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Chilling and Freezing of Foods

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5.1 Introduction to the food cold chain

The principle of the refrigerated preservation of foods is to reduce, and maintain, the temperature of the food such that it stops, or significantly reduces, the rate at which detrimental changes occur in the food. These changes can be microbiological (i.e. growth of microorganisms), physiological (e.g. ripening, senescence, and respiration), biochemical (e.g. browning reactions, lipid oxidation, and pigment degradation), and/or physical (such as moisture loss). An efficient and effective cold chain is designed to provide the best conditions for slowing, or preventing, these changes for as long as is practical. Effective refrigeration produces safe food with a long, high-quality shelf life. In the “chill” chain, the overall objective is to achieve the desired shelf life of a “fresh” product without the commonly perceived quality deterioration resulting from ice crystal formation. Freezing substantially increases the safe storage and distribution life of a food, but ice crystal formation might result in changes that are perceived to be detrimental to the quality of the food.

To provide safe food products of high organoleptic quality (i.e. taste, texture, smell, appearance), attention must be paid to every aspect of the cold chain from initial chilling or freezing of the raw ingredients, through storage and transport, to retail display and domestic handling. The cold chain (which includes both chilled and frozen foods) consists of two distinct types of operation. In processes such as primary and secondary chilling or freezing, the aim is to lower the average temperature of the food. In others, such as chilled or frozen storage, transport, and retail display, the prime aim is to maintain the temperature of the food at a constant optimal value. Removing the required amount of heat from a food is a difficult, time- and energy-consuming operation, but is critical to

the operation of the cold chain. As a food moves along the cold chain it becomes increasingly difficult to control and maintain its temperature. This is because the temperatures of bulk packs of refrigerated products in large storerooms are far less sensitive to small heat inputs than single consumer packs in open display cases or in a domestic refrigerator/freezer. Failure to understand the needs of each process results in excessive weight loss, higher energy use, reduced shelf life, and/or deterioration in product quality.

There are, however, examples where maintaining a particular food at temperatures that severely limit, if not completely stop, chemical changes does not achieve the desired final product quality. Examples of this are in the maturing of meat, ripening of fruits, and flavor development (aging) in cheese. In all these cases, the time-temperature history of the food must be carefully controlled so that periods are provided at temperatures where the desired changes can occur. However, the combination of time and temperature needs to be controlled such that undesirable, and especially unsafe, changes, such as the growth of pathogenic bacteria, do not occur.

5.2 Effect of refrigeration on food safety and quality

Refrigeration (cooling) is the total process of reducing the temperature of a food and maintaining that temperature during storage, transport, and retailing. If the temperature of the food does not fall below one where ice is formed in the food, the food is considered chilled and the temperature reduction process is called chilling. If ice is formed then the food is considered frozen, and the temperature reduction process is called freezing.

5.2.1 Microbiology and food safety

Temperature is a major factor affecting microbial growth. Microbial growth is described in terms of the lag phase and the generation time. When a microorganism is introduced to a particular environment, there is a time (the lag phase) in which no increase in microbial numbers is apparent, followed by a period when microbial growth occurs exponentially. The generation time is a measure of the time it takes for the population. Microorganisms have an optimum growth temperature at which a particular strain grows most rapidly, i.e. the lag phase and generation times are both at their shortest time. They also have a maximum growth temperature above which growth no longer occurs. Above this temperature, one or more of the enzymes essential for growth are inactivated and the cell is considered to be heat-injured. However, in general, unless the temperature is raised to a point substantially above the maximum growth temperature, the injury is not lethal and growth will recommence as the temperature is reduced. Attaining temperatures substantially above the maximum growth temperature is therefore critical during cooking and reheating operations.

Of most concern during storage, distribution, and retail display of food is a third temperature threshold, the minimum growth temperature for a microorganism. As the temperature of an organism is reduced below that for optimum growth, the lag phase and generation time both increase. The minimum growth temperature can be considered to be the highest temperature at which either of the growth criteria, i.e. lag phase and generation time, becomes infinitely long. The minimum growth temperature is not only a function of the particular organism but also the type of food or growth media that is used for the incubation. Although some pathogens can grow at 0°C or even slightly lower (Table 5.1), from a practical point of view the risks to food safety are considerably reduced if food is maintained below 5°C. However, food spoilage may still be an issue (see later). There are few data available on the impact of the initial freezing process on the safety of foods. However, it is difficult to envisage any sensible freezing process that would result in most foods being held for substantial periods at temperatures that would support a dangerous growth of pathogens. Providing that the food does not rise above -12°C during frozen storage and display, there should be no issues of food safety with frozen storage and display.

