability under frozen storage to preserve the functionality, quality and overall success of these products. In such cases, it is suggested that freezing can be considered as a means of both preserving foods from microbial activity and preserving the necessary microbial activity in frozen foods.  

However, for many other foods the freezing process can preserve not only the food material itself, but also any microbiological contamination that may have already been present in the food material. For food products such as ready meals or prepared foods, the freezing process may also preserve bacteria or micro-organisms within the food, which will then be regenerated upon thawing or heating. Although frozen foods have an enviable safety record with respect to food poisoning, it is imperative that prior to preservation by freezing, food materials are subject to the same strict hygiene controls as for their chilled or fresh counterparts.

5.2 THE PHYSICAL AND CHEMICAL ASPECTS OF FREEZING

Since the freezing process and the mechanisms for changing liquid water into solid ice are of critical importance with regard to its ability to effectively preserve food materials, it is important to have a fundamental scientific understanding of the basis of food freezing processes. Freezing is a thermodynamic process and can be described as a series of thermal events that approach conditions of equilibrium within the food. It is these states of equilibrium, as well as the kinetic changes that occur in reaching equilibrium, that describe the physical and chemical changes that occur in the food during freezing.

Temperature is the major parameter governing the success of freezing and the rate of removal of heat and the rate of change of internal food temperatures have the most influential effects on the phase change process (rate of freezing) and the spatial patterns of phase changes (uniformity of freezing). However, other factors also have to be considered because heat removal alone is not sufficient to induce a phase change. Additional factors are involved in the initiation and continuation of the growth of ice within the food, such as the rate of nucleation of ice crystals (how rapidly the initial formation of ice occurs within the food material) and the rate of growth of these ice crystals (the subsequent freezing of the remaining water available in the food material). These growth-related factors are influenced by the composition of the material and the physical and thermal properties of the food. They will also change according to the physical state of the system to be frozen. For example, an ice cream freezing
system will have different freezing characteristics and will require a different freezing system to a vegetable freezing station. 3

Thermodynamics indicates that ice is the most stable form of water at temperatures lower than 0°C. However, for the crystalline ice phase to grow, there must be an initial nucleus or ‘seed’ to form the basis of the ice crystal. Forming an ice crystal (nucleation) is the process of attracting enough molecules into a site of sufficient size to survive and serve as a substrate for further growth of the crystal. Nucleation is necessary for freezing to start, but at the onset of nucleation, the temperature of the material will fall to below the initial freezing point, a process known as supercooling, before rising again to the initial freezing point. The process of supercooling is analogous to an energy barrier that must be overcome before freezing can commence. The probability of nucleation depends on the volume of the sample and the rate of heat removal. When the sample volume is small, the probability of nucleation is small and very low temperatures will be required for freezing. At high freezing rates, the rate of production of ice crystals increases more quickly than the ice crystals can grow, making more nucleation sites active and increasing the number of ice crystals formed.

Once ice nuclei have been formed, ice crystals can grow. The growth of ice crystals is not instantaneous but is dictated by the rate at which the water present in the food can flow or diffuse to the surfaces of the formed ice crystals (the nucleation sites). The size of ice crystals present in the food is governed by the number of nuclei present. If there are many ice nuclei within the food, the resulting crystals will tend to be smaller in size, as the water available in the food has more nuclei to serve. If there are only a few ice nucleation sites, there will be more water available for each nucleus and the ice crystals will be large. Consequently, a rapid freezing rate produces numerous ice nucleation sites and small ice crystals. Slower freezing rates produce fewer ice nucleation sites, and the water available in the food – coalescing onto these sites – will form large ice crystals. The benefits of smaller ice crystals include less damage to the internal structure of the food, which in turn leads to a reduced degree of disruption to the cellular structure that is characteristic of the food material.

The freezing of foods is more complex than the freezing of water as foods will contain a mixture of both water and solutes. Fig. 5.1 shows typical time–temperature freezing curves for water and an aqueous solution representing a typical foodstuff.

In the case of the freezing of water, temperature decreases from the initial temperature as sensible heat is removed (portion A–B of the curve).
represents the region of supercooling at which ice crystal nucleation initially takes place and there is a small rise in temperature as the energy of the freezing process now goes into changing the state of the water from liquid to solid. The water will remain at this temperature until all the water is converted into ice, an energy requirement of 333.15 kJ/kg (the latent heat of fusion of water). When solidification of the water is complete there is a further drop in temperature, which then approaches the final temperature of the freezing medium.

In the case of the aqueous food material, it is common to analyse the time–temperature curve obtained under the slowest cooling conditions, as this reasonably represents an equilibrium situation. Following the onset of the supercooling stage ($S_2$), the released heat of crystallization causes the temperature to increase and reach the initial freezing point of the system ($T_i$). The subsequent plateau region denotes the period during which the major portion of the water available within the system being frozen is converted to solid ice. The freezing curve then follows a similar pattern to that of water until the final desired frozen food temperature is reached.

The initial freezing point of a food material depends on the molar concentration of dissolved substances in the food, those with higher solute concentrations having a lower freezing point. Typical values of freezing points for common foods are: $-1.1^\circ C$ for beef, $-0.9$ to $-2.7^\circ C$ for fruits, $-0.8$ to $-2.8^\circ C$ for vegetables and approximately $-0.5^\circ C$ for eggs and milk. As foods are cooled below their initial freezing point, more water is converted into ice and the residual solution becomes more concentrated. The ratio of ice to residual solution is a function of the temperature and initial concentration of solutes. At each temperature there is a mass of ice
in equilibrium with the unfrozen fraction and this is characteristic of a particular food. Table 5.1 shows the effect of temperature on the fraction of frozen water for a selection of foods. At very low freezer temperatures (below $-40^\circ\text{C}$) there is little discernible change in the amount of ice present in most foods, although there exists an amount of non-freezable water remaining in most foods and this is, again, a function of temperature and initial concentration of solutes.

In practical terms, the freezing of foods is considered complete when most of the water at the thermal centre of the product has been converted to ice. The universally accepted desired freezer temperature is $-18^\circ\text{C}$ (0°F) or colder.\(^5\) According to the International Institute of Refrigeration (IIR), the rate of freezing of a food is defined as the ratio between the minimum distance from the surface to the thermal centre, and the time elapsed between the surface temperature reaching 0°C and the thermal centre 10°C lower than the temperature of initial ice formation. In commercial practice, typical freezing rates (as measured by the speed of progress of the advancing ice front) vary between 0.2 and 100 cm/hour. Figures for slow freezing (e.g. bulk freezing in cold chambers) range from 0.2 to 0.5 cm/hour, quick freezing (e.g. air-blast and contact freezers) range from 0.5 to 3 cm/hour, rapid freezing (e.g. individual quick freezing of small individual food items) range from 5 to 10 cm/hour, and ultra-rapid freezing (e.g. cryogenic spraying or immersion) range from 10 to 100 cm/hour.

In tissue systems, as would be the case for many foods, the existence of permeability barriers such as cell walls increases the complexity of defining the true freezing rate. For the general matrix (outside the cell walls), the standard definitions of freezing rate would apply adequately. However, an understanding of freezing within each cell must also consider the contributions from both the permeability of the cell wall and the

<table>
<thead>
<tr>
<th>Product</th>
<th>Total water content (%)</th>
<th>Frozen water as % of total water</th>
<th>Non-freezable water as % of total water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-5^\circ\text{C}$</td>
<td>$-10^\circ\text{C}$</td>
<td>$-15^\circ\text{C}$</td>
</tr>
<tr>
<td>Lean beef</td>
<td>74</td>
<td>74</td>
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<tr>
<td>Liquid egg</td>
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<tr>
<td>White bread</td>
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<td>Fruit juice</td>
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<tr>
<td>Spinach</td>
<td>90</td>
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<td>93</td>
</tr>
</tbody>
</table>

Source: International Institute of Refrigeration. "Recommendations for the processing and handling of frozen foods."\(^5\)
internal properties of the cell. Two major factors influence the cellular freezing process. Loss of water as a result of osmosis to the external matrix increases the internal osmotic concentration, and has the effect of lowering the cell’s initial freezing point. The second factor is the nature of the cell contents. These interact with the concentration effect to cause cell freezing at different rates to that of the bulk tissue. If the membrane permeability is high, internal freezing is minimized. For low rates of heat removal, water can transfer from the internal cell to the surrounding matrix before it reaches its freezing temperature. In this case, the cell contents will dehydrate and the lost cellular water will manifest as ice crystals in the surrounding matrix. As freezing rates increase, cellular ice formation increases, and although there may be some structural damage to the cells, there is little water loss and cells can regenerate upon thawing to approach the conditions of their initial natural characteristics. For cellular systems, definitions of freezing rates might be modified to suggest that fast freezing produces internal freezing in cells and slow freezing promotes cellular dehydration and extracellular ice.

Freezing damage may thus be attributable to a variety of effects, although it should be recognized that thawing may play just as important a role. Sources of damage can arise from:

- formation of ice within cells or in extracellular space
- the physical expansion of water into ice
- cell dehydration and shrinkage and the potential rupture of membranes
- changes in solute concentrations, both within and surrounding cells
- migration of water from cells to extracellular space; potential dehydration.

Of course, despite its important role in promoting physical and chemical changes in the state of the food material, freezing is a relatively short process. At its most rapid, the freezing of a food product may occur in a few minutes. At its slowest, large portions of food can be frozen in 24–48 hours, even when the food material itself is insulated from rapid heat removal by the presence of packaging and the thermal protection offered by surrounding food products on a pallet arrangement. Of equal importance to an understanding of the effects of freezing on food quality and safety is the period of frozen storage, which can often last for several months or years. It is not uncommon for food ingredients or minor items to be frozen and stored for up to 18–24 months before being reconstituted and used as a component in other chilled, frozen or heat-processed food products. Even foods intended to be marketed as frozen products have shelf lives that extend up to 24 months. Table 5.2 indicates some suggested practical storage lives for various food commodities at different frozen storage temperatures. This illustrates the role of temperature in dictating the stability of frozen foods.
Having taken great care to freeze as rapidly as appropriate to preserve food quality and safety, equal care and consideration are needed to preserve the ice crystals formed within the food during the longer period of frozen storage. Even at a consistently low frozen storage temperature, there will be a tendency for ice crystals to reduce in number and increase in size. This is a natural consequence of the surface energy that exists between the ice crystal and the unfrozen matrix and the need for the system to achieve an equilibrium that minimizes the active surface area between the two phases. This will occur at both steady and fluctuating frozen storage temperatures, although the effect is greatly accelerated when temperatures are subjected to change. The resulting growth in the size of ice crystals can significantly influence the damage that occurs within foods during frozen storage. A further effect that may occur during frozen storage under fluctuating temperatures is that temperature
gradients will be established throughout the food. This has the detrimental effect of promoting the migration of moisture from areas of high water vapour pressure to areas of lower pressure. In practice, the migration will tend to be towards the surface of the food material, where temperatures are most likely to be highest. The accumulation of moisture at the surface of the product and on the inside surface of any packaging material associated with the product is one factor that limits the practical storage life of many foods and is a consideration when determining the shelf life and best-before dates on product packaging.

5.3 THE EFFECT OF FREEZING ON MICRO-ORGANISMS

Although it is widely accepted that freezing and frozen storage have some beneficial effect on the inactivation of micro-organisms, and it is true that some cells may be killed or undergo sub-lethal or metabolic injury, other cells may suffer no detrimental effects. Freezing, frozen storage and thawing cannot be considered as a means of reliably inactivating micro-organisms. The different categories of micro-organisms are affected differently by the freezing process. Many micro-organisms are resistant to the freezing (and thawing) process, such as bacterial spores and fungal spores, where survival after freezing and storage often exceeds 90% and 80%, respectively. Relatively resistant micro-organisms include Gram-positive Staphylococci, Streptococci, Bacillus, Clostridium, Lactobacillus, Micrococcus, Staphylococcus, Streptococcus and Listeria, with reported survival rates between 50 and 70%. There are, however, some micro-organisms that can be described as sensitive to the combined effects of freezing and frozen storage. Gram-negative bacteria such as Escherichia and Pseudomonas are not resistant and can sometimes be destroyed during processing. In general, higher organisms are much more sensitive to freezing than bacteria; parasitic protozoa and nematodes are very sensitive and are killed after a period of frozen storage, often 2 weeks or less at temperatures of −18°C or lower. This effect is sometimes beneficially used in the food industry, e.g. freezing preservation is used as a means of destroying Anisakis in the fish-processing sector.

It has been suggested that the detrimental effects of freezing on micro-organisms can be attributed to a number of factors, including:

- thermal (cold) shock injury to the micro-organism
- increased cell dehydration as a result of the liquid–solid phase transformation and osmotic dehydration through cell walls
- increased concentration of solutes within the extracellular food matrix to create an unfavourable environment for the micro-organism


- increased concentration of solutes with the cells, creating an increasingly toxic environment for the micro-organism
- formation of ice within the cell walls and its physical and mechanical impact on adjacent micro-organisms
- contraction of cell volume resulting from dehydration during freezing.

Cold shock is most commonly associated with Gram-negative bacteria, and it has been suggested that many yeasts and moulds are not susceptible to cold shock. Cold shock has also been suggested as having only a sub-lethal effect on a wide range of micro-organisms. This is of importance to the food manufacturer as it is well known that if the cause of sub-lethal injury (e.g. cold shock) is removed or reduced, then the micro-organisms can recover and continue to grow normally under the less severe conditions. Further, under the conditions of post-injury recovery, partially viable micro-organisms can become more susceptible to chemical agents and therefore may be more difficult to detect in a frozen product when selective media are used for recovery and enumeration. It may also be true that injured micro-organisms will ultimately die if conditions are not favourable, although the time required for complete cell death to occur may exceed the practical storage lifetime of the frozen food.2

The removal of water from within cells and extracellular space and the associated increasing concentration of solutes also have a significant effect on microbial destruction during freezing and the creation of an inhospitable environment during frozen storage. Micro-organisms need water to maintain their metabolic function, and the availability of water in a food, frozen or otherwise, can be expressed in terms of its water activity, which is the ratio of the water vapour pressure of the food to that of pure water (or ice in the case of a frozen food) at the same temperature. Table 5.3 illustrates the relationship between temperature and water activity.

### Table 5.3 Effect of frozen temperatures on water activity.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Water activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>−2</td>
<td>0.981</td>
</tr>
<tr>
<td>−5</td>
<td>0.953</td>
</tr>
<tr>
<td>−10</td>
<td>0.907</td>
</tr>
<tr>
<td>−15</td>
<td>0.864</td>
</tr>
<tr>
<td>−20</td>
<td>0.823</td>
</tr>
<tr>
<td>−30</td>
<td>0.746</td>
</tr>
<tr>
<td>−40</td>
<td>0.680</td>
</tr>
<tr>
<td>−50</td>
<td>0.620</td>
</tr>
</tbody>
</table>

Source: Golden and Arroyo-Gallyoun.2
The table above would suggest that microbiological activity in frozen food systems takes place at an \( a_w \) below that which exists in the same food in the unfrozen state. The table, however, relates to the idealized case of a pure water substrate. Foods are complex systems containing both water and solutes such as salts that can also contribute to increasing \( a_w \). Consequently, some micro-organisms can grow at frozen temperatures despite the low levels of water activity at those temperatures. These figures, when compared with experimental observations of microbial growth characteristics, suggest that consideration of \( a_w \) alone cannot account for the inhibition of microbiological activity in frozen foods, otherwise some micro-organisms would continue to grow at water activities down to 0.6 and, consequently, at temperatures below \(-50^\circ\text{C}\).

The formation of ice within the cell walls has a physical and mechanical impact on adjacent micro-organisms. As freezing progresses, the liquid water is converted into solid ice during the period of release of latent heat, and micro-organisms distributed throughout the previously liquid matrix then become progressively more concentrated in the unfrozen phase of the food matrix. If freezing is slow, then ice crystals will predominantly form in the extracellular space and there will be migration and diffusion of water from within adjacent cells to support the growth of the ice crystal during continued freezing or frozen storage. The effect is that cell contents become dehydrated and more concentrated. Microbial cells may show distortion and loss of membrane integrity. Such damage to the cell membranes can result in leakage of intracellular constituents and the cell will ultimately lose its ability to maintain its characteristic internal environment. Similarly, intracellular ice crystals formed within microbial cells during more rapid freezing will be small enough to disrupt the cellular membrane.

Contraction of cell volume will also result during freezing, partly as a result of thermal contraction of cell membranes, and partly as a result of the volumetric expansion of water during its transformation from liquid to solid. Souzu et al.\(^8\) suggested that freeze-induced injury in microbial cells is due primarily to the dehydration of lipid-rich membranes.

It has been suggested that the principal cause of microbial destruction during the freezing process is the physical deterioration of the microbial cell membrane and the resultant leakage of internal cell material through the disrupted membrane. Additionally, it is thought that the cell membrane may lose many of its barrier properties at temperatures below \(-15^\circ\text{C}\).\(^7\) However, there is still little known of the actual mechanisms, as most studies on the influence of freezing and thawing on the death kinetics of micro-organisms have been based on model experiments. Such experimental
studies are on a much smaller scale than commercial food freezing applications and, consequently, it is possible to use much faster rates of freezing and thawing than can be achieved in commercial practice. One conclusion that emerges from all experimental work is that the survival of micro-organisms depends on many factors, including both freezing and thawing rates. In practice, it is difficult to achieve freezing so rapidly that intracellular ice crystals are formed homogeneously throughout the food. Consequently, although parts of a food product, e.g. the surface layer directly exposed to a low-temperature cryogen, may achieve relatively rapid freezing, the bulk of the food will not freeze at the same rate. It is for these reasons that freezing and frozen storage cannot be relied upon to reproducibly destroy micro-organisms present in the food. Prior to freezing, food materials need to have the same degree of control of raw materials, hygienic handling and processing and compliance with good manufacturing practice (GMP) and Hazard Analysis and Critical Control Point (HACCP) principles as food materials destined for chilled or fresh markets. Freezing and frozen storage do not constitute reliable biocides for foods.

5.4 FOOD FREEZING OPERATIONS

A number of different refrigeration systems exist and the correct choice of system will allow the food manufacturer to achieve maximum product quality and flexibility in operation, minimal operating costs and waste generation, and a return on investment. Food freezers can be classified in several ways, e.g. by the source of refrigeration, the speed of freezing or the mode of freezer operation. The choice of freezing system for food manufacturers will be either mechanical freezers (such as air-blast freezers or contact plate freezers) or cryogenic freezers, utilizing liquid nitrogen or liquid carbon dioxide as the refrigerant. The choice between mechanical and cryogenic freezing operations involves considering both the technical and economic factors governing the design, installation, operation, maintenance, manufacturing costs and technical support to the freezing installation.

To a large extent the type of food to be frozen will dictate the choice of appropriate freezing system. For small food components such as quick frozen vegetables or seafoods, the most appropriate freezing equipment will be either a mechanical freezer of the fluidized bed design, or a cryogenic immersion freezer. For larger food items such as whole poultry or meat carcasses, then liquid immersion freezing in brine or a liquid cryogen will be the most appropriate method. For whole fish or fish fillets, the uniform slab-like shape lends itself well to freezing using a contact or
plate freezer. It is often true that the rate of temperature change needed by a food product during freezing will also have an influence on the choice of freezing equipment, e.g. the freezing of chicken immediately after cooking will need to reduce the temperature within a defined timescale to comply with the requirements of relevant legislation and industry codes of practice.

The choice of freezing system is also governed by the process economics. Although recognized as having low running costs, mechanical freezing systems are generally considered to require a significant capital investment – this may be an acceptable criterion for an already established food product, but will be a major commercial risk for a new food product line or where a food product may have regular changes to format, shape or packaging. Cryogenic food freezers are considered to have low capital costs and are often a good choice for new food product lines that are not yet established in the market, but they are also noted for relatively high running costs, because the liquid nitrogen (or liquid CO₂) used for refrigeration is irreversibly expended during the freezing process and needs to be replenished by delivery from the gas supplier at regular intervals.

The most common type of freezers used throughout the food industry are blast freezers, which include the well-known variants of belt freezers, tunnel freezers and spiral freezers. These are available for both mechanical (air-blast) and cryogenic freezing modes. The freezer is a simple design, consisting of a conveyor belt made from perforated stainless steel or high tensile, temperature-tolerant plastic. Electric fans mounted above or adjacent to the conveyor circulate the freezing air over the surface of the product, through the perforations in the belt and back to the refrigeration plant for recirculation through the system. Fig. 5.2 shows a schematic
representation of the principles of blast freezing. Such systems are used for a wide range of foods, including individual items such as chicken fillets, pizzas and ready meals.

Heat transfer to the food product is predominantly via convective heat transfer between the freezing air and the surface of the food product. Mechanical air-blast systems use freezing air at a temperature of $-40^\circ C$, and cryogenic systems have gas temperatures closer to the temperature of boiling of liquid nitrogen (or liquid $CO_2$), typically $-196^\circ C$ (or $-98^\circ C$). The mode of heat transfer relies upon good thermal contact between the food surface and the cooling medium, and a well-designed circulation system to ensure that the cryogenic gas passes over all the available surfaces of the food material to be frozen is essential for efficient operation. The aim of the freezing operation is to create a turbulent zone at the product surface so that heat transfer is maximized, and this is often achieved by utilizing relatively high air velocities perpendicular to the surface of the food. There are also contributions to heat transfer from the lower surface of the food, but this will normally be dominated by conductive heat transfer between the food and the conveyor belt, which is itself cooled by convection from the freezing air. Some variants of this mode of freezing utilize a solid stainless steel belt to convey the food product; in this case the belt is cooled by spraying with cooled brine solution, and the process of heat conduction becomes much more dominant in the heat transfer process. Mechanical air-blast freezers often have extremely large capacities, from 200 kg/hour to more than 5000 kg/hour, and a large system might extend to a length of over 25 m. The food remains on the conveyor until a temperature of, usually, lower than $-15^\circ C$ is achieved at the warmest point within the food; in modern commercial systems the length of time on the conveyor would be just a few minutes. Fig. 5.3 shows a typical air-blast mechanical freezing system designed to operate with high air velocities normal to the food product surface to achieve rapid freezing.

The cryogenic version of this freezing system replaces the mechanical freezing coils of the evaporator with an array of spray nozzles to inject liquid nitrogen or liquid carbon dioxide into the freezing chamber and, as much as possible, directly onto the surface of the food. The very low temperature of the cryogen ($-196^\circ C$ for liquid nitrogen and $-98^\circ C$ for liquid $CO_2$) has a large temperature difference to the surface of the food and, consequently, a rapid cooling effect. This is further enhanced by evaporation or sublimation of refrigerant from the surface of the food product. Fig. 5.4 shows a modern cryogenic food-frezing tunnel.

A significant disadvantage with conventional blast freezing tunnels is the amount of floor space that they take up in the food factory. For larger food
freezing operations, the straight belt of the tunnel is replaced with a vertical-axis spiral, which reduces the floor area considerably, although the complexity of mechanical conveying of the product is increased. Spiral freezers are one of the commonest freezer types in the food industry, and capacities can extend up to 10,000 kg/hour with a factory footprint now extending to only some 5 m in length. Fig. 5.5 illustrates a typical spiral freezer installation.
Other types of freezer installation are more specialized and tend to be directed towards individual applications. Plate freezers, once the mainstay of the fish processing industry, are now much less common. These utilize flat metal plates, themselves cooled by direct contact with a closed-circuit circulating refrigerant, which are placed in direct contact with the food to be frozen. Heat transfer is purely conductive and for large blocks of food, or foods packaged in regularly shaped containers, this can be an extremely good method of freezing. High heat transfer coefficients are possible.

Immersion freezers, in which the food products come into direct contact with the liquid refrigerant, are also used for some specialist food freezing operations. The liquid refrigerant can be liquid nitrogen or liquid CO₂, but can also be aqueous solutions of low-freezing point solutions such as brines. The immersion process consists of soaking the foodstuff in the cooled solution. Binary brine solutions (such as sodium chloride or calcium chloride brines) are generally used, although ternary or more complex freezing solutions such as mixtures of water, salts and ethanol have also been used.¹⁰ The advantages claimed for immersion freezing systems include shorter processing times, energy savings and improved food quality when compared with conventional blast freezing techniques. However,
immersion freezing is not yet widely used and it has been suggested that the major difficulty is the problem of uncontrolled penetration of the freezing liquid into the food material.\textsuperscript{10}

5.5 MONITORING THE QUALITY AND SAFETY OF FROZEN FOODS

An overview of the factors necessary for maintaining the safety and quality of foods in the frozen food chain is given by Bøgh-Sørensen.\textsuperscript{7} Effective monitoring of the freezing process and the period of frozen storage can be summarized in a series of key recommendations:

- The microbiology of frozen foods is not very different from the microbiology of the fresh (unprocessed) or chilled counterpart. Frozen foods have the great advantage that micro-organisms do not grow at the low temperatures associated with frozen storage of foods, provided that the food is maintained in the frozen state during the storage period.
- The degree of monitoring of frozen food for safety and quality should be the same as would be the case for the monitoring and control of chilled food. This will include an HACCP assessment of the safety issues that are likely to occur during freezing and frozen storage. While the temperatures associated with frozen storage are not capable of supporting the growth of micro-organisms, the presence of micro-organisms or bacteria within the food prior to freezing will lead to potential food safety issues as the food is thawed or regenerated. Freezing is an excellent means of preserving foods – but it is also an excellent means of preserving micro-organisms. Hygiene rules for frozen food production are just as necessary as for all other food production processes.
- The particular control point for frozen foods is the freezing process. It is important to ensure that there is as little delay as possible and practicable in initiating the freezing process. It is also important to ensure that the freezing time is sufficiently short, i.e. the freezing rate is sufficiently high to ensure rapid and uniform temperature reduction within the food material.
- A critical control point for the safety of frozen foods that is often overlooked is the thawing process. Thawing is not merely the reverse of freezing, and the thawing process may expose the surface of the food material to relatively high temperatures, well above the food freezing point, for long periods of time. This is a time when the growth of micro-organisms at the surface of the product needs to be well controlled.
- The growth characteristics of micro-organisms in thawed foods are thought to be the same as those found in unfrozen foods, although there
is little scientific information available to confirm or refute this general guideline.

5.6 CONCLUSIONS

Freezing is an effective preservation technology because of the role of temperature in biosystem stability and the reduction of moisture levels within foods after freezing and during frozen storage. Both factors combine to significantly slow down the chemical, physical and biological reactions that govern the deterioration of foods. The process of freezing involves the removal of heat from a food material accompanied by a phase change as liquid water becomes solid ice. Both product and process factors dictate the success of the freezing process, and the rate of formation of ice crystals (nucleation), the subsequent increase in ice crystal size (growth) and the rate of propagation of ice throughout the food govern the quality and safety of frozen foods. Attention in recent years has focused on freezing as rapidly as possible, so that a large number of small ice crystals are formed within the food material, minimizing disruption and damage to the cellular structure of the food.

