Chapter 11
HEAT PROCESSING, COOLING AND PRESERVATION METHODS

The Science of Poultry and Meat Processing
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Preface

The aim of The Science of Poultry and Meat Processing book is to provide students and industry personnel with a comprehensive view of the modernized primary poultry meat industry and further processing of both red meat and poultry. An emphasis is placed on basic concepts as well as recent advancements such as automation (e.g. increasing poultry line speed from 3,000 to 13,000 birds per hour over the last 40 years) and food safety (e.g. HACCP in primary and the further processing areas). The book also includes chapters explaining basic muscle biology, protein gelation, heat and mass transfer, microbiology, as well as meat colour and texture to help the reader understand the underlying scientific concepts of meat processing. The Science of Poultry and Meat Processing book is based on over two decades of university teaching experiences, and is designed to be used as a course textbook by students, as well as a resource for professionals working in the food industry. The book is available online, at no cost, to any interested learner. Using this format has also allowed me to include many colour pictures, illustrations and graphs to help the reader.
The book is dedicated to my past and current students who have inspired me to learn more and conduct challenging research projects. I see this as an opportunity to give back to the field that I have received so much from as a student and as a faculty member. Looking back, I have learned a great deal from my MSc and PhD advisor, Dr. A. Maurer, who was the student of Dr. R. Baker - the father of poultry processing in North America. I would also like to thank Dr. H. Swatland with whom I worked for almost 20 years, for the many challenging scientific discussions.

Writing The Science of Poultry and Meat Processing book was a long process, which also included having all chapters peer reviewed. I appreciate the help of my colleagues, but I still take responsibility for any inaccuracy in the book. If you have comments or suggestions, I would appreciate hearing from you (sbarbut@uoguelph.ca), as I am planning to revise and update a few chapters on a yearly basis.

I would like to thank the many people who have helped me during the writing process. To Deb Drake who entered all of the material for the book, to Mary Anne Smith who assisted in editing, and to ArtWorks Media for the design and desktop publishing of the book. I greatly appreciate the help of my colleagues who reviewed chapters and provided useful discussions. They include Mark B., Ori B., Sarge B., Gregory B., Joseph C., Mike D., Hans G., Theo H., Melvin H., Myra H., Walter K., Roland K., Anneke L., Massimo M., Johan M., Erik P., Robert R., Uwe T., Rachel T., Jos V., Keith W., and Richard Z. I would also like to thank my family for their love and support during the entire process.

About the Author

Shai Barbut is a professor in the Department of Food Science at the University of Guelph in Ontario, Canada. He received his MSc and PhD at the University of Wisconsin in meat science and food science. He specializes in primary and further processing of poultry and red meat. His research focuses on factors affecting the quality of meat, as well as protein gelation with an emphasis on structure / function relationships, rheological properties and food safety aspects. He has published over two hundred peer reviewed research papers and is the author of the Poultry Products Processing – An Industry Guide textbook. He is a fellow of the Institute of Food Technologists and has received awards from the Meat Science Association, Poultry Science Association, and the Canadian Institute of Food Science and Technology. He is involved in a number of government committees as well as academic and industrial research projects.
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HEAT PROCESSING, COOLING AND PRESERVATION METHODS

11.1 Introduction

Food preservation has played a very important role in human development. Cultures that could gather/grow food and keep it during harsh times survived, while those that could not, died, or had to go to war. Some foods are easy to process and preserve while others, like fresh meat, present a challenge to processors, retailers, and the consumer. Meat is a perishable item because it contains most nutrients required for bacterial growth, the pH is not prohibitive to most bacteria, and it has abundant amounts of free water. If proper storage conditions (e.g., refrigeration) or preservation treatments (e.g., salting, heating, irradiation) are not employed, the meat will spoil within a matter of hours or days. In areas where refrigeration is not available, a live market is very popular. In other places, special procedures are used (e.g., HACCP; see Chapter 6) to ensure low microbial counts during processing and to guarantee consumer product’s safety. The latter is also very important because meat, as well as other foods, can carry pathogens that could harm the consumer. Today, all countries employ rules and regulations to supervise food production and guarantee wholesomeness.

Some of the most prevalent preservation techniques used today were established thousands of years ago, before scientific knowledge about microbial/chemical spoilage and pathogens was available. Our ancestors preserved food by drying, heating, cooling, freezing, fermenting, and adding ingredients (e.g., salt). Scientific development has helped us learn more about the processes involved in food preservation. Today we can even use molecular biology to select strains of microorganisms to produce antimicrobial compounds that inactivate pathogens during the fermentation of meat and dairy products (e.g., bacteriocins, discussed later in the chapter). Scientific advancement has also contributed to the development of equipment such as microwave ovens and to mathematical
models that can be used to optimize heating (Fig. 11.1.1), cooling, and other processes. In this chapter you will find more examples and descriptions of the main processes used by the industry.

![Figure 11.1.1 Visualization of simulation results showing the temperature (T) and water mass fraction (y_w) distribution in various horizontal cross sections of a chicken filet. Experiments were performed at T_oven = 170°C and T_dew = 90°C (see text for more information). The snapshot is taken after 28 min of heating. From van der Sman (2013).]

As indicated above, food preservation by humans has a long history. Historians describe two major periods in terms of food consumption. The first is called the food-gathering period, which spans from the time of human origin, over one million years ago, to eight to ten thousand years ago. The second is called the food-producing period, which continues until today (Jay et al., 2005). It is believed that food spoilage problems were encountered early in the second period when people started to produce and store their own food for extended periods of time. Spoilage and disease problems caused by improper storage required innovations and solutions. Drying was one of the earliest methods employed to store foods like grain and meat slices. Sun dried grain and meat could be stored for extended periods of time. Some cultures discovered that drying meat while smoking it over an open fire substantially extended the shelf life. Later, fermentation of grains resulted in the production of beer. This innovation can be traced back to ancient Babylonia around 7000 BC. The Samaritans are believed to have been the first great livestock breeders as well as dairymen who were among the first to make butter around 3000 BC. They were also known to use salted meat, fish, and dried skins.
The early Egyptians in 3000 BC were known for their knowledge in fermenting dairy products and making cheese. Salted meat was also known to be used by the Israelites, the Chinese, and the Greeks; the latter also passed it to the Romans. Evidence of sausage fermentation by the ancient Chinese and Babylonians go as far back as 1500 BC. While it is certain that people did not understand the nature of food preservation by fermenting microorganisms, they used fermentation fairly successfully. This was probably done by “seeding” new batches with material from a successful previous batch (known today as transferring the “right culture”). Advances in understanding food poisoning and spoilage are believed to have been made within the first millennium AD (Jay et al., 2005). Concern over butchering practices is mentioned for the first time in documents regarding Swiss butchers handling marketable and non-marketable meat in 1156. In 1276, a compulsory slaughter and inspection order was issued in Augsburg. Although people were aware of quality attributes at that time, it is doubtful that there was any substantial knowledge of the actual causal relationship between meat and microorganisms. A monk named A. Kircher was one of the first to suggest the role of bacteria in food spoilage and carcass decay. He referred to “worms” that were invisible to the naked eye but his observations did not receive wide acceptance. In 1765, L. Spallanzani showed that beef bouillon that had been boiled for an hour and sealed, remained sterile and did not spoil. His experiment was designed to disprove the theory of spontaneous generation but it did not convince critics since they thought oxygen was vital to the process. A hundred years later, Schwann repeated a similar experiment, but allowed sterile air to be supplied (by passing it through a heated coil) and demonstrated no spontaneous generation.

Pasteurization, developed about 200 years ago, was one of the most important events in food preservation. Francois Appert succeeded in preserving meat in glass jars after keeping it in boiling water for extended periods of time. His discovery of the canning process happened in 1795 as a result of the French government prize offer for discovering a practical method for food preservation. In 1810, Appert was issued a patent for his process. This discovery actually preceded Lois Pasteur by about fifty years. Pasteur, who is considered the father of modern microbiology, demonstrated the role of bacteria in wine spoilage and suggested ways to prevent contamination/recontamination and thus prevent spoilage. The process developed by Pasteur is now known as pasteurization.

Below are the origination dates of common food preservation processes:

- 1774 – first extensive use of ice in transporting meat by sea (Jay et al., 2005)
- 1810 – commercial canning started
11.2 Heating

11.2.1 General

Heating is one of the most common ways to prepare food items (e.g., meat, baked goods, jams). It is used for a variety of reasons that include texture modification, the creation of flavours and colours, and the inactivation or destruction of microorganisms. The latter is also used in other industries (e.g., medical), and the degree of microbial inactivation depends on the temperature and exposure time. Generally speaking, two levels of heat are used for microbial inactivation in food.
a. Pasteurization at a moderate temperature of about 60-90°C is designed to inactivate some of the spoilage and most of the non-spore forming food poisoning microorganisms. Pasteurization extends the product’s shelf life but the product must be refrigerated or preserved by other means (e.g., reducing water activity).

b. Sterilization at temperatures > 100°C achieves “commercial” sterility, whereby food products (e.g., canned food at 121°C) can be stored at room temperature for long periods of time. This process results in inactivation of all spoilage and food poisoning microorganisms and their spores.

It is important to note that both heat treatments will result in changes to the texture, flavour, odour, and microbial load of the product. The extent of change increases with temperature and exposure time.

Cooking methods vary from cooking the meat in its own juices (usually at < 100°C) to frying in oil (usually 180-195°C) and grilling (BBQ temperature can be 350°C). Heat can be transferred to the product by:

a. Conduction – heat transfer between substances in direct contact. Heat is conducted from an outside source and is directly transferred from one particle to the next with relatively no mixing and no movement of the product (Fig. 11.2.1.1). This is usually true for solid and very viscous foods.

b. Convection – heat transfer by the mixing and moving of fluid particles. Heated particles are less dense and move up to the top, whereas colder particles are denser and sink to the bottom in a so called natural convection (note: forced convection is also possible by using a fan in an oven or a pump in a circulating water bath). Convection is more efficient than conduction because it results in mixing hot and cold particles through heat currents. Agitating, pumping, or steering can achieve additional mixing during heating. When a commercial sterilizer is used to heat food cans, it is important to determine and place thermocouples at the coldest point(s). In liquid food (e.g., a can of chicken soup with small particles), the coldest point in the can is approximately one-third up from the base. In solid food, however, the coldest point will be in the geometrical center of the can.

c. Radiation – heat energy is transferred through space, where a hot object gives up heat. For food applications, electrical heating elements and infrared lamps are commonly used to emit energy, which is absorbed by the product’s surface.
Heat transfer depends on factors such as the temperature difference between the heat source and the product (ΔT), the length of heating, the food’s composition (e.g., moisture to fat ratio), and the heat transfer medium (e.g., water, oil). Thermal conductivity is the term used to express the rate of heat movement through a material (i.e., movement can be by conduction or convection). The other term needed for the calculation is the specific heat, which quantifies the amount of energy (heat) required to change the temperature of one gram of material by 1°C. Lean meat has more moisture and thus has a higher specific heat than fatty meat, meaning that it required more energy to heat up identical quantities.

Heating meat and other foods is done in hot air ovens, microwave ovens, water, and oil. The different methods provide certain textural and flavour characteristics to the product. Choosing one method over another is usually based on factors such as the desired product identity (e.g., crust on a fried product), equipment available, operating costs, and government regulations. Part of a meat cooking operation can also include a smoke application, which takes place in specially designed ovens. The effect of smoking on preservation is discussed later in the chapter.

11.2.2 Use of Hot Air Ovens

Hot air is frequently used to heat and cook different food products including meat. Small, home type ovens are designed to handle a few kilograms of product
whereas industrial ovens can handle a few tonnes of product every hour. In home type ovens, the air is usually heated and dried by electrical elements. This is not the best medium to transfer heat but is commonly used because other characteristics can be developed (browning of the surface, crust formation, etc.). In general, when moisture is added to the air, heat transfer is improved. This option is commonly used in industrial ovens where yield is a critical factor. Air heating can be done in several ways and can include passing the air over a hot surface (e.g., metal surface heated by electricity or hot oil) or using a flame to directly heat the air (e.g., a gas burner inside an oven). The hot air is then circulated around the product and heat is transferred by convection to a solid piece of meat. Figure 11.2.2.1 shows an industrial hot air oven. There are different configurations that include stand-alone heating cabinets, linear ovens that use a belt to move food through, and spiral ovens that have a smaller footprint than linear ovens because the product is moved to different levels. The climate inside the oven can be controlled by adjusting air speed, relative humidity, and air temperature. Controlling these parameters allows the operator to estimate the required cook time, yield, degree of microbial inactivation, colour, texture, etc. To optimize conditions and determine microbial inactivation, the operator needs data from the oven and the products. Sensors to measure temperature, relative humidity, air speed, colour, and weight can be positioned at different places inside the oven. The most common sensor is the thermometer, which shows temperature changes and can be used for HACCP plan validation. Monitoring the heating profile of a specific product is also done to obtain important information that can help optimize cooking conditions. Table 11.2.2.1 shows six heating conditions used to treat chicken breast fillet samples and Figure 11.2.2.2 shows the temperature profiles of the skin (surface) and core.
Table 11.2.2.1 Setup of the cooking experiments showing six heating conditions used to treat chicken breast fillet samples. Adapted from van der Sman. (2013).