Campylobacter is the most common reported bacterial cause of infectious intestinal disease in many countries.

Table 5.1 Minimum and optimum growth temperatures for pathogens associated with foods

	Minimum temperature (°C)	Optimum temperature (°C)
<i>Campylobacter</i> spp.	30	42–43
<i>Clostridium perfringens</i>	12	43–47
<i>Clostridium botulinum</i> proteolytic	10	–
<i>Staphylococcus aureus</i>	7	–
Pathogenic <i>Escherichia coli</i> strains	7	35–40
<i>Escherichia coli</i> O157:H7	6–7	42
<i>Salmonella</i> spp.	5	35–43
<i>Bacillus cereus</i>	5	–
<i>Clostridium botulinum</i> non-proteolytic	3	–
<i>Aeromonas hydrophila</i>	-0.1 to 1.2	–
<i>Listeria monocytogenes</i>	-1 to 0	30–37
<i>Yersinia enterocolitica</i>	-2	28–29

Two species account for the majority of infections: *C. jejuni* and *C. coli*. Illness is characterized by severe diarrhoea and abdominal pain. Freezing and crust-freezing (freezing only the surface of the food) have been suggested as ways to reduce numbers of *Campylobacter* organisms on poultry carcasses, and have been recommended as control measures for reducing *Campylobacter* by the European Food Safety Authority (EFSA). Freezing to below -20°C has been reported by a number of studies to result in an initial fall in numbers of *Campylobacter* organisms, followed by a slower decline during storage. The mechanism of damage during freezing has been attributed to mechanical damage caused by ice crystals, desiccation due to the reduced water activity, and oxidative damage.

In addition to bacterial pathogens, histamine, viruses, and nematodes can also compromise food safety. Histamine (scombrotoxin or scombrototoxin food) fish poisoning is a food-borne chemical intoxication associated with the consumption of spoiled fish flesh that is high in histidine (from species such as mackerel, sardines, and certain tuna species). In these fish, bacterial histidine decarboxylase converts muscle histidine into histamine. In recent years, viruses have been increasingly recognized as important causes of outbreaks of food-borne disease. While noroviruses and hepatitis A are currently recognized as the most important food-borne viruses, a range

of other enteric viruses have also been linked to food-borne illness. Freezing in general has little effect on viruses or on histamine. Inadequate freezing and thawing procedures have been identified as factors in histamine formation.

Nematode parasites are very susceptible to freezing. Nematodes are slender worms, typically less than 2.5 mm (0.10 in) long. The smallest nematodes are microscopic, while free-living species can reach as much as 5 cm (2 in), and some parasitic species are larger still, reaching over a meter in length. Nematodes are responsible for a range of food-borne parasitic diseases in humans. Freezing is a control measure for inactivating trichinae in pork and nematode parasites in seafood (particularly for lightly processed seafood that will receive no cooking before consumption). Freezing is also used as a control measure for inactivating tapeworms (*Taenia saginata*) in beef carcasses.

Even if completely safe, food can become microbiologically unacceptable as a result of the growth of spoilage microorganisms. Their growth, which is highly temperature dependent, can produce unacceptable changes in the sensory quality of many foods. The development of off-odors is usually the first sign of putrefaction, and in meat, it occurs when bacterial levels reach approximately 10^7 cm^{-2} of surface area (Ingram, 1972). When bacterial levels have increased a further 10-fold, slime begins to appear on the surface and meat received in this condition is usually condemned out of hand. At 0°C , beef with average initial contamination levels can be kept for at least 15 days before any off-odors can be detected. Every 5°C rise in the storage temperature above 0°C will approximately halve the storage time that can be achieved. For example, a study by Hong and Flick (1994) reported that the shelf life of blue crab meat, determined by sensory analysis, was 15.5 days at 0°C , 12.5 days at 2.2°C , and 8.5 days at 5.6°C .