The effects of freezing on micro-organisms vary according to the species being considered and, ultimately, freezing by itself cannot be considered a reliable biocide. Many micro-organisms are resistant to damage from the effects of freezing, e.g. bacterial and fungal spores. Others are partly resistant, such as most Gram-positive bacteria including *Bacillus*, *Clostridium*, *Lactobacillus*, *Micrococcus*, *Staphylococci*, *Streptococci*, *Listeria*, *Staphylococcus* and *Streptococcus*. Some micro-organisms can be described as sensitive to the combined effects of freezing and frozen storage. This category includes Gram-negative bacteria such as *Escherichia* and *Pseudomonas*. Generally, higher organisms are much more sensitive to damage by freezing than bacteria.

The effects of freezing on micro-organisms can be attributed to a number of factors, including thermal (cold) shock injury, increased cell dehydration and increased concentration of solutes within cells, formation of ice within the cell walls and the contraction of cell volume resulting from dehydration during freezing. It is evident that the destruction of micro-organisms by the freezing and thawing processes themselves is unreliable and that, consequently, pre-freezing treatment of foods needs to ensure the same degree of care and attention to hygiene and microbial decontamination as would be the case for either freshly-prepared or chilled foods. Industrial codes of practice in the area of frozen food production stress the need to comply with rigorous programmes of HACCP and GMP
to control and maintain the excellent safety record of frozen foods. Commercial food freezing systems are geared towards freezing foods as rapidly as possible both to achieve high-quality frozen foods and to minimize the length of time that foods spend in the range of temperature most capable of supporting the growth of bacteria.

REFERENCES

6 Drying as a Means of Controlling Food Biodeterioration

Xiao Dong Chen

6.1 DRYING TO MINIMIZE BIODEGRADATION

Why drying? Drying is one of the oldest methods of food preservation against microbiological spoilage as well as pathogens. Drying helps to maintain the edible status of foods and, generally speaking, extends their shelf life. The required level of moisture content to prevent spoilage achieved in a drying process depends on the micro-organisms present. Sometimes, pre-drying operations such as osmotic dehydration, evaporation–concentration, freeze concentration or membrane concentration are employed to reduce the water concentration to the desired level. Drying itself usually refers to the process of liquid water being evaporated from the surface of the product or from the pores within the product, the water vapour subsequently being removed by, e.g., hot air.

Additional heat is usually required to accelerate the drying process. The heat can be supplied in many ways, such as solar energy, microwave/radio-frequency radiation, hot gas stream (including superheated steam), etc. The dryers are often named according as to how heat is supplied or what the drying or heating medium is, e.g., solar dryer, superheated steam dryer, microwave dryer and so on. Heat can be supplied through direct contact conduction, e.g. drum drying. Radiation is also frequently used as the way of heating, e.g. infrared drying.

It is clear that a microbial cell is not a simple osmometer that stops working as soon as the moisture level has been reduced.\(^1\) In many cases food-borne poisoning bacteria can outlive drying. For instance, \textit{Salmonella} can survive spray-drying processes.\(^2\) A semi-qualitative illustration of the effect of water activity (\(a_w\)) on micro-organisms is shown in Fig. 6.1, which is modified from Roos\(^3\) after Rockland and Beuchat.\(^4\)

In a diagram proposed by Roos\(^3\) for dairy products, the structural transformation was the phenomenon of glass-transition of amorphous sugar. To the right of the structural transformation line stickiness, caking, structure
collapse and crystallization of a sugar phase can be expected. The structural change is significant insofar as it affects how the material becomes more exposed to oxygen (owing to the opening up of more channels or cracks) to induce a greater degree of oxidation of the lipids. Usually, when structural collapse occurs, the fat that is encapsulated in the matrix made up of sugar and protein is more exposed to oxygen, causing an oxidative flavour development.

The most important point arising from this diagram is that as the water activity (relative humidity of the air) increases to beyond a certain level (generally higher than 0.6), the growth of micro-organisms can cause significant problems to maintaining food quality and safety. At high water activities (>0.6) micro-organisms have finite growth rates that can take off to affect the product quality (the food would ‘go off’). This has been the primary drive for employing drying operations to reduce the water content – and hence \( a_w \) – to lower than this threshold level. Basically, when food materials have been dried to a water content lower than the critical limit, and kept in this environment or in sealed packages so that no re-absorption of water (vapour) can occur, the food is said to be safe from microbial spoilage for a defined shelf life (for example, six months or 12 months, etc.). Microbial spoilage in food after it has been dried may be termed post-process behaviour or growth/storage behaviour (see Fig. 6.1).

A given micro-organism has different levels of resistance to heat treatment when the water activity of the system is different. It is also dependent on
the food system that the organism lives in. The thermal resistance of B. stearothermophilus spores, known to be a highly thermal resistant microbe, is strongly affected by the water activity.\(^5\) For example, in the food system egg albumin powder, when experiments were conducted under controlled humidity and temperature conditions, it was found that at $a_w = 0.98 \text{ (20°C)}$, the decimal reduction time, $D$ – the time required at a constant temperature to reduce a population of spores by 90% – is 15 min; at $a_w = 0.68 \text{ (20°C)}$, $D = 51$ min; at $a_w = 0.33 \text{ (20°C)}$, $D = 460$ min; and at $a_w = 0 \text{ (20°C)}$, $D = 7$ min. Therefore the initial reduction in water content increases the thermal resistance of cells in the dried product, but when the water content is very low, lower than the tolerance of the cells, one should expect a rapid death of the microbes. Thus drying food to a low water content level can prevent the extensive growth of micro-organisms.

The drying process itself may be viewed as a thermal processing step, and microbial deactivation is said to be in-process.\(^6\) However owing to the retarding effect of evaporation, which can delay or minimize temperature rise, food-drying procedures usually do not induce elevated temperatures. Drying is not as lethal for micro-organisms as is thermal processing, where the temperature of a liquid food can reach 121°C and be held there for some time. Drying does not usually lead to high temperatures within the material except when carried out using superheated steam. Drying or, more precisely, a low water content slows down significantly the (further) development of any microbial-related spoilage problem. High temperature thermal processing, though effective in deactivating unwanted bacterial activity, also degrades other active food ingredients such as vitamins.\(^7\)

### 6.2 DRYING PROCESSES AND DRYING EQUIPMENT

There are numerous methods or processes for drying food materials, whose merits can be judged by energy efficiency, time to dry, product quality achieved, etc. A balance among these factors is often required to achieve the economic aim of the manufacturing procedure while ensuring that safe and tasty food is delivered to the consumer. In general, dehydration processes may be divided in two large groups: in-air or in-vacuum. In-air processes can be generalized to include those where a gas other than air is used as the drying medium. Vacuum processes are useful for removing water vapour when the products are best treated in the absence of air and where relatively low temperatures are preferred. In-air processes can involve elevated temperatures, which are used to achieve high rates of drying. Vacuum drying is, perhaps, more useful for preserving
micro-organisms rather than destroying them, as in cases when probiotic bacteria are involved and the maximum level of activity of the microbes is desired in the product.

### 6.2.1 Air drying

No matter what the mechanism of the heat supply – e.g. as microwave, conduction, convection, radiation – air is frequently used as the medium to convey water vapour away from the moist material. Water vapour would have to diffuse through still air (molecular diffusion) without a significant momentum exchange, a slow process, so usually air flow with a high velocity relative to the food product being dried is employed to increase mass and heat transfer. As mentioned earlier, it is necessary to transfer heat to the moist, porous material and to infuse it into the material in order to transport water (vapour) away from it. ‘Infusion’ can be achieved by using microwave or radio-frequency radiation or the ohmic heating method, where the material is easily penetrated and heat absorption (or generation) occurs more-or-less uniformly within the material.

Hot-air drying is the most common method used in the industry for large-scale operations such as spray drying, fluidized bed drying, tunnel or tray drying, etc. Hot air is directed at the material in order to remove water by causing it to evaporate, as shown schematically Fig. 6.2.

At the product’s surface, the water vapour flux $\dot{m}_v$ (kg m$^{-2}$s$^{-1}$) can be expressed as follows for the situation illustrated in Fig. 6.2:

$$\dot{m}_v = h_m (\rho_{v,2} - \rho_{v,\infty})$$  \hspace{1cm} (Eqn. 6.1)
where $h_m$ is the mass transfer coefficient for the convection boundary (ms$^{-1}$) and is usually taken as the average value over the sample geometry and size; $\rho_{v,s}$ is the vapour concentration at the surface (kgm$^{-3}$); and $\rho_{v,\infty}$ is the vapour concentration in the gas medium (hot air for instance) (kgm$^{-3}$). $h_m$ can be readily calculated based on the mass transfer correlations for Sherwood number ($Sh$) that have been established for various geometries.\(^8\)

When $h_m$ is not dependent much on the boundary layer humidity, and the temperature at the interface is more-or-less constant, equation 6.1 represents a ‘constant-rate of drying’. This means that the surface vapour concentration $\rho_{v,s}$ remains relatively constant. It also means that the surface relative humidity remains constant at near 100%, a level that can be maintained at the surface for some period of time when the water content of the surface remains high (see Fig. 6.3). This is related to the concept of the constant drying rate period. More in-depth analysis about this period of drying has been explored by Schlunder\(^9,10\) and related to cell level information on food surfaces by Chen.\(^11\)

Sometimes a drying rate that is not based on surface area – e.g. the rate per kg water per unit time – has been used, giving results that can be misinterpreted as not having a constant drying rate period. In fact, when

![Equilibrium relationship (isotherm) for surface water content and the relative humidity (RH) of the drying medium at constant temperature of the material being dried (for example the wet-bulb temperature). The dashed line indicates the probable actual RH at the surface as it gets dried and warmed up. $X_{s,c}$ is a critical surface water content below which RH is lower than 100%. The region to the left of $X_{s,c}$ represents the falling drying flux period and to the right of $X_{s,c}$ is the constant drying flux period.](image_url)
taking into account the area change (due to shrinkage) in vegetables, for example, it is found that a constant drying rate period does exist.\textsuperscript{12} May and Perre\textsuperscript{12} suggest that the term constant drying flux period may be better than constant drying rate period.

In general, the drying rate for the whole material may be expressed as:

\[
\frac{dX}{dt} = -m_r \cdot A = -h_m \cdot A \cdot (\rho_{v,s} - \rho_{v,\infty}) \quad \text{(Eqn. 6.2)}
\]

where \(A\) is the surface area that changes as drying takes place (m\(^2\)) and \(m_r\) is the dry mass in the material (kg). One can see that when the concentration is maintained constant, the unit area based drying rate remains constant.

The Sherwood number is usually established in relation to the Reynold’s number, \(Re\), and Schmidt number, \(Sc\):

\[
Sh = \frac{h_m L}{D_v} = f \left( Re = \frac{\rho u L}{\mu}, \ Sc = \frac{\nu}{D_v} \right) \quad \text{(Eqn. 6.3)}
\]

Some standard correlations are given in Appendix I as examples. One can also work out the heat transfer coefficient \(h\) using these correlations by replacing the Sherwood number by the Nusselt number, \(Nu\), and the Prandtl number, \(Pr\), by the Schmidt number, \(Sc\).

When the vapour concentration difference is positive in equation 6.1, water vapour is being removed from the material (product) and the material gets dried. When this difference becomes zero, no more drying takes place. Wetting or vapour re-absorption occurs when this difference becomes negative. Drying ceases when the surface water vapour concentration reaches the equilibrium level that corresponds to the drying medium conditions.

This driving force for drying is sometimes expressed in terms of the difference between the surface water content and the equilibrium water content, \(X_{\infty}\), that corresponds to the drying medium conditions:\textsuperscript{13}

\[
m_r = \beta(X_s - X_{\infty}) \quad \text{(Eqn. 6.4)}
\]

This is qualitatively correct. \(X_{\infty}\) is the equilibrium water content corresponding to the drying medium conditions in terms of temperature and relative humidity. The mass transfer coefficient, \(\beta\), in this case is not a straightforward parameter that can be a non-linear function of some sort, and is not well defined as \(h_m\). Its relationship to the convective vapour transfer coefficient \(h_m\) may be written as follows, by combining equations 6.1 and 6.2:
Drying as a Means of Controlling Food Biodeterioration

\[ \beta = h_m \left( \frac{\rho_{v,\text{sat}} - \rho_{v,\text{eq}}}{X_s - X_{\infty}} \right) \]  \hspace{1cm} (Eqn. 6.5)

Unless the ratio in the brackets remains constant, it is hard to see that \( \beta \) would become constant for a practical range of drying conditions. Nevertheless equations 6.1 and 6.2 convey the same message qualitatively – that water removal in drying processes is due to the difference between the actual and the equilibrium conditions. In cases when \( Sh \) (equation 6.3) is approximately constant, the following equation may be used to illustrate water loss with time:

\[ m_s \cdot \frac{dX}{dt} \approx -\beta \cdot A \cdot (X_s - X_{\infty}) \]  \hspace{1cm} (Eqn. 6.6)

It can be seen that water loss is high at the beginning of drying, as the surface water content is at its highest in the early stages. The surface water content, however, reduces fairly quickly at first and the rate of drying falls as water is removed from the material. This represents the falling drying rate period, when drying rate per unit area is used in the calculations.

As mentioned earlier, the constant drying rate period is well represented by equation 6.1 as the surface vapour concentration can be at the saturated level, i.e. \( \rho_{v,\text{sat}} = \rho_{v,\text{sat}}(T_s) \), which is a function of the surface temperature \( T_s \) only. This often corresponds to a so-called wet-bulb temperature (i.e. \( T_s \approx T_{wb} \)), at which temperature the heat input is balanced by the evaporative heat loss. Constant drying flux period may be a better fundamental term to use. Before the surface reaches the constant drying flux stage, a warming up period (initial drying rate is lower than the constant one) or cooling down period (initial drying rate is higher than the constant one), though they are generally of short duration, may be encountered depending on the initial product temperature (Fig. 6.4). If the initial water content of the material is quite low, for example in the secondary drying stage such as fluidized bed drying after spray drying, the constant drying rate period, whether based on unit area or not, does not exist.

The saturated vapour concentration can be maintained for some time even after the surface water content reduces to some extent. This is determined by the equilibrium relationship between the liquid water content and the relative humidity of the drying medium (see Fig. 6.3). When the surface vapour concentration is below the saturated level, a so-called falling drying rate period or falling drying flux period starts to occur, provided there is not much increase in surface temperature (Fig. 6.3). Different materials exhibit different equilibrium relationships, called the equilibrium isotherms (Figs 6.5 and 6.6). These equilibrium isotherms are commonly
correlated using a GAB model, parameters of which for many food materials are summarized by Rahman.\textsuperscript{14}

Based on the psychrometric charts of gas–vapour systems, measurement of dry- and wet-bulb temperatures can be used to work out the relative humidity of a drying medium.\textsuperscript{1} The vapour concentration in the drying gas

---

**Fig. 6.4** Schematic diagram of the drying periods defined using the relationship between the drying flux and average water content (the surface water content $X_{s,c}$ is lower than $X_c$ under the same drying conditions).

**Fig. 6.5** Qualitative equilibrium isotherms for various types of food material (crystalline sugar is an example of a ‘nearly non-hygroscopic’ material while its amorphous form is an example of a ‘hygroscopic porous medium’).
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at any location inside a dryer is an important parameter for controlling its performance.

The localized evaporation rate within a moist material should be determined by the driving force locally, i.e. the vapour pressure in the dense phase (usually solid structures) and its difference from that in the local ‘headspace’ such as pores or pore-channel space at the same location (Fig. 6.7).

The microstructure has a significant impact on how the evaporation zone is distributed, i.e. whether it is sharp or fuzzy. Microbial cells themselves can be regarded as a sample unit and the drying process across each cell boundary is itself a topic of interest. Their physical size can vary from...
about 1 to 20 µm and their shapes vary as well.\textsuperscript{17} To date modelling or analysis has not gone to this level of detail, but it is expected to move towards this microscopic level in the near future. The transport of water (liquid and vapour) in moist foods can be regarded as transport in porous media, thus many of the recognized principles of heat and mass transfer in such media can be readily used in its analysis. Transport in liquid form is often considered to be capillary flow while vapour flow is diffusive in nature. Transport and vaporization within the material matrix are not easy processes to visualize, and many mechanisms have been proposed; perhaps the best approach may be through the liquid diffusion model.\textsuperscript{18}

In order to provide the latent heat of evaporation, heat must be supplied to the evaporating surface and into the porous material. Fig. 6.2 shows a typical scenario where the heat coming from the hot air is transferred to the product–air interface and subsequently conducted into the moist product. For hot-air drying, the ‘centre and surface’ temperature history of a moist porous material (points A and B, respectively, in Fig. 6.2) and average water loss versus time may be depicted (Fig. 6.8).

![Fig. 6.8 Qualitative illustration of the temperature–time profiles and moisture content–time profile of a material being dried. (It is assumed that the initial water content is fairly high; for natural food materials, this assumption is generally true as their water contents are in the order of 80% by weight. For highly concentrated materials, such as high solids concentrate droplets such as that in milk drying, the pseudo-wet-bulb period may be very short or not exist). $T_A$, temperature of the centre of the material being dried; $T_B$, temperature of the surface of the material being dried; $X$, moisture content.](image-url)
Air drying can also be conducted at temperatures below the freezing point of water provided that the water vapour pressure in the air stream is lower than that at the surface of the material being dried. This low temperature operation – which has been investigated only recently – is called atmospheric freeze drying (AFD). Though the surface vapour concentration at 0°C is approximately only 1/20 of that at 20°C, in the presence of air flow it is possible to compensate for this to some extent by increasing the flow velocity (increasing the mass transfer coefficient).

Analogously to air drying, one can also use an inert gas such as nitrogen as the drying medium. Industrial nitrogen production, using membranes for gas separation, is not so costly these days so it presents an excellent opportunity to keep foods at high quality levels without the introduction of oxygen.

In order to infuse heat more efficiently into the material being dried, microwave radiation is often used. Microwave radiation can penetrate solid materials, and the absorption of energy inside the material is greater where the water content is higher. Liquid diffusion alone may not be the best mechanism to describe this process, as the build-up of pressure inside the material due to a local temperature rise can be significant. The localized formation of vapour bubbles, such as that in bread baking, can be significant, and the bubbles drive liquid ‘columns’ through the capillaries or channels.

Superheated steam drying may be a way of achieving high sterility of the dried product as the product temperature reaches a fairly high value (the boiling temperature of water at one atmosphere, for example). The steam sweeping over the product surface can be used like hot air to accelerate mass transfer.

### 6.2.2 Vacuum drying

Vacuum drying is a process that can be described by equation 6.1, as it is intended that the vapour in the headspace (represented by $\rho_{v,\infty}$) be sucked away. This can be conducted at high or low temperatures. Heat is supplied by either radiation or direct contact conduction. The low temperature (sub-zero) operation is called vacuum freeze drying. The heat supplied is intended to provide the heat of sublimation of ice to water vapour. This process is usually intended to preserve bioactivity rather than to reduce it. However, the same purpose is served as far as the post-process effects are concerned. Vacuum freeze drying is usually aimed at the retention of high levels of nutrient values, and the original structure and colour of natural products.
6.2.3 Drying equipment

In order to dry moist products, a dryer provides a drying medium (usually hot gas) with a temperature and humidity combination such that the vapour pressure at the product surface is higher than that of the drying medium. A large number of such devices are manufactured today, details of which can be found in Mujumdar’s industrial drying handbook and which are summarized by Kudra and Strumillo. Some dryers consume large quantities of energy and usually the energy required by a drying system for every kg of water removed is the most important practical criterion. The heat pump principle is employed for processes at moderate drying rates, but for large-capacity operations it is necessary to remove tonnes of liquid water, which necessitates spray-drying devices. The single stage spray dryer is very energy hungry as it is not easy to recover the lower temperature energy in the warm air coming out of it. Incorporation of internal and external fluidized beds into spray-drying devices is now common as it improves the overall energy consumption.

In pressure driven devices, on the other hand, such as vacuum dryers and vacuum freeze dryers, there is a higher initial capital investment but the energy required for running them is much lower than for a straight evaprotive process. Here, the water vapour pressure around the material being dried is lowered by the vacuum, and lower temperatures can be used.

6.3 BACTERIA DEACTIVATION KINETICS DURING THE DRYING PROCESS (IN-PROCESS PROBLEM)

As already mentioned, significant growth of micro-organisms in a food product can be prevented by lowering its water content by an appropriate drying process to below a certain threshold, giving the desired shelf life, i.e. improving the post-process properties.

For thermal deactivation of micro-organisms, three stages must be considered: pre-treatment, heat treatment and post-treatment. Similarly, treating the drying process as a thermal treatment process, it is appropriate to discuss the effects of drying on micro-organisms in three stages, i.e. pre-drying, in-drying and post-drying. There have been many studies carried out on pre-treatment and post-treatment. It was post-treatment studies or, indeed, common practical observations that established the beneficial effect of the drying procedure as a food preservation technique.

In this section, the in-process or in-drying stage is treated as a thermal processing operation, where, through the influence of heat and mass transfer
going on simultaneously, micro-organisms within the product are deactivated. The in-drying stage may be regarded as a process of inactivation, which generally is good for product safety (of course it is bad for maintaining high levels of useful bioactivity). A fundamental understanding of both sides of the story – heat transfer and mass transfer – can help to improve the quality of the dried product.

Living cells are composed of high-molecular-weight polymeric compounds – proteins, nucleic acids, polysaccharides, lipids and other storage materials such as fat, polyhydroxybutyrate and glycogen. These – the major structural elements of living cells – are called biopolymers. A typical microbial cell wall is comprised of polysaccharides, proteins and lipids. The cell cytoplasm contains proteins that are mostly in the form of enzymes; in eukaryotes, the cell nucleus contains nucleic acids mostly in the form of DNA. Inorganic salts also form part of the cell content and are crucial for keeping cells functioning normally. The macromolecules can only be functional if they are in their proper three-dimensional configurations. The interactions between these molecules are complex. A living cell may be viewed as a chemical reactor in which more than 2000 reactions take place. These interactions can be disturbed or influenced by environmental changes in pH, humidity and temperature, or chemical composition. Both pH and temperature have significant effects on the stability of enzymes, with optimal values of the two parameters conferring the highest stability. In some situations the protein molecular structures are altered irreversibly (unfolding and aggregation) and the functions of the living cell cease. Indeed, most of the macromolecules change to some extent when subjected to elevated temperatures or extremes of pH.

The death of a particular cell is likely to be due to the thermal denaturation of one or more of the essential proteins. The kinetics of the changes in morphology of these molecules may make different contributions to the overall picture of ‘cell death’, and environmental conditions such as pH and water activity all have impacts on cell death. The process is also complicated by the age distribution of the cell populations. As one example, the temperature needed to achieve coagulation of egg protein albumin is very much dependent upon water content. (See Fig. 6.9.)

The thermal stability of micro-organisms is intimately affected by pH. Heat-induced protein molecular changes and cell surface structure and function all vary with varying environmental pH. The pH of foods ranges from 2 to 7. Micro-organisms of different types have corresponding optimal pH values at which they have their highest heat stabilities. These optimal pH values tend to be on the slightly more acidic side (Table 6.1).
Raising or lowering the pH away from the optimal value reduces the thermal stability or the heat resistance of the micro-organisms within a food system. Thermal inactivation of bacteria has been studied extensively for the related kinetics. In their work on *Escherichia coli*, they showed that the following model is useful for describing constant treatment conditions (temperature and pH). The first-order inactivation kinetics follow equation 6.7:

\[
\ln \frac{N}{N_0} = -kt
\]  
(Eqn. 6.7)

where the rate constant, \( k \), is given by:

\[
\ln k = C_o + \frac{C_1}{T} + \frac{C_2}{T^2} + C_3pH + C_4pH^2
\]  
(Eqn. 6.8)

\( C_o \) to \( C_d \) are \(-3613, 2.44 \times 10^6, -4.11 \times 10^8, -1.523 \) and 0.124, respectively, and \( N \) and \( N_0 \) are the numbers of micro-organisms at a given time.

Fig. 6.9  Temperature required for initiating massive irreversible cross-linking of egg protein albumin at different water contents.

Table 6.1  Optimal pH values for selected micro-organisms.

<table>
<thead>
<tr>
<th>Micro-organism</th>
<th>Optimal pH</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Strept. faecalis</em></td>
<td>6.8</td>
</tr>
<tr>
<td><em>Staph. aureus</em></td>
<td>6.5</td>
</tr>
<tr>
<td><em>B. subtilis</em></td>
<td>7.0–7.5</td>
</tr>
<tr>
<td><em>C. sporogenes</em></td>
<td>6.6–7.5</td>
</tr>
<tr>
<td><em>C. botulinum</em></td>
<td>6.7–7.0</td>
</tr>
</tbody>
</table>
and the number at time zero. Experiments on the thermal treatment of micro-organisms at different relative humidity (RH) or water activity ($a_w$) values have revealed a general trend. As the water content is reduced the thermal stability (survival of the micro-organisms in the pre-equilibrated food system (or product)) increases at first and peaks at a water activity between 0.2 and 0.5, but it then reduces rapidly as the material is dried to a very low water content. (This is considered to be the pre-drying or pre-heat treatment phase.) (See Fig. 6.10.) Given this trend, it appears that the in-drying deactivation of micro-organisms is a complex phenomenon.

As drying proceeds, the concentration of the solute in the material increases, which in some cases can lead to pH changes or osmotic imbalance. The residual water within acidic food materials gets more acidic as drying proceeds. One possibility is that drying fixes or ‘freezes’ the structures of the long-chain molecules, causing changes in their preferred three-dimensional configurations and, hence, irreversible damage. When the water content is reduced, the water that associates with the cell constituents that are considered to be protective of cell functions is less available, thus causing reduced thermal stability or heat resistance. Elevated temperatures can cause denaturation (unfolding) of proteins. The combination of temperature and water content is important in determining the extent of micro-organism deactivation. The two are interactive and may sometimes act synergistically. The effect of fixing or freezing may be viewed simply as a ‘scarring of the burnt tissue’ to make it more visual.