<table>
<thead>
<tr>
<th>Index</th>
<th>$T_{\text{oven}}$ (°C)</th>
<th>$T_{\text{dew}}$ (°C)</th>
<th>$v_{\text{air}}$ (m/s)</th>
<th>$t_e$ (min)</th>
<th>Mass (g)</th>
</tr>
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<tbody>
<tr>
<td>Heat 0</td>
<td>45</td>
<td>45</td>
<td>10</td>
<td>160</td>
<td>192</td>
</tr>
<tr>
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<td>45</td>
<td>45</td>
<td>10</td>
<td>80</td>
<td>164</td>
</tr>
<tr>
<td>Heat 5</td>
<td>60</td>
<td>60</td>
<td>10</td>
<td>60</td>
<td>174</td>
</tr>
<tr>
<td>Heat 7</td>
<td>60</td>
<td>60</td>
<td>10</td>
<td>40</td>
<td>142</td>
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<tr>
<td>Heat 10</td>
<td>80</td>
<td>70</td>
<td>10</td>
<td>40</td>
<td>196</td>
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<tr>
<td>Heat 12</td>
<td>80</td>
<td>70</td>
<td>10</td>
<td>20</td>
<td>156</td>
</tr>
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</table>

Data were obtained from a linear industrial tunnel oven where chicken breast fillets were placed on a grid (note: the grid might have caused slight differences in air flow compared to a linear oven without a grid; however all treatments were subjected to the same tray configuration). Oven temperature ($T_{\text{oven}}$), dew point ($T_{\text{dew}}$), and air velocity ($V_{\text{air}}$) were all controlled in this relatively closed environment. The results are typical of meat heated in an oven and the graphs show that the surface and core temperatures reach a steady value after 20 min. This steady value is equal to the so-called wet bulb temperature, which is quite near the dew point of the air flowing over the chicken fillets. The author (van der Sman, 2013) also presented data for heating at 55, 70, and 100°C where similar behaviours were observed. The time to reach this steady state value depends on the airflow velocity, which determines the external heat transfer coefficient and thus the time scale of the energy transport. During extensive cooking the surface temperature starts to deviate from the wet bulb temperature because water activity at the surface drops below unity. In that case, local equilibrium at the surface demands that the surface temperature rise. The surface temperature will then approach the air temperature. After a lag time, the core temperature will also start to rise. At air temperatures below boiling the core temperature will also move towards the air temperature. At air temperatures above boiling, internal evaporation will occur and the core temperature will remain at the boiling point.

As indicated in the introduction, modeling of the heating process is becoming more popular. This procedure allows for simulations that can help predict the product’s temperature and optimize oven conditions. An example of a model developed for oven heating and how it was created is provided below. Figure 11.1.1 shows simulation results from the experiment with the chicken breast fillets mentioned above.
To simulate moisture content, the authors obtained experimental data for water holding capacity as a function of temperature, together with a fitted sigmoid function (Fig. 11.2.2.3). Such curves have also been published by other groups in the past. In order to do the simulation, good data regarding the shape and volume of the sample was required. Figure 11.2.2.4 shows a line scan obtained for a chicken fillet. This was used later on for the heating simulation at 170°C (Fig. 11.1.1). The simulation shows temperature and moisture distribution after 28 min where the surface temperature is near boiling point and the product is drying out. A step gradient in moisture content is also seen. The model predictions (some presented in Fig. 11.2.2.2) were obtained after fitting the model to the experimental data via least squares. The parameter estimation was done via trial and error, as the non-linear parameter estimation, using Levenberg–Marquardt, did not converge. By comparing the model predictions and the experimental results (Fig. 11.2.2.2), the author concluded that the evolution of temperature is well predicted in the majority of the experiments, which were characterized by cooking times ≤ 40 min (i.e., common cooking time used by the industry and consumers under such climate settings). For these experiments, cooked yield prediction was reasonably good (within 5% of the experimental data). However, for some experiments there
was poor quantitative agreement between the model and the experimental results. For temperature, the predictions started to deviate when cooked times were longer than 40 min, which is about the end of the constant drying rate regime. For these experiments, the model also failed to accurately predict the final mass of the cooked meat. It appeared that, after reaching the falling drying rate regime, the model’s prediction for moisture transport was too low. There was too little evaporative cooling effect and the core temperature rose too quickly to the oven temperature. However, the author observed that the model predictions were qualitatively in agreement with the temperature behaviours shown in the experiments. In the constant drying rate regime the surface temperature was at the wet bulb/dew point and in the falling rate regime it gradually rose towards the oven temperature.

Figure 11.2.2.3 Water holding capacity as a function of temperature T, as obtained from cooking loss experiments. The WHC is expressed in mass fraction of water. From van der Sman (2013).
11.2.3 Use of Water Heating (Boiling, Canning)

Water is a better medium than air for transferring heat to a meat product. The meat industry uses water to heat different types of meat cuts and further processed products. The meat can be heated outside or inside packaging. When cooking without a package, the meat interacts with the cooking medium where liquid/flavour compounds can be transferred into or out of the product. This is usually done by cooking raw meat in boiling water or broth. Processed products such as sausages and marinaded cured muscle products are usually packaged in moisture proof casings prior to putting them in a kettle filled with hot water (e.g., 80-100°C).

For high temperature heat processing of canned food, water is also used as the heat transfer medium. Because temperatures of 120°C are usually used in canning operations, high pressure equipment is employed (i.e., need to suppress the boiling temperature of water). High pressure vessels come in a variety of sizes and forms. Small pressure cookers are often found in homes, whereas large scale cookers are used by the industry.
The canning process achieves so-called “commercial sterility” and is commonly done in a retort (a large metal chamber capable of operating under pressure). The high temperature (120-122°C) helps reduce the time required to destroy heat resistant microorganisms that are capable of forming spores (e.g., *Clostridium botulinum*; see Chapter 15). Meat products that are processed in this way include canned soups, chunked meat in gravy, stews of meat cubes with vegetables, etc. These products are usually packed in metal cans, glass jars, or flexible retort pouches and can be stored at room temperature. As indicated above, the nature of the food dictates the way heat penetrates the product. For solid foods, such as chicken rolls, heat is transferred by conduction, and for liquid or particulate food, such as chicken soup with small particles, convection currents provide a faster heat transfer than for solid foods. Other factors that determine the rate of heat transfer are the container’s packaging material (stainless steel containers have a thermal conductivity of about 20 W m⁻¹ K⁻¹ whereas glass and polyethylene containers have values of 0.52 W m⁻¹ K⁻¹ and 0.55 W m⁻¹ K⁻¹, respectively; Fellows, 2009), the size of the container, the temperature difference between the food and the heating medium, the shape of the container, and container agitation.

The rate of heat penetration must be measured so the required residence time for microbial destruction at the coldest point of the container can be calculated. As indicated previously, thermocouples are placed in sample cans, and the slowest heating point depends on whether the food is solid or liquid. The time-temperature calculations to achieve commercial sterility (also known as 12 log reduction or 12-D) can be found in Fellows (2009) and other textbooks.

Different types of retorts are available on the market and can be divided into batch and continuous operations. In a batch-type operation, cans/jars/pouches are placed in a large basket and lowered into a chamber that is then sealed. Then the temperature is raised by injecting live steam. In a continuous operation, the cans are moved through a system where a hydrostatic head is produced between two columns (“legs”) of water. This allows for finer control over the processing conditions and, hence, produces a more uniform product. The first “leg” time is used to raise the temperature of the product gradually before it is transferred into the steam chamber. In the steam chamber the food is heated to the required temperature (usually 121°C) and kept at this temperature for a predetermined time. The second “leg” cools the product initially before it is further cooled by water sprays and cold water dips. Sealing the can prior to the operation is extremely important. The high temperature causes pressure build up inside the can and therefore the seams should be able to withstand pressure. Plastic polymer is usually placed within the seal groove (e.g., white plastic ring in a metal lid of a glass jar). Incorrect sealing or defects in the seam will cause leakage and suction of outside water or air, which will contaminate the food inside. Metal cans commonly have a double seam construction, which is done by a seaming machine. In the first step a roller forms
the cover hook around the body of the can. The second operation tightens the two hooks together to produce the double seam. A thermal plastic sealing compound is also placed between the can and the lid and melts during the heating process to fill the space and provide an additional barrier against contamination. Retort pouches are composed of various layers (e.g., aluminum foil, polyethylene) where one is a thermal plastic material that becomes semi-fluid when heated and sealed.

11.2.4 Use of Oil (Frying)

As a cooking medium, oil allows for a very high cooking temperature (175-195°C). The oil temperature is kept below the smoke point, where the oil starts to burn and degrades very quickly. Frying allows for very fast heating and the formation of a unique surface texture called a crust (note: crust can also be formed during hot air heating). Frying time is directly related to oil temperature: the higher the temperature, the faster the product will cook. Kovácsné-Oroszvári et al. (2005) examined the effect of pan temperature and meat patty diameter on heating rate and mass transfer of hamburgers prepared by double sided frying. Overall, pan frying is a process that involves simultaneous heat and mass transfer and the quality of the final product is influenced by cooking temperature, time, product shape, and the thermo physical characteristics of the food. Temperature profiles of patties prepared from brisket (fat content 39%) are shown in Figure 11.2.4.1 as a function of frying time [measured at the center (5 mm) and 2 mm below the surface] at 150 and 175°C. The heat transfer at 100°C (measured 2 mm below the surface) was slower than during frying. It also resulted in minimal crust formation compared to the frying treatment (visual observation).

![Figure 11.2.4.1](image-url)

**Figure 11.2.4.1** Measured temperature profiles (at the centre (5 mm) and 2 mm below the surface) of a beef burger (D = 10 cm) prepared from fat brisket as a function of the frying time. Three lines on the left are for 2 mm below surface (175, 150 and 100°C). Next three lines for 5 mm, in the same order. From Kovácsné-Oroszvári et al. (2005).
Water loss was related to the initial water content and increased with frying temperature and decreasing patty diameter (Fig. 11.2.4.2). At a pan temperature of 100°C the average water loss value for patties that were 10 cm in diameter was 33%, whereas it was 39% for patties that were 3 cm in diameter. After frying, the temperature 2 mm below the surface was about 88°C for all diameters, which was well below the boiling point of water. Therefore, it can be assumed that the water losses at the lowest cooking temperature occur mainly in the form of drip.

![Water loss related to the initial water content expressed as a function of the frying temperature for fat brisket, lean brisket and shank. Mean values are shown with standard errors. From Kovácsné-Oroszvári et al. (2005).](image)

**Figure 11.2.4.2** Water loss related to the initial water content expressed as a function of the frying temperature for fat brisket, lean brisket and shank. Mean values are shown with standard errors. From Kovácsné-Oroszvári et al. (2005).

### 11.2.5 Microwave and Radio Frequency Heating

Microwave and radio frequency energy belong to the non-ionizing radiation category (Fig. 11.2.5.1). In order to prevent disturbance with other communication bands, the frequencies that are permitted for use are 433, 915, 2450 and 5800 MHz for microwave, and 13.5, 27.1 and 40.6 MHz for radio (i.e., also depends on the
Frequency heating is based on inducing molecular friction within the water molecules of a food (e.g., lean meat 70% water). Water molecules consist of two hydrogen atoms attached to an oxygen atom and are considered to have electric dipoles because the oxygen atom carries a slight negative charge and the hydrogen atoms carry a slight positive charge as a result of the angle between them (107°). Microwave heating applies a rapidly oscillating electric field that reorients the water molecules. This realignment causes friction, which heats the product. There is a short delay of a fraction of a millisecond before the dipoles respond to the oscillating electrical field called the relaxation time. Relaxation time is affected by the viscosity of the media and depends on temperature. When water changes to ice, the dielectric constant (i.e., the ratio of capacitance of the food to the capacitance of air or, in some cases, vacuum) falls and continues to decrease as the ice is further cooled. This means that ice is more “transparent” to microwave energy than water, and can cause problems when food is thawed in a microwave, as will be discussed below.

**Figure 11.2.5.1** The frequencies, wavelengths and photon energies of the major part of the electromagnetic spectrum. The boundaries of the named segments are more or less arbitrary, and there is now some tendency to reduce the overlapping by defining the range between TV and infrared radiation as microwaves and the range between visible radiation and x-radiation as ultraviolet. From CAST (1986).

Microwave designs can vary but all have a power source called a magnetron (a cylindrical diode) and a waveguide to bring the radiation to the area where the product is positioned. The magnetron (power can range between 300 to 3000 W) consists of a ring of resonant cavities that form the anode, while the cathode is a
hot metal cylinder capable of producing free electrons; the cathode is positioned inside the anode ring. When a high voltage is applied, the electrons give up energy to form rapidly oscillating microwave energy, which is directed to the waveguide by electromagnets. The food in the heating chamber may rotate on a turntable, or a rotating antenna can be used to evenly distribute the energy (Fellows, 2009) in order to reduce "shadowing" or areas not exposed to radiation.