5.2.2 Nutritional quality

Microbial safety and spoilage are not the only aspects of food quality that are temperature dependent. The rate of vitamin loss from fruit and vegetables during storage also depends upon the storage temperature. In general, storage just above the freezing point of the fruit or vegetable will have the greatest effect on retarding respiration and transpiration (McCarthy & Matthews, 1994) and maintaining vitamin content (Paull, 1999). Humidity control is also important to prevent wilting and maintain crispness (McCarthy & Matthews, 1994), which in turn prevents the loss of water-soluble vitamins such as vitamin C (Paull, 1999). It is of interest to note that it is not always

a case of the lower the temperature, the better the quality, especially with citrus and tropical fruits. The optimum temperature for orange storage is approximately 12°C , with the rate of vitamin loss increasing at temperatures warmer or colder than this value.

There is a wealth of data available that shows that freezing is excellent at retaining nutrient content in comparison to “fresh” (chilled) equivalents (Berry et al., 2008). Although blanching will reduce some of the total initial nutrient content, there is very little reduction in nutrient content during subsequent frozen storage, whereas the nutrient content of many foods drops significantly during chilled storage. In general, more data are available on fruits and vegetables than meat, poultry, and fish (Berry et al., 2008).

5.2.3 Weight loss

Some foods exhibit particular quality advantages as a result of rapid cooling. In meat, the pH starts to fall immediately after slaughter and protein denaturation begins. The result of this denaturation is a pink proteinaceous fluid, commonly called “drip,” often seen in prepackaged cuts of meat. The rate of denaturation is directly related to temperature and it therefore follows that the faster the chilling rate, the less the drip. Investigations using pork and beef muscles have shown that faster rates of chilling (e.g. reducing the deep leg temperature of a pig in 10 hours to 5°C compared with 14°C) can halve the amount of drip loss (Taylor, 1972).

Another quality and economic advantage of temperature control is a reduction in weight loss, which results in a higher yield of saleable material. Meats, fruits, and vegetables, for example, have high water contents and the rate of evaporation depends directly on the vapor pressure at the surface. Vapor pressure increases with temperature and thus any reduction in the surface temperature will reduce the rate of evaporation. The use of very rapid chilling systems (3–4 h compared with overnight) for pork carcasses has been shown to reduce weight loss by at least 1% when compared with conventional systems (James et al., 1983).

Traditionally, the frozen food industry was interested in two particular problems to do with weight loss that were detrimental to the appearance of the frozen food: freezer burn and in-package frosting. Freezer burn is caused by water loss from the surface of the frozen food due to sublimation. The resulting desiccation produces a dry fibrous layer at the surface that has the appearance of a burn. It only occurs in unwrapped or poorly wrapped

foods and its development is fastest at high storage temperatures and high air movements. It is not caused by fast freezing. In-package frosting results from a combination of water loss from the surface, loose packaging, and temperature fluctuations during storage. The water lost from the surface is deposited and frozen on the inner surface of the packaging. The use of suitable packaging and good temperature control should eliminate both problems. Temperature fluctuations during storage will enhance both phenomena.

5.2.4 Flavor

The flavor and aroma of fruits and vegetables can be significantly affected by temperature, during both initial cooling and storage. Flavor is determined largely in these foods by the sugar to acid ratio (Paull, 1999). The rate of sugar loss (sweetness) in freshly harvested sweetcorn is very temperature dependent. After 20 h at 30°C, almost 60% of the sweetness is lost compared with 16% at 10°C and less than 4% at 0°C. Prompt cooling is clearly required if this vegetable is to retain its desirable sweetness. Similarly, the ripening of fruit can be controlled by rapid cooling, the rate of ripening declining as temperature is reduced and ceasing below about 4°C (Honikel, 1986).

Although freezing inhibits the rate of chemical reactions that promote off-flavor formation during frozen storage, it does not prevent these reactions, such as moisture migration, lipid oxidation and protein denaturation, taking place (Ponce-Alquicira, 2005). In many cases it is the production of off-flavors, such as by lipid oxidation in frozen meats, that limits the high-quality storage life of frozen foods.