The surface of a moist material dries at the fastest rate, and the temperature rise here would be more rapid than anywhere within the material.
(see Fig. 6.8). Fig. 6.11 shows in a qualitative way how the water content at the surface and at the centre of a food material varies with time in the drying process. It is to be expected that the water content distribution inside the material being dried and temperature distribution in the same material are both important in influencing the local rate of micro-organism deactivation. The deactivation of micro-organisms located at or near the surface would have a different rate profile from that inside the material. Furthermore, the status of mineral components and the possibility of generating insoluble metal compounds may also have an impact on bioactivity.\textsuperscript{24}

The inactivation by drying of the microbial population in food systems is dependent on how it is distributed within the food. The micro-organisms may be totally encapsulated and stay in the core region or they may stay near the boundary region. Also food ingredients or additives can have an impact on protecting the cells from thermal damage during drying.\textsuperscript{25–27} For example, when trehalose was added to yeast suspension, there was a significant reduction in damage to the yeast cells.\textsuperscript{28–30}

It is a difficult task to correlate the data concerning cell death before and after a drying operation, largely owing to the complex nature of the inactivation kinetics, as water content and temperature, and sometimes their distributions within the material being dried, have to be taken into account. When the material is in a particulate form, the particles have complicated trajectories when being dried in a spray dryer, a pneumatic dryer or a fluidised-bed dryer. Carrying out measurements on moving particles is virtually impossible.
Lievense et al.\textsuperscript{31} proposed an inactivation kinetics model for the degradation of \textit{Lactobacillus plantarum} during drying by considering thermal and dehydration inactivation as two separate influences but operating simultaneously. The model had ten parameters to be deduced from experimental work. Measurements of the drying parameters were obtained from fluidized-bed drying with drying temperatures below 50°C. The ‘effective diffusivity’ concept was used to take into account the spatial distribution of the moisture. The inactivation parameters were measured from non-drying heating experiments in which approximately 1 mm thick \textit{L. plantarum}-starch granulate was placed in a Petri dish and stored at 5.0 ± 0.5°C in a vacuum desiccator for 48 hours. After 48 hours, the glucose fermenting activity and moisture concentration of the sample were measured. They found that thermal inactivation is insignificant at drying temperatures lower than 50°C. Furthermore, they stated that dehydration inactivation depends on the reached moisture content of the material only and is independent of the drying rate. However, they did not find the same thing for high-temperature drying processes, where drying rates are much higher.\textsuperscript{31}

A similar trend was seen by Yamamoto & Sano\textsuperscript{32}, who proposed a five-parameter model for enzyme inactivation during drying using a single suspended droplet drying experiment. A sucrose solution of fixed water content containing different enzymes such as β-galactosidase, glucose oxidase and alkaline phosphatase was incubated at a constant temperature. The thickness of the material used and the air temperature were not reported in the study. The deactivation energy, $E_d$, was described as a function of the average water content. Again, a binary (water and dissolved solids) diffusion coefficient was introduced to the drying analysis for taking care of the water distribution inside a droplet. They concluded that air temperature and droplet size significantly affect the inactivation rate, while the effect of the initial water content was shown to be insignificant. However, enzyme activity was measured using constant-temperature and constant-moisture content heating experiments, where no evaporation was involved. This work may be classified as a pre-equilibration experiment.

In general, the inactivation kinetics of micro-organisms has been conventionally expressed using a first-order reaction equation:

$$\frac{d(N/N_0)}{dt} = -k_d(N/N_0) \quad \text{(Eqn. 6.9)}$$

where $N$ is the number of live micro-organisms in suspension (cell.m\textsuperscript{-3}), $k_d$ is the inactivation rate constant (s\textsuperscript{-1}) and $N_0$ is the initial cell concentration.
For enzyme inactivation, \( N \) may be replaced by the ‘live’ enzyme concentration (units\( \text{m}^{-3} \)). However, it is now thought that equation 6.9 is not the most appropriate one for describing inactivation kinetics. It is an unstructured model. A structured model that deals with non-log-linear behaviour has been developed, accounting in particular for the tail end of the survival curve.\(^{33}\) However, the in-process behaviour during an industrial drying process may be considered as short-term behaviour, so the tailing effect is not so important. Furthermore, there are complications when involving water removal that would themselves introduce the non-log-linear effect anyway. Therefore, in the discussion here, it is sufficient to consider the first-order inactivation kinetics.

For micro-organisms distributed in a moist material that is not yet dried (i.e. in a saturated medium), \( k_d \) is usually considered to be a function of temperature and is described using the Arrhenius equation.\(^{32,34–36}\) When the in-drying process is considered, the inactivation kinetics should include the material’s temperature as well as moisture concentration effects. In the literature, the temperature dependence of the inactivation rate constant, \( k_d \), during drying has been described using equation 6.10:

\[
k_d = k_0 \exp\left(-\frac{E_d}{RT}\right)
\]  

(Eqn. 6.10)

The moisture content has a significant non-uniformity within the material being dried owing to the nature of the drying process. The temperature distribution may also have an impact on the local distribution of the inactivation rate. The temperature gradient can be significant if the Biot number is quite large (\( Bi = hL/k; h \) is the convective heat transfer coefficient (W\( \text{m}^{-2}\cdot\text{K}^{-1} \)), which can be determined similarly to that for \( h_m; k \) is the thermal conductivity of the moist material (W\( \text{m}^{-1}\cdot\text{K}^{-1} \))). Usually a \( Bi \) of less than 0.1 is considered, beyond which temperature non-uniformity cannot be ignored.\(^8\) However, when evaporation takes place, this non-uniformity is damped and even for some large \( Bi \) values such as 0.5 or 1 a small evaporating water droplet can have negligible temperature gradient.\(^{37,38}\)

Meerdink and Van’t Riet\(^{36}\) studied the inactivation of the enzyme \( \alpha \)-amylase during droplet drying, describing deactivation energy \( E_d \) to be dependent on water content. Their approach is attractive, as it requires only four parameters (\( a, b, k_0 \) and \( E_d \)); two more coefficients are required compared with the simple first-order kinetics (equation 6.9). These parameters have to be obtained from experimental work. The inactivation rate constant is expressed using the following formula:

\[
k_d = k_0 \exp\left(aX - \frac{E_d + bX}{RT}\right)
\]  

(Eqn. 6.11)
where \( k_0 \) is a pre-exponential factor and \( X \) is the water content expressed as a fraction of the dry weight. Meerdink and Van’t Riet\(^{36} \) concluded that the inactivation rate is more sensitive to a material’s temperature changes than the drying rate. As a reference, equation 6.11 for \( \alpha \)-amylase had the following approximate correlation constants: \( k_0 = 1.2426 \times 10^{32} \text{ (s}^{-1}) \); \( a = 121.8 \text{ (J.mol}^{-1}) \); \( b = 341 \); and \( E_d = 247.3 \times 10^3 \text{ (J.mol}^{-1}) \). \( R \) is the universal gas constant (8.31 J.mol\(^{-1}\).K\(^{-1}\)). In order to show the effect of local water content and temperature during the drying process, equation 6.11 is assumed to be valid for both enzymes and cell materials. Equation 6.11 can be modified as:

\[
k_d = k_0 e^{ax} \exp \left( -\frac{E_d}{RT} - \frac{bX}{RT} \right) \quad \text{(Eqn. 6.11a)}
\]

The nature of the equation is such that:

- if \( a > 0, b > 0 \), \( k_d \) may have a peak value in the water content range considered
- if \( a > 0, b < 0 \), \( k_d \) would just reduce as water content decreases
- if \( a < 0, b > 0 \), \( k_d \) may have a minimum in the water content range considered.

These possibilities are dependent on the coefficients’ value ranges, which may or may not show a minimum or maximum in the water content range considered. In order to show the effect of drying on the survival of microorganisms, equation 6.11a should be integrated across the material domain of interest. The first-order kinetics as in equation 6.9, where \( \phi = N/N_0 \), are modified as:

\[
\frac{d\phi}{dt} = -k_0 e^{ax} \exp \left( -\frac{E_d}{RT} - \frac{bX}{RT} \right) \cdot \phi \quad \text{(Eqn. 6.9a)}
\]

For simplicity, an infinite slab geometry is considered (see Fig. 6.12). \( x = 0 \) is the symmetry of the slab, which is symmetrically heated and dried. The derivation procedure is given below. Integrating equation 6.9a from \( x = 0 \) to \( x = L \), gives the average change in average activity or average cell concentration as:

\[
\frac{d\bar{\phi}}{dt} \approx \frac{k_0}{L} \int_{0}^{L} e^{ax} \exp \left( -\frac{E_d}{RT} \right) \exp \left( \frac{bX}{RT} \right) \cdot \phi \cdot dx \quad \text{(Eqn. 6.12)}
\]

\[
= \frac{k_0}{L} \int_{0}^{L} e^{\left( \frac{a-b}{RT} \right)x} \exp \left( \frac{E_d}{RT} \right) dx
\]
In this step the average temperature is chosen for the second term in the exponential function in equation 6.9a, so that the effect of water content \( X \) and the temperature effect can be separated for ease of analysis.

This equation can be further simplified based on the Frank–Kamenetskii transformation to yield the following:

\[
\frac{1}{\theta} \frac{d\theta}{dt} = -k(X, T) \cdot N
\]

(Eqn. 6.13)

where \( \theta = \frac{E}{RT_{ref}}(T - T_{ref}) \)

(Eqn. 6.14)

In general, industrial drying operations involve reduction in the moisture content of the material during processing, as well as an increase in the temperature of the material. It should be noted that the inactivation rate usually increases with increasing temperature and is reduced with reducing moisture content. Hence, the overall inactivation is a ‘competitive’ process between the two different inactivation mechanisms. However, the contribution of each inactivation mechanism during processing is not very well understood, though as mentioned earlier, the lowering water content...
may have less effect that the rising temperature. It would be an interesting task to discover the controlling inactivation parameters during different phases of a drying process. This information could be very helpful for process design and optimization to achieve higher ‘kill’ of unwanted bacteria. Equation 6.13 can be further written as:

\[
\frac{1}{\phi} \frac{d\phi}{dt} = -\frac{\kappa_0}{L} \int_{x=0}^{x=L} \exp(\tilde{a}X + \theta)dx 
\]  
(Eqn. 6.15)

where \( \kappa_0 = k_0e^{E_0/RT_{ref}} \) and \( \tilde{a} = \left(a - \frac{b}{R \cdot T}ight) \).

By rearranging equation 6.15, one can obtain the following:

\[
\frac{1}{\phi} \frac{d\phi}{dt} = -\frac{\kappa_0}{L} \left[ \int_{x=0}^{x=L} d(e^{\tilde{a}X + \theta}) - \int_{x=0}^{x=L} xd(e^{\tilde{a}X + \theta}) \right] 
\]  
(Eqn. 6.16),

introducing a characteristic dimension \( (x_c < L) \) in such a way that the second integral on the right hand side of the above equation can be simplified. This expression further results in a simple formula from equation 6.16 as follows:

\[
\frac{1}{\phi} \frac{d\phi}{dt} = -\frac{\kappa_0}{L} \left[ e^{\tilde{a}x_c + \theta}L - \int_{x=0}^{x=L} xd(e^{\tilde{a}X + \theta}) \right] 
\]  
(Eqn. 6.17)

The dynamics of the above equation are shown to be clearly dependent on the surface water content and surface temperature, as well as the progression of the characteristic distance \( x_c \) into the droplet/particle or a thin-layer slab as drying proceeds. This characteristic distance may be a fraction of \( L \) that would stay relatively constant in the falling drying flux period if the mass transfer process is viewed as a similar process to that in the heat conduction situation considered by van der Sman.\(^{40}\) In other words similarity of the moisture-content profile is maintained in this period of drying.

For the case of a moist slab, where the surface and the centre temperatures can be considered similar (i.e. \( \theta_s \approx \theta_c \)), equation 6.17 can be further re-written as:
This expression illustrates that the dynamics of the inactivation kinetics are determined by both the surface and the centre water content.

When the drying kinetics are modelled using a common lumped-parameter model where the rate is expressed as a function of the mean water content, the different but perhaps rather significant roles played by the surface and the centre water content cannot be addressed. This is interesting, and it has been argued that the moisture distribution effect can be significant depending on how quickly the water content is distributed. The apparent ‘drying rate dependent inactivation model’ has been found to be a useful correlation if one uses the lumped-parameter model to describe the bulk behaviour (rather than local cell content) for constant drying conditions. Chen and Patel have shown that the drying rate dependency is a reasonable approach by deriving the rate dependency from equation 6.18. All these studies have shown that even if the cells are uniformly distributed in the porous medium to be dried, the local water content can be influential to the average inactivation rate. If the initial cell distribution in a product to be dried is not uniform, it is likely that the uneven distribution will affect the rate of reduction of average cell concentration. It is, therefore, highly desirable for process simulation and process optimization purposes (for either protecting or deactivating cell matter in drying), that the local moisture content distribution should be describable. Most often, the local water moisture content is predicted using a Fickian type effective liquid diffusion model, an approach that can be found in many previous studies (Chen, 2006).

With the development of cellular level or even biomolecular level studies, one may expect that how individual components \( i \) (in each micro-organism) denature or deactivate and their ‘weighted’ contribution to the overall inactivation kinetics will eventually be revealed. For instance for a microbial population \( N \), the rate expression for inactivation may be written as:

\[
\frac{dN}{dt} = -\sum_{i=1}^{I} \xi_i \cdot a_i \quad \text{(Eqn. 6.19)}
\]

where \( I \) is the total number of components that are influential in the survival of the micro-organism of concern and \( \xi_i \) is the weight factor of each contributing component. \( a_i \) is the remaining activity (or sometimes concentration) of each component (for example, it could be an enzyme inside a microbe). Each activity is determined by its own inactivation kinetics. If they are considered to have a format as in equation 6.9, for example, the following would have to be determined:
The sum of $\zeta_i$ is unity. It may be that for one or two enzymes or components in the micro-organism even a small amount of damage to their structures could lead to the micro-organism’s being pronounced ‘dead’. In this case, the contributions made by them to the overall inactivation of the cell would be $\geq 90\%$. The above must be taken as a qualitative understanding that should be useful in thinking about strategies for drying–inactivation problems with regard to the contribution of individual cell contents.

Drying can not only minimize the potential for food spoilage as a post-process effect, but it can also act as a thermal treatment procedure (i.e. an in-process operation) to reduce the populations of micro-organisms.

6.4 CONCLUDING REMARKS

Drying can be used for controlling food biodeterioration for two reasons: the in-process and post-process effects, the latter being much better understood than the former. Drying (an in-process operation) can be regarded as a thermal treatment procedure that deactivates undesirable micro-organisms that are distributed or embedded in the food systems (protein, carbohydrate and fat matrices in different proportions). The process of inactivation is dependent on cell structure and composition. It is intuitive to think that the constituents of each micro-organism – enzymes for instance – with their sensitivities to temperature, water content and pH (and even pressure) changes have their own inactivation kinetics that must contribute to the overall cell inactivation kinetics. The average inactivation rate of the micro-organisms in a food being dried is dependent on the thermal and water content history of the food system during processing or storage. It is also dependent on the food’s composition, microstructure (leading to different heat and mass transfer properties) and physical size. How drying is conducted has to be determined in the interests of preserving nutrients and beneficial bacteria, and yet for eliminating toxic bacterial activities. It is not a simple matter, so the process has to be looked at in conjunction with pre-drying and post-drying procedures to achieve an optimized (and most likely a compromised) outcome. Most studies reported in the literature are not aimed at inactivation of the bacteria but are aimed at high retention of bioactivity. Therefore, there is still considerable scope for more fundamental research in this area so that one can make better and more informed decisions for future operations.
APPENDIX 1: TYPICAL MASS TRANSFER CORRELATIONS

Heat convection is a well-studied subject and is described in many texts. Mass transfer calculations can be done, as a first approximation, based on heat transfer correlations. The mass transfer coefficient ($h_m$) is obtained from established correlations for the Sherwood number ($\frac{h_m \cdot L}{D}$) (originally for Nusselt number ($\frac{h \cdot L}{k}$)). $L$ is the characteristic length of the object (m) and $k$ is the thermal conductivity of the bulk fluid (W.m$^{-1}$.K$^{-1}$). The two principal numbers are related to the Reynolds number ($\frac{\rho \cdot u \cdot L}{\mu}$), the Prandtl number ($\frac{\nu}{\alpha}$) or Schmidt number ($\frac{\nu}{D}$), respectively. $u$ is the bulk fluid velocity (m.s$^{-1}$), $\rho$ is the fluid density (kg.m$^{-3}$), $\mu$ is the viscosity (Pa.s) and $\alpha$ is the thermal diffusivity (m$^{2}$.s$^{-1}$) and $D$ is the mass diffusivity (m$^{2}$.s$^{-1}$). All the physical properties used in the calculations are usually determined at the film temperature ($T_f$) and film concentration ($C_f$). Table A1 shows typical correlations that may be used as a first approximation for evaluating mass transfer coefficients.

Table A1 Commonly used mass transfer correlations for average Sherwood number calculations (modified from Incropera and De Witt). 8

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Geometry</th>
<th>Conditions</th>
<th>Correlation</th>
</tr>
</thead>
</table>
| External flow (forced convection) | Flat plate | Laminar, $0.6 \leq Pr \leq 50$  
Mixed, $Re_{t,\alpha} = 5 \times 10^3$, $Re_t \leq 10^3$, $0.6 \leq Pr \leq 50$, $L$ - length of the plate (m) | $\tilde{S}_h = 0.664Re_{t}^{1/2}Sc^{1/3}$ |
| Cylinder (pipe or tube) | Cylinder (pipe or tube) | $Re_{Pr} > 0.2$, $L$ - diameter ($L = d$)  
$L$ - length of the plate (m) | $\tilde{S}_h = (0.037Re_{t}^{4/5} - 871)Sc^{1/3}$ |
| External flow (natural convection) | Sphere | $L$ - diameter ($L = d$)  
$L$ - length of the plate | $\tilde{S}_h = 0.3 + \left[1 + \left(\frac{0.4}{Sc}\right)^{1/3}\right]^{-1/4}$ |
| | Vertical plate | | $\tilde{S}_h = 2 + 0.6Re_{t}^{1/2}Sc^{1/3}$ |
| | | | $\tilde{S}_h = \left[0.825 + \left(\frac{0.387Re_{t}^{1/6}}{1 + \left(\frac{0.492}{Sc}\right)^{1/16}}\right)^{6/27}\right]^{-2}$ |
### Table A1 (continued)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Geometry</th>
<th>Conditions</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder [pipe or tube]</td>
<td>$L = d$ (diameter), $Ra_1 \leq 10^{12}$</td>
<td>$\overline{Sh}_t = \left[0.60 + \frac{0.387Ra_1^{1/6}}{1 + \frac{0.559}{Sc}}\right]^{2}$</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td>$L = d$ (diameter), $Pr \geq 0.7$, $Ra_1 \leq 10^{11}$</td>
<td>$\overline{Sh}_t = 2 + \frac{0.589Ra_1^{1/6}}{1 + \frac{0.469}{Sc}}$</td>
<td></td>
</tr>
<tr>
<td>Internal flow [forced convection]</td>
<td>Laminar</td>
<td>Fully developed, uniform wall heat flux, $Pr \geq 0.6$, $L = 4A_r/P$ (hydraulic diameter), $A_r$ = flow cross-sectional area, $P$ = wetted perimeter</td>
<td>$\overline{Sh}_t = 4.36$</td>
</tr>
<tr>
<td></td>
<td>Fully developed, uniform wall temperature, $Pr \geq 0.6$, $0.6 \leq Pr \leq 16,700$, Length/diameter $\geq 10$, $Re_1 \geq 10,000$, $\mu_s$ = viscosity at wall</td>
<td>$\overline{Sh}_t = 3.66$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turbulent, fully developed, $0.6 \leq Pr \leq 16,700$, $\beta = \frac{1}{T_f}$, $\alpha = \frac{1}{T_w}$,</td>
<td>$\overline{Sh}_t = 0.027Re_1^{2/3}Sc^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14}$</td>
<td></td>
</tr>
<tr>
<td>Internal flow [natural convection]</td>
<td>Horizontal cavity heated from below</td>
<td>$Ra_1 = \frac{g\beta(T_b - T_s)\nu^3}{\alpha V}$</td>
<td>$\overline{Sh}_n = 0.069Re_1^{1/3}Sc^{0.074}$</td>
</tr>
<tr>
<td></td>
<td>$T_b$ = the bottom surface temperature, $T_s$ = the upper surface temperature, $\beta$ = thermal expansion coefficient (= $1/T_f$), $L$ = distance between two horizontal walls, $3 \times 10^6 \leq Ra_1 \leq 7 \times 10^9$, $2 &lt; H/L \ll 10$, $Pr \leq 10^4$, $10^3 \leq Ra_1 \leq 10^{10}$, $H$ = height of the cavity, $L$ = distance between two vertical walls</td>
<td>$\overline{Sh}_n = 0.22\left(Sc^{0.28}Ra_1^{0.28}\nu^{0.29}\frac{H}{T}\right)^{0.25}$</td>
<td></td>
</tr>
<tr>
<td>Combined natural and forced convection</td>
<td>Vertical cavity heated from one side and cooled at the other</td>
<td>$n$ is often quoted to be 3 though 7/2 and 4 are better for transverse flows (i.e. two effects are 'opposite to each other' and the sign in the correction is '−')</td>
<td>$\overline{Sh}_n = \overline{Sh}_n^{\text{forced}} \pm \overline{Sh}_n^{\text{natural}}$</td>
</tr>
</tbody>
</table>
REFERENCES

15. Aguilera and Stanley . . .


7 Modified Atmosphere Packaging (MAP)

Brian P.F. Day

7.1 INTRODUCTION

Food preservation technology and packaging developments often go hand-in-hand, with MAP being one of the most popular and innovative techniques. MAP is an increasingly used food preservation technique that minimally affects the characteristics of fresh food, and hence fits in well with current consumer demands for fresh, healthy, convenient and additive-free food. MAP is now being used for extending the shelf life, improving the product image and reducing the wastage of a wide range of chilled perishable foods, as well as ambient-stable food products. 1–3

The application of MAP for maintaining the quality and assuring the safety of perishable food items is a complicated subject, but guideline documents are available to help food manufacturers with the implementation of MAP technology.1,3,4 This chapter provides an overview of MAP technology and highlights the effects of MAP on the spoilage mechanisms of selected major food applications. The MAP of fresh fruit and vegetables is covered in more depth as an example of how this preservation technology extends shelf life by inhibiting the rate of biodeterioration. Finally, summary details of an expert system for MAP are outlined along with concluding remarks about future MAP trends.3,5

7.2 BACKGROUND INFORMATION

The use of gases for the preservation of food products has been known for over a century but during the last three decades there has been considerable growth in the volume and applications of MAP for extending the shelf life of foods. Retail sales of fresh, healthy and convenient perishable food products have shown explosive growth during recent years. Such foods demand rationalization and control throughout the entire chilled distribution chain and major retailers have embraced MAP as a preservation technique to meet their logistical supply requirements.
7.2.1 MAP and related terminologies and technologies

MAP involves the removal of air from the package and its replacement with a single gas or mixture of gases that are different from the normal composition of air (78.08% nitrogen (N₂), 20.96% oxygen (O₂), 0.04% carbon dioxide (CO₂), variable amounts of water vapour and traces of inert gases). It should be noted that the gaseous atmosphere inside a modified atmosphere (MA) pack changes continuously during storage owing to absorption of gases, respiration of certain food products, biochemical reactions and exchange of gases through the MA pack. MAP is related to the following technologies:

1. Controlled atmosphere packaging (CAP) is often used synonymously with MAP but this terminology is a misnomer since it is not possible to control the in-pack atmosphere once the pack has been hermetically sealed.

2. Controlled atmosphere storage (CAS) is similar to MAP in that it involves the storage of food in an atmosphere different from air. However, in CAS the gaseous components are precisely adjusted to specific concentrations throughout the storage and distribution of perishable foods. CAS is used in the bulk warehouse storage of fruit and vegetables and the road or sea-freight transportation of perishable foods. Hypobaric or low-pressure storage is a form of CAS where the pressure is accurately controlled along with the temperature and relative humidity. Although hypobaric storage is relatively expensive, it has been used for the bulk storage of soft fruits.

3. Vacuum packaging (VP) involves the simple evacuation of air from within a pack prior to hermetic sealing. Hence, VP does not involve the replacement of the evacuated air with a gas mixture, as is the case with MAP. Nevertheless, VP does reduce the partial pressure of atmospheric gases within the vacuum packs and hence is capable of extending the shelf life of perishable foods.

4. Active packaging (AP) refers to the incorporation of certain additives into packaging film or within packaging containers with the aim of maintaining and extending food product shelf life. Packaging may be termed active when it performs some desired role in food preservation other than providing an inert barrier to external conditions. AP includes additives or ‘freshness enhancers’ that are capable of scavenging or releasing O₂ and CO₂ and hence the effects of AP on food products can be similar to those achieved through MAP.

7.2.2 Gases used for MAP

The gas mixture used in MAP (Table 7.1) must be chosen to meet the needs of the specific food product, but for nearly all products this will be some combination of CO₂, O₂ and N₂.1–3,5
7.2.2.1 Carbon dioxide (CO₂)

CO₂ has bacteriostatic and fungistatic properties and will retard the growth of mould and aerobic bacteria. The combined negative effects on various enzymic and biochemical pathways result in an increase in the lag-phase and generation time of susceptible spoilage microorganisms. However, CO₂ does not retard the growth of all types of microorganisms. For example, the growth of lactic acid bacteria is improved in the presence of CO₂ and a low O₂ content. CO₂ has little effect on the growth of yeast cells. The inhibitory effect of CO₂ is increased at low temperatures because of its enhanced solubility in water to form a mild carbonic acid. The practical significance of this is that MAP does not eliminate the need for refrigeration. The absorption of CO₂ is highly dependent on the water and fat content of the product. Excess CO₂ absorption can reduce the water-holding capacity of meats, resulting in unsightly drip. In addition, some dairy products can be tainted, and fruit and vegetables can suffer physiological damage owing to high CO₂ levels. If products absorb excess CO₂, the total volume inside the package will be reduced, giving a vacuum package look known as ‘pack collapse’.