A radio frequency oven is equipped with a generator coupled with a pair of electrodes, called the RF applicator. For industrial equipment there are two different applicators on the market. The first is conventional RF equipment where the electrodes and generator are closely connected. The second is 50Ω RF equipment where the electrodes and the generator are connected with a high power coaxial cable and are controlled by a matching box. Each system has advantages and disadvantages and selection depends on the application (Aymerich et al., 2008).

High frequency heating, especially in the microwave, tends to create hot and cold spots as a result of product geometry, composition, dielectric properties, and packaging. A way to control the generation of hot and cold spots is to insert vapour into the oven cavity to help distribute the heat (Aymerich et al., 2008). These designs require trained staff, good maintenance, and must be done in collaboration with equipment producers.

Radio frequency heating can result in more even cooking and a better penetration depth than microwave heating because of the lower frequency. However, there are some challenges related to the physics of radio frequency heating (Tornberg, 2013) such as arching, which occurs when electric field strength across the sample is too high and thermal run away heating, which is the formation of hot spots in a heterogeneous medium.

Microwave heating is not dependent on product thickness, takes less time than conduction in a conventional oven, and is sometimes referred to as "heating from the inside". However, the rapid heating usually does not allow enough time for browning on meat cuts. Therefore, some new commercial and residential ovens include both microwave and convection heating to speed up cooking and provide browning.

Microwave heating is also used to thaw meat, where fairly large blocks of frozen meat can be tempered fairly quickly. However, as mentioned before, water has a higher dielectric constant than ice and, as a result, heats faster than ice. This can result in non-uniform heating where some portions of the food may be cooked, while others remain frozen. To overcome this problem, microwave power should
be reduced during thawing to allow enough time for temperature equilibrium. When the meat industry uses microwaves to temper meat (i.e., raising the temperature from -25° to -3°C), there is a limited phase change and overheating does not present a major problem. Tempered meat blocks can then be easily sliced or boned. Using microwaves for defrosting is advantageous in reducing thaw time (e.g., minutes instead of days for large meat blocks), drip loss, and microbial counts, since very little time is allowed for microorganism recovery and growth. High frequency heating can also be used to inactivate microorganisms. For example, Apostolou et al. (2005) reported a 6 log reduction of *E. coli* O157:H7 in chicken portions exposed to 2450 MHz, 650 W for 35 sec. However, attention to sample size, uniformity within the microwave, and temperature are critical.

Packaging material should be transparent to microwave energy as materials such as metal will reflect microwave energy and result in arcing as well as excessive heating of the packaging material. Therefore, various plastics, glass, and paper with low dielectric loss are commonly used (Fellows, 2009).

### 11.2.6 Infrared heating

Infrared heating is mainly used to heat food surfaces, keep food hot on a display, and to dry food. There is no contact between the lamp and the food. The technology employs electromagnetic radiation that is emitted by hot objects and absorbed by the food. Infrared heat is less controlled and has a wider useable range of frequencies compared to microwave heating (Fig. 11.2.5.1). In addition, penetration depth is lower and heat transfer actually relies upon conduction from the surface to the interior of the food. The rate of heat transfer depends on factors such as the distance from the heat source, the food’s surface property, and the temperature difference between the food and the heating lamp. Equipment includes quartz/halogen tubes fitted with electric filaments, ceramic heaters, and metal heaters. The temperature of the heating element can range from 900°C for a quartz tube operating at a medium wavelength, to 2,200°C for a heat lamp operating at a short wavelength. Infrared radiation is frequently used by the industry to keep display food hot and to dry products such as cocoa, pasta, and flours. Drying is mentioned here because solar energy (indicated earlier as a historic was of drying meat) consists of approximately 48% infrared energy.

### 11.2.7 Ohmic Heating

Ohmic heating is based on the resistance of food to convert electrical energy into heat and is also known as electro-heating. The rate of heat generation depends on the voltage gradient and the electrical conductivity of the food (Yildiz-Turp et al.,
Ohmic heating is used more often for liquid processing, as solid food is more heterogeneous. Overall, the energy conversion is very efficient as most of it (e.g., 90%) can be converted to heat.

Meat products commonly have heterogeneous structures, which affect the uniform distribution of heat. Ingredients with poor conductivity (e.g., fat) do not generate heat at the same rate as lean muscle and thus create cold spots. In order to be effective, product conductivity should be in the range of 0.1–10 S/min (Piette et al., 2004). In animal fat the electrical conductivity is low (0.1 S/min) compared with that of processed meats (0.5 to 3.5 S/min). Ohmic heating also inactivates microorganisms through its thermal effects and electroporation. Piette et al. (2014) reported on the treatment of bologna inoculated with *Enterococcus faecalis* processed in an enclosed heating unit. Heating the core temperature to 80°C within 14 min resulted in a 9.0 log$_{10}$ CFU/g reduction. When core temperature was reduced to 70°C it took 31 to 40 min to achieve the same inactivation rate. The authors also demonstrated that product size and shape were important when using this technology. Flat meat patties and plate heating were suggested to ensure good contact between the sample and the electrode surface.

Another advantage of ohmic treatments over conventional methods is the departure from the limiting heat transfer coefficient and the need for high surface temperatures. As compared to conventional heating, ohmic cooking results in shorter processing times and higher yields, while still maintaining the colour and nutritional value of the food. With the development of solid-state power supply technology, it is now possible to use ohmic heating in pulse mode, to economically control electrolytic effects to innocuous levels. Ohmic systems are now better engineered, more sophisticated, and far less expensive than their predecessors and currently four manufacturers produce ohmic heating equipment for general food processing (Yildiz-Turp et al., 2013).

### 11.3 Cooling

The practice of cooling meat and other perishable food products has been used for thousands of years, although most improvements in chilling and freezing technologies for large scale operations have occurred in the past century (Leygonie et al., 2012). The global meat industry uses chilling and freezing to preserve meat during primary processing, transportation, and marketing (e.g., large refrigeration and frozen storage cabinets in a modern supermarket). In addition, many customers
own smaller units to keep meat cold/frozen. This section focuses on methods used to chill, freeze, and later thaw meat.

### 11.3.1 Chilling

Chilling is the most common way of extending the shelf life of fresh meat. At the processing plant meat is chilled by cold water or air immediately after evisceration (see Chapter 5). The process decreases the heat of the product from 37–39°C to about 5°C within a few hours. The rate of temperature decline depends on factors such as carcass size, chilling medium, temperature differential, amount of insulating fat, capacity of the refrigeration unit, and the amount of product moving through the system. A number of countries regulate the time allowed to reach a certain final temperature (e.g., 8 hr to reach ≤ 5°C after poultry slaughter). Chilling the meat quickly prevents/slow down microbial growth but can also be associated with cold-shortening (see Chapter 3). Chilling times for different animal producing species are designed to allow sufficient time to eliminate toughening associated with cold-shortening, while some processors also apply electrical stimulation to speed up the rigor process. In some operations of large animal processing, meat is only deboned 24 hrs after slaughter, while in small meat producing animals (e.g., broilers), carcasses are cut and deboned within 4-6 h after slaughter. In such a case, care should be taken to minimize toughening and allow even cooling of all parts. It is important to reduce the meat temperature to discourage the growth of mesophilic bacteria (e.g., *Salmonella*, *Staph. aureus*). The dangerous temperature zone where food should not be kept is shown in Figure 11.3.1.1, as well as the safe ranges to store food. The shelf life of refrigerated fresh meat, including poultry carcasses or parts, is generally limited to 1-2 weeks and depends on factors such as initial contamination load, storage temperature, temperature fluctuation over the storage period, and packaging conditions including modified atmosphere (see additional discussion below). Storing the meat at low temperature (-2°C to 0°C) will significantly prolong shelf life compared to storing the meat at 4°C to 6°C. Additional discussion on microbial growth during storage can be found in Chapter 15.
Figure 11.3.1.1 Microorganism growth and recommended poultry meat storage temperatures.
http://www.strogoff.nl/content/594/download/clnt/27449_The_Meat_Buyers_Guide.pdf
11.3.2 Freezing

Freezing is used to store meat for extended periods of time (weeks, months), but does result in physical and chemical changes (e.g., ice crystal growth, lipid oxidation) that limit the storage life of the product. Even under optimal conditions, meat should not be stored for more than one year. It should be mentioned that the global meat trade (export and domestic) heavily depends on frozen storage for keeping and shipping meat (Leygonie et al., 2012).

Although freezing is a good method, it requires added cost and planning. In terms of maintaining quality over an extended storage time, temperature is key. Examples of recommended storage times for poultry are 2 months at -12°C, 4 months at -18°C, 8 months at -24°C, and 10 months at -30°C (Aberle et al., 2012). Storage times are longer for beef, which has more saturated fat, and shorter for fish, which has more unsaturated fat.

Overall, lower temperatures reduce the rate of chemical deterioration, mainly oxidative rancidity, which results in off flavour development (e.g., described as old, stale, and cardboard-like). Other changes might result from dehydration (e.g., freezer burn if the product is not packaged correctly). Freezing rate has a significant effect on texture as slow freezing results in large ice crystal formation, while fast freezing results in small crystals. Such ice damage is only seen later, during the thawing phase, where drip loss is increased in products that were slowly frozen because large crystals are more damaging to the cellular and membrane structures of muscle tissue. Fast freezing refers to a process where the temperature is lowered to about -20°C within an hour. This can be achieved by direct immersion in a very cold medium (e.g., liquid nitrogen), direct contact of the meat with a cold plate, or air blasts with very cold air. On the other hand, slow freezing refers to a process whereby the desired temperature is achieved within 3-72 h. Fast freezing is advantageous in maintaining the product’s quality but is substantially more expensive. From a microbiological standpoint, quick freezing does not allow microorganisms time to adapt to the fast decline in temperature and can cause a greater thermal shock as opposed to slow freezing. However, in some cases, slow freezing can be more damaging to microorganisms because they are exposed to injurious factors for a longer period of time as well as the phenomenon known as freeze concentration of certain components in the cell.

The meat industry uses a number of freezing methods including air (still or blast) and plate freezing, liquid immersion/spray, and cryogenic freezing. Figure 11.3.2.1 illustrates the relative freezing rates of various methods. The time it takes water at 0°C to change to ice is referred to as the latent heat removal period.
low freezing temperature, the time required to change physical states (liquid to solid) is shortened and ice crystals are actually formed at a lower temperature, which results in smaller ice crystal formation. Water has a high specific heat (4,200 J kg\(^{-1}\)K\(^{-1}\)) and a high latent heat of fusion (335 kJ kg\(^{-1}\)). The energy required to freeze the material is either supplied by an outside source such as melting carbon dioxide snow or by circulating cold air (i.e., produced by electrical energy). Figure 13.3.2.1 shows a characteristic curve when food is first cooled down below its freezing point (around -2°C for lean meat). This is known as super cooling and, at this point, the water is still liquid. Then the temperature slightly increases (to the freezing point, or only slightly below) and ice crystals are formed as the latent heat of crystallization is released. At this point, the temperature remains almost constant until the product is frozen. During slow freezing, a smaller number of large ice crystals are formed compared to a larger number of small crystals during fast/cryogenic freezing. The rate of ice crystal growth is determined by the rate of heat transferred during the freezing period.

![Figure 11.3.2.1](image)

**Figure 11.3.2.1** Effect of freezing method on the relative freezing time. CF = crystallization period.

Another drawback of a slow freezing rate is the formation of a eutectic solution. This is the result of solutes (e.g., salt) becoming super saturated in certain areas while the water around them freezes. This can create areas with high solute concentration (eutectic temperature for sodium chloride is -21°C), which will depress the freezing point. However, it is difficult to identify individual eutectic
temperatures in a complex system such as meat. Most foods are not totally frozen even at a temperature where all water seems to be solid (e.g., about 10% remains unfrozen in meat kept at -20°C).