5.2.5 Texture

Fish passing through rigor mortis above 17°C are to a great extent unusable because the fillets shrink and become tough (Morrison, 1993). A relatively short delay of an hour or two before chilling can demonstrably reduce shelf life. However, chilling has serious effects on the texture of meat if it is carried out rapidly when the meat is still in the pre-rigor condition; that is, before the pH of the meat has fallen below about 6.2 (Bendall, 1972). A phenomenon known as cold shortening occurs when chilled pre-rigor, resulting in the production of very tough meat after cooking. As a “rule of thumb,” cooling to temperatures not below 10°C in 10 h for beef and lamb, and in 5 h for pork can prevent cold shortening (James & James, 2002). Poultry meat is generally less prone to cold

Table 5.2 Fruits and vegetables susceptible to chilling damage (sources: Hardenburg et al., 1986; IIR, 2000; McGlasson et al., 1979; McGregor, 1989)

Commodity	Lowest safe temperature (°C)	Damage
Apples certain varieties	1–2	Internal browning, brown core
Avocados West Indian	11	Pitting, internal browning
Other varieties	5–7	Pitting, internal browning
Bananas	12–13	Dull color, blackening of skin
Beans	7–10	Pitting and russetting
Cucumbers	7–10	Pitting, water-soaked spots, decay
Grapefruit	7	Scald, pitting, watery breakdown, internal browning
Lemons	13–14	Internal discoloration, pitting
Mangoes	5–10	Internal discoloration, abnormal ripening
Melons Cantaloupe	7	Pitting, surface decay
Honeydew	4–10	Pitting, surface decay
Watermelons	2–4	Pitting, objectionable flavor
Oranges	3	Pitting, brown stains
Papaya	6	Pitting, water soaking of flesh, abnormal ripening
Potatoes	3–4	Mahogany browning, sweetening
Tomatoes	7–10	Water soaking and softening

shortening. However, electrical stimulation, i.e. passing an electrical current through the carcass within a short time of death, can be utilized to enable more rapid cooling to be carried out without the occurrence of cold shortening. Electrical stimulation shortens the time to the onset of rigor mortis by the acceleration of glycolysis with the pH falling by the order of 0.7 units during the first 2 min.

For several fruits and vegetables (Table 5.2), exposure to temperatures below a critical limit, but above the initial freezing temperature, may result in chilling injury. Typical symptoms of chilling injury are internal or external browning, superficial spots, failure to ripen, development of off-flavors, etc. It is primarily fruits and vegetables from

the tropical and subtropical zones that are susceptible to chilling injury, but several Mediterranean products are also susceptible (International Institute of Refrigeration, 2000). The extent of damage depends on the temperature, duration of exposure, and sensitivity of the fruit and vegetable. Some commodities have high sensitivity, while others have moderate or low sensitivity. For each commodity, the critical temperature depends on species and/or variety. In some cases, unripe fruits are more sensitive than ripe fruits.

One critical quality factor affected by freezing is food texture (Kerr, 2005). Loss of water-holding capacity due to tissue damage during freezing is a problem for many frozen foods. Such foods exhibit excessive drip loss on thawing and may lack proper juiciness when chewed (Kerr, 2005). Due to the chemical and structural differences in different food groups, each has unique issues associated with changes in textural quality due to freezing.

There is a general view that fast freezing offers some quality advantage, with “quick frozen” appearing on many frozen foods, with the expectation that consumers will pay more for a “quick frozen” product. This is because the rate of freezing has an effect on how and where ice crystals are formed within a food and the size of the ice crystals. Fast freezing rates will promote more nucleation and a greater number of crystals of smaller size which should result in less physical damage to the structure of the food.

However, the rate of freezing is not important for all foods. Foods may be classified into four groups (Poulsen, 1977; Spiess, 1979) according to their sensitivity regarding freezing rate.

1. Products that remain practically unaffected by variations in freezing rate, i.e. products with a high content of dry matter. For example, peas, meat products with a high fat content, and certain ready meals.
2. Products which require a minimum freezing rate (0.5–1 °C/min), but are relatively unaffected by higher freezing rates. For example, fish, lean meat, and many starch- and flour-thickened ready meals.
3. Products whose quality improves when freezing rates are increased (3–6 °C/min). For example, many fruits, egg products, and flour-thickened sauces.
4. Poulsen (1977) defined Group 4 as “products that are sensitive to too high freezing rates and tend to crack.” For example, fish and many fruits. Spiess (1979) refined this definition as covering “products in which high freezing rates are advantageous for the product quality, but where temperature tensions in the product result in a destruction of the tissue.” For example, fruits and vegetables such as raspberries, tomatoes, and cucumbers.