### Table 7.1 Gas-mix guide for the MAP of retail food products (adapted with permission from Air Products PLC³).

<table>
<thead>
<tr>
<th>Food Item</th>
<th>CO₂ (%)</th>
<th>O₂ (%)</th>
<th>N₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat (red)</td>
<td>15–30</td>
<td>70–85</td>
<td>–</td>
</tr>
<tr>
<td>Meat (cured)</td>
<td>30–40</td>
<td>–</td>
<td>60–70</td>
</tr>
<tr>
<td>Meat (cooked)</td>
<td>30–40</td>
<td>–</td>
<td>60–70</td>
</tr>
<tr>
<td>Offal (raw)</td>
<td>15–25</td>
<td>75–85</td>
<td>–</td>
</tr>
<tr>
<td>Poultry (white)</td>
<td>30–40</td>
<td>0–20</td>
<td>50–70</td>
</tr>
<tr>
<td>Poultry (reddish)</td>
<td>25–35</td>
<td>65–75</td>
<td>–</td>
</tr>
<tr>
<td>Fish (white)</td>
<td>35–45</td>
<td>25–35</td>
<td>25–35</td>
</tr>
<tr>
<td>Fish (oily)</td>
<td>35–45</td>
<td>–</td>
<td>55–65</td>
</tr>
<tr>
<td>Crustaceans and molluscs</td>
<td>35–45</td>
<td>25–35</td>
<td>25–35</td>
</tr>
<tr>
<td>Fish (cooked)</td>
<td>25–35</td>
<td>–</td>
<td>65–75</td>
</tr>
<tr>
<td>Pasta (fresh)</td>
<td>25–35</td>
<td>–</td>
<td>65–75</td>
</tr>
<tr>
<td>Ready meals</td>
<td>25–35</td>
<td>–</td>
<td>65–75</td>
</tr>
<tr>
<td>Combination products</td>
<td>25–35</td>
<td>–</td>
<td>65–75</td>
</tr>
<tr>
<td>Cheese (hard)</td>
<td>100</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cheese (soft)</td>
<td>35–45</td>
<td>–</td>
<td>55–65</td>
</tr>
<tr>
<td>Other dairy products</td>
<td>–</td>
<td>–</td>
<td>100</td>
</tr>
<tr>
<td>Fresh fruit/vegetables</td>
<td>3–10</td>
<td>2–10</td>
<td>80–95</td>
</tr>
<tr>
<td>Vegetables (cooked)</td>
<td>25–35</td>
<td>–</td>
<td>65–75</td>
</tr>
<tr>
<td>Liquid foods &amp; beverages</td>
<td>–</td>
<td>–</td>
<td>100</td>
</tr>
<tr>
<td>Carbonated soft drinks</td>
<td>–</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Bakery products</td>
<td>60–100</td>
<td>–</td>
<td>0–40</td>
</tr>
<tr>
<td>Dried food products</td>
<td>–</td>
<td>–</td>
<td>100</td>
</tr>
</tbody>
</table>
7.2.2.2 Oxygen ($O_2$)

In MAP, $O_2$ levels are normally set as low as possible to inhibit the growth of aerobic spoilage micro-organisms and to reduce the rate of oxidative deterioration of foods. However, there are exceptions; for example, $O_2$ is needed for fruit and vegetable respiration, colour retention in red meats or to avoid anaerobic conditions in white fish MA packs.

7.2.2.3 Nitrogen ($N_2$)

$N_2$ is effectively an inert gas and has a low solubility in both water and fat. In MAP, $N_2$ is used primarily to displace $O_2$ in order to retard aerobic spoilage and oxidative deterioration. Another role of $N_2$ is to act as a filler gas so as to prevent pack collapse.

7.2.2.4 Carbon monoxide (CO)

CO produces a stable, cherry red colour of meat (carboxymyoglobin) owing to its strong binding to the muscle pigment deoxymyoglobin (see Fig. 7.1). CO in MAP has been used commercially for retail red meat

![Fig. 7.1](image_url)
packaging in Norway since 1985. In 2002, CO in MAP was introduced for industrial master-bag packaging in the USA. Growing interest for commercial use and research on CO has lately been seen in the USA, and planned commercialization of CO technology took place in New Zealand and Australia during 2004. Low concentrations of CO (<0.5%) combined with anaerobic high CO₂ atmospheres improve meat colour; inhibit lipid oxidation, bone discoloration and premature browning of cooked meat; extend microbiological shelf life; reduce the growth of certain pathogenic bacteria; pose no toxic hazard to consumers and are safe to use in meat packaging plants.⁷

7.2.2.5 Argon (Ar)

Ar is classified as a miscellaneous additive and is a permitted gas for food use in the European Union. Air Liquide SA (Paris, France) has stimulated commercial interest in the potential MAP applications of using Ar. Spencer⁸ claims that >200 food products in the UK and elsewhere in Europe, including a wide range of ready-to-eat foods, are MA packed in Ar-containing gas mixtures. Air Liquide’s broad range of patents claim that in comparison with N₂, Ar can more effectively inhibit enzymic activity, microbial growth and degradative chemical reactions in selected perishable foods.

Although Ar is chemically inert, Air Liquide’s research has indicated that it does have biochemical effects, probably owing to its similar atomic size to molecular O₂ and its higher density and solubility in water compared with N₂ and O₂.⁹ Hence Ar is probably more effective at displacing O₂ from cellular sites and enzymic O₂ receptors, with the result that oxidative deterioration reactions are likely to be inhibited.¹⁰ More independent research is needed to better understand the potential beneficial effects of Ar. Research carried out by Air Products has shown that Ar demonstrates some properties that are beneficial, but the argument for replacing N₂ with Ar is marginal, especially when the additional costs of the gas and associated piping are taken into account.³

7.2.2.6 Other gases

Other gases such as ozone, nitrous oxide, ethylene oxide, helium, neon, propylene oxide, ethanol vapour, hydrogen, sulphur dioxide and chlorine have been used experimentally or on a restricted commercial basis to extend the shelf life of a number of food products. However, the commercial use of these other gases is severely limited owing to safety concerns, regulatory constraints, negative effects on sensory quality or economic factors.¹
7.2.3 The benefits and disadvantages of MAP

Any food manufacturer considering the use of MAP should first evaluate the benefits of extended shelf life under MAP, and then compare these benefits against the additional cost of using this preservation system. The benefits of MAP include:

- the ability to use centralized packaging and distribution and hence alleviate the need for in-store packaging
- better utilization of labour and equipment by flattening production peaks and allowing longer runs of individual food products
- economies of scale by facilitating the purchase of larger quantities of raw materials
- enhancement of sales appeal owing to the attractive colour and presentation of food products
- sealed hygienic packs that prevent drips and odours emanating from them during distribution
- enables longer supply chain distances and helps increase product markets
- eliminates the need for artificial preservatives.

Against these benefits, the following disadvantages of MAP must be considered:

- the capital cost of MAP machinery and accessories
- the cost of gases and specialized MAP materials
- the cost of gas analysis and seal integrity testing equipment
- increased pack volume, which will affect transport costs and display in retail stores.

7.2.4 Effects of MAP on microbial spoilage

In order to assess the potential responses of micro-organisms to modifications in gaseous atmospheres, it is necessary to understand the varying gaseous requirements that bacteria, yeasts and moulds need for respiration and metabolism. Micro-organisms are classified according to their O₂ requirements as follows:

- Aerobic micro-organisms require O₂ for growth, e.g. *Pseudomonas* species, some *Bacillus* species, *Acinetobacter/Moraxella* species, *Micrococcus* species, film yeasts and moulds. Therefore some control of the growth of these micro-organisms can be obtained by excluding O₂ from MA packs.
- Microaerophilic micro-organisms require low levels of O₂ for optimal growth. In addition, some may require increased levels of CO₂ for optimal growth, e.g. Campylobacter and Lactobacillus species.
- Facultative anaerobic micro-organisms are able to grow in the presence or absence of O₂, e.g. Escherichia coli, Staphylococcus aureus, Listeria monocytogenes, Brochothrix species, Salmonella species, Vibrio species, fermentative yeasts and some Bacillus species.
- Anaerobic micro-organisms are inhibited or killed by O₂, e.g. Clostridium species.

From a microbiological point of view, CO₂ is the most important gas used in MAP. CO₂ may kill, inhibit, have no effect on, or stimulate the growth of micro-organisms. The ability of CO₂ to inhibit micro-organisms is a complex phenomenon that depends not only on the concentration of CO₂ but also on the water activity (a_w), acidity (pH), temperature, and numbers and age of the micro-organisms present.

N₂ has no direct inhibitory effect on microbial growth. Its indirect effect is due to its displacement of O₂, thereby creating an anaerobic or microaerophilic environment. Facultative, microaerophilic or anaerobic organisms may therefore grow in place of normal aerobic microbial flora.

### 7.2.4.1 Effects on spoilage micro-organisms

In order to extend the shelf life of foods by retarding microbial spoilage, CO₂ is used either alone or with N₂ and/or O₂. Concentrations of CO₂ > 5% inhibit the growth of a broad spectrum of food spoilage bacteria, yeasts and moulds. Inhibition increases almost linearly with increasing concentration from 5% to about 25–50%, depending on the food and microflora involved. Still higher concentrations generally show little or no increased effect. CO₂ is particularly inhibitory to many spoilage micro-organisms that grow on a wide range of chilled foods. The degree of inhibition varies widely because the effect is distinctly selective, but certain generalizations can be made. Moulds are sensitive, yeasts comparatively resistant (except for some of the non-fermentative types), and bacteria are highly variable in their sensitivity. The most affected bacteria are Pseudomonas species and Acinetobacter/Moraxella species, which grow rapidly and produce off-odours and flavours in raw meats and other flesh foods. Other common spoilage bacteria, such as Micrococcus species and Bacillus species, are also strongly inhibited by CO₂. Lactobacillus species are generally among the most resistant bacteria to CO₂. They do not readily spoil foods, unless present at very high levels, and commonly outgrow aerobic spoilage bacteria in most MAP applications.
7.2.4.2 Effects on food poisoning micro-organisms

Knowledge of the effects of CO₂ on food poisoning micro-organisms is incomplete, especially for *Listeria monocytogenes*, *Aeromonas hydrophilia* and *Yersinia enterocolitica*. Generally speaking, high levels of CO₂ have been found to have an inhibitory effect on *Staphylococcus aureus*, *Salmonella* species, *Escherichia coli* and *Listeria monocytogenes*. The degree of inhibition increases as the temperature decreases, but high CO₂ levels alone cannot be relied on to inhibit the growth of the above bacteria.

Many concerns have been raised regarding the potential growth of anaerobic *Clostridium* species in MAP. *Clostridium botulinum* and *Clostridium perfringens* are not markedly affected by the presence of CO₂ and their growth is encouraged by anaerobic conditions that may exist in MAP. Strict temperature control is essential to prevent the growth of *Clostridium* species. Although *C. perfringens* exhibits a 12–20°C growth minimum and most strains of *C. botulinum* do not grow below 10°C, non-proteolytic *C. botulinum*, i.e. types B, E and F, have been demonstrated to grow at temperatures as low as 3.3°C. Consequently, the use of additional barriers to microbial growth (such as acidification, use of preservatives and/or a reduction in aw), wherever appropriate, is strongly recommended. ¹

7.3 MAP MATERIALS

Specifically with regard to MAP, the main characteristics to consider when selecting packaging materials are gas permeability, water vapour transmission rate (WVTR), mechanical properties, reliability of sealing, transparency, type of package and microwaveability.¹,³

7.3.1 Gas permeability

In most MAP applications, excluding fresh fruit and vegetables, it is desirable to maintain the atmosphere initially incorporated into the MA pack for as long a period as possible. The correct atmosphere at the start will not serve for long if the packaging material allows it to change too rapidly. Consequently, packaging materials used with all forms of MA-packed foods (with the exception of fresh fruit and vegetables) should have barrier properties (Table 7.2).

The permeability of a particular packaging material depends on several factors such as the nature of the gas, the structure and thickness of the material, the temperature and the relative humidity (RH). Although CO₂, O₂ and N₂ permeate at quite different rates, the order CO₂ > O₂ > N₂ is
Table 7.2  Oxygen permeability and water vapour transmission rates of selected MAP materials (adapted with permission from Day1).

<table>
<thead>
<tr>
<th>Packaging film* (25 µm)</th>
<th>Oxygen transmission rate (cm³m⁻² day⁻¹ atm⁻¹)</th>
<th>Relative permeability at 23°C:0% RH</th>
<th>Water vapour transmission rate (g m⁻² day⁻¹)</th>
<th>Relative water vapour transmission rate at 38°C:90% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium (Al)</td>
<td>&lt;0.1c</td>
<td>&lt;0.1c</td>
<td>Barrier, &lt;10</td>
<td>Variable</td>
</tr>
<tr>
<td>Ethylene–vinyl alcohol (EVOH)</td>
<td>0.2–1.6d</td>
<td>Barrier &lt;50</td>
<td>0.3–3.2</td>
<td>Barrier, &lt;10</td>
</tr>
<tr>
<td>Polyvinylidene chloride (PVdC)</td>
<td>0.8–9.2</td>
<td>Semi-barrier 50–200</td>
<td>25</td>
<td>Semi-barrier, 10–30</td>
</tr>
<tr>
<td>Modified nylon (MXDE)</td>
<td>2.4d</td>
<td>Medium 200–5000</td>
<td>6–8</td>
<td>Barrier, &lt;10</td>
</tr>
<tr>
<td>Polyester (PET)</td>
<td>50–100</td>
<td>Barrier &lt;10</td>
<td>20–30</td>
<td>Semi-barrier, 10–30</td>
</tr>
<tr>
<td>Polyamide (nylon) (PA6)</td>
<td>80d</td>
<td>Barrier &lt;10</td>
<td>200</td>
<td>Very high, 200–300</td>
</tr>
<tr>
<td>Modified polyester (PETG)</td>
<td>100</td>
<td>Semi-barrier 50–200</td>
<td>60</td>
<td>Medium, 30–100</td>
</tr>
<tr>
<td>Metallized orientated polypropylene (MOPP)</td>
<td>100–200d</td>
<td>High 5000–10000</td>
<td>200</td>
<td>Very high, 200–300</td>
</tr>
<tr>
<td>Polyvinyl chloride (plasticized) (PVC)</td>
<td>2000–5000e</td>
<td>Very high, 200–300</td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Oriented polypropylene (OPP)</td>
<td>2000–2500</td>
<td>Barrier, &lt;10</td>
<td>7</td>
<td>Barrier, &lt;10</td>
</tr>
<tr>
<td>High density polyethylene (HDPE)</td>
<td>2100</td>
<td>Barrier, &lt;10</td>
<td>170</td>
<td>High, 100–200</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>2500–5000</td>
<td>110–160</td>
<td>High, 100–200</td>
<td></td>
</tr>
<tr>
<td>Oriented polystyrene (OPS)</td>
<td>2500–5000</td>
<td>170</td>
<td>High, 100–200</td>
<td></td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>3000–3700</td>
<td>10–12</td>
<td>Semi-barrier, 10–30</td>
<td></td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>4300</td>
<td>180</td>
<td>Very high, 100–200</td>
<td></td>
</tr>
<tr>
<td>Low density polyethylene (LDPE)</td>
<td>7100</td>
<td>16–24</td>
<td>Semi-barrier, 10–30</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl chloride (highly plasticized) (PVC)</td>
<td>5000–10000e</td>
<td>High 5000–10000</td>
<td>200</td>
<td>Very high, 200–300</td>
</tr>
<tr>
<td>Ethylene–vinyl acetate (EVA)</td>
<td>12000</td>
<td>Very high 10000–15000</td>
<td>110–160</td>
<td>Very high, 100–200</td>
</tr>
<tr>
<td>Microperforated (MP)</td>
<td>&gt;15000d</td>
<td>Extremely high &gt;15000</td>
<td>Variable</td>
<td>Extremely high, &gt;300</td>
</tr>
<tr>
<td>Microporous (MPOR)</td>
<td>&gt;15000d</td>
<td>Variable</td>
<td>Extremely high, &gt;300</td>
<td></td>
</tr>
</tbody>
</table>

* Most packaging films for fresh produce are not single films but laminates and co-extrusions
† Conditions of O₂ and water vapour transmission rate measurements are not at realistic chill conditions
‡ Dependent on pinholes
§ Dependent on moisture
∥ Dependent on moisture and level of plasticizer
¶ Dependent on film and degree of microperforation or microporosity.
always maintained and the permeability ratios CO₂/O₂ and O₂/N₂ are usually in the range 3 to 5. Hence, it is possible to estimate the permeability of a material to CO₂ or N₂ when only the O₂ permeability is known. As a general rule, packaging materials with O₂ transmission rates <100 cm³ m⁻² day⁻¹ atm⁻¹ are used in MAP. Packaging materials are usually laminated or co-extruded in order to have the necessary barrier properties required.

7.3.2 Water vapour transmission rate (WVTR)
WVTRs are quoted in g m⁻² day⁻¹ at a given temperature and RH. Similar to gas permeabilities, there is a wide variation between different packaging materials (see Table 7.2). However, there is no correlation between what is a good barrier to gas and what is a good barrier to water. A further complication is that some materials (e.g. nylon) are sensitive to moisture and their gas permeabilities are dependent on RH.

7.3.3 Mechanical properties
Packaging materials used for MAP must have sufficient strength to resist puncture, withstand repeated flexing and endure the mechanical stresses encountered during handling and distribution. Additionally, if trays are to be thermoformed, the web must draw evenly and not thin excessively on the corners. Poor mechanical properties can lead to pack damage and gas leakage.

7.3.4 Sealing reliability
It is essential that an integral seal is formed in order to maintain the correct atmosphere within an MA pack. Therefore, it is important to select the correct heat-sealable packaging materials and to control the sealing operation. For example, in high-speed form-fill-seal operations, it is important to consider the hot tack of the material. Additionally, there is often a requirement for a peelable seal so that the consumer can gain easy access to the contents. However, a balance between peelability and integrity of the seal must be determined.

7.3.5 Transparency
For most MA-packed foods, a transparent package is desirable so that the product is clearly visible to the consumer. However, high-moisture foods stored at chilled temperatures have the tendency to create a fog on the inside of the package, thereby obscuring the product. Consequently, many MAP films are treated with coatings or additives to impart antifog properties so as to improve visibility. These treatments only affect the wetability of the film and have no effect on the permeability of the film. For some
MA-packed foods (e.g. green pasta and cured meats), it may be desirable to exclude light in order to reduce undesirable light-induced oxidation reactions. In these cases, light barriers such as colour-printed or metallized films may be used.

7.3.6 Type of package

The type of package used will depend on whether the product is destined for the retail or the catering trade. Popular options include flexible ‘pillow-packs’, ‘bag-in-box’ and semi-rigid tray and lidding film systems.

7.3.7 Microwaveability

The ability of MAP materials to withstand microwave heating is important, particularly in the case of ready-to-eat food products. For example, the low softening point of polyvinyl chloride (PVC) makes the popular PVC/low density polyethylene (LDPE) thermoformed trays unsuitable for microwave oven heating. Hence, materials with greater heat resistance, such as cast polypropylene (CPP), crystallized polyethylene terephthalate (CPET), polypropylene (PP) and polystyrene-high temperature (PSHT) are used for MA-packed food products intended to be heated in a microwave oven.

7.4 MAP MACHINERY

Depending on the product to be packed and the desired presentation, six major types of MAP machinery are commercially used. Only brief details of such equipment are provided here but further information on these and other less commonly used MAP machinery can be obtained from MAP machinery suppliers.

7.4.1 Horizontal form-fill-seal (HFFS)

These so-called flow-pack machines are capable of making flexible pillow-pack pouches from only one reel of film. HFFS machines can also overwrap a pre-filled tray of product. The air in the package is removed by continuous gas flushing, but gas mixtures containing levels of O2 higher than 21% cannot be used owing to the use of hot sealing jaws at the end of the machine. For certain very porous products (e.g. some bakery goods), gas flushing is not capable of reducing the residual O2 within the package to low enough levels. In such cases, a gas injection station can be fitted to the machine infeed so that the product itself is purged with gas immediately prior to packaging. Flow-pack machines are mainly suitable for the retail MAP of bakery products, dried foods, cooked meats, combination products, cheese, fruit and vegetables.
7.4.2 **Vertical form-fill-seal (VFFS)**

Similar to HFFS machines, VFFS machines are capable of making flexible pillow-pack pouches from only one reel of film. The air in the package is removed by continuous flushing with a gas mixture that does not contain more than 21% of $O_2$. In VFFS machines, gas-flushed packages are gravity fed by loose product that has been pre-weighed on a multihead weigher. Pre-flushing with gas may be necessary for porous products. VFFS machines are mainly suitable for the retail MAP of prepared salads, grated cheese and dried foods.

7.4.3 **Thermoform-fill-seal (TFFS)**

TFFS machines produce packages consisting of a thermoformed semi-rigid tray that is hermetically sealed to a flexible lidding material. Rollstock film is automatically conveyed into a thermoforming section where a vacuum or compressed air is used to draw the film into dies, giving the trays their desired shape. Alternatively, TFFS machines can be used to thermoform pillow-pack type pouches. The product is then manually or automatically loaded into the trays before evacuation, back-flushing with the desired gas mixture and heat sealing with lidding material. The hermetically sealed packages are then finally separated by cross-cutting and longitudinal cutting units.

TFFS machines use a compensated vacuum technique to replace air. TFFS machines are primarily suitable for the retail packaging of red meats, offal, seafood products, poultry, cured and cooked meat products, cook–chill foods, combination products and pasta. As an alternative to HFFS and VFFS machines, TFFS machines can also be used for the retail packaging of bakery products, prepared fruit and vegetables, cheese and dried products.

7.4.4 **Preformed tray and lidding film (PTLF)**

PTLF machines are essentially the same as TFFS machines, except that preformed trays are used instead of thermoformed semi-rigid trays. Consequently, PTLF machines use a compensated vacuum technique to replace air and have similar MAP food applications to TFFS machines.

7.4.5 **Vacuum chamber (VC)**

VC machines use preformed bags and utilize the compensated vacuum technique to replace air. Preformed plastics bags are manually placed within the chamber before evacuation, back-flushing with the desired gas mixture and heat sealing. VC machines can be used for the small-scale production of vacuum or gas-flushed catering packs of primal meat cuts,
cooked meats, seafood, poultry, bakery products, dried foods and combination products.

7.4.6 Snorkel type (ST)

ST machines use the compensated vacuum technique to produce bulk MA catering bag-in-box packs. Alternatively, they can gas-flush conventionally packaged retail products such as overwrapped packs of red meat, into large master packs. In these machines, preformed plastic bags are positioned on a heat seal mandrel and retractable snorkels pull a vacuum and then back-flush with a desired gas mixture before heat sealing. ST machines can be used for the MAP of red meats, poultry, seafood, cooked meats, cheese, bakery products, pasta, combination products, dried foods, fruit and vegetables.

7.5 SELECTED MAP FOOD APPLICATIONS

MAP has applications in virtually every food product category. In 1995 the MAP Gas Selector expert system was developed by Air Products PLC in conjunction with the Campden & Chorleywood Food Research Association, who provided the technical input information. The MAP Gas Selector has recently been updated and is freely available to interested parties via the Air Products PLC Freshline™ web site on http://www.airproducts.com/freshline. The MAP Gas Selector was designed to provide technical advice on the MAP of over 450 individual food items, which have been grouped within 17 different food categories. Users can select any food item (in a retail, bulk or primal pack format) and the MAP Gas Selector will provide tabulated information on the recommended MAP gas mixture, labelling requirements, storage temperatures, achievable shelf lives in air and in MAP, principal spoilage mechanisms, possible food poisoning hazards, typical MAP machines and types of packages, and examples of typical MAP materials. In addition, concise technical advice and help information are provided on the following:

- definitions and terminology of MAP related topics
- abbreviations of commonly used MAP materials
- line diagrams of the most common types of MAP machinery
- descriptive paragraphs and available growth data on 23 groups of micro-organisms
- descriptive paragraphs on the principal food spoilage mechanisms of different categories of food
- recommendations on food hygiene, temperature control, stock rotation and quality assurance tests
The following six food categories of MAP applications have been extracted and edited from the Freshline™ Guide to MAP (with permission and thanks to Air Products PLC).

### 7.5.1 Raw red meat products

The two principal spoilage mechanisms affecting the shelf life of raw red meats are microbial growth and oxidation of the red oxymyoglobin pigment. When red meat is kept under proper chilled conditions, the controlling influence on the shelf life of the product is the rate of oxidation of the red oxymyoglobin pigment to its brown oxidized form, metmyoglobin (see Fig. 7.1). For this reason, high concentrations of O₂ are necessary for the MAP of red meats in order to maintain the desirable bright red colour for a longer period. Highly pigmented red meats, such as venison and wild boar, require higher concentrations of O₂. Alternatively, as mentioned in section 7.2.2.4, low concentrations of CO (<0.5%) are currently allowed in the USA, Australia and New Zealand to produce a stable cherry-red meat colour that is similar to the red oxymyoglobin colour that forms when meat is exposed to O₂ in the air or within high-O₂ MA packs. However, the use of CO in MAP is controversial, and it is currently not a permitted packaging gas within the European Union countries.

Red meats provide an ideal medium for the growth of a wide range of spoilage and food poisoning micro-organisms. It should be noted that raw red meats are usually cooked before consumption and thorough heating is sufficient to kill the vegetative cells of food poisoning bacteria. Consequently, the risk of food poisoning is greatly minimized by proper cooking. Aerobic spoilage bacteria, such as *Pseudomonas* species, which are normally predominant on red meats, are inhibited by CO₂. Consequently, to create the dual effect of red colour stability and microbial inhibition, gas mixtures containing 15–30% CO₂ and 70–85% O₂ are recommended for extending the chilled shelf life of red meats from 2–4 days to 5–8 days and even longer. The maintenance of recommended chilled temperatures and good hygiene and handling throughout the butchery, MAP, distribution and retailing chain is also of vital importance in ensuring the safety and extended shelf life of red meat products.

### 7.5.2 Raw fish and seafood products

The principal spoilage mechanisms affecting the quality of fish and seafood are the result of microbial and oxidative activities. Fish and
seafood products are very perishable owing to their high $a_w$, neutral pH, and presence of autolytic enzymes that cause the rapid development of undesirable odours and flavours. Fish normally have a particularly heavy microbial load owing to their cold water origin, method of capture and transport to shore, evisceration and retention of skin in retail portions. Microbial activity causes a breakdown of fish protein, with the resulting production of undesirable fishy odours. Oxidative rancidity of unsaturated fats in oily fish also results in other additional offensive odours and flavours.

Only the highest quality fish and seafood should be used to benefit from the extended shelf life advantages of MAP. The achievable shelf life will depend on the species, fat content, initial microbial load, gas mixture and temperature of storage. The maintenance of recommended chilled temperatures and good hygiene and handling practices throughout the entire capture-to-consumption chain is essential for ensuring the safety and extended shelf life of fish and seafood products.

MAP is a very effective technique for delaying microbial spoilage and oxidative rancidity in fish and seafood products. It is particularly effective at extending the shelf life of white fish products. For white fish, crustaceans and molluscs, a gas mixture containing 30% O$_2$, 40% CO$_2$ and 30% N$_2$ is recommended. A gas mixture containing 40% CO$_2$ and 60% N$_2$ is recommended for oily fish products. The inclusion of CO$_2$ is necessary for inhibiting common aerobic spoilage bacteria, such as Pseudomonas species. However, for retail packs of fish and other seafood, too high a proportion of CO$_2$ in the gas mixture can induce pack collapse, excessive drip and – in cold-eating seafood products such as crab – an acidic, sherbet-like flavour. O$_2$ is necessary to prevent the growth of Clostridium botulinum type E, colour changes and bleaching, and reduce the drip in white fish, crustacean and mollusc MA packs. However, O$_2$ is preferentially excluded from oily fish MA packs so as to inhibit oxidative rancidity.

**7.5.3 Cooked, cured and processed meat products**

The principal spoilage mechanisms for cooked, cured and processed meat products are microbial growth, colour changes and oxidative rancidity. In such products the heating process should kill vegetative bacterial cells, inactivate degradable enzymes, and fix the colour. Problems can arise primarily from post-process contamination and/or poor hygiene and handling practices.