Overall, the most common freezing methods used by the meat industry are:

a. **Plate freezing** – usually used for individual meat patties and patties packaged in wrapped trays. Products are placed in direct contact with very cold (e.g., -12°C to -35°C) metal freezer plates or shelves. Plate freezing can also be used for thinly packed meat (fillets). Heat transfer is by conduction. The thermal conductivity of the freezer plates is much higher than circulating air and therefore used to quickly freeze meat. Using plates from both sides as well as colder plates can increase the freezing rate.

b. **Liquid immersion/spray** – used for smaller products (e.g., cut up meat, cubes, nuggets) and, sometimes, larger trims. If liquids such as a sodium chloride brine, glycol, or propylene glycol are used, the products are first packaged in a plastic bag. The product can also be conveyed on a belt through a freezing tunnel where it is continuously sprayed with a cold liquid. The length of time the product is exposed to the liquid, its temperature, and the size of the meat cut determine the extent of freezing. In the case of large parts it is common to freeze the outside and form a so-called “crust” prior to transferring the meat to an air blast freezer to complete the process. After the product is removed from the immersion tank or freezing tunnel, the freezing liquid must be rinsed off. The integrity of the packaging material is important to avoid any leakage problems. The freezing liquid must be non-toxic and approved by the local food inspection agency.

c. **Cold air freezing** – can be done by still/slow moving air (home freezer) or in a blast freezer where air movement is very rapid. Using still air is a relatively slow method, which is sometimes employed in refrigerated rooms in a meat processing plant. The air temperature is usually -10°C to -25°C and removes heat slowly from the product. Blast freezing refers to using high-velocity cold air that is circulated by large fans. Figure 11.3.2.1 shows that, in blast freezing, the rate of heat transfer is greatly improved over that of still air and the freezing rate is higher. Air velocities commonly used in commercial air blast freezers can range from 1.5 to 6.0 m/s and the temperature from -15°C to -50°C (Aberle et al., 2012). Adequate spacing among units is very important to allow proper air movement. In other cases, air blast tunnels are used where meat is moved on a conveyor belt. In the case of a large bird, this is done to freeze and harden the surface, and form a crust that later provides a lighter appearance; the product is then packaged and moved into a regular blast freezer to complete the process.
d. Cryogenic freezing – a very fast method using very cold gases. Gases such as nitrogen ($N_2$) and carbon dioxide ($CO_2$) are liquefied or condensed and then used. The freezing rate is rapid, since the boiling points are very low (liquid $N_2$ and $CO_2$ are -196°C and -78.5°C, respectively). When liquid $N_2$ is sprayed onto food, about 48% of the total freezing capacity is taken up by the latent heat of vaporization needed to form the gas (Fellows, 2009). The remaining 52% of the heating capacity (enthalpy) is available in the cold gas and the gas is therefore recirculated to achieve optimum use of its freezing capacity. Carbon dioxide has a lower enthalpy than liquid nitrogen and its lower boiling point causes less severe thermal shock. Most of its freezing capacity (85%) is available from the sublimating solid. Therefore, it is usually sprayed onto the product as a fine snow that sublimates on contact and the gas is not recirculated (Fellows, 2009). $CO_2$ consumption is usually higher than liquid $N_2$ consumption, but storage losses are lower. The choice between the two is usually determined by cost, the nature of the product, and available equipment.

Figure 11.3.2.2 shows a freezing tunnel where either $CO_2$ or $N_2$ can be used for packaged or unpackaged food moving on a perforated belt. When liquid $N_2$ is used the food can either be sprayed or immersed. An initial exposure of the food to the gas itself can somewhat reduce the thermal shock. A very cold medium that results in fast freezing can cause stress (e.g., cracking or splitting) to the food. Therefore, it is common to use cryogenic freezing with small particulates (cubes, nuggets), which are less susceptible to stress. This type of process is called individual quick
freezing (IQF). In both \( \text{N}_2 \) and \( \text{CO}_2 \) freezers, the meat’s temperature is allowed to equilibrate at the desired storage temperature (commonly below \(-20^\circ\text{C}\)) before the food is discharged. Liquid \( \text{N}_2 \) and \( \text{CO}_2 \) snow are also used in spiral freezers (Figure 11.3.2.3), where the main advantage is employing a higher freezing rate at a smaller footprint (see also the spiral oven cooking concept in this chapter). Liquid \( \text{N}_2 \) or \( \text{CO}_2 \) is sprayed down the perforated belt to maximize efficiency. An example of a popular product that goes through such a process is par-fried chicken nuggets (battered, breaded and fried for about 30 sec; see Chapter 14) that are sold to fast food outlets. Cryogenic freezing provides the best way to preserve the fresh-like characteristics because of the small ice crystal formation (see explanation above). However, low storage temperature maintenance during storage and distribution is critical in preserving the quality. Otherwise, the ice crystals will grow (recrystallization), rupture cell membranes, damage the texture of the food, and diminish the benefit of quick freezing. Many consumers are familiar with the phenomena of getting a “sandy” texture in an ice cream that was stored for a few weeks in a home type freezer that fluctuated in temperature.

Figure 11.3.3.1 Temperature changes during freezing and thawing for similar size packages. Adapted from Fennema and Powrie (1964).

Figure 11.3.2.3 A large-scale cryogenic freezing unit. Courtesy of JBT Food Tech.
Liquid $\text{N}_2$ and $\text{CO}_2$ snow are also used to maintain cold temperatures as meat is mechanically deboned and there is a corresponding rise in temperature due to high pressure. However, some reports indicate that $\text{CO}_2$ can affect the pH ($\text{CO}_2$ can dissolve and form carbonic acid), and in a sensitive product such as mechanically deboned meat, increase lipid oxidation during frozen storage.

Protecting the product’s surface during and after freezing is another important issue, as air exposure will dry the product during freezing or result in freezer burns during storage. If freezing time is short, no extra measures are taken. However, if freezing is a long process the product must be protected/packaged. Packaging material must be approved by the appropriate regulatory agency. In addition, it should have good moisture barrier properties and strength (see packaging section below). When meat is going to be stored for a long time, vacuum packaging and oxygen impermeable films are often used. Air removal reduces insulation while oxygen removal decreases the rate of oxidation and the development of off flavours due to rancidity. The shelf life of frozen cooked meat products is shorter than for frozen fresh meat because some oxidation processes have already been induced by heating. The overall storage life also depends on factors such as cooking temperature and additives (e.g., salt, antioxidants). Aberle et al. (2012) provided a few examples for meats stored at -18°C: fried chicken nuggets in vacuum package - 3 months; steamed chicken nuggets - 9 months; the same product with tripolyphosphate (serves as a chelating agent that suppresses lipid oxidation) – 12 months. If these times are exceeded, the products will remain safe, but product flavours and odours will differ from a freshly prepared product.

The processor should also be aware of problems that might occur during freezing. For example, bone darkening is sometimes seen in young chickens after freezing. It shows as a dark/bloody appearance of the tips of the bones and the muscle area close to the bone. It occurs during freezing because as water expands, hemoglobin can be squeezed out of the bone marrow through the porous bone structure. When present at the bone surface, it will turn a dark colour during cooking and the product can become unacceptable to consumers though it is not a food safety issue. Most often, this is seen around the leg, thigh, and wing bones, and sometimes in the breast and backbone area.

11.3.3 Thawing

Thawing can occur under different conditions that affect the meat product’s water holding capacity (Leygonie et al., 2012) and rate of ice crystal melting. There is a substantial difference in thermal conductivity between ice and water (e.g., 2.1 vs. 0.6 W.m$^{-1}$.K$^{-1}$), which is an important factor to consider when thawing food. During thawing, the temperature rises fairly quickly to the near melting point
(depending on the products’ thickness) and remains there throughout the relatively long thawing process. This results in a longer thawing period (Fig. 11.3.3.1) compared to freezing and can allow more time for chemical and microbial changes. In general, thawing is inherently slower than freezing when conducted under comparable temperature differentials. At the beginning, a water layer starts to form on the outside of the product and this layer has a lower thermal conductivity and a lower thermal diffusivity than ice (or the frozen meat). This insulating effect actually increases as the layer of thawed water grows. Figure 11.3.3.1 illustrates how thawing is a substantially longer process than freezing when temperature differences and other conditions are similar. Initially, the thawing curve shows a rapid rise when there is still no significant layer of water around the food. This is followed by an extended zone when the temperature is near the melting point.

![Thawing vs Freezing Graph](image)

**Figure 11.3.3.1** Temperature changes during freezing and thawing for similar size packages. Adapted from Fennema and Powrie (1964).

Commerically, thawing is done under different conditions:

- a. Cold, running water (relatively fast)
- b. Cold room (temperature should be cold enough not to encourage microbial growth; few hours to a few days)
- c. Microwave at a lower level (fast)
- d. During cooking (very fast)
Overall, the time required for thawing depends on the size of the meat cut, packaging materials, temperature differential, and air circulation. Thawing at room temperature should be avoided at all costs in order to prevent extensive microbial growth.

11.4 Use of Chemical Preservatives

11.4.1 General

Mankind has used various additives to preserve food for thousands of years. The most common additive has been salt, which, at a high enough level, can reduce water activity such that microorganisms cannot grow. Other chemical preservatives, such as smoke, have been used for centuries in conjunction with drying to produce shelf stable products. This is a primitive example of Hurdle Technology (more than one means of preservation is used to enhance microbial inhibition), which will be discussed later in the chapter. Fermentation is another example, where lactic acid (by bacteria) or alcohol (by yeast) production can inhibit pathogens and spoilage bacteria. Even though our ancestors did not understand what bacteria were they were still able to develop effective preservation methods for their food.

11.4.2 Salt

Sodium chloride (NaCl) is one of the oldest ingredients used to preserve meat. Preservation is achieved by lowering the water activity and hence reducing the water available for microbial growth. High salt concentrations can also interfere with the cell metabolism, since the salt draws water from the cell. Salt concentration in a living cell is around 0.90% and when the outside concentration is about the same, the cells experience an isotonic condition. When more salt is added to the surrounding environment, water moves outside the cell in an attempt to maintain equilibrium. This, in turn, results in a condition known as plasmolysis, and the withdrawal of water inhibits growth and possibly kills the cell. In order to make a food product shelf stable, a concentration of 10-15% salt should be used. This level is much higher than the 1.0-2.5% salt commonly used in most meat products (Barbut and Findlay, 1989; Sindelar and Milkowski, 2011), which is insufficient to preserve the product on its own but together with other additives and heating can significantly extend the shelf life. It should be mentioned that some microorganisms are actually inhibited by a salt level of 2.0%, but the high water activity (around 0.98-0.99) is insufficient to inhibit most bacteria, molds, and yeasts (see Chapter 15). It is also important to remember that salt is water soluble
and the calculation for salt concentration used for preservation should be based on lean meat portion (e.g., 2.5% salt added to a sausage with 30% fat will result in a salt concentration, as experienced by bacteria, of 3.6%). Other water soluble compounds such as sugar can also be added to reduce water activity but the high levels needed (e.g., 30-50%) are not commonly used in meat products but rather in fruit preservatives.

11.4.3 Phosphate

Different types of phosphate are used by the industry and the most common is tripolyphosphate (TPP). Phosphates can alter pH, cause a salt imbalance outside bacterial cells, and emulsify fat (i.e., affect cell membranes). Phosphate rinses and dips for decontaminating fresh meat were suggested over 50 years ago (Barbut and Findlay, 1989). Due to their detergent activity (i.e., resulting from their hydrophilic/hydrophobic structure), they have been successfully used as antimicrobial agents for removing bacteria from meat including from poultry skin. For example, in 1992, a commercial mixture of TPP and a few other ingredients was approved, in the US, for poultry skin decontamination and reprocessing (note that the level required is about 10% phosphate). See Chapter 15 for more information regarding phosphates.

11.4.4 Nitrite

Nitrite can be used by the meat industry as sodium nitrite (NaNO₂), sodium nitrate (NaNO₃), or as potassium salts. Nitrite is used in the curing process of different meat products (see also Chapter 13). Nitrite/nitrate is added for three main reasons:

a. inhibit the growth of harmful microorganisms such as Clostridium botulinum and other spoilage microorganisms
b. stabilize the pink meat colour in cured meats by forming the nitrosohemochrome complex
c. contribute to flavour development and inhibit oxidation e.g., the formation of the so-called warmed-over flavour.

The major reason for adding nitrite is to inhibit the growth of C. botulinum spores since they are not destroyed at temp < 100°C (i.e., most meat products are not cooked > 100°C). The active compound in nitrite is nitric oxide (NO), which inhibits C. botulinum by interfering with iron/sulphur enzymes such as ferredoxin that prevent adenosine-triphosphate (ATP) synthesis from pyruvate.
When sodium nitrate is used, it should be first reduced to nitrite, by microorganisms present in the meat (see also Chapter 13). Sodium nitrate is usually added to fermented meat products where a slow release of nitrite is required over a longer period of time.

Nitrite levels used in processed meat products are very low and usually range from 100-200 parts per million (ppm). Levels are regulated by government agencies because of the potential for nitrosamine formation, some of which are known to be carcinogenic. Nitrosamines can be formed by the reaction of nitrite and secondary/tertiary amines, under acidic conditions at high temperatures. In meat products that are processed shortly after nitrite addition (e.g., hot dogs), a reducing agent (e.g., ascorbate at a level of about 500 ppm) is commonly used to quickly convert most of the nitrite into nitric oxide and reduce the chance of nitrosamine formation. In certain products, where exposure to high temperatures is expected (e.g., fried pork/turkey bacon), lower levels of nitrite are allowed.

Sindelar and Milkowski (2011) reviewed the large volume of literature published on the use of nitrite and examined the risks and benefits. Overall, nitrite is recognized as beneficial in reducing food borne disease risk. Additionally, one should be aware that meat products are not the major source of nitrite in our diet. Certain vegetables (e.g., celery) have nitrite levels in the range of 300 ppm. In addition, microorganism presence in the human gut produces a lot of nitrite within the body. As well, as meat products are heated, nitrite is converted to nitric oxide gas and nitrite levels are substantially reduced. During storage, there is further reduction in the amount of measurable nitrite, and by the time the product is consumed, the nitrite level can be as low as 10-30 ppm (initially ~150 ppm). In the past few decades several attempts have been made to reduce or eliminate nitrite levels in meat productions, but none have gained wide acceptance. One example was the addition of 0.25% potassium sorbate to a product with 40 to 80 ppm nitrite. This combination inhibited *C. botulinum* but flavour problems were reported. Another patented alternative was the use of 35 ppm encapsulated dinitrosyl ferrohemochrome as a colouring agent and 3,000 ppm sodium hypophosphite as an antimicrobial agent in a nitrite-free curing formulation for wiener (Yun et al., 1987; Sindelar and Milkowski, 2011). However, that formulation is also not used today on a commercial scale.