Terms such as slow, rapid, ultra-rapid, etc. often used in industry have no strict definitions, particularly since in many foods conduction within the food itself significantly slows the rate of freezing. Though rapid freezing may not offer particular advantages in terms of quality or extended shelf life for all foods, it may in terms of throughput. Though not always their sole consideration, throughput is of considerable importance to most producers.

There is evidence that since many plant tissues (fruit and vegetable) have a semi-rigid cellular structure that has less resistance to the expansion of ice crystals in volume, they are more prone to irreversible freezing damage than muscle tissues (Reid, 1994). In respect of the mechanisms of freezing damage in plant tissues, four contributory processes have been proposed: chill damage, solute-concentration damage, dehydration damage, and mechanical damage from ice crystals (Reid, 1994).

1. Chilling damage is a result of exposing the plant tissue to low temperature.
2. Solute-concentration damage is due to the increase in the concentration of solutes in the unfrozen liquid with the formation of ice crystals.
3. Dehydration damage results from increased solute concentration in the unfrozen liquid and the osmotic transfer of water from a cell interior.
4. Mechanical damage occurs as a result of the formation of hard ice crystals.

These types of damage in plant tissues would result in loss of function in cell membrane, disruption of metabolic systems, protein denaturation, permanent transfer of intracellular water to the extracellular environment, enzyme inactivation, and extensive cell rupture (Reid, 1994). Properties that reflect freshness and turgidity would also be lost in frozen food, because they depend largely upon the structural arrangement and chemical composition of the cell wall and the intercellular spaces where pectic substances are the primary constituents (Cano, 1996).

5.3 Blanching

Four groups of enzymes (Table 5.3) are primarily responsible for quality deterioration in vegetables. For vegetables, and to a lesser degree fruits, where enzymic deterioration during frozen storage is a problem, blanching is required to deactivate the undesirable enzymes. This is usually done with a mild heat treatment, typically by treating the product with steam or hot water for 1–10 min at 75–95 °C (International Institute of Refrigeration,

Table 5.3 Enzymes responsible for quality deterioration in unblanched vegetables (Williams et al., 1986)

	Enzyme
Off-flavors	Lipoxygenases, lipases, proteases
Textural changes	Pectic enzymes, cellulases
Color changes	Polyphenol oxidase, chlorophyllase, peroxidase
Nutritional changes	Ascorbic acid oxidase, thiaminase

2006), the time-temperature combination depending on the specific product. Blanching provides a number of other advantages, including improving color and flavor of some vegetables. However, it can also cause undesirable and irreversible textural changes and degrade heat-labile nutrients.

5.4 Principles of refrigeration systems

A detailed analysis of refrigeration cycles and systems may be found in numerous refrigeration textbooks (ASHRAE, 2006; Gosney, 1982; Trott, 1989). Nevertheless, a basic understanding of the principles of how a refrigeration system works is necessary for all users of refrigeration equipment. There are two main types of refrigeration system: total loss refrigeration systems, and mechanical refrigeration systems.

The rate of heat removed from the food ($Q_{product}$, J/s) accounts for the majority of the refrigeration load and can be determined from:

$$Q_{product} = \frac{mc_p(T_{initial} - T_{final})}{\Delta t} \quad (5.1)$$

where:

- m = total mass, kg
- c_p = specific heat capacity, J/kg °C
- $T_{initial}$ = initial temperature of the food, °C
- T_{final} = final temperature of food, °C and Δt is the time taken to remove the heat

5.4.1 Total loss refrigeration systems

Total loss refrigeration systems utilize the direct contact of a phase-changing refrigerant with a food. The refrigerant changes state during use, which requires latent heat and provides part of the heat extraction. The other part

is provided by the heat required to warm the resulting cold gas. The refrigerant is released to the atmosphere/environment and not recovered (hence the term “total loss”).

One of the most common total loss refrigerants is ice, with the majority of fish and shellfish being cooled and transported using it. During melting, ice requires $333 \text{ kJ}\cdot\text{kg}^{-1}$ of latent heat energy to convert from the solid to liquid phase.