Some uncooked, uncured meat products (such as beefburgers and British sausages) contain sulphur dioxide (often added in the form of sodium...
metabisulphite). This additive (use of which is restricted to products having a minimum of 6% cereal content) is an effective preservative against a wide range of spoilage mechanisms. Cured meat products, whether cooked or not, owe their characteristic pink colour to the use of nitrate, which reacts with the myoglobin in the meat to form nitrosylmyoglobin. Although this pigment is fairly stable it is prone to oxidative bleaching, especially when exposed to light. Cured meat products should therefore be MA-packed with the exclusion of O₂. Meat products containing appreciable levels of unsaturated fat are liable to be spoiled by oxidative rancidity, but MAP with the elimination of O₂ will also inhibit this.

The addition of nitrate and salt inhibits the growth of most food poisoning bacteria. This inhibition may, however, be compromised in products formulated with reduced levels of salt, nitrate or other preservatives. Therefore, caution must be exercised in assessing the potential effects of any changes in product formulation. Simple cooked meats without any added preservatives may be at risk from the growth of Clostridium botulinum under anaerobic MAP and incorrect chilled storage.

### 7.5.4 Dairy products

The principal spoilage mechanisms affecting dairy products are microbial growth and oxidative rancidity. The type of spoilage affecting a dairy product will depend on its intrinsic properties. For example, low aw products such as hard cheeses are generally spoiled by mould growth, whereas higher aw products such as creams and soft cheeses are susceptible to yeast and bacterial spoilage, oxidative rancidity and physical separation.

MAP can significantly extend the shelf life of dairy products. Similar shelf lives are achieved for MAP in comparison with vacuum packaging. Hard cheeses are generally packed in CO₂, which is very effective at inhibiting mould growth. Soft cheeses are packed in CO₂/N₂ mixtures, which can also inhibit bacterial spoilage and oxidative rancidity. For soft or grated cheese, 40% CO₂/60% N₂ is recommended. MAP is particularly effective for crumbly cheeses such as Lancashire and grated cheese, where vacuum packaging would cause undesirable compression.

MAP is not recommended for mould-ripened cheeses since CO₂/N₂ gas mixtures would kill desirable mould growth. Creams are adversely affected by CO₂-containing atmospheres, which cause acidification of the cream, giving it a sharp rather than smooth taste. Consequently, N₂ is recommended for MAP of creams and cream-containing products. By excluding air, N₂ is also capable of inhibiting aerobic microbial growth
and oxidative rancidity. Aerosol creams use nitrous oxide (N₂O) as a propellant, which also inhibits oxidative rancidity.

Other dairy products such as butter and yogurt are not usually MA-packed but would benefit from packaging under N₂. Possible food poisoning hazards associated with dairy products are primarily due to either inadequate pasteurization or cross-contamination during or after packaging. Consequently, adequate pasteurization, the maintenance of recommended chill temperatures, and good hygiene and handling throughout are essential for ensuring the safety of dairy products.

### 7.5.5 Bakery products

The principal spoilage mechanisms for non-dairy bakery products are mould growth, staling, and moisture migration. Yeasts may cause problems in certain filled or iced products. Since the aw of non-dairy bakery products is generally <0.96, bacterial growth is inhibited and rarely a problem. However, it is possible that *Staphylococcus aureus* and *Bacillus* species may be able to grow in certain products and hence pose a potential food poisoning hazard. Consequently, good hygiene and handling practices must be observed throughout.

The use of MAP can significantly extend the shelf life of non-dairy bakery products. Since moulds are aerobic micro-organisms, they are very effectively inhibited by CO₂/N₂ gas mixtures. Moisture migration from the pack is prevented by using barrier materials for MAP. MAP appears to have little effect on the rate of staling. It should be noted that staling rates are increased at chilled temperatures and hence most cold-eating bakery products are normally stored at ambient temperatures. For hot-eating bakery products, such as pizza bases, the staling process, which is caused by starch retrogradation, is partially reversed during the reheating cycle.

### 7.5.6 Dried food products

The principal spoilage mechanism affecting dried foods containing a high proportion of unsaturated fatty acids, such as cereals, potato crisps, nuts, cocoa powder and dried milk, is oxidative rancidity. This damaging reaction is very effectively inhibited by MAP in N₂. Owing to the very long achievable shelf lives in MAP for dried foods, MAP materials must have very high moisture and gas barrier properties. Metallized films possess these necessary properties. Certain dried foods, such as dried baby milk, are particularly susceptible to oxidative rancidity, and
residual $O_2$ levels should be below 0.2%. In order to achieve very low residual $O_2$ levels, $O_2$ scavengers may be incorporated into MA packs. These $O_2$ scavengers may also be used for other low-$a_w$ foods such as bakery products. The low $a_w$ of dried foods will prevent the growth of bacteria, yeasts and moulds. It should be noted, however, that many food poisoning bacteria may survive on dried foods, particularly herbs and spices, and may pose a hazard when subsequently reconstituted or used as an ingredient in high-$a_w$ foods. Consequently, strict standards of hygiene and handling should be observed to minimize such food poisoning hazards.

7.6 MAP OF FRESH PRODUCE

Unlike other chilled perishable foods that are MA-packed, fresh produce continues to respire after harvesting, and any subsequent packaging must take into account this respiratory activity. The depletion of $O_2$ and enrichment of $CO_2$ are natural consequences of the progress of respiration when fresh produce is stored in hermetically sealed packs. Such modification of the atmosphere results in a decrease in respiratory rate with a consequent extension of shelf life. MAs can passively evolve within hermetically air-sealed packs as a consequence of produce respiration. If a produce item’s respiratory characteristics are properly matched to film permeability values, then a beneficial equilibrium MA (EMA) can be passively established. However, in the MAP of fresh produce, there is a limited ability to regulate passively established MAs within hermetically air-sealed packs. There are many circumstances when it is desirable to rapidly establish the atmosphere within produce packs. By replacing the pack atmosphere with a desired mixture of $O_2$, $CO_2$ and $N_2$, a beneficial EMA may be established more rapidly than a passively generated EMA. For example, flushing packs with $N_2$ or a mixture of 5–10% $O_2$, 5–10% $CO_2$ and 80–90% $N_2$ is commercial practice for inhibiting undesirable browning and pinking of prepared leafy green salad vegetables.

The key to successful retail MAP of freshly prepared produce is currently to use packaging film of the correct permeability so as to establish optimal EMAs of typically 3–10% $O_2$ and 3–10% $CO_2$. The EMAs attained are influenced by produce respiration rate (which itself is affected by temperature, type of produce, variety, size, maturity and severity of preparation); packaging film permeability; pack volume, surface area and fill weight; and degree of illumination. Consequently, the establishment of an optimum EMA for individual produce items is very complex. Furthermore, in many commercial situations, produce is sealed in packaging
Modified Atmosphere Packaging (MAP)

film of insufficient permeability, resulting in the development of undesirable anaerobic conditions (e.g. <2% O₂ and >20% CO₂). Microperforated films, which have very high gas transmission rates, are now commercially used for maintaining aerobic EMAs (e.g. 5–15% O₂ and 5–15% CO₂) for highly respiring prepared produce items such as broccoli and cauliflower florets, baton carrots, beansprouts, mushrooms and spinach. However, microperforated films are relatively expensive, permit moisture and odour losses, and may allow for the ingress of micro-organisms into sealed packs during wet handling situations. 

7.6.1 Factors that affect the shelf life of fresh produce

The primary goal of MAP for fresh produce is the extension of shelf life. It should be stressed that this extension of produce shelf life may allow for the growth of pathogenic bacteria to higher levels as compared with air-stored samples. Since fruit and vegetables continue to respire after harvest, there are many other factors that affect the post-harvest shelf life extension of fresh produce and the success of MAP.

The achievable shelf life of a fruit or vegetable is inversely proportional to its respiration rate, thus higher respiration rates are associated with shorter shelf life. Generally speaking, produce items with increased wounding, such as freshly cut produce, will have a shorter shelf life owing to their increased respiration rates. Respiration, which can be measured by the production rate of CO₂ or by the consumption rate of O₂, also results in the production of heat and water vapour. Consequently, one goal of MAP is to decrease produce respiration rate, which can be successfully achieved with decreased O₂ levels (e.g. 2–5%) and good chilled storage (i.e. 0–5°C). However, O₂ concentrations below 1–2% can lead to anaerobic respiration and the production of off-odours and flavours (e.g. ethanol, aldehydes and ketones), as well as creating conditions for the growth of anaerobic pathogenic bacteria such as Clostridium botulinum. High levels of O₂ (70–100%) combined with CO₂ for MAP have been tested and shown to have beneficial effects on product quality, however, more research is required to support and explain this novel MAP concept.

Senescence, the natural form of produce deterioration, is endogenously controlled and results in the breakdown of plant membranes. It is marked by chlorophyll loss, a decrease in protein content and tissue softening. Senescence is driven by an increase in respiration, as well as by an increase in ethylene production in some climacteric products, e.g. tomatoes, apples and pears. The delay of senescence is the main goal in the preservation of fresh produce by MAP, since senescence accounts
for a large proportion of post-harvest losses.\textsuperscript{17} Therefore, it is a reasonable assumption that reducing ethylene production may effectively delay senescence.\textsuperscript{15}

The plant hormone ethylene plays an important role in produce shelf life and can cause a marked increase in respiration rates as well as enhancing ripening and senescence.\textsuperscript{16,22} In some produce items, accelerated ageing and the initiation of ripening can occur following exposure to very low levels of ethylene.\textsuperscript{17} As senescence begins, spoilage due to the growth of indigenous micro-organisms can be augmented.\textsuperscript{15} Also, the different biological structures of assorted produce varieties contribute to the sensitivity response to ethylene, as well as to the response to O\textsubscript{2} and CO\textsubscript{2} levels. Furthermore, different stages of maturity, cultivar and post-harvest storage conditions also influence the sensitivity of produce items to ethylene.\textsuperscript{17}

Post-harvest control measures taken to minimize the production of ethylene include CAS and MAP at optimal chilled temperatures (just above the chilling or freezing injury threshold) and oxidizing any ethylene by various means. MAP can maintain the quality of respiring produce items by greatly reducing the damaging effects of exposure to ethylene. In MAP, CO\textsubscript{2} can inhibit ethylene action as well as autocatalytic production of ethylene by climacteric products such as apples, pears and tomatoes. However, CO\textsubscript{2} levels above 15–20\% can cause undesirable physiological damage to whole leaf plants and therefore it is important to take into account the specific CO\textsubscript{2} tolerance level of individual produce items before designing an MA package for a particular commodity.\textsuperscript{16}

As previously mentioned, the control of produce respiration and ethylene production by MAP can help maintain produce quality and extend shelf life. However, the control of produce respiration and ethylene production is also highly dependent on optimal chilled temperature control throughout the entire supply chain, ‘from farm to fork’. Furthermore, the microbiological safety of MA-packed produce items is also dependent on controlled chilled temperature storage and the individual characteristics of each produce item. For example, most MA-packed fresh-cut (i.e. prepared) produce items, which are stored at optimal chilled temperatures, tend to spoil overtly before becoming microbiologically unsafe. However, incorrect storage at elevated temperatures will greatly enhance the food safety risks of MA-packed fresh-cut produce items by allowing for the growth of pathogenic bacteria. Hence the necessity for storage at optimal chilled temperatures cannot be overemphasized. Recent advances in the chilled storage industry show promise for improved temperature control.
of produce items during transport as well as during retail and domestic storage.\textsuperscript{15}

\subsection*{7.6.2 Effects of MAP on fresh produce microbial growth and safety}

\subsubsection*{7.6.2.1 Spoilage micro-organisms}

Fresh produce can support the growth of a plethora of spoilage micro-organisms. The most commonly encountered micro-organisms on fresh produce are \textit{Pseudomonas} species, lactic acid bacteria such as \textit{Leuconostoc mesenteroides} and \textit{Lactobacillus} species, \textit{Erwinia herbicola}, \textit{Flavobacterium}, \textit{Xanthomonas}, \textit{Enterobacter agglomerans}, yeasts and moulds.\textsuperscript{22,23} Although these micro-organisms can be responsible for the spoilage of fresh produce, the type and magnitude of microbial growth can vary greatly for different produce items and storage conditions. Storage temperature has a huge influence on determining the type and magnitude of microbial growth found on chilled produce items. For example, good chilled storage conditions (e.g. 0–5°C) lead to the preferential growth of psychrotrophic (cold-tolerant) micro-organisms and a subsequent decrease in the growth of mesophilic (warm-preferring) micro-organisms.\textsuperscript{15}

Good chilled storage (0–5°C) not only decreases the growth rate of spoilage and pathogenic micro-organisms on fresh produce but also increases the inhibitory effects of MAP by increasing the solubility of antimicrobial \textit{CO}_2 into fruit and vegetable tissues. For example, the depleted levels of \textit{O}_2 and elevated levels of \textit{CO}_2 used in MAP generally inhibit the growth of aerobic spoilage bacteria such as \textit{Pseudomonas} species, but can favour the growth of lactic acid bacteria. This can hasten the spoilage of produce that is sensitive to lactic acid bacteria, such as lettuce, chicory leaves and carrots.\textsuperscript{22} The effects of MAP on yeasts are negligible since they are capable of both aerobic and anaerobic respiratory growth. However, depleted levels of \textit{O}_2 (2–5\%) and elevated levels of \textit{CO}_2 (>10\%) cause growth inhibition of moulds since they are aerobic micro-organisms.\textsuperscript{24}

A possible concern when using MAP for respiring fresh produce arises from the potential for pathogenic bacteria, which may be resistant to depleted levels of \textit{O}_2 (2–5\%) and elevated levels of \textit{CO}_2 (>10\%), to outgrow spoilage micro-organisms that may be susceptible to the same MAP conditions.\textsuperscript{25} This dynamic interaction between the growth of pathogenic bacteria and spoilage micro-organisms has been extensively reviewed for
meat and milk products; however, further research is still required for the MAP of fresh produce.22,26

7.6.2.2 Pathogenic bacteria

Freshly prepared produce that is MA packed can be vulnerable from a food safety standpoint since depleted levels of $\text{O}_2$ (2–5%) and elevated levels of $\text{CO}_2$ (>10%) may inhibit the growth of micro-organisms that usually warn consumers of spoilage, while the growth of pathogenic bacteria may be encouraged. In addition, slow growing pathogenic bacteria may have the opportunity to further increase in number owing to the extended shelf life of MA-packed fresh produce. Of most concern in relation to MA-packed fresh produce are the psychrotrophic pathogenic bacteria such as *Listeria monocytogenes* and *Aeromonas hydrophila*. Also, non-proteolytic *Clostridium botulinum*, *Salmonella* species, *E. coli* 0157:H7 and *Shigella* species are capable of growth and can be potential health risks when present on MA-packed fresh produce.27

*Clostridium botulinum*

*C. botulinum* spores are commonly found in agricultural soils and consequently on the surfaces of fresh produce. Proteolytic *C. botulinum* has difficulty growing and producing toxin at temperatures below 12°C, pH < 4.6, $a_w < 0.95$ and NaCl concentrations >10%.28 Non-proteolytic *C. botulinum* can grow at a minimum temperature of 3.3°C, pH > 5.0, $a_w > 0.97$ and NaCl concentrations >4%. Therefore, there is some concern about the use of MAP with respect to non-proteolytic *C. botulinum*.4,18 As described previously, the level of $\text{O}_2$ in MA-packed fresh produce packs can be depleted rapidly, particularly if the produce is temperature-abused and the produce respiration increases. This scenario would lead to the development of an anaerobic environment that is ideal for the growth and toxin production of *C. botulinum*.29 However, in a study that looked at this potential in lettuce, cabbage, broccoli, carrots and green beans that had been packed under vacuum or in air, Larson *et al.*30 found that these produce items were almost always grossly spoiled before any significant production of toxin was detected. Many other research studies have shown similar results, and a study by Larson and Johnson31 demonstrated the ability of produce spoilage micro-organisms to protect against the overgrowth of pathogenic bacteria.

Fresh mushrooms and tomatoes have been shown to contain spores of *Clostridium* species, and therefore the possibility of botulism associated with these MA-packed produce items must not be ignored.18 However, the acidic nature of tomatoes (pH < 4.6) does not provide suitable growth
conditions for *C. botulinum*. This supposition was supported by the results of Hotchkiss *et al.*32, who demonstrated that MA-packed tomatoes (1.0–2.9% O₂), stored at 13°C and 23°C, only became toxic after becoming severely spoiled. The initial level of O₂ used for high-respiring produce items such as mushrooms can be very important since it will deplete more rapidly, resulting in an anaerobic environment that is conducive to toxin production.33 The industry practice of using microperforated MAP films discourages the growth of *C. botulinum*, although mushroom shelf life is shortened.

The absence of outbreaks of botulism linked to MA-packed fresh produce items indicates that *C. botulinum* is probably competitively inhibited by the natural microbial flora and storage conditions of these products. However, more research is required to examine the potential for growth of *C. botulinum* in a wide variety of MA-packed fresh produce items, stored at mildly abusive temperatures (e.g. 7–12°C). In addition, other hurdles to *C. botulinum* growth, besides good chilled temperature storage, need to be investigated so as to prevent potential toxin production.15

**Listeria monocytogenes**

*L. monocytogenes* is a psychrotrophic and pathogenic bacterium that can remain largely unaffected by MAP, while the normal microflora is inhibited.19,27 Consequently, *L. monocytogenes* can grow to potentially harmful levels, at low chilled temperatures, during the extended shelf life of an MA-packed fresh produce item.26,34 For example, Berrang *et al.*35 showed that the growth of *L. monocytogenes* inoculated onto broccoli, asparagus and cauliflower was not affected by MA conditions of 3% CO₂/18% O₂/79% N₂ for 10 days at 10°C. Similarly Beuchat and Brackett36 clearly demonstrated that the levels of *L. monocytogenes* increased significantly on lettuce stored at chilled temperatures in an MA of 3% O₂/97% N₂, while Francis and O’Beirne34 reported that MAP, under predominantly N₂, stimulated the growth of *L. monocytogenes* on fresh lettuce at 8°C. Furthermore, elevated CO₂ levels (10–20%) have been reported to stimulate the growth of *L. monocytogenes* in a surface model system.19

Jacxsens *et al.*37 investigated the growth of *L. monocytogenes* and *Aeromonas* species on fresh-cut vegetables, packaged under either an MA (2–3% O₂/2–3% CO₂/94–96% N₂) or air, and clearly found that the sensory quality of the produce items deteriorated to an unacceptable degree before the levels of *L. monocytogenes* and *Aeromonas* species increased significantly. They concluded that the growth of psychrotrophic pathogenic bacteria was more influenced by the type of fresh-cut vegetable and the temperature of storage than the MA conditions, a conclusion that
has been supported strongly by the research results of Nguyen-the and Carlin\textsuperscript{22} and Farber \textit{et al.}\textsuperscript{15}

Francis and O’Beirne\textsuperscript{26} and many other research groups have recommended that more investigations need to be carried out to thoroughly examine the influence of different MAP conditions, competing background microflora and storage temperatures on the survival and growth of \textit{L. monocytogenes} on MA-packed fresh-cut produce items.

\textbf{Aeromonas hydrophila}

\textit{Aeromonas hydrophila} is a psychrotrophic and pathogenic bacterium that can be found on a wide variety of foods, as well as in most aquatic environments, and can cause gastroenteritis and occasionally septicemia.\textsuperscript{38} A microbiological survey of 97 freshly prepared salads found \textit{A. hydrophila} to be present in 21.6\% of them.\textsuperscript{39} Similarly to \textit{L. monocytogenes}, \textit{A. hydrophila} can grow at chilled temperatures, and growth does not seem to be affected by depleted O\textsubscript{2} levels (e.g. 2–5\%) and elevated CO\textsubscript{2} levels (up to 50\%).\textsuperscript{29} As mentioned previously, CO\textsubscript{2} levels above 50\% are detrimental to the quality of fresh produce, even though these elevated levels have been found to inhibit the growth of \textit{A. hydrophila} and \textit{L. monocytogenes}.\textsuperscript{40} Furthermore, Berrang \textit{et al.}\textsuperscript{41} determined that the shelf life of broccoli, asparagus and cauliflower was extended by MAP (i.e. 11–18\% O\textsubscript{2}/2–10\% CO\textsubscript{2}/balance N\textsubscript{2}), but that the growth of naturally occurring or inoculated \textit{A. hydrophila} was not inhibited at storage temperatures of 4°C and 15°C.

7.6.2.3 \textit{Other pathogenic micro-organisms}

Other pathogenic micro-organisms such as \textit{Salmonella} species, \textit{Shigella} species, \textit{E. coli} 0157:H7, and various enteric viruses, such as hepatitis A, can survive and grow on fresh produce, and they have been implicated in a few food poisoning outbreaks, hence there is concern about their growth behaviour under MAP conditions.\textsuperscript{18,19,27,29} However, reassuringly, Farber \textit{et al.}\textsuperscript{15} have extensively reviewed the relevant literature and concluded that MA-packed produce items have an excellent food safety record. They stated that to their knowledge, only two MA-packed produce items, i.e. coleslaw mix and ready-to-eat salad vegetables, have been directly implicated in food-borne illness outbreaks – of botulism and \textit{Salmonella Newport}, respectively. They also stated that there has been a noticeable increase in the consumption of fresh fruit and vegetables during the last two decades, and more consumers are now choosing the more convenient fresh-cut produce items. Since there has been a parallel rise in the number of produce-linked food-borne outbreaks, it is important that vigilance is maintained with respect to the safety of MA-packed fresh-cut produce.
7.7 CONCLUSIONS

MAP is one of the most exciting and innovative areas of the packaging industry. New developments in both packaging materials/machinery and food product applications seem to be opening up at an increasing rate. The MAP market in Europe is substantial and has enjoyed considerable growth in recent years because of the important benefits it provides to food manufacturers, retailers and consumers alike. The success of MA-packed products in the UK is expected to stimulate future growth in other countries around the globe.

REFERENCES


8 Hurdle Techniques
Gail Betts and Linda Everis

8.1 INTRODUCTION

Unless they have received a commercial sterility heat process, i.e. $>F_03$, most foods will contain micro-organisms that have the potential to grow in the food. Growth of these micro-organisms may either affect the quality of the product, ultimately causing spoilage – i.e. an undesirable change in the taste, smell or appearance of the food – or may result in an increased food safety risk, potentially leading to food poisoning, i.e. illness in consumers due to the presence of pathogenic micro-organisms or a toxin they have produced in the food.

Whether these micro-organisms will grow in the food will depend on the process design, product formulation characteristics and subsequent storage conditions of the food. For example, in a pasteurized acidic product only a few specific spoilage organisms will be able to grow, whereas a chilled perishable food that has received no heat treatment and has a high pH will be more susceptible to general microbial spoilage and may allow the growth of a range of food poisoning organisms.

The growth of micro-organisms present in foodstuffs can be controlled by careful formulation of the product and by the choice of storage conditions. Knowledge of the levels of the factors required to control microbial growth can aid in product formulation and process design. Values of limiting factors for the growth of organisms can be found in the literature (Table 8.1) and are a useful guide for assisting in product formulation in order to achieve a desired shelf life with respect to microbial growth. It is worth noting that such information assumes that only one inhibitory factor is present at once, or that the other factors present are near optimal for growth. In foods that have a number of factors present, the minimum values may be higher than those noted in Table 8.1.

Factors that can influence microbial growth are often termed ‘intrinsic’ or ‘extrinsic’ factors. Properties contained within the food itself are deemed
Food Biodeterioration and Preservation

Table 8.1 Minimum growth conditions for food-borne micro-organisms (Adapted from Betts et al.3).

<table>
<thead>
<tr>
<th>Type of micro-organism</th>
<th>Minimum pH for growth</th>
<th>Minimum a_w for growth</th>
<th>Anaerobic growth (e.g. in vacuum pack)</th>
<th>Minimum growth temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salmonella</td>
<td>3.8</td>
<td>0.92–0.95</td>
<td>Yes</td>
<td>4–5.2</td>
</tr>
<tr>
<td>Staphylococcus aureus</td>
<td>4.0</td>
<td>0.83</td>
<td>Yes</td>
<td>7</td>
</tr>
<tr>
<td>Bacillus cereus</td>
<td>4.9</td>
<td>0.93–0.95</td>
<td>Yes</td>
<td>4</td>
</tr>
<tr>
<td>Clostridium botulinum proteolytic A, B, F</td>
<td>4.6</td>
<td>0.94</td>
<td>Yes</td>
<td>10</td>
</tr>
<tr>
<td>non-proteolytic B, E, F</td>
<td>5.0</td>
<td>0.97</td>
<td>Yes</td>
<td>3.3</td>
</tr>
<tr>
<td>Listeria monocytogenes</td>
<td>4.3</td>
<td>0.92</td>
<td>Yes</td>
<td>–0.4</td>
</tr>
<tr>
<td>Escherichia coli</td>
<td>4.4</td>
<td>0.935</td>
<td>Yes</td>
<td>7–8</td>
</tr>
<tr>
<td>Clostridium perfringens</td>
<td>4.5</td>
<td>0.93–0.95</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td>Vibrio parahaemolyticus</td>
<td>4.9</td>
<td>0.94</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>Yersinia enterocolitica</td>
<td>4.4</td>
<td>0.96</td>
<td>Yes</td>
<td>–1.3</td>
</tr>
<tr>
<td>Aeromonas hydrophila spoilage</td>
<td>&lt;4.5</td>
<td>0.97</td>
<td>Yes</td>
<td>–0.1</td>
</tr>
<tr>
<td>Pseudomonas</td>
<td>5.0</td>
<td>0.97</td>
<td>No</td>
<td>0</td>
</tr>
<tr>
<td>Lactic acid bacteria</td>
<td>3.5</td>
<td>0.90</td>
<td>Yes</td>
<td>4</td>
</tr>
<tr>
<td>Yeasts</td>
<td>1.5</td>
<td>0.62</td>
<td>Yes</td>
<td>–34</td>
</tr>
<tr>
<td>Mould</td>
<td>1.5</td>
<td>0.61</td>
<td>No</td>
<td>–12</td>
</tr>
</tbody>
</table>

NOTE: Minimum growth characteristics are given for each factor when other conditions are optimum for growth. If more than one stress is present, then it is likely that these minimum characteristics will change.

Table 8.2 Examples of intrinsic and extrinsic factors controlling the growth of micro-organisms.