### 11.4.5 Acids

Organic acids found in food (e.g., citric acid in citrus fruits), can be directly added to other products as marinades, sprays/rinses, or can even be produced within the product during fermentation (e.g., lactic acid during the fermentation of summer
sausages). Some acids can effectively reduce pH and inhibit microbial growth; the inhibition depends on the type and concentration of acid used. Acids are used as part of the Hurdle Technology system because relying only on an acid would require a high concentration that might negatively affect flavour, texture, and colour. Use of an acid rinse to inhibit/remove microorganisms during primary processing is also a common practice and is discussed further in Chapter 15.

Marinating meat cuts with ingredients such as lemon juice and vinegar is inhibitory to many pathogens and can also help extend shelf life. Marinated meat (e.g., chicken wings; see recipe in Chapter 13) is becoming very popular and many products are sold as convenience items that only require grilling. The antimicrobial inhibition of organic acids is due to both the reduction in pH (below the growth range of microorganisms) and metabolic inhibition by the un-dissociated acid molecules (see review by Theron and Lues, 2007). Overall, determining the inhibitory effect of a specific organic acid can be better measured by titratable acidity than by examining the pH alone. The latter is a measure of hydrogen ion concentration, as organic acids do not ionize completely. Measuring titratable acidity indicates the amount of acid that is capable of reacting with a known amount of base and is a better indicator of acidity (Jay et al., 2005). In the case of fermented/acidified meat products, lactic acid is produced within the product by lactic acid bacteria or added as an encapsulated acid to help reduce pH and preserve the product. Reports about the use of other encapsulated acids used in meat include citric and glucono-delta-lactone (Barbut, 2006). Lactic acid and its salts have also been extensively used by the meat industry to inhibit pathogens such as Salmonella, Listeria and E. coli in raw and cooked products (Aymerich et al., 2008). Sommers et al. (2010) reported on the beneficial effect of using potassium lactate and sodium diacetate together with ultraviolet light (i.e., Hurdle Technology) to suppress the growth of Salmonella and Listeria in packaged hot dogs stored at 10°C.

Sorbic acid is a preservative that is used as a fungal inhibitor (at a level of < 0.2%) and, more specifically, as an inhibitor of mold growth on products such as meat and bread. Sorbic acid can be used as a spray on fermented sausages as it works best below pH 6 and is not effective above pH 6.5. In general, catalase-positive cocci are more sensitive to sorbic acid than catalase-negative bacteria, and aerobes are more sensitive than anaerobes. The resistance of lactic acid bacteria to sorbate allows it to be used as a fungistat in fermented meat products (Jay et al., 2005). As mentioned in the nitrite discussion, a combination of sorbate and nitrite can be effective against C. botulinum, however, it can also cause flavour problems.
11.4.6 Spices and Extracts from Vegetables

Plants produce different compounds to protect themselves against microbial attacks. The antimicrobial efficacy has been attributed to various phenolic compounds, acids, alkaloids, quinones, flavanols and lectins (Gao et al., 2015; Gupta and Abu-Ghannam, 2012). There is a growing interest in using natural spices (Fig. 11.4.6.1) to improve the shelf life and safety of foods, but extracts are usually needed because spices are used at low concentrations. The antimicrobial activity of a specific spice depends on the chemicals found in the plant. Examples are:

- Oregano – carvacrol and thymol
- Cinnamon – sinnamic aldehyde and eugenol
- Cloves – eugenol
- Mustard – isothiocyanate
- Sage – thymol and eugenol

Figure 11.4.6.1 Spices that can be used for flavour and colour enhancement in food preparation. Showing here thyme, red pepper, cardemon, etc.

More comprehensive lists can be found in Shelef (1983), Jay et al. (2005), and Gao et al. (2015). It should also be mentioned that several natural antioxidants that prevent lipid oxidation also possess antibacterial activity. The phenolic structure of antioxidants such as BHA and BHT are inhibitory to Gram-positive and Gram-negative bacteria, yeast, and molds at concentrations ranging from 10 to 1,000 ppm. Food borne pathogens such as Salmonella typhimurium, Staphylococcus...
*aureus*, and *Bacillus cereus* are inhibited by BHA/BHT concentrations of > 500 ppm, while *Pseudomonas* spp are among the most resistant bacteria to BHA/BHT (Jay et al., 2005).

### 11.4.7 Smoke

Smoke has been used for centuries to preserve meat and other foods because burning wood releases various antimicrobial compounds. In general, there are four groups of compounds that have a bacteriostatic and/or bactericidal effect: phenols, ketones, aldehydes, and organic acids. Compound concentration depends on the type of wood and burning temperature. Phenols and organic acids contribute most to the preservative effect of smoke, but > 400 compounds have been isolated from wood smoke (see Chapter 13). In the past, when meat cuts were traditionally smoked over an open fire for an extended period of time, a high chemical concentration and the actual drying helped preserve the product. Today, however, most smoked meat products are only lightly smoked in order to enhance the exterior colour, contribute special flavour notes (hickory, oak), and provide some antimicrobial inhibition. This means that the smoke is only deposited on the surface of the product and penetrates to a depth of 1-3 mm. Consequently, the bacteriostatic/bactericidal effect is only on the surface of the product. Cold smoking can also be used to inhibit mold growth on uncooked, dry fermented sausages where a chemical spray such as sorbic acid (mold inhibitor) is prohibited for use (e.g., in Canada). Such a smoke application can be very effective.

### 11.4.8 Antibiotics and Bacteriocins

Microorganisms naturally produce antibiotics and bacteriocins to inactivate or kill competing microorganisms. Bio-preservation can also be applied to food where, for example, lactic acid bacteria can produce bacteriocins and lactic acid that inhibit pathogen growth during meat fermentation (e.g., preparation of salami). Bacteriocins usually have a narrow spectrum and only affect very specific groups of microorganisms. Castellano et al. (2008) reviewed the effectiveness and use of bacteriocins by the meat industry. Nisin was the most widely used bacteriocin in food preservation and is permitted for use in around 50 countries. It is also used by the cheese industry to prevent Swiss cheese spoilage by *Clostridium butyricum*. Nisin is naturally produced, heat stable, has an excellent storage stability, is destroyed by digestive enzymes in the body, does not contribute to off flavour or odours, is not toxic to humans, and it is not employed in human medicine. Nisin is considered to be a Class I bacteriocin. Like antibiotics, bacteriocins inhibit or kill other microorganisms, but only of closely related species or strains of the same species (Jay et al., 2005).
Antibiotics are also metabolites of microorganisms. One of the most familiar and useful antibiotics in human medicine (penicillin) is produced by the mold *Penicillium*. Antibiotics such as penicillin, tetracycline, and subtilin are strictly prohibited from use in meat producing animals. If any antibiotic is used for therapy during the growing period of farm animals, a withdrawal time is required until no residues can be found in the meat/milk/eggs. Tetracycline and subtilin were previously approved for use in meat in the US in the 1950s but were later removed due to concerns of having residues transferred to the consumer, and the development of antibiotic resistant bacteria (e.g., difficult to treat patients with bacteria resistant to tetracycline).

11.4.9 Sugars

Sugars preserve foods in the same manner as NaCl (i.e., reduction of water activity), but a main difference between them is the required relative concentration. To achieve the same inhibition effect, about six times more sucrose is required than NaCl (Jay et al., 2005). Most meat products are not preserved by high sugar concentrations, but there are some specialty products where high sugar content is used. More commonly, sugar such as dextrose is added to fermented meat products as a substrate for lactic acid bacteria and, thereby, indirectly assists in microbial inhibition. Dextrose concentrations of around 0.5-2% are commonly used and, by the end of the fermentation, most, if not all, of the dextrose has been converted to lactic acid.

11.5 Drying

11.5.1 General

Drying is one of the oldest methods of food preservation and drying thin slices of meat/fish over a fire or under the sun has been practiced since prehistoric times. The goal of the process is to reduce the amount of water in foods where the water content is 75-95% (considered highly perishable products). The scientific principle is based on reducing the water activity ($A_w$) to a level that will not support microorganism growth. Dried foods usually contain ≤ 25% moisture and have an $A_w$ of 0.05 to 0.60. There are also intermediate-moisture foods, which contain between 15 to 50% moisture and have water activities between 0.60 and 0.85 (Jay et al., 2005). Overall, drying adds cost but also improves shelf life, reduces transportation costs, increases convenience, and allows out of season consumption of dried meats and produce that can be used in dry soup mixes, dried foods for camping, and food carried to space.
11.5.2 Air Drying

Air drying is one of the most common ways to reduce $A_w$. It is estimated that most industrial dryers (85%) are hot air or combustion gas ovens that are based on convective heat transfer. This is an energy-intensive process, which accounts for up to 15% of all industrial energy expenditures. In an energy-intensive industry like heating and drying, improving energy efficiency by 1% can result in as much as 10% increase in profit (Kumar et al., 2014). The most common way of drying meat is by circulating dry, hot air, inside a drying cabinet where small or thin slices are placed on trays. Open air drying is also used commercially for products such as raw fish, which are often salted prior to drying. Large meat chunks (e.g., Prosciutto ham) are also dried by air over a long period of time. In that case it is very important to avoid the so-called case hardening (i.e., fast water migration from the surface that causes the formation of a “shell” that prevents further drying). Attention should also be given to the final shape of the product, since drying may shrink, twist, or deform it. This is especially true for thin meat products such as beef/turkey jerky, which are later sold in flat packages. In addition, fat oxidation can be accelerated during drying due to the large surface area exposed to oxygen. In order to overcome this problem, anti-oxidants are usually added. The anti-oxidants may be synthetic (e.g., BHA and BHT) or natural such as rosemary oleoresin (see Chapter 13).

The state of the drying air affects the quality of the final product. Higher drying temperatures reduce drying time but may result in poor quality, heat damage to the surface, and a higher energy cost. On the other hand, mild drying may improve quality by increasing drying time and reducing cost. When product shape and texture are very important, freeze drying is used (see Section 11.5.3). Intermittent drying has also been considered as a technical solution to reduce drying time while maintaining quality (Kumar et al., 2014). According to this concept, drying conditions change over time by continuously varying air temperature, humidity, pressure, and, when needed, the mode of heat input. At the plant, ultrasound, infrared, and microwave energy can be used during certain parts of the drying cycle to help design shorter and more efficient processes.

11.5.3 Freeze Drying

Freeze drying is used for high-end, delicate food products that can justify the higher cost of the process, which removes moisture from the product while maintaining its original shape. The frozen product is placed in a freeze dryer chamber and vacuum is applied (usually 1.0-1.5 mm of Mercury). The ice sublimates from the product without passing through an intermediate liquid phase. In commercial freeze dryers, rapid sublimation is achieved by applying both a vacuum and raising the
chamber temperature while the product is placed on a colder surface (e.g., cooled by a refrigeration coil). The product maintains its original shape since the water is sublimated while the product is frozen and structural changes (shrinking, collapse) cannot occur. Preserving the structure is important in products such as soup mixes where fast re-hydration and the textural characteristics are better compared to air dried products. The final moisture content of freeze dried meat is usually ≤ 5%. Therefore, a good package is required to protect the product and prevent moisture entry. As with air dried products, the freeze dried products are susceptible to lipid oxidation because of the large surface area of the fat. Note that re-hydration of the product usually does not return it to its original moisture content. This can also result in lower flavour notes and usually flavourings and seasonings are added to enhance meaty flavour. Cooking the meat prior to freeze drying usually results in a more stable product compared to drying fresh meat, in part because enzymes have been inactivated. If the product is properly packaged, the overall shelf life of cooked, freeze dried products can be a couple years, which is 2-4 times greater than the shelf life of freeze dried fresh meat.

11.6 Packaging

11.6.1 General

Packaging is used to protect food from contamination during storage, shipping, and distribution, to delay spoilage, and to reduce evaporation/weight loss, freezer burn, etc. After processing, the product is packaged and usually stays there until used by the customer. This time period may be days (ground meat), weeks (vacuum packaged hotdogs), or even years (canned food). Therefore, it is very important to control the conditions inside the package. Packaging technologies today range from a simple non-barrier overwrapping film, to barrier film (e.g., oxygen, water vapor), to modified atmosphere packaging, and active packaging. The packaging material can also be pretreated prior to use to sterilize it (e.g., hydrogen peroxide, pulsed light) or active ingredients added to the film (e.g., antioxidants, oxygen scavengers) that protect the product during storage.

In the early 1950s, as stores began pre-packaging meats in refrigerated self-service display cases rather than serving customers on demand, advanced meat packaging materials and technologies were required (McMillin, 2008; Kerry et al., 2006). Initially, oxygen-permeable and moisture-proof polyvinyl chloride films were developed that would stretch around a polystyrene tray of raw, fresh meat. The oxygen permeability was important because consumers began to associate
the bright red colour (called bloom) of pre-packaged meat with meat freshness because this was the colour of the meat they saw at the butcher shop.