Liquid nitrogen and solid carbon dioxide are also common total loss refrigerants. These refrigerants are usually referred to as “cryogenics” and refrigeration using these as “cryogenic.” The term “cryogenic” simply means very low temperatures. Liquid air was first used commercially in the 1930s (Willhoft, 1991) as a cryogen. However, liquid air contains a high proportion of liquid oxygen, which is a powerful oxidizing agent and its use has been superseded by less harmful liquid nitrogen (LN) and liquid or solid carbon dioxide (CO_2). What distinguishes cryogenic refrigeration from standard liquid immersion/spray systems is that a proportion of the heat removal is accomplished by a change in state of the heat transfer medium (Fennema, 1975). As well as using the latent heat absorbed by the boiling liquid, sensible heat is absorbed by the resulting cold gas.

Nitrogen at atmospheric pressure liquefies at a temperature of -196°C , giving a refrigerating capacity of 378 kJ per kg of liquid nitrogen. It is usually supplied and stored at a pressure of 3–6 bar, with corresponding boiling points of -185°C to -177°C (Heap & Mansfield, 1983; Hoffmanns, 1994). A useful rule of thumb is that $1 \text{ ton}\cdot\text{h}^{-1}$ of liquid nitrogen is approximately equivalent to 100 kW of mechanical refrigeration.

Carbon dioxide, if stored as a pressurized liquid and released into the atmosphere, changes partly to gas and partly to a frozen solid at -78.5°C , which sublimates directly into gas without going through a liquid phase. Liquid carbon dioxide is generally supplied either at ambient temperature (e.g. 25°C and 65 bar), giving a refrigerating capacity of 199 kJ per kg of liquid carbon dioxide, or at -16°C and 22 bar, giving a refrigerating capacity of 311 kJ per kg of liquid carbon dioxide. Solid carbon dioxide has a refrigerating capacity of 620 kJ per kg of solid carbon dioxide.

Due to very low operating temperatures and high surface heat transfer coefficients between product and medium, cooling rates of cryogenic systems are often substantially higher than other refrigeration systems. Cryogenic systems are best suited to cooling thin products with a high surface area to weight ratio in which heat

conduction within the product is not rate limiting, such as pizza, seafood, sliced/diced meats, and vegetables. Cryogenics can be used to chill foods, but their very low temperature can lead to undesirable surface freezing of the product. This can be avoided by indirect use (using the cryogen to cool down a secondary refrigeration medium, such as air) and/or by careful control of processing temperatures, such as ramp control in which the refrigeration medium temperature rises as the product temperature falls.

5.4.2 Mechanical refrigeration systems

Mechanical refrigeration systems operate using the same basic refrigeration cycle (Figure 5.1). At its simplest, it utilizes four interlinked components: the evaporator, compressor, condenser, and expansion valve. A low-pressure cold liquid refrigerant is allowed to evaporate to a gas within the “evaporator” coil. This process requires heat, which is extracted (e.g. ultimately from the product), thus cooling any medium surrounding the evaporator (e.g. air). The low-pressure hot gas from the evaporator is compressed in the “compressor” to a high-pressure hot gas. This high-pressure hot gas is then passed through another coil, where it condenses back to a high-pressure cold liquid. This process releases heat into any medium surrounding

the “condenser” coil (e.g. outside air). This high-pressure cold liquid refrigerant then passes through a valve, the “expansion valve,” to a lower pressure section. The now low-pressure liquid then passes back to the evaporator.

In a direct expansion system, the evaporator coil is in direct contact with either the food to be refrigerated or the cooling medium (i.e. air, brine, etc.) surrounding the food. In a secondary refrigeration system, liquid is cooled by passing over the evaporator coil, which in turn is used to cool the cooling medium (i.e. air, water, brine, etc.) surrounding the food. The energy used by a refrigeration system depends on its design, but generally the larger the temperature difference between the evaporator and condenser, the greater the energy used in the compressor for a given amount of cooling duty.

Traditionally, fluorocarbons, especially hydrochlorofluorocarbons (HCFCs) such as R22 (chlorodifluoromethane), were used as refrigerants but they are being phased out because of their ozone-depleting potential (ODP), as discussed later in this chapter. Thus, R22 is being replaced with refrigerants such as R404A (a mixture of refrigerants R125 pentafluoroethane, R143a 1,1,1-trifluoroethane and R134a 1,1,1,2-tetrafluoroethane) and R407c (a mixture of refrigerants R32 difluoromethane, R125 pentafluoroethane and R134a 1,1,1,2-tetrafluoroethane), ammonia, and propane.