<table>
<thead>
<tr>
<th>Intrinsic</th>
<th>Extrinsic</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH or acidity</td>
<td>Temperature</td>
</tr>
<tr>
<td>Water activity</td>
<td>Modified atmosphere (oxygen tension, level of CO₂)</td>
</tr>
<tr>
<td>Salt</td>
<td>Heat treatment</td>
</tr>
<tr>
<td>Sugars</td>
<td>Light, UV</td>
</tr>
<tr>
<td>Preservatives</td>
<td>Other novel processes (e.g. high pressure, electric field)</td>
</tr>
<tr>
<td>Microbial antagonism</td>
<td></td>
</tr>
</tbody>
</table>

intrinsic and include the level of acidity, added salt or other preservatives. Extrinsic factors are the environmental factors to which a food is exposed and include cooking temperature, storage temperature and packaging format. These factors are listed in Table 8.2.

It is important to understand that the intrinsic factors and most extrinsic factors, with the exception of heat and other non-thermal physical processes, result in a slowing down of microbial growth rather than cell death.
There are many food products that do not rely exclusively on a single controlling factor for preservation. Combinations of preservatives can be more effective than just using one. The use of combinations is referred to as the *hurdle effect*.4–6

Hurdle technology is therefore the application of two or more controlling factors to products in order to control or inhibit microbial growth. By using a number of different means of inhibition, it is possible to apply each individual hurdle at a reduced level to give food products that are safe, have adequate shelf life and may be more acceptable to consumers.5,7 The combined hurdles may have an additive or even a synergistic effect, allowing combinations that achieve microbial stability and safety to be chosen.

When using the hurdle approach, it is important that all hurdles are correct and the preservative factors meet their target level for every batch of product. Each of the hurdles is a critical control point within the production process and if any of the hurdles are incorrect then the food preservation system will be affected, and may fail.

There are various hurdles that can be employed to help stabilize foodstuffs. These include:

- temperature (heat treatment/chill)
- acidification (low pH)
- low water activity ($a_w$)
- packaging (MAP)
- preservatives (chemical and natural)
- competitive flora.

A brief description of how each of the factors above can affect microbial activity is given below.

### 8.2 HURDLE TECHNOLOGIES

#### 8.2.1 Heat treatment

There are two main types of heat treatment a product may undergo. These are sterilization and pasteurization. Sterilization treatments are intended to result in products that are commercially sterile, i.e. free from vegetative and spore-forming micro-organisms that could grow/affect the quality and safety of the product. If the sterilization treatment is applied when the food is in a sealed pack (as in canning) the resulting product can have a long shelf life. If the product is packed after treatment considerable care...
must be taken to avoid recontamination if the product is required to have a long life (e.g. aseptic packing).

Pasteurization is designed to reduce the levels of micro-organisms in a foodstuff and can be used either alone or in combination with other factors such as the presence of salt and nitrite. There are various different levels of pasteurization treatment (times and temperatures) that can be given, depending on the target micro-organism. These will usually be related to other characteristics of the product such as pH or water activity and will be intended to inactivate those organisms that could grow under the conditions present in the product.

The pasteurization treatment that is widely recognized as the minimum for cooked, chilled non-modified atmosphere packaged products is 70°C for 2 minutes or higher unless other inhibitory factors are present. This process is designed to give a 6-log reduction in vegetative organisms like *Listeria monocytogenes*.

However, this process is not sufficient for all chilled products. Chilled products requiring a shelf life of more than 10 days that are modified atmosphere or vacuum packed, deep filled or packaged in a way in which the oxygen level is reduced and an anaerobic environment is created require treatment at 90°C for 10 minutes or equivalent, unless specific controlling factors are in place. This requirement is owing to the risk of non-proteolytic *C. botulinum* growth if this organism is present. Other pasteurization treatments are described by Gaze.

A critical factor in the final microbiological levels in a heat-treated food is whether the components were fully cooked and then assembled or whether they were packaged prior to the pasteurization treatment. For products that are assembled and packaged after cooking, there is the potential for re-contamination with spoilage organisms or pathogens. For in-pack pasteurized product, e.g. sous-vide products, the potential for recontamination should be minimal.

8.2.2 Chilling

Micro-organisms can be divided into four main categories relating to the range of temperatures under which growth can occur. These groups are psychrophiles, psychrotrophs, mesophiles and thermophiles. As a general rule, psychrotrophic and psychrophilic organisms can grow at chill temperatures, mesophilic organisms do not tend to grow below 6–8°C and thermophiles do not generally grow below 25–30°C. The group of most concern to chill foods is psychrotrophic organisms, which contain food
pathogens such as *Listeria monocytogenes*, and food spoilage organisms such as *Pseudomonas* species.

Temperature will have two main effects on micro-organisms. First, the growth of all organisms (even psychrotrophs) will slow down as the temperature is reduced; therefore, a lower chill storage temperature will be beneficial to shelf life. Second, the inhibitory effect of reduced pH and higher water activity is increased at lower temperatures. Correct maintenance of storage temperature is one of the most critical factors for ensuring the safety and stability of chilled products. Products must be appropriately labelled to ensure that they are stored at the correct temperature throughout their life, especially if they look similar to ambient-stable products. When assessing the shelf life of chilled products, consideration must be given to the potential storage temperatures throughout their life. While very low temperatures may be maintained during distribution and retail storage, the potential for temperature abuse by consumers must be considered.

### 8.2.3 Acidification or low pH

All micro-organisms have a defined range of external pH under which they can grow and survive, and even mild acidification of a food can be effective in controlling microbial growth. In general, bacteria require pH values that are between 4 and 8, whereas yeasts and moulds are able to grow and survive at a wider range of pH; in some instances, the range can be between pH 2 and 11.

Some micro-organisms may well die at reduced pH, but this will be dependent on the final pH achieved, the type of acid used and the storage temperature. Death is generally more rapid in low-pH foods stored at ambient temperatures, where the metabolic activity of the cells is higher than at chill temperature. If death does not occur and the micro-organisms survive, growth may be inhibited but the cells may still be metabolically active. The inside of a bacterial cell is at a pH close to neutral and needs to be maintained at this level for the organism to grow. Therefore, growth is often reduced or prevented in acidic environments, as micro-organisms use increasing amounts of energy in an attempt to counteract the effects of the acid and maintain the correct pH inside the cell.

There are two main types of acid: ‘strong’ or ‘inorganic’ acids, which are unable to enter the microbial cell, and ‘weak’ or ‘organic’ acids, which are able to enter the microbial cell and exert their action within the micro-organism. The type of acid used will determine the minimum pH level at which micro-organisms can grow. The organic acids acetic, citric, malic, tartaric and lactic are used most often in food production.
The organic acids exist in two forms (dissociated and undissociated), depending on the pH of the environment. This is shown below for acetic acid.

\[
\begin{align*}
\text{Low pH, e.g. 4.5–5.5, as found in foods} & : \text{CH}_3\text{COOH} \\
& \quad \text{Undissociated molecule} \\
\text{High pH, e.g. 7.0, as found inside microbial cells} & : \text{CH}_3\text{COO}^- + \text{H}^+ \\
& \quad \text{Dissociated molecule}
\end{align*}
\]

This is important for food preservation because only the undissociated form of the acid is able to enter the bacterial cell. Charged molecules such as the dissociated form are not able to cross the bacterial membranes. All organic acids have a particular pH (the pKa) value at which half of their molecules are undissociated, and they work most effectively as the pH approaches or falls below this value, as more acid is in the undissociated state and thus able to enter the microbial cell.

The choice of acid will depend on the desired sensory properties in the final product. Generally, the acids are most effective against microorganisms in the order: acetic > lactic > citric > tartaric. Acetic acid is the most antimicrobial of the organic acids, but has a strong vinegary odour and taste. Tomato-based products naturally contain citric acid and this is therefore the acidulant that is most often added to these products to further reduce the pH. Reduced pH works well with salt as a preservation system. Choosing the right level of each factor is critical for product safety and is best done using predictive models or challenge tests.

Not all acids used in food manufacture are organic acids, for example phosphoric acid is used in the beverages industry. The main effects of non-organic acids are due to the general reduction in pH rather than any additional effects due to the acid ions themselves.

Many of the published studies on the growth of food pathogens and spoilage organisms in different pH environments will have used strong acids. As most foods will contain weak acids as acidulants, this may result in the minimum pH values for growth reported in the literature being different to those observed in real foods. Generally speaking, weak acids are more effective than strong acids at inhibiting microbial growth, so the pH required to prevent growth is higher for weak acids than strong acids.

### 8.2.4 Water activity

Water activity \((a_w)\) is a term used to describe the amount of free or unbound water that is available within a system and that can be used by...
micro-organisms. It is measured on a scale of 0 to 1, where 1 is pure water. The level of available water can be lowered by physical processes that remove water, such as drying and concentration, or by the addition of solutes such as salt and sugar that form chemical bonds with water and prevent it from being used. Compounds capable of reducing \(a_w\) are known as humectants.

The \(a_w\) of a product is also affected by the addition of starches and emulsifiers and by the presence of fats and proteins. The measurement of \(a_w\) in a food product can be quite complex. For example, in emulsions, e.g. mayonnaise, the overall \(a_w\) may be low owing to the high level of fat present; however, the water will be present in the mayonnaise as discrete droplets within the product. The \(a_w\) within the droplets will be higher than that measured for the product as a whole and may allow microbial growth. In this case, other preservation factors, e.g. low pH, will be important for the prevention of growth of certain spoilage organisms. Also, in multi-component or layered products, where the different ingredients have different \(a_w\) values, there is a potential for migration of water from one component to another. This could affect the overall stability of the product and thus the shelf life and safety.

Reducing the \(a_w\) of the environment can have a dramatic effect on microorganisms, increasing the lag phase and decreasing the growth rate.\(^1\) There is no reported microbial growth below an \(a_w\) of 0.6, and most bacteria (except \(S.\) aureus) do not generally grow below an \(a_w\) of 0.90. The limiting \(a_w\) value for growth will depend on the type of humectant used. Salts (e.g. NaCl, KCl) and sugars (e.g. glucose and sucrose) have comparable effects to each other on the growth of bacteria; glycerol acts differently. Bacteria can generally tolerate higher levels of glycerol as it is able to enter the cell freely and does not induce the osmotic stress mechanisms seen with non-permanent solutes. For example, it has been shown that the minimum \(a_w\) allowing growth when NaCl was used as a humectant was 0.957 for \(Pseudomonas\ fragi\) and 0.963 for lactic acid bacteria.\(^1\) When glycerol was used, the minimum \(a_w\) for growth was 0.94 and 0.928, respectively.

When a micro-organism is placed in a low-\(a_w\) environment, the water from the inside of the cells will move across the microbial cell membranes towards the outside, where there is a higher concentration of solutes. This loss of water results in plasmolysis of the cell and the rigid structure of the cell is lost. Plasmolysed cells are unable to grow and need to restore the correct internal water levels before growth can begin.

There are two mechanisms by which cells can return to a balanced state:
1. The external solute can be transported into the cell via a suitable transport mechanism until it is at a similar level inside and outside the cell. The enzyme systems inside the micro-organisms will have to be able to work in the presence of high levels of the solute, which they are generally unable to do.

2. The cell could accumulate or produce a different solute from the one exerting the osmotic stress; this will allow the osmotic potential to be balanced and will allow the cytoplasmic enzymes to function correctly. Such solutes are called compatible solutes and include glutamate, carnitine and betaine.

In most bacteria it is the second mechanism that is used to counteract the majority of salts and sugars used in food manufacture, except for glycerol, where the first mechanism is used. Energy is required to return the organism back to a balanced state and therefore growth does not occur. Once a balanced state has returned growth can begin again.

8.2.5 Modified atmosphere

Micro-organisms have different oxygen requirements for growth. Aerobic organisms, e.g. *Pseudomonas* species and many moulds, need oxygen in order to grow. Anaerobic organisms, e.g. *Clostridium* species, cannot grow in the presence of oxygen, although they may remain dormant until the conditions become favourable for growth. Another group of organisms, known as ‘facultative’ organisms, can grow either in the presence or in the absence of oxygen. This group contains spoilage organisms, e.g. *Enterobacteriaceae*, and food pathogens, e.g. *S. aureus*. A final group of organisms require some oxygen to grow but at levels lower than that seen in air. In addition, an increased level of carbon dioxide is required. These organisms are called microaerophilic and include *Campylobacter*.

Many chilled foods are packaged in an atmosphere that is different from air. It may be modified to contain elevated levels of carbon dioxide and/or nitrogen and a decreased level of oxygen. In some cases the level of oxygen may be increased. The role of these gases has been described by Day, but essentially carbon dioxide exerts an antimicrobial effect on a range of aerobic spoilage organisms and pathogens and can reduce or prevent their growth; nitrogen does not exert any antimicrobial properties itself but is used to replace oxygen. This can have the effect of inhibiting strict aerobic organisms such as moulds.

Chilled foods are often stored in a mixture of gases from which oxygen has been excluded in order to minimize the growth of aerobic spoilage organisms such as *Pseudomonas* species. Typical gas mixtures will contain carbon
dioxide at a level of 25–40% and nitrogen at 60–75%. The use of such a
gas mixture will affect the microbial population within a food. While the
growth of Pseudomonas will be minimized, facultative spoilage organisms
such as lactic acid bacteria, Enterobacteriaceae and yeasts (all of which
can grow with or without oxygen) may dominate.

There is also the potential for growth of anaerobic pathogens such as
Clostridium botulinum in MAP (modified atmosphere packaging) foods.
Owing to these risks, it is currently recommended in the UK that the shelf
life of chilled MAP or vacuum-packaged foods should be restricted to
10 days or less if adequate controlling factors – i.e. a pH of 5.0 or less, aw
of 0.97 or less, aqueous salt level of 3.5% or greater – are not present or
if they have not been subjected to in-pack heat treatment equivalent to
90°C for 10 minutes. This applies to all VP/MAP foods stored between
3°C and 8°C. If none of these controlling factors are in place, a shelf life
of greater than 10 days can be assigned if a C. botulinum challenge test
has been undertaken and has proved that C. botulinum is unable to grow
in the product under the defined storage conditions.

8.2.6 Chemical preservatives

There are a range of chemical preservatives than can be used in food
products to inhibit the growth of micro-organisms. The salts of organic
acids are often added to low-pH foods to reduce the growth of yeasts and
moulds. For example, sodium benzoate and potassium sorbate are used for
fruit products, pickles, mayonnaises and dried fruit. Some preservatives,
such as sorbate and benzoate, are generally used for lower pH foods
because they work better in acidic environments at or near their pK_a values.2

8.2.6.1 Sorbate

Sorbic acid and potassium sorbate are widely used throughout the food
industry for the preservation of vegetable-based products (pickles, olives,
fresh salads), fruit-based products (dried fruits, fruit juices), cheese,
bakery products, beverages and some other products such as smoked
fish, margarine and mayonnaises. Sorbate is more inhibitory to yeasts and
moulds than bacteria. The mould species inhibited include Aspergillus,
Cladosporium, Penicillium and Fusarium. The yeast species inhibited
by sorbates include Candida, Saccharomyces, and Zygossaccharomyces.
Bacteria that are inhibited by sorbates include Bacillus, Clostridium,
Enterobacter, Pseudomonas, Salmonella and Serratia.14

Sorbates are selective in their antimicrobial activity; they are more
effective against catalase positive organisms than catalase negative, and
aerobes rather than anaerobes,\textsuperscript{14} which means that they are extremely useful in the preservation of fermented foods, where the growth of pathogens such as \textit{S. typhimurium}, \textit{E. coli}, and staphylococci will be inhibited, but the lactic acid bacteria used in fermentation will still be able to grow. The antimicrobial activity of sorbate is dependent on pH, and is greatest at lower pH values, with 98\% of sorbic acid being undissociated at pH 3 compared to just 37\% at pH 5.

8.2.6.2 Benzoate

Sodium benzoate or benzoic acid tends to be used in products where the pH is low, for example mayonnaises, pickled vegetables, fruit products and drinks. It is often combined with potassium sorbate in mayonnaise type products. This is because the mixture of the two preservatives is more effective than either of them individually and also sorbate is relatively tasteless compared to benzoate.\textsuperscript{15} Benzoate exerts its primary antimicrobial action upon yeasts and moulds, including the aflatoxin-producing moulds. Many bacteria are also inhibited by benzoate. However, clostridia and the lactic acid bacteria are resistant.\textsuperscript{15} The antimicrobial action of benzoic acid is due to interactions with cell membrane enzymes; it can also interfere with the cell wall.

8.2.6.3 Propionate

The main forms used are sodium and calcium propionate. Propionate is used widely with bakery products, and like sorbate and benzoate its action is pH dependent. However, it is able to work at higher pH values, which makes it more suitable for bakery use. Its mode of action is similar to that of sorbate and benzoate, as it accumulates within the cell and acts upon enzymes.\textsuperscript{15} Gram-negative bacteria are inhibited by propionate but its action against yeasts is weak and therefore the yeasts used in bakery products are not inhibited.

8.2.6.4 Nitrite

Nitrite is a food preservative typically used, along with salt, in cured and fermented meat products. In these types of products, safety is reliant on a careful balance between these two compounds. Nitrite was originally added to meat products to inhibit the growth of spore-forming bacteria, particularly \textit{Clostridium botulinum}. It has been extensively studied since the early 1950s and minimum inhibitory concentrations against a range of organisms have been established.\textsuperscript{16} Nitrite has a limited effect against yeasts\textsuperscript{17} and many of the microbial groups associated with meat products such as \textit{Enterobacteriaceae}, \textit{Pseudomonas} and \textit{Lactobacillus}.\textsuperscript{18}
Reports suggest that *Enterobacteriaceae*, *Brochothrix thermosphacta*, and *Moraxella* spp. are inhibited by 200 ppm sodium nitrite in Bologna-type sausages, whereas yeasts and lactic acid bacteria are only marginally inhibited and hence tend to predominate in these products.¹⁷,¹⁹

These findings contrast with those of Gibson and Roberts,²⁰ who reported that growth of *E. coli* and *Salmonella* at between 10°C and 35°C was not prevented by most combinations of salt (1–6% w/v), pH (5.6, 6.2 and 6.8) and sodium nitrite (0–400 ppm). Inhibition only occurred under extreme conditions of pH (5.6), temperature (10°C) and nitrite (400 ppm).

Despite many years of research, the exact mode of action of nitrite is still not understood and there are considered to be many possible target sites of action in the microbial cell. The inhibition of respiration by inactivation of key enzymes, release of nitrous acid and nitric oxides and the formation of S-nitroso compounds by reaction of nitrite with haem proteins have all been suggested.¹⁸,²¹

Like many food preservatives, nitrite works better under acidic conditions, which favour the production of undisassociated nitrous acid and thus permit its entry into the bacterial cell.

### 8.2.7 Natural antimicrobials

Many natural food ingredients that are added to food to achieve a desired flavour also have the potential to control microbial growth. These ingredients include vegetable extracts, mustard, onion, garlic, horseradish and a range of other herb and spice ingredients. Extracts and essential oils from plants have been shown to inhibit the growth of a range of microorganisms. Natural antimicrobial compounds and their possible modes of action have been reviewed extensively,²²,²³ but because they belong to a variety of different chemical classes, it has not been possible to identify a single mechanism by which they act on micro-organisms.

There has been much interest in recent years in the use of natural antimicrobials to help in food preservation as an alternative to chemical preservatives, which at present are used to prolong shelf life and safety. The active components found in herbs and spices (e.g. thymol from thyme and oregano, cinnamaldehyde from cinnamon, and eugenol from clove) have been shown to have a wide spectrum of antimicrobial activity.²⁴–²⁶

Work has been carried out to try to establish the potential for the use of natural antimicrobials instead of traditional chemical preservatives.²² Most of this work has been performed in laboratory broths, and few trials...
have been done in real foods. It would appear that the effectiveness of antimicrobial compounds decreases when they are used in real foods, or a higher level of the compound needs to be added to achieve an antimicrobial effect. If a higher level of the natural antimicrobial is required this can have an effect on product flavour and therefore alter the sensory properties of the product. The type of food product has been shown to affect the antimicrobial effects observed. It has been suggested that this may be due to the composition of the food, which immobilizes and inactivates the components, particularly in high-fat foods.

8.2.8 Microbial interactions

Usually the main factors that determine the growth of micro-organisms are chemical and physical in nature (e.g. pH, temperature); however, interactions between micro-organisms themselves may also affect their growth and spoilage activity.

Organisms will compete for the same substances or may produce inhibitory metabolites, which change the local environment, or directly affect other organisms. The growth characteristics of the weaker organism will be affected by the stronger competitor. In many cases, the final maximum population of the weakest organism is decreased, although this may not occur until levels of the competitor have become high, e.g. $10^8 \text{g}^{-1}$.

Microbial interaction is not always easy to measure but can contribute greatly to the stability of many foods. For example, many fermented food products rely on the use of lactic acid bacteria as starter cultures. The rapid growth of these organisms and the acid they produce contribute to the stability and safety of these products, including fermented meats such as salamis and dairy products such as yogurt.

8.3 PREDICTIVE MODELLING

As described, there are a range of factors that can influence the growth and survival of micro-organisms in food products. Information about the limiting factors for microbial growth is readily available (see Table 8.1). However, these limits are based on one factor only and assume that all other conditions are optimal. Therefore, if a product is preserved using a variety of different factors (pH, $a_w$, preservative) it can be difficult to assess the potential for microbial growth. In these situations, predictive microbiological models are extremely useful.
Predictive microbiological models are mathematical equations that can be used to predict the likely growth of micro-organisms under different product formulation or storage conditions. The power of predictive microbiological models is that they use laboratory data from one set of experimental conditions to predict the likely responses under a new set of conditions not previously tested. For example, data describing the effect of temperature on an organism at 5, 10 and 15°C can be used to predict the likely growth at 8°C. The same principle applies to any hurdle included in the model such as salt, pH or preservatives. The power of this tool for new product development is very apparent. Modifications of new or existing recipes can be tried on the computer using a model before embarking on expensive laboratory experiments or pilot scale production runs. The effect of new combinations of hurdles on extending product shelf life can be assessed using models, as can the effect of reducing current levels of hurdles.

There are currently a number of publicly available modelling systems that can be accessed by the food industry. For food pathogens there is the USDA Pathogen Modelling Program (PMP) (www.arserrc.gov), and the Combase Predictor (www.ifr.ac.uk) (which is based on the data that were formerly available as FoodMicromodel™), and for spoilage organisms there is the Campden & Chorleywood Food Research Association (CCFRA) FORECAST Service (www.campden.co.uk). The FORECAST system contains models for specific spoilage groups, for example Pseudomonas species, Enterobacteriaceae and lactic acid bacteria, or for a mixture of spoilage organisms relevant to food commodities, e.g. fish products and meat products.

Predictive models can be used to assess the likely change in growth characteristics caused by changing the product formulation such as the effect of changing levels of salt and nitrite.

These modelling systems are not suitable for use with all product types; in particular, acidified products are not well modelled. This type of product has many preservation factors (salt, sugar, acid, oil) that all aid safety and stability. Not all of these factors are included in the predictive systems previously mentioned. However, there are a number of systems that can be used to predict the safety/stability of this type of product. One of these systems is outlined in the CIMSCEE code, which is a code for the production of microbiologically safe and stable emulsified and non-emulsified sauces containing acetic acid. This was published in 1992 by the Comité des Industries des Mayonnaises et Sauces Condimentaires de la Communauté Economique Européenne. This code includes two equations
that can be used to predict the safety and stability of mayonnaise and sauce type products. The equations are based on the salt, sugar, and acetic acid content, pH, and dissociation constant of acetic acid, all in the aqueous phase of the product. A numerical value is calculated from the stability equation and if this value is greater than 63, this indicates that the intrinsic properties of the product are sufficient to confer microbiological stability, i.e. growth of spoilage organisms should not be observed. This is equivalent to a 3-log reduction of Salmonella or E. coli in 72 hours. These equations allow many product formulations to be evaluated for safety and stability rapidly and efficiently.

There is another equation that can be used to predict the stability of pickles and sauces, which is termed the preservation index. This is based on acetic acid content of the product and states that a minimum of 3.6% acetic acid is required to ensure that stability is achieved.35

A further way in which stability and safety of acidified products can be assessed is by using a series of models developed by the Campden and Chorleywood Food Research Association. These are based on $a_w$, pH (adjusted by citric, lactic and acetic acid) and preservative (sorbate, benzoate). These models predict whether growth of pathogens (E. coli, Salmonella, S. aureus) or spoilage organisms (yeasts, moulds, lactic acid bacteria) will occur in a nine-month period. With the spoilage model there are five categories of growth predicted: growth in 1–2 weeks, 2–4 weeks, 1–2 months, and 2–6 months or no growth within 9 months. These models can be used to predict the potential for microbial growth in a range of acidified products.

Models are very useful in providing cost-effective guidance with respect to potential microbiological shelf life and the effects of theoretical process or formulation variables, but there can be occasions when the predictions are not accurate. It is, therefore, important to consider limited practical testing in conjunction with any predictive microbiology model. Models are perhaps best viewed as a good first step in the evaluation of the microbiological shelf life and the effects of process and formulation changes, and can be used as a guide to focus attention on product development and limited shelf-life evaluation and challenge testing.

Shelf-life evaluation is designed to determine how long a product remains within the designated quality parameters during normal production and storage conditions. Only the growth of those micro-organisms that are likely to be present in, or able to cross-contaminate, the batch of product will be assessed. Ideally, under good manufacturing conditions, there will be minimal chance of food pathogens, e.g. Salmonella, being present.
in the product, and the effect of product formulation on the growth of such pathogens will, therefore, not be evaluated during shelf-life studies. Reliance should not be placed on shelf-life evaluation to establish the safety of the product with respect to microbiological pathogens; other risk management measures such as HACCP and separation of high/low risk operations should be the primary tools for identification and control of microbiological safety hazards.

As part of an HACCP study it may be considered appropriate to carry out a challenge test study. Challenge testing is designed to determine whether a particular product formulation and/or storage condition would control the growth of organisms during the designated shelf life, if they were present in a food. Challenge testing involves deliberate inoculation of the product with relevant micro-organisms that have the potential to survive or grow within the product during normal storage conditions. Careful consideration needs to be given to the planning and interpretation of results from challenge tests. It may be possible to demonstrate that a pathogen can grow in a product; however, the challenge test does not imply that the pathogen would be present in the product, nor does it attempt to quantify the likelihood of its being present. The use of HACCP with appropriate verification by routine microbiological analysis can help to answer this question.

However, challenge tests can enable the risk of growth of food poisoning or spoilage organisms to be evaluated if contamination were to occur. The organisms used in challenge studies should have been identified as being likely to be present in the product from ingredients or from cross-contamination after cooking/preparation. The levels of organisms inoculated into the product must be consistent with those likely to occur in practice.