Later, the economies of carcass portioning in centralized processing plants and shipment of cut up portions (steaks, fillets) rather than whole carcasses, sides, or quarters to retail stores for cutting also propelled advances in vacuum packaging materials and equipment. Packaging was also influenced by the increased competition of retail stores and chains (e.g., the need to provide an attractive package), requirements for safe and wholesome products, shortages of skilled butchers, and the need for a fully stocked meat case with longer store operation hours. Case-ready or centralized packaging is the concept of fabricating and packaging of consumer-sized retail items in a non-retail location. The items are then transported to retail stores with minimal or no package manipulation after removal from the shipping box. Centralized packaging is done on a large scale and provides opportunities for automation as well as improvements in space and labour resource utilization, quality, waste reduction, and inventory control. Packaging ranges from flexible films to rigid packages and rigid packages covered with a flexible film (Fig. 11.6.1.1) where different high speed automated machines can be employed. A modern high speed packaging area is shown in Figure 11.6.1.2.

Figure 11.6.1.1 Packaging equipment for rigid trays that after filling are covered with a plastic film. Courtesy of Ross Industries.
11.6.2 Modified, Vacuum, and Non-Vacuum Packaging

This category of packaging actively changes the environmental conditions within the package. Plastic is used most commonly because it is highly suitable for food packaging, as it has a low density, breakage resistance, no sharp edges, ready sealability, fabrication flexibility, environmental durability, barrier and permeability properties, printability, and flexibility at low temperatures. Other important physical and chemical properties of plastic used for food applications are: glass transition temperature, crystalline melting point, flexural modulus, tensile strength, tear strength, impact strength, flex life, water vapour transmission rate, $O_2$ permeability, optical properties, heat sealing properties, and bonding strength. Table 11.6.2.1 provides examples of common plastic films used by the food industry. Each type of packaging film has advantages, disadvantages, consumer and marketing issues, environmental considerations, and cost. A single layer plastic generally does not have all required properties for a food package application. Therefore, lamination, coating, or co-extrusion are used to create layers of different plastic polymers to achieve the desired properties. Heat sealing and barrier properties are often improved by application of different coatings to the surfaces of plastic films.

Today most fresh and cooked meats are packaged to prevent contamination and moisture loss (weight) during distribution. Sometimes fresh meat is also aged in a plastic pack to permit enzymatic activity that enhances tenderness.
<table>
<thead>
<tr>
<th>Packaging resin</th>
<th>Abbrev.</th>
<th>Water vapor transmission rate (g/m²/24h)</th>
<th>O₂ transmission rate (cc/m²/24h)</th>
<th>Tensile strength (MPa)</th>
<th>Tear strength (g/mL)</th>
<th>Impact strength (J/m)</th>
<th>Haze (%)</th>
<th>Light transmission (%)</th>
<th>Heat seal temperature range (°C)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyvinyl chloride</td>
<td>PVC</td>
<td>1.5-5</td>
<td>8-25</td>
<td>9-45</td>
<td>400-700</td>
<td>180-290</td>
<td>1-2</td>
<td>90</td>
<td>135-170</td>
<td>Moisture impermeable; resistant to chemicals</td>
</tr>
<tr>
<td>Polyvinylidene chloride</td>
<td>PVdC</td>
<td>0.5-1</td>
<td>2-4</td>
<td>55-110</td>
<td>10-19</td>
<td>–</td>
<td>1-5</td>
<td>90</td>
<td>200-150</td>
<td>Vapor barrier; high hardness; abrasion resistant</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>PP</td>
<td>5-12</td>
<td>2000-4500</td>
<td>35.8</td>
<td>340</td>
<td>43</td>
<td>3</td>
<td>80</td>
<td>93-150</td>
<td>Clear, readily processed</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>HDPE</td>
<td>7-10</td>
<td>1600-2000</td>
<td>38.2</td>
<td>200-350</td>
<td>373</td>
<td>3</td>
<td>–</td>
<td>135-155</td>
<td>Used for structure</td>
</tr>
<tr>
<td>Low density polyethylene</td>
<td>LDPE</td>
<td>10-20</td>
<td>6500-8500</td>
<td>11.6</td>
<td>100-200</td>
<td>375</td>
<td>5-10</td>
<td>65</td>
<td>120-177</td>
<td>Lidding film use; high strength, low cost sealant</td>
</tr>
<tr>
<td>Linear low density polyethylene</td>
<td>LLDPE</td>
<td>15.5-18.5</td>
<td>200</td>
<td>7-135</td>
<td>150-900</td>
<td>200</td>
<td>6-13</td>
<td>–</td>
<td>104-170</td>
<td>Superior hot tack; poor sealing through grease</td>
</tr>
<tr>
<td>Ionomer</td>
<td></td>
<td>25-35</td>
<td>6000</td>
<td>24-35</td>
<td>20-40</td>
<td>150</td>
<td>–</td>
<td>–</td>
<td>107-150</td>
<td>Metallic salts of acid copolymers of PE; broad heat sealant range</td>
</tr>
<tr>
<td>Ethylene vinyl acetate</td>
<td>EVA</td>
<td>40-60</td>
<td>12,500</td>
<td>14-21</td>
<td>40-200</td>
<td>45</td>
<td>2-10</td>
<td>55-75</td>
<td>66-177</td>
<td>4% improves heat sealability; 8% increases toughness and elasticity</td>
</tr>
<tr>
<td>Ethylene vinyl alcohol</td>
<td>EVOH</td>
<td>1000</td>
<td>0.5</td>
<td>8-12</td>
<td>400-600</td>
<td>–</td>
<td>1-2</td>
<td>90</td>
<td>177-205</td>
<td>Vapor barrier</td>
</tr>
<tr>
<td>Polyamide (nylon)</td>
<td>PA</td>
<td>300-400</td>
<td>50.75</td>
<td>81</td>
<td>15-30</td>
<td>50-60</td>
<td>1.5</td>
<td>88</td>
<td>120-177</td>
<td>High heat and abrasion resistance, clear, easily thermoformed; printable</td>
</tr>
<tr>
<td>Polyethylene terephthalate</td>
<td>PET</td>
<td>15-20</td>
<td>100-150</td>
<td>159</td>
<td>20-100</td>
<td>100</td>
<td>2</td>
<td>88</td>
<td>135-177</td>
<td>Polyester from terephthalic acid reaction with ethylene glycol; abrasion and chemical resistant; structure use</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>PS</td>
<td>70-150</td>
<td>4500-6000</td>
<td>45.1</td>
<td>2-15</td>
<td>59</td>
<td>1</td>
<td>92</td>
<td>121-177</td>
<td>High impact PS (HIPS) for multilayer sheet extrusion; strong; structure use</td>
</tr>
</tbody>
</table>
When meat is overwrapped in packaging film, the initial environment is roughly 79% nitrogen ($N_2$), 20% oxygen ($O_2$), and 0.03% carbon dioxide ($CO_2$). Modified atmosphere packaging is the process of altering the normal mixture of atmospheric gases into an atmosphere that will discourage microbial growth. The process involves either the evacuation of all air (vacuum packaging) or an artificial increase of the concentration of one or two gases (modified atmosphere packaging, also known as MAP). Table 11.6.2.2 shows examples of the major packaging systems used for fresh meat, including MAP. It is interesting to note that modified atmosphere storage of plant material has been used since the early 1920s, where fruits such as apples and pears were stored in large rooms with an elevated $CO_2$ environment. This was done to retard fungal rotting and the gas concentration could be continuously adjusted. During the 1930s, meat was shipped from Australia and New Zealand to England in large containers enriched with $CO_2$ in order to extend the shelf life. This was a very successful development for the red meat industry as it extended the shelf life of unfrozen meat to 3-4 months (Jay et al., 2005). In his review, Genigeorgis (1985) discussed numerous findings showing that high $CO_2$ concentrations increased the shelf life of different meats. It is important to note that the packaging material should be of high quality and meet specific characteristics that maintain the desired conditions (e.g., good $O_2/CO_2$ barrier to prevent gas migration). Various gas mixtures ranging from 0 to 100% $CO_2$ with or without nitrogen and/or oxygen have been suggested as a means of prolonging packaged meat’s shelf life. During a week of refrigerated storage the amount of $CO_2$ in vacuum packaged meat can accumulate and reach 30%. The increase in $CO_2$ is the result of the residual oxygen consumed by microorganisms and their resulting respiratory activity (Jay et al., 2005).

At the plant, modified atmosphere conditions can be achieved in several ways:

a. Evacuating air from the package with a vacuum pump, where pressure usually ranges anywhere from 10-200 mm Hg
b. Physically removing air by squeezing or placing the lower part of the package in water
c. Flushing the product with a gas mixture of choice using special equipment.

There are many similarities between vacuum packed and gas flushed meats, since the primary inhibitory effect is caused by $CO_2$. Overall, Gram-negative bacteria are more sensitive to $CO_2$ than Gram-positive, with *Pseudomonas* (a typical spoilage bacteria) being among the most sensitive and lactic acid bacteria and some anaerobes being among the most resistant.
<table>
<thead>
<tr>
<th>Package</th>
<th>System</th>
<th>Description</th>
<th>Gases in headspace</th>
<th>O₂ scavengers</th>
<th>Meat color in storage</th>
<th>Meat color for display</th>
<th>Shelf life, d at 4°C</th>
<th>Drip loss, %</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-permeable overwrap in master pack</td>
<td>Atmosphere-air</td>
<td>Air-permeable film overwrap of product on tray; product displayed in package</td>
<td>Atmosphere-air</td>
<td>none</td>
<td>Red</td>
<td>Red</td>
<td>5 - 7</td>
<td>8 - 10</td>
<td>Consumers familiar with packaging; high product visibility; lowest cost; multiple sizes on same equipment</td>
<td>Short shelf life due to air exposure; inconsistent at ends; increased package costs; MAP scavengers increase costs; spoilage at edges; decreased tenderness; headspace required; may be premature browning of cooked meat</td>
</tr>
<tr>
<td></td>
<td>Vacuum skin packaging (VSP)</td>
<td>Barrier bag with single or multiple trays of product in air-permeable packaging; trays removed for retail display</td>
<td>No gas headspace with VSP; CO₂ and/or N₂</td>
<td>Recommended</td>
<td>Purple</td>
<td>Red</td>
<td>30 - 45</td>
<td>0 - 5</td>
<td>Long shelf life before display; high product visibility with VSP</td>
<td>Lipid oxidation may be bone darkening or decreased tenderness; headspace required; may be premature browning of cooked meat</td>
</tr>
<tr>
<td>Air-permeable overwrap</td>
<td>Vacuum skin packaging (VSP)</td>
<td>Flexible film shrunk around product on a rigid base web; product displayed in package</td>
<td>No gas headspace with VSP; CO₂ and/or N₂</td>
<td>Recommended</td>
<td>Purple</td>
<td>Red</td>
<td>30 - 40</td>
<td>0 - 7</td>
<td>Long shelf life before display; high product visibility</td>
<td>Lipid oxidation may be bone darkening or decreased tenderness; headspace required; may be premature browning of cooked meat</td>
</tr>
<tr>
<td></td>
<td>Peelable VSP or low O₂ with CO₂ and N₂</td>
<td>Thermoformed or preformed trays with lidding film; product displayed in package before product display</td>
<td>CO₂ and/or N₂; no headspace with VSP</td>
<td>Recommended</td>
<td>Purple</td>
<td>Red</td>
<td>2 - 3</td>
<td>1 - 7</td>
<td>Digital red color stability and no lipid oxidation; high product visibility with VSP</td>
<td>Negative image by consumers; concern red products may be spoiled in other factors; scavengers increase costs; cooked meat color may be pink</td>
</tr>
</tbody>
</table>

Table 11.2.2 Major packaging types and characteristics for fresh retail meat. Based on information from different sources. Based on McMillin (2008).
The main differences between the microflora of fresh and vacuum packed meat are the dominancy of Gram-positive bacteria and fewer yeasts in the vacuum packaged meats (Jay et al., 2005; Sebranek et al., 2006). Two main mechanisms have been offered to explain the inhibitory effect of CO₂ (Enfors and Molin, 1978). The first suggests that CO₂ blocks the enzymatic decarbonization system in bacteria such as *P. aeruginosa*. The second mechanism suggests that CO₂ affects the permeability of the lipid bilayer within the cell membrane and increases its fluidity. At 1 ATM CO₂, Enfors and Molin (1978) showed that spore germination in *B. cereus* was inhibited. The same was reported for *P. fluorescence*. Other reports have shown that CO₂ inhibition increases as temperature is reduced. This concept is used today to enhance the shelf life of fresh and further processed meat products. Hotchkiss et al. (1985) reported that the shelf life of fresh chicken quarters could be extended up to 35 d at 2°C when packaged with 60-80% CO₂. Marshall et al. (1992) looked at further processed chicken nuggets and showed that competitive growth of *L. monocytogenes* and *P. fluorescence* was reduced by using a modified atmosphere (80% CO₂, 20% N₂) and 4°C storage.