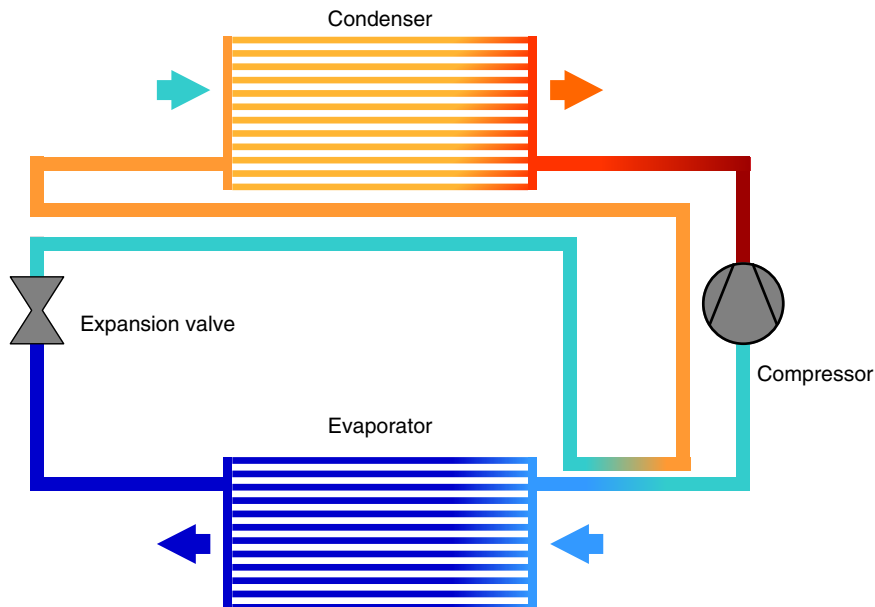


Figure 5.1 A mechanical vapor compression refrigeration system. For color details, please see color plate section.

5.5 Heat transfer during chilling and freezing

Heat transfer is a dynamic process that concerns the exchange of thermal energy from one physical system with a higher temperature to another with a lower temperature. It should be remembered that heat only flows from hot to cold. There are four modes of heat transfer: conduction, convection, radiation, and evaporation/condensation. In practice, they can occur individually or combined. In many applications, all four occur simultaneously but with different levels of importance. During chilling or freezing, heat is removed from the food usually by the combined mechanisms of convection, radiation, and evaporation. The rate of heat transfer ($Q_{\text{convection/radiation/evaporation}}$, J/s) between the food and the surrounding medium at any time can be expressed as:

$$Q_{\text{convection/radiation/evaporation}} = hA\Delta T = hA(T_{\text{surface}} - T_{\text{ambient}}) \quad (5.2)$$

where:

h = surface heat transfer coefficient for combined convection, radiation and evaporation, $\text{W/m}^2\text{ }^\circ\text{C}$

A = exposed surface area of the food, m^2

T_{surface} = surface temperature of the food, $^\circ\text{C}$

T_{ambient} = temperature of the heat transfer medium in contact with the food surface, $^\circ\text{C}$.

The surface heat transfer coefficient (h) is not a property of the food. Its value will depend on the shape of the food and its surface roughness, the type of heat transfer medium, the velocity of the heat transfer medium, and the flow regime. Typical surface heat transfer values for different chilling/freezing methods are shown in Figure 5.1.

5.5.1 Conduction

Conduction, or diffusion, is the transfer of energy between objects that are in physical contact. In conduction, the heat is transferred by means of molecular agitation within a material without any motion of the material as a whole. The heat transfer is made from points with greater energy to points with less energy in an attempt to establish a thermal equilibrium (Zheleva & Kamburova, 2009). Conduction is the main mode of heat transfer within a solid food, such as meats and vegetables, or between solid objects in thermal contact, such as plate conduction chillers. The rate of heat transfer

($Q_{\text{conduction}}$, J/s) within the food through conduction at any time can be expressed as:

$$Q_{\text{conduction}} = kA \frac{\Delta T}{\Delta x} \quad (5.3)$$

where:

k = thermal conductivity of the food, $\text{W/m }^\circ\text{C}$

A = surface area of the food, m^2

ΔT = temperature difference within the food, $^\circ\text{C}$

Δx = thickness of the food, m .