There are some instances where published protocols for challenge testing exist. There are two challenge-test protocols outlined in the CIMSCEE code in order to establish whether acetic acid-based sauces are safe and stable. The safety challenge test involves inoculating a product with a specific \textit{E. coli} strain and evaluating levels of the micro-organism to establish if there has been a 3-log reduction in 3 days. The stability protocol involves adapting specific strains of yeasts, moulds and lactic acid bacteria to acetic acid. Once adapted, these organisms are inoculated into the product and the levels of these organisms are evaluated on day 0 and day 1 and in week 3. If levels are lower in week 3 than on day 1 then the product can be deemed to be intrinsically stable. Continued testing is recommended if levels remain the same; if growth is observed then the product is unstable.
8.4 CONCLUSIONS

Many food products do not rely exclusively on a single microbiological controlling factor for their preservation, as combinations of factors or ‘hurdles’ may be used. Each individual hurdle is applied at a reduced intensity, and the combination of factors results in food products that are safe and have an acceptable shelf life. As the trend is for foods with fewer preservatives, less salt and less sugar, there will be a need for increased use of hurdle technology using innovative combinations of antimicrobial factors to ensure the maintenance of food safety and an acceptable shelf life. The use of hurdle technology is not easy and requires the use of many tools (e.g. predictive microbiology, challenge testing and expert knowledge). Companies considering the use of such techniques should obtain expert advice during product development. The results of the commercial application of hurdle technology will be high-quality, safe and stable food products.

REFERENCES


9 Novel Commercial Preservation Methods

Craig Leadley

9.1 INTRODUCTION

Conventional preservation processes are, in general, well understood and have a long history of safe use when applied correctly. However, in many instances the sensorial and nutritional properties of the preserved food are somewhat different from those of the original raw material. In recent years there has been both industrial ‘push’ and consumer ‘pull’ for minimally processed foods that are closer in nature to, for example, freshly prepared meals. There are many new and emerging technologies attracting research interest for food preservation. These range from technologies still very much in their infancy for food preservation (such as plasma processing or pasteurization using dense phase carbon dioxide) to technologies that are relatively well developed and in some cases commercialized, albeit on a rather limited scale (examples include ohmic heating and high-pressure processing). To adequately describe the many and varied emerging technologies for food preservation, a book running to several volumes would be required. Instead this chapter has been restricted to a number of relatively well developed emerging preservation technologies. The intention is to give an overview of the main principles of each technology and to provide sources for further information should the reader wish to undertake more detailed studies.

9.2 OHMIC HEATING

9.2.1 Background

Ohmic heating works on the principle that all food materials have an inherent resistance to the flow of electricity. When an alternating electrical current (AC) is passed through a food product, the electrical resistance of that food causes it to heat up. Other names for this technology include resistance heating, direct resistance heating, Joule heating and
Electroheating™ (Raztek Corp., Sunnyvale, CA, US). Since ohmic heating technology relies on the electrical resistance of the food to generate heat, if the electrical resistances of all components of the product are constant then the product heats uniformly. Particulate products can be heated uniformly, and since the process does not rely exclusively on heat transfer from the carrier fluid to the particulate, this can overcome some of the limitations of heat transfer found in conventional high-temperature/short-time (HTST) systems such as plate, tubular or scraped surface heat exchangers. Products such as fruit juices and concentrates, shelf-stable milk, puddings, soups and liquid egg products can all be heated rapidly, uniformly, and with a reduced impact on the organoleptic properties of the product.

The advantages of ohmic heating over conventional heat exchangers can be summarized as follows:

- rapid and uniform heating
- higher particulate temperatures are attainable
- enhanced product quality owing to rapid heating
- reduced fouling of certain products
- greater energy efficiency
- instant switch-on/switch-off
- reduced maintenance
- quiet (dependent on type of pumps, etc)
- environmentally friendly.

Ohmic heating is not a new technology; several processes patented the use of electrical currents to heat pumpable liquids in the 19th century\(^1\) and ohmic heating was used for milk pasteurization in the early 20th century. APV Baker licensed a continuous ohmic heater developed by the Electricity Council of Great Britain with improved electrode material in 1988\(^2\) and were, for many years, the principal suppliers of the technology.

Interest in ohmic heating was limited for a number of years primarily owing to the lack of suitably inert electrodes and a lack of supplier competition in the market place. Since the 1980s improved materials have become available. For example, specially treated, pure carbon electrodes are employed to avoid metal dissolution by electrolysis in the system developed by the Raztek Corporation.

The main advantage of the technology, i.e. that heating is volumetric and dependent on electrical resistance, can, in some instances, be a significant disadvantage in that materials such as fats, oils and distilled water, that are not ionically loaded, are not suitable for processing using ohmic heating.
9.2.2 Industrial applications

Fig. 9.1 shows the basic principle of the operation of an ohmic heating system.

The food presents an electrical resistance to the current. The rate of heating is directly proportional to the square of the electric field strength, $E$, and the electrical conductivity, $\sigma$. The electrolyte (e.g. salt) content can be altered to improve the effectiveness of heating, as the conductivity is influenced by the ionic content. As the temperature increases so does the electrical conductivity, meaning that efficiency increases at higher temperatures. This can cause potential problems of over heating; consequently, sophisticated controls are required on the applied voltage to ensure that the temperature of the product at the outlet is accurately controlled. Fig. 9.2 shows a diagram of a typical ohmic heating plant from the point at which the product has been manufactured and is ready for heat processing. The product is pumped through the ohmic heating column and then enters a holding tube that is designed to ensure that the required minimum level of micro-organism lethality has been achieved throughout the fluid volume, based on the target process temperature and time, the length of the holding tube and the flow properties of the product – in much the same way as would be the case for conventional continuous flow heating systems.

A peculiarity of ohmic heating technology is that, in some products, the particulates could heat preferentially to the carrier fluid. As a result the particulates would give up heat to the carrier fluid along the holding tube.
so that the carrier fluid could be hotter at the exit of the tube than at the inlet. This would effectively change the critical control point in the system from the outlet of the holding tube to the inlet.

After exiting the holding tube, the product is pumped through conventional coolers before being transferred to storage tanks. Filling options include ultra-clean, aseptic or hot-fill technology depending on the intrinsic nature of the product and the required shelf life. The use of an aseptic fill can allow preservatives to be removed from the product where appropriate. Summaries of products processed and industrial plants installed by Emmpiemme SRL are given in Tables 9.1 and 9.2, respectively.

### 9.2.3 Equipment

Commercial systems are now available from a number of suppliers including Invesys APV (Crawley, UK), Raztek Corp. (Sunnyvale, CA, USA) and Emmpiemme SRL (Piacenza, Italy). An example of an Emmpiemme system can be seen in Fig. 9.3.
### Table 9.1

Industrially processed products in Emmepiemme equipment based on 2002 data (plant capacities from 1000 to 6000 kg/hr).

<table>
<thead>
<tr>
<th>Product (packaged in aseptic bags, 2-20 kg or 200 kg)</th>
<th>Process temperature $(^\circ\text{C})$</th>
<th>$\Delta T, ^\circ\text{C}$</th>
<th>Heater power, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato ready-to-serve sauces*</td>
<td>110</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Mango purée</td>
<td>105</td>
<td>20</td>
<td>64</td>
</tr>
<tr>
<td>Tomato paste</td>
<td>100</td>
<td>30</td>
<td>64</td>
</tr>
<tr>
<td>Diced tomatoes</td>
<td>105</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Tomato purée</td>
<td>120</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Peaches/apricots (dices, slices, halves)</td>
<td>95</td>
<td>50 and 30</td>
<td>100, 150–200</td>
</tr>
<tr>
<td>Diced sweet peppers – zucchini</td>
<td>115</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Carrot slices</td>
<td>135</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Low-acid vegetable purées</td>
<td>95</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>Strawberries (whole, diced)</td>
<td>92</td>
<td>70</td>
<td>30</td>
</tr>
</tbody>
</table>

* Packaged in glass jars.

### Table 9.2

List of industrial plants installed globally by Emmepiemme (as of 2006).

<table>
<thead>
<tr>
<th>Country</th>
<th>Installation year</th>
<th>Product</th>
<th>Heating power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy</td>
<td>1994</td>
<td>Aseptic process and filling – tomato sauces and pastes</td>
<td>50</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>1996</td>
<td>Aseptic process and filling – tomato paste and mango purée</td>
<td>64</td>
</tr>
<tr>
<td>Italy (through Simarco)</td>
<td>1996</td>
<td>Aseptic process and filling – fruit slice and dice</td>
<td>100</td>
</tr>
<tr>
<td>Greece (through Simarco)</td>
<td>1998</td>
<td>Aseptic process and filling – peach and apricot slice and dice</td>
<td>150</td>
</tr>
<tr>
<td>Greece (through Simarco)</td>
<td>1999/2000</td>
<td>Aseptic process and filling – peach and apricot dices, slices and halves</td>
<td>150, 200, 240 respectively</td>
</tr>
<tr>
<td>Italy</td>
<td>2000</td>
<td>Aseptic process and filling – diced pears and apples</td>
<td>150</td>
</tr>
<tr>
<td>Italy</td>
<td>2001</td>
<td>Aseptic process and filling – low-acid vegetable purées</td>
<td>100</td>
</tr>
<tr>
<td>Mexico</td>
<td>2002</td>
<td>Strawberries</td>
<td>250</td>
</tr>
<tr>
<td>France</td>
<td>2002</td>
<td>Fruit preparations</td>
<td>100</td>
</tr>
<tr>
<td>France</td>
<td>2003</td>
<td>Processing line for special meat recipes</td>
<td>50</td>
</tr>
<tr>
<td>Italy</td>
<td>2004</td>
<td>Aseptic process and filling – plum peeled tomato and tomato dices</td>
<td>480</td>
</tr>
<tr>
<td>Italy</td>
<td>2005</td>
<td>New vegetable sauces and special recipes</td>
<td>60</td>
</tr>
<tr>
<td>Italy</td>
<td>Start-up in June 2006</td>
<td>Aseptic processing line for diced mushrooms and tomato</td>
<td>240</td>
</tr>
<tr>
<td>Italy</td>
<td>Forecasted in July 2006</td>
<td>Aseptic line for tomato dices, pulp and sauces</td>
<td>480</td>
</tr>
<tr>
<td>Italy</td>
<td>Expected 2006</td>
<td>Tomato sauces and other derivative</td>
<td>100</td>
</tr>
<tr>
<td>Greece</td>
<td>Forecasted June/July 2006</td>
<td>Processing and aseptic filling line for peach and apricot dices and slices</td>
<td>120</td>
</tr>
</tbody>
</table>
It is estimated that there are at least 18 commercial plants in operation across Europe, the USA and Japan. In addition, Emmepiemme SRL equipment has been supplied to Mexico and the Ivory Coast for strawberry processing and tomato and mango processing, respectively (personal communication, 2006). Arguably the most successful application of this technology has been in the area of fruit and vegetable processing, and multiphase products.

Invensys APV (UK) produces two commercial systems with power outputs of 75 kW and 300 kW, corresponding to product capacities of 750 kg/h and 3,000 kg/h respectively, for a temperature rise of 75°C in water. Approximate costs for these units in an aseptic system are £1,300,000 to £2,000,000. Emmepiemme SRL (Italy) produces systems in the range of 60 kW to 480 kW, for production throughputs of 1000 kg/h to 6500 kg/h. Cost estimates as of 2004 were approximately €60,000 to €220,000, depending on the power output; these estimates are for indication only, as more detailed costings need to be made on a case-by-case basis.

### 9.2.4 Packaging considerations

Since the product is being processed in a continuous flow and is packed post process, there are no technology-specific packaging requirements. As
for any product, the requirement is that appropriate food contact materials are selected with the required barrier properties for the intended shelf life of the product. The packaging needs to be selected such that a hermetic seal is assured throughout the shelf life of the product.

9.2.5 Shelf life and product safety

Ohmic heating can be used to pasteurize or sterilize and as such it is possible to produce a full spectrum of products from chilled short shelf life through to ambient shelf-stable. Since the main advantage is rapid heating with reduced quality losses, the primary application for the technology is in the production of ambient stable products with improved quality. The mechanism of inactivation of micro-organisms by ohmic heating is thought to be thermal in nature.

9.3 HIGH-PRESSURE PROCESSING

9.3.1 Background

High-pressure processing (HPP) is a non-thermal pasteurization process in which a food is subjected to pressures in the region of 300 to 600 MPa (3000 to 6000 bar) and held at pressure for a time, generally under 10 minutes. The applied pressure is usually transmitted via water in commercial systems but alternative materials such as propylene glycol or oil-in-water emulsions are employed in laboratory systems. A small temperature rise is observed during pressurization. This rise is typically around 3–4°C per 100 MPa of applied pressure for predominantly aqueous materials, but varies depending on the composition of the product. Typical compression heating effects for real foods have been reported by various authors and are summarized in a separate review. Although this is a small temperature rise, it can have significant implications on the overall lethality of the process, especially when pressure is combined with moderate heating, and it certainly must be considered within the development of a safe process.

The extremely high pressures employed in HPP inactivate vegetative micro-organisms, and because the process does not involve heating, the sensory and nutritional qualities of HPP products can be remarkably similar to those of their unprocessed counterparts. Bacterial spores are very resistant to commercially achievable pressures and, as a result, products that are currently on the market are chilled, and many are high acid or contain additional preservation hurdles such as the presence of antimicrobial compounds.
9.3.2 Industrial applications

Commercial pasteurization using high pressure as a replacement for heating was not considered feasible until the late 1980s. Pioneering work in Japan led to the launch of the world’s first high-pressure pasteurized food in 1990 – a jam product manufactured by the Meidi-ya Food Factory Co. Further high added-value products such as juices and dairy desserts appeared in Japan shortly afterwards. Since then, high pressure has been used as an alternative to heat pasteurization by a number of companies throughout the world. Table 9.3 shows a selection of manufacturers widely reported to be using HPP, and some of the typical products manufactured in Europe and the USA using high-pressure processing.

Growth in the commercial use of HPP for pasteurization has been steady; in 2005 it was estimated that there were around 82 commercial-scale high-pressure food presses in use worldwide.° Around half of these commercial vessels were located in the USA and around a quarter were in Europe. These vessels were distributed around 55 different food companies. Of the 82 vessels, 21% were in use for juice and beverage production, 32% for fruit and vegetable products, 24% for meat products and 17% for shellfish production, the balance being other speciality applications. Total worldwide production in 2004 was estimated to be 100,000 tons.

9.3.3 Equipment

There are two main types of HPP equipment available – batch and semi-continuous. In a batch process, the product is filled into bulk or individual primary packaging and loaded into the vessel, usually in some sort of
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Basket or crate in much the same way as happens in a conventional retort process. Water is pumped into the vessel until the target processing pressure is reached and the batch is held at this pressure for the required time. The pressure is released and the product is removed from the vessel. In a semi-continuous system, the product is pumped directly into a treatment chamber and is separated from the pressure medium by a floating piston. As the pressure medium is introduced, the piston moves up to pressurize the product. By using a number of units in parallel it is possible to coordinate the process such that one unit is emptying as another is filling and a third is pressurizing. In this manner, a continuous stream of product can be supplied to a clean or aseptic filling system. Batch systems are the most prevalent systems used industrially. Examples of batch pressure-processing equipment for food use can be seen in Fig. 9.4 and Fig. 9.5.

Process economics are dependent on a number of factors, including the product type, pressure used, fill ratio and the come-up-time to pressure. As an example, a typical lobster process of 300 MPa with a 1 minute hold would cost in the region of €0.05 per kg. This estimate is based on:

- 300-l vessel with a 75% fill ratio
- 2.9 minutes to load and unload
9.3.4 Packaging requirements

There has been relatively little research into the effects of high-pressure processing on food packaging. Lambert et al.\textsuperscript{7} investigated the effects of pressure on a range of PA/PE based packaging films using 200–500 MPa for 30 minutes and found that the physicochemical and mechanical properties of the films were largely unaffected with the exception of one cast co-extruded material that de-laminated under pressure. Dobiáš et al.\textsuperscript{8} investigated the effects of a 600-MPa, 1-hour treatment on a range of packaging materials. There were no statistically significant differences in tensile strength, absorbance at 450 and 600 nm or water vapour permeability in the homogeneous materials. Tensile strength was increased in some laminates as was absorbance at 450 and 600 nm. Water vapour permeability was also increased in some laminates. Overall migration into ethanol and/or isooctane was also increased in some cases but was, according to the author, below the EU maximum permitted migration limits. While some changes were observed in the work by Dobiáš et al.\textsuperscript{8}, it is important to recognize that the treatment times used were considerably longer than would be employed for commercial processing.

**Fig. 9.5** A horizontal batch high-pressure processing vessel from NC Hyperbaric (reproduced with permission from Carole Tonello, NC Hyperbaric).
At the most fundamental level, the main requirement of packaging for HPP is that it is able to reversibly flex such that any distortion occurring during the process is lost on removal of the pressure. There is a need for further research to investigate how the physicochemical and mechanical properties of packaging films are affected by high pressure.

9.3.5 Shelf life and product safety

All HPP products currently in the market are chilled products. There are no technology-specific food safety issues to be addressed for the use of high-pressure technology other than those associated with the production of any other chilled product, where due consideration must be given to the full spectrum of pathogens that could be capable of growth over the intended shelf life and storage conditions. One of the challenges for HPP, however, is in understanding the response of the target pathogen to high pressure in the food of interest. The response of micro-organisms to high pressure is influenced by the food substrate. In the foreseeable future it seems likely that process establishment for HPP will take the form of challenge testing in the product rather than using generic lethality models as can be done in thermal processing. In reality, even in thermal processing the food substrate is known to influence inactivation kinetics, but the models used for thermal process establishment have a proven safety record, which in many ways justifies their continued usage in a commercial context.

Commercial HPP products vary in shelf life according to product type. For example, fruit-based, chilled HPP products are typically assigned a shelf life in the region of 21–28 days. Some Spanish meat products have a shelf life in the region of 30–60 days, but it should be noted that such products have additional hurdles to prevent the growth of psychrotrophic strains of Clostridium botulinum, e.g. the presence of curing agents.

9.4 MICROWAVE AND RADIO-FREQUENCY HEATING

9.4.1 Background

Microwave and radio-frequency (RF) heating are well established thermal processing technologies that have found application in many process sectors. Commercial installations are common in the plastics, textiles, paper and board, wood and food processing industries. Food applications for the prevention of biodeterioration are not, however, in widespread use. Microwave and RF heating are similar in that, as is the case for ohmic heating, heat is generated volumetrically throughout a product rather than
Microwave and RF heating refers to the use of electromagnetic waves at particular frequency to generate heat in a food material. The frequency bands allocated for industrial, scientific and medical (ISM) use are listed in Table 9.4. Of these, 896/915 MHz is generally used for microwave processing applications and 2450 MHz is used for domestic microwave ovens and some industrial process applications. RF heating utilizes each of the frequencies outlined, depending on the application, although 40.68 MHz is rarely used.

The major advantage of microwave/RF heating is, as for ohmic heating, the rapid and volumetric temperature rise that can be achieved in foods. This results from two primary heating mechanisms – a dielectric effect and an ionic heating effect. Dielectric heating occurs when water molecules, the principal constituent in most food materials, oscillate at the very high frequency of the microwave/RF field; such oscillations produce rapid heating. Ionic heating occurs when the oscillatory motion of ions in the food, under the influence of the microwave/RF field, produces a heating effect. In food processing, the advantages of the rapid heating effects are amplified by the fact that both microwave and RF radiation can penetrate the food to a depth of several cm (microwave) or tens of cm (RF), promoting a volumetric heating effect throughout the food. This can have huge advantages over slower conventional heating processes, as the high-temperature/short-time process can achieve bacterial reduction, while thermal degradation of desired components is reduced.

The major difference between microwave and RF heating relates to the electrical field. In RF heating, the electrical field is generated in a directional manner between a pair of electrode plates; the food material to be heated is placed between the two plates to achieve the desired effect. In microwave heating, the electrical component of the microwave field
approaches the food product from all directions; microwave heating usually takes place in an enclosed cavity, or in close vicinity to a waveguide applicator.

The rate of heat generation per unit volume at a particular location within a food material during microwave/RF heating can be characterized by the equation:

\[ Q = 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon'' \cdot E^2 \]  
(Eqn. 9.1)

where \( E \) is the strength of the electric field of the wave at that location, \( f \) is the microwave/RF frequency, \( \varepsilon_0 \) is the permittivity of free space (a physical constant) and \( \varepsilon'' \) is the dielectric loss factor representing the food material’s ability to absorb the wave. The dielectric properties depend on the composition (or formulation) of the food, the dominant constituents being water and salt. Along with this dielectric factor, the temperature rise in the food depends on the duration of heating, the location in the food, the convective heat transfer at the surface of the food and the extent of surface evaporation.

Microwave and RF heating can be relatively more uniform than conventional heating, although the design and geometry of the food product and the food packaging play an important role in promoting uniform heating.

Important design factors are component geometry and size, component layout and distribution, product size and mass, and packaging material, shape and dimensions.

The volumetric nature of both microwave and RF heating leads to a number of significant advantages over traditional surface heating techniques. Among the most important advantages are:

- improved food quality
- increased product throughput
- improved energy efficiency
- improved control of the heating process.

It should, however, be recognized that there is something of a trade-off to realize these key advantages. There are several disadvantages associated with both microwave and RF process operations, the major drawbacks being:

- difficulties in validating the heat treatment
- high equipment and operating costs.

In addition, there are factors to be considered in the choice between microwave and RF systems. Although both techniques offer rapid, non-contact volumetric heating, the longer wavelength of RF compared with
microwave radiation and the nature of the dielectric properties of foods, mean that RF radiation will penetrate deeper into most products than microwave energy. The difference can be dramatic, e.g. for meat the penetration depths can be just a few mm for microwaves, but tens of cm for RF waves. RF systems are also, currently, simpler in their construction than microwave systems, although RF power systems are significantly larger in size than microwave systems of equivalent power output.

### 9.4.2 Industrial applications

The promise of rapid and volumetric heating has prompted much R&D and pilot-scale application over the years. A list of potential food applications is shown in Table 9.5.

Although microwave heating of foods has been practised since around 1945, and more than 20 million domestic microwave ovens are sold in the US and Europe each year, there has been only a slow uptake of microwave (and RF) heating technologies in food processing, apart from in specific niche sectors, e.g. RF drying at the outlet of biscuit baking ovens to prevent ‘checking’. There are many reasons for this, including the traditional conservative nature of food manufacturing businesses, the high costs associated with the technology (particularly as individual food applications are often bespoke designs) and the lack of scientific and technical understanding of the dielectric heating of foods.

There are, however, many successful applications for both microwave and RF heating in the food and drink sectors. Since the focus of this text is methods for the prevention of biodeterioration, microwave and RF applications are here discussed only in the context of preservation – primarily through drying.

#### 9.4.2.1 Microwave pasteurization and sterilization

Industrial microwave pasteurization and sterilization systems have been investigated and reported on for many years, and a wealth of

<table>
<thead>
<tr>
<th>Process step</th>
<th>Process need</th>
<th>Application</th>
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<tbody>
<tr>
<td>Tempering and thawing</td>
<td>Increase temperature</td>
<td>Frozen food blocks</td>
</tr>
<tr>
<td>Drying</td>
<td>Expell moisture</td>
<td>Crisps, snacks</td>
</tr>
<tr>
<td>Blanching</td>
<td>Inactivate enzymic activity</td>
<td>Vegetables and fruit</td>
</tr>
<tr>
<td>Cooking</td>
<td>Promote chemical change</td>
<td>Bacon, sausages</td>
</tr>
<tr>
<td>Baking</td>
<td>Develop texture/structure</td>
<td>Cakes, bread</td>
</tr>
<tr>
<td>Pasteurization and sterilization</td>
<td>Inactivate micro-organisms</td>
<td>Ready meals</td>
</tr>
</tbody>
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information now exists. One well-known commercial system (using a microwave frequency of 2450 MHz) is that of Tops Foods in Belgium. The company produced over 13 million ready meals in 1998 and installed a new system in 1999. The system consists of microwave tunnels with several launchers distributed across a number of ready-meal packages. Microwave-transparent and heat-resistant packaging is used, with optimized shapes for uniform microwave heating. The importance of exact positioning of the package within the microwave chamber is recognized and, using guide rails within the conveying system, precise positioning of the package ensures that each package receives a pre-calculated, spatially varying microwave power profile. It is reported that the central areas of the product are provided with higher power levels, in an attempt to direct more heating toward areas likely to contain the slowest heating point. In such an application, process control is achieved via infrared surface temperature measurement and the detection of in-pack steam generation, by means of a deflection monitoring system. Visual control using maximum thermometers and visual inspection are also used. The process consists of heating, holding and cooling sections in pressurized tunnels, with a high degree of automation.

In such a system, process parameters under the direct control of the operator include levels of microwave power, cycling of microwave power, spatial distribution of microwave power and time of exposure. Owing to the rapid nature of microwave heating, small changes to these process parameters need to be carefully controlled, as even small process deviations can have a significant effect on the temperature of the food.

Commercial RF systems for food pasteurization and sterilization are not known to be in current use.

9.4.2.2 Microwave drying of foods

The major limitations of conventional drying processes are the thermally induced damage to sensory and nutritional components due to the long holding times at elevated temperatures. Low thermal conductivities of the food (particularly with low moisture content, or as drying removes moisture) limit the speed at which mass transfer can occur. Also, case-hardening due to the non-homogeneous ‘surface-first’ drying delivers products of reduced quality.

Microwave-assisted drying can be applied either at atmospheric pressure or under vacuum. Most common in the food industry is the use of microwave radiation to accelerate an existing conventional hot-air drying process. A review of microwave drying applications has been given by Roques and Zagrouba.
The key to controlling heat input to a microwave drying process is the control of the relatively high frequency of the radiation. Microwave energy oscillates at a constant frequency, although controlling its direction and flow toward the product has been the biggest hurdle in achieving acceptable results from the technology. In a method proposed by Industrial Microwave Systems,18 the microwave energy passes through a slotted waveguide that compensates for attenuation and aligns the hot spots in the natural power fluctuations of the waves. Essentially, this regulates power peaks by balancing them with power dips, protecting against localized high temperatures. Because the microwave field oscillates at the constant microwave frequency, the system can control the energy distribution across a plane surface, or in an elliptical format for a cylindrical microwave applicator.

The proposed planar system can function in a vertical or horizontal mode and usually operates at a constant 915 MHz for better energy management. IMS claims a 95–99% energy conversion through its energy management. The physical size of the system is governed by the microwave frequency used: the higher the frequency, the smaller the size. This relates directly to the drying speeds and footprint of the machines. For example, a 25–50% increase in drying speeds (over conventional drying plant) can occur in a footprint of less than 2.5 m. The efficiency is some 100% greater than that available 10 years ago, which is attributable to improvements in components such as circulators and magnetrons.

The optimal use of the system is as part of a hybrid system, e.g. as a pre-dryer or post-dryer. For post-drying after gas-fired oven baking of a biscuit, the microwave system can reduce the product moisture from 20% to less than 8% with a post-bake process line length of c. 2.5 m; conventional post-bake drying would necessitate a post-bake line length of some 25 m.