Various reports have shown that the predominant organisms in spoiled vacuum packaged meats are *lactobacilli* and *B. thermosphacta*, although other microorganisms can sometimes dominate. Among the determining factors influencing the microflora are: whether the product has been cooked, relative load of psychrotrophic bacteria, the degree to which oxygen was excluded, and the product’s pH level and nitrite concentration (Jay et al., 2005).

Many cooked meat products (e.g., bologna, salami, frankfurters) are vacuum packaged to minimize lipid and colour oxidation, extend shelf life, and suppress spoilage microorganisms. Neilson and Zeuthen (1985) examined the microflora of cooked, bologna-type sausage in vacuum packaging and showed that the normal flora restricted growth of *Y. enterocolitica* and *Salmonella*, but not *S. aureus*. The normal microflora also inhibited *C. perfringens* and all pathogens were inhibited by the lactic acid bacteria, with greater inhibition when storage temperature was lowered. Additional discussion on spoilage microorganisms is provided in Chapter 15.

### 11.6.3 Active and Intelligent Packaging

Active and intelligent packaging are fairly new categories that have become popular over the past few years. Active packaging refers to the incorporation of additives into the packaging system with the goal of maintaining quality and extending shelf life (Kerry et al., 2006; Aymerich et al., 2008). Additives may be selected for:
a. Absorbing/scavenging properties – oxygen, carbon dioxide, moisture, flavours, UV light
b. Releasing/emitting properties – carbon dioxide, antioxidants, preservatives, sulphur dioxide, flavours
c. Removing properties – catalyze a food component such as cholesterol
d. Temperature control – self-heating and self-cooling packaging, insulation materials, microwave susceptors, and modifiers
e. Antimicrobial and quality control – antimicrobial agents such as organic acids and chelators.

The second category, intelligent packaging, refers to sensors/indicators that can monitor the condition of packaged foods and provide quality information during storage. Sensors can be used to monitor integrity, freshness, time, temperature (e.g., detect temperature abused conditions), and provide radio frequency identification (Kerry et al., 2006). Currently, this area mainly involves physical sensors that can monitor the concentration of a certain chemical (e.g., O\(_2\), CO\(_2\), acid). However, the industry is also interested in biosensors such as enzymes, antigens, nucleic acids, and hormones to help monitor metabolite development during food storage.

While there is a lot of interest in intelligent packaging, it is not yet popular in the meat industry. It is expected that this area will grow substantially over the next few years and help the industry and consumers monitor condition changes within the package.

11.7 Other Non-Thermal Processes

11.7.1 General

Non-thermal processes can also be used to inactivate spoilage and pathogenic microorganisms. They are usually based on transferring some energy to the food without noticeably raising its temperature. In that sense, they are usually regarded as treatments that have a minimal effect on the texture and nutritional value of the product. However, some (e.g., irradiation) can initiate lipid oxidation and, therefore, measures should be taken to reduce such effects (e.g., low temperature/freezing during application).

11.7.2 Radiation

Radiation, in general, is defined as the emission and propagation of energy through space or a material medium. Use of ionizing radiation as a preservation method has
already gained acceptance in various countries and is gaining acceptance in others. The wavelengths and photon energies employed are part of the electromagnetic spectrum and are presented in Figure 11.2.5.1; the shorter a wavelength is, the greater its energy. Electromagnetic radiation occurs in units called quanta or photons. When the energy in a quantum exceeds the energy that binds adjacent molecule atoms, the chemical bonds between atoms can be cleaved off, resulting in smaller fragments that may be electrically charged (ions) or neutral. Ultraviolet rays, x-rays, and gamma rays are capable of breaking fairly stable bonds and even expelling electrons from atoms. Therefore, they are known as ionizing radiation or ionizing energy. Ionizing radiation is defined as radiation with a wavelength of ≤ 2,000 angstroms (Å). Radiation particles of primary interest to the food industry are: gamma rays, beta rays, x-rays, and alpha particles. Their quanta contain enough energy to ionize molecules in their path. Ionizing radiation can destroy microorganisms without increasing temperature and is therefore also called “cold sterilization” (CAST, 1986; Ahn et al., 2006). It is important to point out that irradiated food is not radioactive. The radiation sources used by the food industry include machine-type and isotopic (Fig. 11.7.2.1) radiation. Machine-type radiation is produced by an electron accelerator that generates a high energy electron beam or high energy x-rays for treating food. Isotopic radiation uses isotopes such as cobalt-60 (\(^{60}\)Co) or cesium-137 (\(^{137}\)Cs) as a source of gamma rays. \(^{60}\)Co is produced in nuclear reactors by neutron-induced transmutation of naturally occurring \(^{59}\)Co. \(^{137}\)Cs is a fusion product and is extracted from byproducts of nuclear reactor fuel elements. The “strength” of an isotopic source is commonly expressed in terms of the rate of disintegration of radionuclide. The standard unit for activity is the curie and is defined as 37 billion disintegrations per sec. In addition to activity, the frequency of gamma ray emission should also be described. In the case of \(^{137}\)Cs, gamma ray emission is only 85% of its disintegrations, while \(^{60}\)Co emits 2 gamma rays per disintegration. Another important characteristic is the isotopic half-life, which describes the length of time for the activity of the source to be halved as a result of decay. The half-life of cesium is 30 yr and for cobalt it is 5.2 yr. The majority of facilities use \(^{60}\)Co because of its stronger gamma ray and water insolubility (Ahn et al., 2006; Aymerich et al., 2008).

The amount of radiation absorbed by the material (e.g., food) is known as the “dose” and can roughly be compared to the amount of heat a food product absorbs when placed in a hot oven. The process of measuring radiation absorption is called dosimetry and the unit is called a rad. A rad is equivalent to the absorption of 100 ergs/g of matter and a kilorad (krad) and megarad (mrad) are equal to 1,000 rads and one million rads, respectively. A newer dose unit is the gray (G), which is equal to 100 rads (1 G = 100 rads = 11 joule/kg; 1 kGy = \(10^5\) rads).
Radiation dose is usually split into three application levels: low, medium, and high. Similar to heat processing, small amounts of irradiation will result in pasteurization (i.e., killing some spoilage and pathogenic microorganisms), whereas a high dose will result in sterilization. Radurization is a lower level, pasteurization-type dose (0.75-2.5 kGy) that reduces spoilage microorganisms. It is commonly used to extend shelf life in fresh meat, poultry, seafood, fruits, and vegetables. Radicidation is similar to milk pasteurization and is designed to reduce non-spore forming pathogens, other than viruses. Typical doses are 2.5-10 kGy. Radappertization is a high level pasteurization that can achieve similar results to a heat-treated canned food. Usually, doses are about 30-40 kGy.

Similar to heat inactivation, there are D-values assigned to radiation treatments for different microorganisms. These are important when designing irradiation treatments for different foods (Table 11.7.2.1). Similar to conventional heat treatments, spores are more resistant to radiation than non-spore forming microorganisms. There are also differences in the spore resistance of related microorganisms (C. botulinum type E vs type B; Table 11.7.2.1). Once toxin has been formed, a very high dose of radiation is required to inactivate it (36 kGy). The same is true for S. aureus, where the D-value for the live bacteria is 0.16 kGy but is 61 kGy for the toxin. This is an important difference from heat processing where, for example, the C. botulinum toxin is fairly heat sensitive and can be inactivated
by boiling in water for a few minutes whereas the spores would need to be boiled for a few hours. The reason is that the toxin is a small peptide molecule that can be denatured and inactivated fairly easily by heat, but not by irradiation. Table 11.7.2.1 also shows that viruses are more resistant to irradiation compared to bacteria as can be seen by the D-value of the Adenovirus virus.

### Table 11.7.2.1
Overview of average radiation D-values for a variety of foods. Adapted from a summary by Jay et al. (2005).

<table>
<thead>
<tr>
<th>Organisms/Substance</th>
<th>D (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
</tr>
<tr>
<td><em>C. botulinum</em>, type E Beluga</td>
<td>0.8</td>
</tr>
<tr>
<td><em>C. botulinum</em>, 62A spores</td>
<td>1</td>
</tr>
<tr>
<td><em>C. botulinum</em>, type F spores</td>
<td>2.50</td>
</tr>
<tr>
<td><em>C. botulinum</em> A toxin in meat slurry</td>
<td>36.08</td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>0.2</td>
</tr>
<tr>
<td><em>L. monocytogenes</em></td>
<td>0.42 - 0.43</td>
</tr>
<tr>
<td>on meat at 5°C</td>
<td>0.44</td>
</tr>
<tr>
<td>on meat at 0°C</td>
<td>0.45</td>
</tr>
<tr>
<td>on meat at -20°C</td>
<td>1.21</td>
</tr>
<tr>
<td><em>Pseudomonas putida</em></td>
<td>0.08</td>
</tr>
<tr>
<td><em>Salmonella typhimurium</em></td>
<td>0.5</td>
</tr>
<tr>
<td><em>S. enteritidis</em> in poultry meat at 22°C</td>
<td>0.37</td>
</tr>
<tr>
<td><em>Staphylococcus aureus</em></td>
<td>0.16</td>
</tr>
<tr>
<td>toxin A in meat slurry</td>
<td>61.18</td>
</tr>
<tr>
<td><em>Yersinia enterocolitica</em>, in meat</td>
<td>0.19 - 0.38</td>
</tr>
<tr>
<td><strong>Viruses</strong></td>
<td></td>
</tr>
<tr>
<td>Adenovirus (4 strains)</td>
<td>4.1 - 4.9</td>
</tr>
</tbody>
</table>

Determining the exact dose of radiation is very important and dosimetry values are used to show that the product was exposed to/achieved the desired level of pasteurization/sterilization. Two main dosimetry systems are used by the industry. The first is based on ceric sulphate where ceric ions, in acidic aqua-solution are reduced by the action of ionizing radiation to cerous ions. The change in ceric ions can be readily measured by spectrophotometry. The second method is based on
colourimetry and is suitable for short irradiation periods. In most cases, another simpler secondary dosimetry system is used after being calibrated against one of the primary dosimetry systems. One such secondary system involves darkening of polymethyl methacrylate exposed to irradiation. The relative darkening is later measured by a spectrophotometer.

Gamma rays and x-rays can penetrate much deeper than visible light. A source with an energy level of 0.15 to 4 million electron volts (MeV) can penetrate about 30 cm of water. Aymerich et al. (2008) provided a summary table in which they indicated that commercial gamma ray sources usually operate at 1.3 MeV, x-rays at 5 MeV, and electron-beams at 5-10 MeV. Penetration depth also depends on the type of ray used. The authors indicated that gamma ray and x-ray systems used for food processing can penetrate 80-100 cm, while E-beam depth is 8-10 cm (note: also related to packaging materials). Fast, charged particles such as electrons, alpha particles, and protons also have enough energy to cleave molecules as they penetrate the material and that is the reason they are used.

As indicated above, there are two major types of commercial food irradiation facilities. The first uses a radioactive isotope and the second employs an electron beam accelerator (Fig. 11.7.2.2). In most countries irradiated food must be labeled with a special symbol to inform the consumer that the food has been exposed to radiation. The international symbol is a round green circle with two green leaves inside. Some industry personnel have argued against mandatory labeling on the grounds that irradiation is a food process similar to heating and freezing, which do not need to be mentioned on the label. However, most governments agree that food irradiation should be considered differently and a label/logo should appear on the package. In order to alleviate consumer fear, the word picowave has been suggested as a replacement for irradiation. Picowave is based on the wavelength used for irradiation (picowave = 1 trillionth of a meter on the electromagnetic spectrum) and is similar to the word microwave (microwave = 1 millionth of a meter on the electromagnetic spectrum). The term picowave was first suggested in the early 1980s but has not yet gained wide acceptance. In any case, food irradiation is becoming more acceptable in different parts of the world (Ahn et al., 2006). Among the reasons are E. coli O157:H7 problems in ground beef and requests for Salmonella- and Campylobacter-free meat.

In terms of food safety, the World Health Organization concluded in 1981 that “no hazard is involved in processing any food with ionizing energy up to an average dose of 10 kGy; hence, toxicological testing of food so treated is no longer required” (WHO, 1981). The WHO conclusion was based on the following factors:
a. Toxicological studies carried out on a large number of individual foods have produced no evidence of adverse effect as a result of radiation,
b. Studies (radiation chemistry) have shown that the radiolytic products of major food components are identical, regardless of the food from which they are derived. Moreover, for major food components, most of these radiolytic products have also been identified in foods subjected to other acceptable types of food processing. Knowledge of the nature and concentration of these radiolytic products indicates that there is no evidence of a toxicological hazard.
c. A body of supporting evidence has indicated the absence of any adverse effects resulting from the feeding of irradiated diets to laboratory animals, the use of irradiated feeds in livestock production, and the practice of maintaining immunologically incompetent patients on irradiated diets (Ahn et al., 2006).

The WHO conclusion and recommendation was further elaborated into an international standard under the procedure of the Codex Alimentarius Commission and in 1983 was adopted by 130 governments. Radiation was also promoted by the FAO in the 2003 Codex Alimentarius. Overall, the standard has provided an important incentive for national authorities to introduce favourable regulations for food irradiation. Thayer (1994) and later Ahn et al. (2006) reviewed the wholesomeness of irradiated food, including data cited by the Food and Drug Administration in support of the approval of meat for commercial sale in the US.
that had been irradiated with doses of 1.5-3.0 kGy to control food borne pathogens. The reviews showed that neither short nor multi-generation feeding studies had produced evidence of toxicological effects in mammals due to ingestion of irradiated food. This supports the conclusion that properly processed irradiated food is wholesome and that radiolytic changes in the food are minimal and predictable.

Using irradiation to treat meat at the radurization and radication levels can assist in reducing bacteria that cause food borne diseases (e.g., *Salmonella*) and spoilage (e.g., *Pseudomonas* and *Lactobacilli*). The effect of radiation dose on spoilage microorganisms on freshly slaughtered chickens stored at 2°C has been reported by Niemand et al. (1977). The non-irradiated control spoiled within 4-6 d, which is about the normal shelf life of eviscerated poultry. When a 2-5 kGy irradiation was given, however, the reduction in microbial population was in the range of 3 to 4 logs and the shelf life more than doubled. A dose of 5 kGy more than tripled shelf life and these results were in agreement with previous experiments. Others have shown that irradiating eviscerated poultry with 2.5 kGy resulted in an essentially *Salmonella*-free product. In a study involving artificially contaminated broiler skins, Mulder (1982) reported a range of D-values for irradiation at different temperatures (also Table 11.7.2.1). The values were in agreement with D-values obtained for *E. coli* and *Salmonella* reported for other foods, where irradiating at -18°C provided more protection to the microorganisms (than at a higher temperature) and thus required higher doses to achieve the same level of inactivation. Mulder (1982) also indicated that the application of 2.5 kGy to Dutch poultry could not guarantee a *Salmonella*-free product, but would reduce the number of *Salmonella*-positive poultry by a factor of 14. Today, the Dutch situation is quite different as the government implemented measures on farms and in primary processing to eradicate *Salmonella* (farm to plate approach; see Chapter 15).

Employing medium or high irradiation levels can result in the formation of some off flavours and odours due to lipid oxidation that can be induced by irradiation. It is usually suggested that meat irradiated at medium to high levels be vacuum packed and/or frozen in order to minimize off flavour formation. Freezing (at -20 to -40°C) has been recommended (Josephson, 1983). As with heat processed cans, *C. botulinum* spores are the main target and, since they are fairly radiation-resistant organisms (Table 11.7.2.1), a relatively high dose should be used. High level radappertization is used to achieve “commercial sterility” equivalent to thermal processing of canned food. The product can then be stored at room temperature without spoilage. For radappertization, a mild heat pre-treatment, at about 70-77°C, is usually applied in order to inactivate proteolytic and lipolytic enzymes. This
inactivation can minimize flavour, odour and texture deterioration during storage, because not all enzymes will be inactivated by the radiation treatment (Josephson, 1983; Ahn et al., 2006). Although enzyme inactivation, by heat, results in some textural changes and moisture loss, it is necessary to preserve the long-term quality of the product. To ensure complete sterilization, the 12-D concept is used. Anellis et al. (1977) have determined the required 12-D dose for chicken meat with NaCl (0.75%) and tripolyphosphate (0.3%) to be 42.7 kGy when radappertized at -30°C after enzyme inactivation at 74°C. Even though the sensitivity of C. botulinum is highest at 0°C, the product (2,000 cans of inoculated chicken meat) was treated at -30°C to minimize flavour deterioration at this relatively high dose.

When irradiating processed foods, interactions with other additives should be investigated. In a study involving frankfurters formulated with either 1.5% or 2.5% salt and then inoculated with five strains of C. botulinum (10³ spores/g), it was shown that a higher salt level provided better protection from toxin production under abused/high temperature conditions (Barbut et al., 1988). The authors reported that a radiation exposure of 5 kGy or greater, at either 1 or -30°C, was sufficient to inhibit botulinum toxin production for 40 d in turkey frankfurters containing ≥ 2.5% NaCl. Neither 5 nor 10 kGy inhibited toxin production in products formulated with 1.5% NaCl.

Commercial food irradiation technology was developed after World War II and has been available for over half a century. It is currently used to treat many of our medical supplies (e.g., bandages, plastic tubes that are sensitive to heat), spices, and various other foods. However, consumer acceptance of irradiated food products has been a challenge in several places around the world. This attitude is slowly changing due to better education and also attention given to various food borne disease outbreaks (e.g., E. coli O157, Salmonella). It is expected that food irradiation will become more widely used in the future and will help increase food safety standards as well as reduce food waste due to premature spoilage.

11.7.3 High Pressure Processing

High pressure processing (HPP) is another non-thermal process that can be applied both to fresh and cooked food products. HPP is commonly used for fruit juices, oysters, guacamole, and processed meat products and the meat industry is currently using HPP to extend the shelf life and reduce/eliminate pathogens (e.g., Listeria in cooked sliced meat, E. coli in dry fermented products that were not exposed to heat). HPP is also known as isostatic pressure, which is applied at 100 to 900 MPa at room temperature and is generated by a mechanical pump. The pressure chamber (Fig. 11.7.3.1) is filled with water, which transmits the pressure to the sample. A
process applying 500-600 MPa may take about 10 minutes: 2 min to charge, 5 min for pasteurization, and 3 min to discharge. The overall temperature rise can be in the range of 15°C as an increase of 3°C is expected for each 100 MPa (Aymerich et al., 2008). HPP accelerates reactions involving a volume change at the molecular level. The hydrophobic and electrostatic interactions are most affected, but not the hydrogen bonds. The process causes microbial cell inactivation, likely through damage to the cell membrane, without changing the organoleptic characteristics of the product. Other components in the cell that are sensitive to pressure include proteins, DNA, and fatty acids. Cell death increases with increasing pressure but does not follow first order kinetics (Garriga et al., 2005). In general, Gram-positive bacteria are more resistant to high pressure than Gram-negative bacteria. The threshold for inactivation also depends on the growth phase of the microorganism, processing time, composition of the surrounding food, pH, etc. Some microbial spores will need treatments > 900 MPa to destroy them, while various forms of mould and fungi need 200-300 MPa to kill their vegetative form and 400 MPa to destroy their spores (Aymerich et al., 2008). Because of sub-lethal injury to some cells, microbiological evaluation is recommended during the storage period.

Garriga et al. (2005) followed a 400 MPa treatment of sliced, cooked ham, inoculated with *Listeria*. Survival was detected during 42 days of storage at 6°C, but was not detected up to 80 days later when stored at 1°C. In a previous study they reported that 600 MPa was sufficient to prevent *Listeria* growth in meat products when stored at 4°C. In commercial applications, however, differences in pressure and time profiles might not provide a uniform pattern for microbial inactivation. In fresh meat, HPP can also result in some cooked appearance and
sometimes the development of a rubbery texture as a result of myofibrillar and myoglobin protein denaturation. In any case, recent consumer surveys indicated high acceptability for technologies that use no chemicals and have a minimal effect on the food product’s appearance and taste.

### 11.7.4 Pulsed Electric Field

Short exposure (e.g., milliseconds) of microorganisms to high intensity electrical field, also called electroporation, results in structural changes and electrical disruption in the cell membrane. The technology was introduced in the 1960s and recent developments have opened the possibility for moving to a continuous process. Although the precise mechanism of microbial inactivation is not fully understood (Sun, 2014), the major factor seems to be an enlargement or formation of pores in the cell’s membrane, which increases permeability. This can be an irreversible change that results in cell injury/death. Inactivation also depends on the state of the cell (e.g., lag phase vs log phase), food product parameters (e.g., pH, water activity, composition), and process conditions (e.g., number of pulses, electrical field strength). Overall, Gram-negative and positive bacteria are more resistant than yeast to this treatment.

### 11.7.5 Pulsed Light

In this method, microorganisms on the surface of food (can also be in a transparent package) are inactivated by high-energy light pulses (≤ 0.01 sec) in the wavelength range of 170-2600 nm. Processing units have been developed in which electric energy can be stored in a capacitor over a long period, and then released in short bursts, which damages nucleic acids (especially in the UV range), proteins, membranes, and other cellular components. The antimicrobial effectiveness of the process has been studied on food contact surfaces, packaging materials, and on the surface of various foods, including processed meat, bakery, and fishery products (Ray and Bhunia, 2013).

Paskeviciute et al. (2011) showed that a high-energy pulsed light treatment (1,000 pulses, treatment duration 200 s, total ultraviolet light dose 5.4 J/cm²) reduced the population of *S. typhimurium* and *L. monocytogenes* inoculated on the surface of chicken by 2.4 log₁₀ CFU/mL. In addition, the total aerobic mesophile population on the surface of meat was diminished by 2 log₁₀ CFU/mL. Data obtained on the investigation of chemical changes in treated chicken breasts indicated that the intensity of lipid peroxidation in the control and treated chicken samples differed by 0.16 mg malondialdehyde per kilogram of chicken meat. Taste
Panelists examining the organoleptic properties of treated chicken did not detect any changes in raw chicken, chicken broth, or cooked chicken meat flavor when compared to the control. Other researchers have reported similar positive results in fully cooked products.

### 11.7.6 Ultrasound

Ultrasound generates high-frequency sound waves and its antimicrobial effect is attributed to intracellular cavitation that disrupts the cellular structures and functional components. Overall, studies revealed that the antimicrobial effect of ultrasound in food is rather low (Ray and Bhunia, 2013). However, it can be enhanced by combining ultrasound with heat treatment above 50°C. Lawson et al. (2009) compared four technologies to reduce *Salmonella* in commercial Danish abattoirs: hot water, steam plus ultrasound, steam plus vacuum, and lactic acid. The results suggested that all technologies reduced the *Salmonella* population from 2.2% to about 0.2-0.9%. Overall, lactic acid was most cost effective followed by steam plus ultrasound decontamination.

### 11.7.7 Cold Plasma

Cold plasma is a mixture of free electrons, ionized particles, and some neutral atoms and molecules. Some consider plasma the fourth state of matter (the other three are solids, liquids, and gases). Noriega et al. (2011) looked at the efficacy of cold atmospheric gas plasmas for decontaminating chicken skin and lean muscle inoculated with *Listeria innocua*. Operating conditions were optimized for maximum bacterial inactivation by studying membrane filters on which *L. innocua* had been deposited. Higher AC voltage and excitation frequency as well as the presence of oxygen in the carrier gas resulted in the greatest inactivation efficacy. This was later also confirmed in the lean chicken muscle and skin results. Under optimal conditions, a 10 s treatment resulted in a > 3 log reduction of *L. innocua* on membrane filters, an 8 min treatment resulted in a 1 log reduction on skin, and a 4 min treatment resulted in a > 3 log reduction on muscle. These results show that the efficacy of gas plasma treatment is greatly affected by surface topography. Scanning electron microscopy images of chicken muscle and skin revealed surface features that effectively protected bacteria from the reactive chemical species generated within the gas plasma. Further development in gas plasma technology is needed for its commercial application to foods.
11.8 Hurdle Technology

The concept of using a series of preservation methods to enhance food safety has already been introduced in Chapter 6. By using the hurdle concept, one can minimize the negative effects of using a single preservation method at its maximum dose (e.g., pasteurization temperature can cause off-flavours and textural and vitamin losses), reduce preservative use (e.g., salt that also affects flavour and nutritional content), and/or reduce processing cost (e.g., energy required to fully dry a product). Many food products on the market are produced using the hurdle concept (Leistner, 2000). An example is a hotdog, which is prepared with salt, phosphate, nitrite, and is sold in a vacuum packaged container after being heat processed. The latter is a major step in reducing microbial count (usually by about 4 to 6 logs) and also serves as a critical control point in most HACCP plans (see Chapter 12). The added salt serves as an antimicrobial agent (e.g., salt is added at about 2–3% which is below the 15–20% level needed to act as a complete barrier to microbial growth). In addition, the product is refrigerated and consumers are instructed to consume the product within a few days of opening. This is because exposure to oxygen can encourage the growth of spoilage microorganisms. Another example of hurdle technology was provided by Sommers et al. (2010). They demonstrated the combined effect of ultraviolet light (0.5 J/cm²), potassium lactate, lauric arginate ester, and sodium diacetate (all are USDA approved) on the shelf life of frankfurters. The combination resulted in a 3.6–4.1 log reduction of *Salmonella, L. monocytogenes* and *S. aureus* on the product’s surface during a 12 week storage at 10°C. The combined treatments had no significant impact on frankfurter colour or texture. Other studies have investigated this approach and it is expected that more combinations will be introduced in the future. Examples in this chapter have already described the benefits of combining physical methods (e.g., heating, radiation, high pressure), chemical methods (e.g., salt, lactic acid, smoke compounds) and biological methods (e.g., bacteriocins, bacteriophages) to enhance food safety. Use of active packaging to deter microbial growth is another important area, especially when products are shipped long distances, and where longer shelf lives are required. Developments in modified atmosphere and intelligent packaging will continue with the goal of supplying the consumer with high quality products that are safer and more nutritious.
References