9.4.2.3 Radio-frequency drying

RF drying is an application with a growing reputation. RF dryers have been used by the ceramics and glass-fibre industries since the early 1970s, and today process a variety of advanced ceramic products, refractories and fibreglass materials. Other process sector drying applications include building insulation materials, multi-layer bags, catalytic converters for cars, plastic sheets for moulding and patterned glue- and water-based coatings in textiles, glass and ceramic manufacturing.19

RF drying offers several benefits, including precise control of moisture content and uniformity (owing to selective heating of the water component), reduction in surface cracking (owing to more uniform distribution of heat and mass transfer), and savings in energy (all energy applied to the...
process is absorbed by the water component), time and plant space (estimated at approximately 20–25% of the space requirement of a conventional dryer).

Food applications in commercial use include crackers, snack foods, cereals, biscuits and ready-to-eat breakfast cereals. RF drying of crackers is typified by the installation at Pepperidge Farm in Denver, PA, US, where the conversion from conventional hot-air dryers to RF dryers has doubled the capacity of the cracker production line, without adversely affecting quality parameters (colour, size, texture and taste). The added degree of process control and uniform drying has also allowed the company to produce a variety of new line extensions, such as ‘giant’ size crackers with higher moisture levels.19

There is a wide range of food products are good candidates for RF drying. The more difficult an item is to dry with convection heating, the more likely it is to be a good candidate for RF drying. Materials with poor heat-transfer characteristics, such as bakery and aerated products, are traditionally a problem for conventional drying. RF energy simultaneously and volumetrically heats all parts of the product, evaporating the water in situ at relatively low temperatures, usually not exceeding 80°C. Furthermore, the water is able to permeate through the product in gaseous form and is easily released from the product. The effect is that many of the undesirable consequences of conventional drying (e.g. warping, surface discoloration and cracking) are eliminated. The reduced thermal effect also has benefits in terms of preserving sensory and nutritional characteristics.

RF post-baking dryers utilize RF energy, which preferentially heats and dries the moist areas of cookies, crackers, and snack foods to eliminate surface checking and control moisture and colour. Such dryers remove the drying requirement from baking ovens, allowing bakers to maintain their oven settings to achieve the desired product quality attributes.

9.4.2.4 Microwave baking and cooking of foods

Microwave and microwave-assisted baking of bread, cakes, pastry etc. has been studied for many years. The major advantage is the acceleration of the baking process, with an improved product throughput and with the microwave system retro-fitted to an existing baking line. As microwaves do not preferentially heat the surface of the product, the microwave baking process is often combined with other forms of surface heating, e.g. infra-red, to form the familiar and desirable product crust characteristics of baked goods.
An added advantage of the faster generation of heat from a microwave or microwave-assisted process is that lower grade flour (e.g. with lower protein content) can be used; the rapid heating prevents the starch from excessive breakdown and develops sufficient CO₂ and steam to produce the characteristic bubble/crumb structure.

The major use of microwaves in the baking industry today is in the finishing process. A conventional oven is used to heat the high-moisture dough, but as the product develops its gas-retaining structure, microwave energy can be used to overcome the problems with low thermal conductivity towards the end of the baking time.

9.4.2.5 Radio-frequency baking

Using RF in ‘post-baking’ applications can potentially increase product throughput by up to 30%. RF systems can be fully integrated within existing baking lines, even to the extent of operating within the baking oven itself, and tolerate high bake temperatures (ca. 300°C). The advantages of RF-assisted baking include:

- reduced baking time
- reduced equipment footprint
- a wider choice of product characteristics arising from the separate control of the heating rates at product surface and product core
- choice of full baking or part baking for finishing at point of use
- novel product shapes and textures.

9.4.3 Packaging requirements

For in-pack pasteurization and sterilization, the product packaging has to be transparent to microwaves and have a high melting point. The presence of metal in the packaging can shield the food and influence the temperature distribution within the pack. This effect is sometimes deliberately harnessed to prevent over-heating in certain regions of the pack and produce a more uniform temperature distribution. Polypropylene with an ethylene vinyl alcohol (EVOH) barrier and a polyethylene terephthalate (CPET) film are reported to be the most widely tested materials for in-pack microwave processing.

9.4.4 Shelf life and product safety

Although there has been some debate as to whether there are any nonthermal preservation effects that can be attributed to dielectric heating, the general consensus is that microbial inactivation using microwave or
RF radiation has a thermal mechanism. In light of this, there are no technology-specific microbial safety issues relating to the identification of appropriate target pathogens of concern. Temperature variability and the location of the ‘cold-spot’ within a microwave field need to be carefully considered at the process establishment stage, as do the variability of the product formulation, the product shape and the product size, as all could influence rates of heating. Thermocouples cannot be used in a microwave field so fibre-optic systems can be employed as an alternative means of measuring a time–temperature profile. Remote platinum resistance-based loggers are reported to have been used successfully for industrial process establishment when inserted deep within a product. Shelf-life considerations are largely identical to those of conventional thermal processing.

9.5 PULSED ELECTRIC FIELD PROCESSING

9.5.1 Background

The inactivation of micro-organisms and enzymes using electric discharges started as early as the 1920s with the ‘ElectroPure’ process for milk production. This process consisted of heating the milk to 70°C by passing it through carbon electrodes in an electric heating chamber to inactivate *Mycobacterium tuberculosis* and *E. coli*.21,22 The electric field was small, only 220 volts AC, it was not pulsed and the inactivation mechanism was purely thermal.21 There were around 50 plants using the ElectroPure system in the USA up until the 1950s.23

An ‘electrohydraulic’ process was developed in the 1950s as a method of inactivating micro-organisms in liquid food products. A shock wave generated by an electric arc and the formation of highly reactive free radicals was thought to be the main mechanism for microbiological inactivation.22 The process did not find widespread use in the food industry because particulates within the food were damaged by the shock waves and there were issues surrounding electrode erosion and the potential for contaminating the food.23

Pulsed electric field (PEF) processing is a technique in which a food is placed between two electrodes and exposed to a pulsed high-voltage field (typically 20–80 kV/cm).10 Treatment times are of the order of less than 1 second for preservation applications. This process reduces levels of micro-organisms while minimizing undesirable changes in the sensory properties of the food.
9.5.2 Industrial applications

9.5.2.1 Current applications

There is currently only one manufacturer known to be pasteurizing food products using pulsed electric fields. This is a small juice producer, Genesis Juice, in Eugene, OR, USA. Details are still relatively scant but as of January 2006 the company was known to have seven products in the organic market that were sold as high-added-value premium products. The company was selling into local markets and was thought to be running 3 to 4 shifts per week with a flow rate of 200 l/h (personal communication, 2006).

9.5.2.2 Potential applications

A large body of research has demonstrated the anti-microbial effects of PEF. Many studies have been conducted in model food systems, but relatively few publications have related to real food products. From those that have, a number of pumpable food products that potentially could be preserved using PEF have been identified. These include:

- fruit juices
- milk
- liquid whole egg
- soups (likely to be restricted to non-particulate or small particulate products).

9.5.3 Non-preservation applications

A number of non-preservation related potential applications also exist for PEF processing that are beyond the scope of this chapter. However, examples include:

- treatment of wheat dough (50 kV, 20 min), which reportedly decreases water loss during baking and increases the shelf life of the bread subsequently baked from the dough
- treatment of brewer’s yeast to convert non-flocculent yeast to a flocculent form
- extraction processes such as those found in starch production, sugar beet processing and juice extraction. Here PEF is used to render plant cells permeable to enhance the extraction of the target component.

9.5.4 Equipment

To generate a high voltage pulsed electric field of several kV/cm within a food, a large flux of electrical current must flow through the food within...
a treatment chamber, for a very short period of time. This process involves the slow charging of a capacitor followed by a rapid discharge. Fig. 9.6 shows a simple circuit for the generation of an exponentially decaying pulse. The corresponding waveform generated by this circuit along with typical alternative waveforms is shown in Fig. 9.7.

![Fig. 9.6 Circuit for exponential decay pulse generation (courtesy of Professor Barbosa-Cánovas, Washington State University, reproduced with permission from the Journal of Food Science 2000, 65, no. 8, suppl. Kinetics of microbial inactivation for alternative food processing technologies).]

![Fig. 9.7 Examples of pulse wave shapes in PEF (courtesy of Professor Barbosa-Cánovas, Washington State University, reproduced with permission from the Journal of Food Science 2000, 65, no. 8, suppl. Kinetics of microbial inactivation for alternative food processing technologies).]
The most important components of a pulsed power generator include: a power supply, either a high-voltage, low-current supply for an electric circuit or a low-voltage high current supply for an inductive circuit; an energy storage element – either electric (capacitive) or magnetic (inductive); a switch – either closing or opening; a pulse shaping and triggering circuit in some cases.

PEFs can be applied in many wave shapes including exponentially decaying, square wave, bipolar or oscillatory pulses. The square waveform is generally considered to be the better option for microbiological inactivation compared with the exponential waveform because it maintains peak voltage for longer. The exponential waveform is also less energy efficient and the prolonged tailing can lead to excessive heat generation in the food. It is considerably more complex to generate square waveforms compared to exponential ones because a pulse-forming network is required that must have an impedance that matches that of the treatment chamber; this is difficult to achieve in practice. Oscillatory pulses are considered to be the least efficient for microbial inactivation. Instant charge reversal pulses can significantly reduce the energy requirements for the PEF process to as low as 1.3 J/ml.

For further reading on engineering design principles for PEF, the reader is directed to review articles by Ho and Mittal and Barbosa-Cánovas et al.

### 9.5.5 Packaging considerations

Since PEF processing for preservation is likely to be used as a continuous process whereby the un-packaged product is pumped through the PEF treatment chamber, there are no technology-specific packaging requirements. Post processing, the product has to be filled into its packaging in clean or aseptic conditions as appropriate for the intended storage conditions and shelf life.

### 9.5.6 Shelf life and product safety

#### 9.5.6.1 Key factors for microbial inactivation

The three key areas that determine the effectiveness of PEF for microbiological inactivation are process factors, product factors and microbial factors.

**Process factors**

The intensity of the electric field will affect the transmembrane potential of the microbial cell, therefore an increase in inactivation can be expected
with an increase in electric field intensity. The pulse width used affects the level of electric field intensity that is required to achieve inactivation. Larger pulse widths reduce the field intensity that is required to produce a transmembrane potential large enough to initiate pore formation. Unfortunately, longer pulses also increase the degree of heating observed in the food, so a careful balance must be established to maximize inactivation while minimizing product heating. In general, an increase in treatment time (number of pulses multiplied by pulse duration) also increases the level of inactivation.

The shape of the wave also influences the degree of inactivation achievable with PEF. Square wave pulses are more energy efficient and more lethal than exponentially decaying waveforms. Bipolar pulses cause additional stress to the cell membrane, enhance microbial inactivation and are energy efficient. Finally the process temperature has an impact on the lethality of PEF. Moderately elevated temperatures (50–60°C) have a synergistic effect when combined with PEF. This may be due to changes in membrane fluidity and permeability, or an increase in the conductivity of the liquid being treated.

Product factors
The electrical conductivity of the product to be treated is a very important parameter for PEF processing. Foods with a large electrical conductivity are not suitable for processing with PEF because the peak electric field across the chamber is reduced. The ionic strength of a food material directly influences its conductivity: as conductivity rises, the lethality of a process decreases.

Reducing the pH of the product is thought to increase the inactivation achievable for a given field strength. However, work by Berlin University of Technology suggested that pH modification down to pH 5.5 had minimal effect on the lethality of PEF processing of *B. subtilis.* Particulates in the liquid also pose processing problems because high energy inputs may be needed to inactivate micro-organisms in the particulates and there is a risk of dielectric breakdown of the food.

Microbial factors
In general, the order of resistance of micro-organisms to PEF (lowest to highest) is considered to be yeasts, Gram-negative bacteria and Gram-positive bacteria. Lifecycle effects also impact on the lethality of the process; in general, organisms in the log phase of growth are more sensitive to PEF than those in the lag or stationary phase of growth. There is also some evidence to suggest that higher initial concentrations of micro-organisms can impact on the lethality of the process. The anti-microbial effects of PEF are relatively well established. Stabilization of the product
against non-microbiological degradation such as enzymic degradation is less well understood.

### 9.5.6.2 Effects of PEF on food enzymes

Work on PEF effects on food enzymes has been relatively limited to date and variable results have been obtained.\(^3\) Work using simulated milk ultrafiltrate in a continuous flow unit (45 ml/min) resulted in a 20–90% reduction of plasmin (bovine milk). The process conditions used varied between 15 and 45 kV/cm, with a 2-µs pulse, a frequency of 0.1 Hz and between 10 and 50 pulses. Studies on a protease (*Pseudomonas fluorescens* M3/6) highlighted the effect of substrate on the levels of achieved inactivation. A 60% reduction in activity was found in skimmed milk (15 kV/cm, 2-µs pulse, frequency of 2 Hz, 98 pulses, 50°C) whereas no effect was found using the same processing parameters in casein tris buffer.\(^3\) Results on the inactivation of alkaline phosphatase in raw milk have been variable. Washington State University demonstrated a 96% reduction in activity using 13.2 kV/cm and 70 pulses, whereas unpublished data by Verachtert and others showed no inactivation using 13.3 kV/cm, a frequency of 1 Hz and 200 pulses of 2-µs.\(^3\)

Ho and co-workers examined the effects of PEF on a number of enzymes in model systems.\(^3\) They found that the activity of a lipase derived from wheat germ in de-ionized water (pH 7) could be reduced by up to 85% using a treatment of 87 kV/cm at a frequency of 0.5 Hz using 30 pulses of 2-µs duration. The level of inactivation increased with increasing electric field strength. For example at 20 kV/cm only a 20% reduction in activity was achievable. Glucoseoxidase activity in pH 5.1 buffer could be reduced by 20–75% using 17–63 kV/cm, a frequency of 0.5 Hz and 30 pulses of 2-µs at 20°C. Inactivation of α-amylase (from *Bacillus licheniformis*) in de-ionized water (pH 7) varied between less than 5% and around 85% using 20–80 kV/cm, a frequency of 0.5 Hz and 30 pulses of 2-µs duration at 20°C.

Work at the Katholieke Universiteit Leuven (KUL, Leuven, Belgium) has increased the complexity of the materials used in enzyme studies, moving from initial trials in simple model systems towards real food products.\(^3\) In distilled water, KUL could get no better than a 10% reduction in activity of a range of commercial enzymes: lipoxygenase (soyabean), pectinmethylesterase (tomato), α-amylase (*B. subtilis*), polyphenoloxidase (mushroom) and peroxidase (horseradish). Processing conditions evaluated were 10, 20 and 30 kV/cm, frequencies of 1–100 Hz, pulse widths of 5–40-µs and 1–1000 pulses. In raw milk, no inactivation of alkaline phosphatase was
observed using field strengths of up to 20 kV/cm at a frequency of 1 Hz with 200 pulses of 2-μs duration. The only treatment that brought about a reduction in activity (74%) was one using an extended pulse duration (40-μs); this resulted in a temperature rise within the milk of up to 70°C and this is likely to have been responsible for the inactivation. Similarly, lactoperoxidase in milk proved resistant to PEF processing. A maximum of 13% inactivation was achieved using 13 kV/cm, a frequency of 1 Hz and 200 pulses of 10-μs duration. In this experiment, the milk reached a temperature of 52°C. PEF had very little effect on lipoxygenase in pea juice, the maximum reduction in activity that could be achieved being 9%. In apple juice, polyphenoloxidase was similarly resistant, with only a 10% reduction in activity being achievable using 31 kV/cm, a frequency of 1 Hz and 1000 pulses of 1-μs duration.

In summary, results on enzyme inactivation using PEF have been variable; in the case of studies conducted at KUL, very limited effects on enzymes were observed. It is, however, difficult to compare results between laboratories because of differences in the equipment used and the parameters selected. The influence of thermal effects on enzyme activity is also an important factor, which may play a part in some of the observed inactivation.

9.6 IRRADIATION

9.6.1 Background

The use of ionizing radiation to destroy micro-organisms or insects, or to improve the shelf life of perishable materials is well established, but it is a technology that remains highly controversial. X-rays and radioactivity were discovered at the end of the nineteenth century, and in the early years of the twentieth century the possible application of these modalities to the preservation of food was already being investigated. Irradiation of strawberries, for example, was investigated in Sweden in 1916; a paper on the elimination of Trichinella spiralis in pork with X-rays was published in 1921; and a patent for food preservation using ionizing radiation was issued in France in 1930.35

In the 1940s suitable sources of radiation were developed for the commercial treatment of foods. Much of the early research into irradiation of food was carried out by government bodies and universities. The US army carried out extensive trials during the 1950s and 1960s and irradiated foods travelled into space on the Apollo missions. Relatively limited research into irradiation was being conducted by the food industry during
this period. In 1969 the sterilization of food by irradiation was approved in the UK for hospital patients requiring a sterile diet as an essential part of their treatment. It was a further 22 years before irradiated food was approved for general consumption in the UK.

9.6.2 Industrial applications

Irradiation has perhaps been more widely tested for safety than any other novel preservation method. Its tortuous route to commercialization and the arguments for and against the technique have been widely debated. Today, despite the availability of commercial systems and the proven efficacy of the process, industrial use for food is still on a relatively limited scale. In the UK this is largely due to strong consumer resistance. Since 1999, no food has been irradiated in the UK for commercial purposes.36

There are around fifteen facilities in the EU that are approved for food irradiation.37 The exact amount of food irradiated per year in the EU is not certain, but an official estimate for 2001 was around 22,000 tonnes.36 In 2005, estimated production in Europe was 20,000 tonnes.38 Herbs, spices and poultry products accounted for the major proportion of this total.

While food applications for irradiation are relatively low volume, non-food markets are enormous. For example, worldwide, around 45% of all single-use medical devices are sterilized by irradiation. In the UK around 80% of such devices are sterilized using irradiation.38

9.6.3 Equipment

Three types of ionizing radiation can be used for food irradiation – gamma rays, X-rays and electron beam radiation. Both gamma rays and X-rays are photons, whereas an electron beam is made up of β-particles. In all cases, the energy of the radiation source is limited/selected such that when the food is irradiated, electrons can be ejected from their orbits around atomic nuclei, but there is no interaction with the nuclei themselves, which would induce radioactivity.38,39

Gamma rays have very short wavelengths beyond the ultraviolet end of the electromagnetic spectrum. They penetrate deeply into food, making them very useful for food irradiation. The most widely used source of gamma rays is the radioactive isotope cobalt-60 (60Co), which produces gamma radiation during its decomposition to the stable nickel-60, although caesium-137 (137Cs) is also used. Cobalt-60 has a half-life of
5.3 years and its radioactivity reduces by about 1% per month, so it must be replaced at suitable intervals. Cobalt-60 metal pellets are typically double encapsulated in stainless steel ‘pencils’ as shown in Fig. 9.8.

X-rays, like gamma rays, have very short wavelengths and good penetration depth in food materials. They are generated by machines, making them very controllable, but the conversion of electricity to X-rays is inefficient and expensive and hence this technology is less commonly used for food applications.

High-energy electrons generated by an electron accelerator can also be used to irradiate food. However, application of this method is limited by the penetration depth relative to gamma or X-ray radiation. Electron-beam irradiation has a maximum penetration depth of around 4 cm. This effectively limits the maximum sample thickness that can be treated to around 8 cm if irradiated from two sides (Fig. 9.9). Electron beam irradiation therefore tends to be used on products that can be arranged in thin layers during the process.

9.6.3.1 Equipment configuration

Gamma irradiation plants come in a variety of designs, but can be divided broadly into two categories – batch and continuous. In a batch system, a defined quantity of food is exposed to the radiation source for a specified period of time. Food is loaded into the radiation enclosure, irradiated and then unloaded once it has absorbed the target radiation dose. The absorbed dose depends on the time inside the radiation enclosure. In a continuous system, food is passed through the radiation enclosure at a specified rate, which ensures that it receives the required radiation dose. Bulk food or consumer packs are placed on a conveyor, which passes through a room.
where energy from the radiation source is applied to the food. The amount of radiation absorbed is determined by the speed of the conveyor and the flow path around the system. A schematic diagram of a typical continuous gamma irradiation plant is shown in Fig. 9.10.

In both cases the radiation source is housed in specially designed shielded enclosures to minimize exposure of personnel to radiation. Radiation sources such as $^{60}$Co are constantly emitting so the source must be shielded when personnel enter the enclosure. This is usually achieved by lowering the source into a deep pool of water or other shielded enclosure, as shown in Fig. 9.10.
9.6.4 Shelf life and product safety

9.6.4.1 Impact of the process on micro-organisms

Bombardment of a food with gamma rays, X-rays or an electron beam results in atoms and molecules within the food being ionized or excited. These excited molecules and ions break down or react with neighbouring molecules to produce a variety of ‘radiolysis’ products that are known to induce multiple changes, including modification of cell membrane structure, cellular enzyme activity, nucleic acid synthesis and compositional changes in cellular DNA.\(^{39}\) The most important site for inactivation of micro-organisms using irradiation is thought to be the DNA.

In general, Gram-negative micro-organisms such as the common spoilage bacteria *Pseudomonas* and important pathogens such as *Salmonella* and *Escherichia coli* are more sensitive to ionizing radiation than Gram-positive bacteria, but exceptions do occur.\(^{40}\) Different strains of the same organism can differ in their ability to survive irradiation. Pathogens such as *E. coli*, *Salmonella* spp., *Listeria monocytogenes* and *Campylobacter* species are all relatively sensitive to irradiation, generally requiring doses of 0.5 kGy or less to reduce the population by 90% in ground beef and poultry.\(^{41}\) A dose of 2.5 kGy eliminates *Salmonella* from chicken carcasses and extends shelf life by 7 days at 3°C.\(^{41}\) Food-borne pathogens capable of growth at low temperatures, e.g. *Listeria* and *Aeromonas* species, are also sensitive to irradiation and will be eliminated by similar doses to those for *Salmonella*.

Most food spoilage bacteria are sensitive to radiation, although strains of the *Acinetobacter-Moraxella* have some resistance to radiation and may form a large proportion of the bacterial survivors on food irradiated with moderate doses. In experiments carried out on red meat and poultry, certain strains of this genus were shown to be even more resistant to radiation than spores, although their presence in such food is not significant from either a public health or a sensory perspective.\(^{40}\)

The radiation sensitivity of moulds is similar to that of vegetative bacteria. A dose of 2 kGy can inhibit the growth of mould in strawberries, giving an extended shelf life of 14 days in chilled storage compared to 6 days without irradiation.\(^{41}\) Yeasts are more resistant, of a similar order to the most resistant bacteria, while viruses are very resistant to radiation and are unaffected by the maximum dose of 10 kGy permitted for food irradiation.

Bacterial spores are capable of surviving irradiation, but are more sensitive to heat following the process. A dose in the region of 25–50 kGy would
be needed to reduce the level of all micro-organisms to below the limits of detection (radappertization), but this is much higher than the doses typically used for food. If the object of irradiation is the extension of shelf life then the doses used will not destroy all bacterial spores. Care therefore needs to be taken with doses and subsequent storage to ensure that any pathogens capable of growth are controlled within the expected shelf life and storage conditions of the product.

9.6.4.2 Impact on food quality

Vitamin losses as a result of irradiation are generally quite small. Vitamin B$_1$ is the most radiation sensitive of the water-soluble vitamins, while vitamin E is the most sensitive fat-soluble vitamin. However, Vitamin B$_1$ is more sensitive to heat than irradiation. Vitamin losses as a result of irradiation depend upon a number of factors including the radiation dose, the oxygen partial pressure and the composition of the food.

In some cases vitamin levels in food have been found to increase following irradiation; however, it is not known whether this is the result of a radiation-induced conversion of precursors to the vitamins, or because radiation improves the effectiveness of the vitamin extraction for analysis.

While irradiation can cause denaturation of proteins, changes in functionality and destruction of amino acids at high doses, the changes are negligible at the doses employed in commercial food irradiation facilities. The nature of any change will depend on the condition and structure of the protein; for example, the irradiation of denatured protein results in more free radicals being produced than for native protein. Changes are also dependent on amino acid composition — amino acids containing sulphur are more sensitive to irradiation, and their degradation can lead to adverse flavour and odour changes, most notably in dairy products. The irradiation of milk, even at very low levels, e.g. 0.5 kGy, can result in the production of off-flavours. For this reason the irradiation of dairy products is not generally recommended, although Camembert cheese made from unpasteurized milk has been successfully irradiated to control pathogens, providing temperature and ripening conditions are controlled.

Irradiation can cause the oxidation of tallow and lard and it initiates and accelerates the normal process of auto-oxidation during storage, giving rise to off-flavours and taints. For this reason high-fat foods are generally considered to be unsuitable for irradiation. However, the oxidation process can be slowed down by packing food in a modified atmosphere that excludes oxygen.
Irradiation can cause changes in the sensory properties of foods, including changes in flavour, texture and appearance. As already mentioned, off-flavours can develop in milk owing to irradiation, even at very low doses. Irradiation of onions makes their characteristic odour milder, but a study carried out on ginger, cinnamon, fennel and fenugreek found no major differences in sensory quality between irradiated spices and spices treated with ethylene oxide. Textural changes can arise owing to the breakdown of high molecular weight components, causing softening of fruits and vegetables and changes in viscosity of starch-containing products. In general, however, most major sensory changes are observed when food is irradiated at very high doses, and irradiation of food within the current typical limits will not generally affect the sensory quality significantly.

9.7 CONCLUSIONS

Each of the technologies discussed in this chapter has positive potential for the food industry but it is true to say that each, like any ‘conventional’ preservation technology, has specific limitations. In some cases these limitations are technical in nature, for example the resistance of bacterial spores to high pressure; in some cases limitations are cost or ‘image’ related, perhaps the best example of this latter point being irradiation.

The growing industrial interest in thermal processes with optimal quality retention is likely to lead to an increased uptake of ohmic and microwave heating in the coming years. Rapid volumetric heating methods such as these offer excellent opportunities for quality optimization.

An alternative approach is simply to pasteurize without heat and here high-pressure processing and pulsed electric field processing offer exciting potential for producing non-thermally pasteurized high-quality products. However, in an industrial context the technological benefits have to be considered alongside cost considerations. Here the question becomes not one of, for example, ‘is pressure-treated product X of a higher quality than heat-treated product X?’ (it is frequently beyond debate) but instead becomes ‘is the quality differential between pressure-treated product X and heat-treated product X sufficiently large to justify the capital expenditure/changes in supply or distribution chain etc?’ This has proved to be a more difficult question to address for some companies. However, equipment costs have decreased and production throughputs have increased in recent years for both high-pressure processing and pulsed electric field processing – encouraging developments that increase the likelihood of future commercial uptake.
It appears highly unlikely that any emerging preservation technology will see widespread commercial uptake to the extent that it completely replaces a conventional technology such as, for example, in-container thermal processing. What is more likely is that some of these technologies will find niche applications where they meet a need that cannot be met by conventional technology.

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