5.5.2 Convection

Convection is the transfer of heat by circulation or movement of hot particles to cooler areas. It is restricted to liquids and gases, as mass molecular movement does not occur at an appreciable speed in solids. Molecular motion is induced by density changes associated with temperature differences at different points in the liquid or gas (natural convection), or when a liquid or gas is forced to pass over a surface by mechanical means (forced convection) (Toledo, 2007). When liquid is cooled, some particles become denser and consequently drop. The surrounding warmer fluid particles move to replace them and are also cooled. The process continues repeatedly, forming convection currents. Convection is the main mode of heat transfer within a liquid food, such as a milk or a sauce, or within liquid or gaseous heat transfer media, such as air-blast, spray, and immersion chillers.

5.5.3 Radiation

Radiation is the transfer of heat by electromagnetic waves. Unlike conduction and convection, radiation does not require a medium because electromagnetic waves can travel through a vacuum. When a suitable surface intercepts these waves, it will absorb them, raising its energy level. Radiation depends upon the relative temperatures, geometric arrangements, and surface structures of the materials that are emitting or absorbing heat (Earle, 1983). The sun and a simple flame are examples of radiating objects producing heat. To achieve substantial rates of heat loss by radiation, large temperature differences are required between the surface of the product and that of the enclosure. Such differences are not normally present during food chilling operations except in the initial chilling of bakery and cooked products. When used, it is usually in combined systems, for example with contact chilling on metal surfaces under

a cold surface absorbing radiated heat, or with natural convection (Ciobanu, 1976b).

5.5.4 Evaporation

Evaporation is the transfer of energy required to change a liquid to a vapor. Latent heat is the heat energy required to change a substance from one state to another. For the majority of foods, the heat lost through evaporation of water from the surface is a minor component of the total heat loss, though it is the major component in vacuum cooling. Evaporation from a food's surface reduces yield and is not desirable in many refrigeration operations, but can be useful in the initial cooling of unpackaged cooked food products.

5.6 Chilling and freezing systems

There are a large number of different chilling and freezing systems for food, based on moving air, wet air, direct contact, immersion, ice, cryogenics, vacuum and pressure shift, some of which are described below.

For the majority of chilled and frozen foods, air systems are used primarily because of their flexibility and ease of use. However, other systems such as immersion, contact and cryogenics can offer much faster and more controlled chilling or freezing.

From a hygiene/safety-based approach, prepacking the food prior to chilling or freezing will lower the risk of contamination/cross-contamination during the chilling process. However, in most cases it will significantly reduce the rate of cooling, due to the insulating effect of the packaging, and this may allow the growth of any microorganisms, if present. Provided the cooling medium (air, water, etc.) and refrigeration equipment used are kept sufficiently clean, no one cooling method can be said to be intrinsically more hygienic than any other. For unwrapped food, a rapid cooling system allows less time for any contamination/cross-contamination to occur than in slower cooling systems.

It is not unusual for food products (or ingredients found in food products) to be chilled or frozen a number of times before they reach the consumer. For example, during industrial processing, frozen raw material is often thawed or tempered before being turned into meat-based products, (e.g. pies, convenience meals, burgers, etc. or consumer portions, fillets, steaks, etc.). These consumer-sized portions are often refrozen before storage, distribution, and sale. As long as the maximum

food temperatures reached are below those that support pathogen growth, and the exposure times are short, food safety should not be compromised. However, there will be some reduction in the quality of the food. Whether this is commercially important and reduces the practical shelf life will depend on the product and the conditions of exposure.

5.6.1 Air systems

Air is by far the most widely used method of chilling and freezing food, as it is economical, hygienic, and relatively non-corrosive to equipment. Air systems range from the most basic, in which a fan draws air through a refrigerated coil and blows the cooled air around an insulated room, to purpose-built conveyORIZED air-blast tunnels or spirals. They range in size from 2 to 3 m³ batch cabinets (Figure 5.2), used in catering operations, to large continuous chilling systems capable of holding 15,000 whole poultry carcasses (Figure 5.3). Relatively low rates of heat transfer (Figure 5.4) are attained from product surfaces in



Figure 5.2 Simple batch air-cooling system for cooling trays of product.



Figure 5.3 Continuous air-chilling system for whole poultry carcasses.

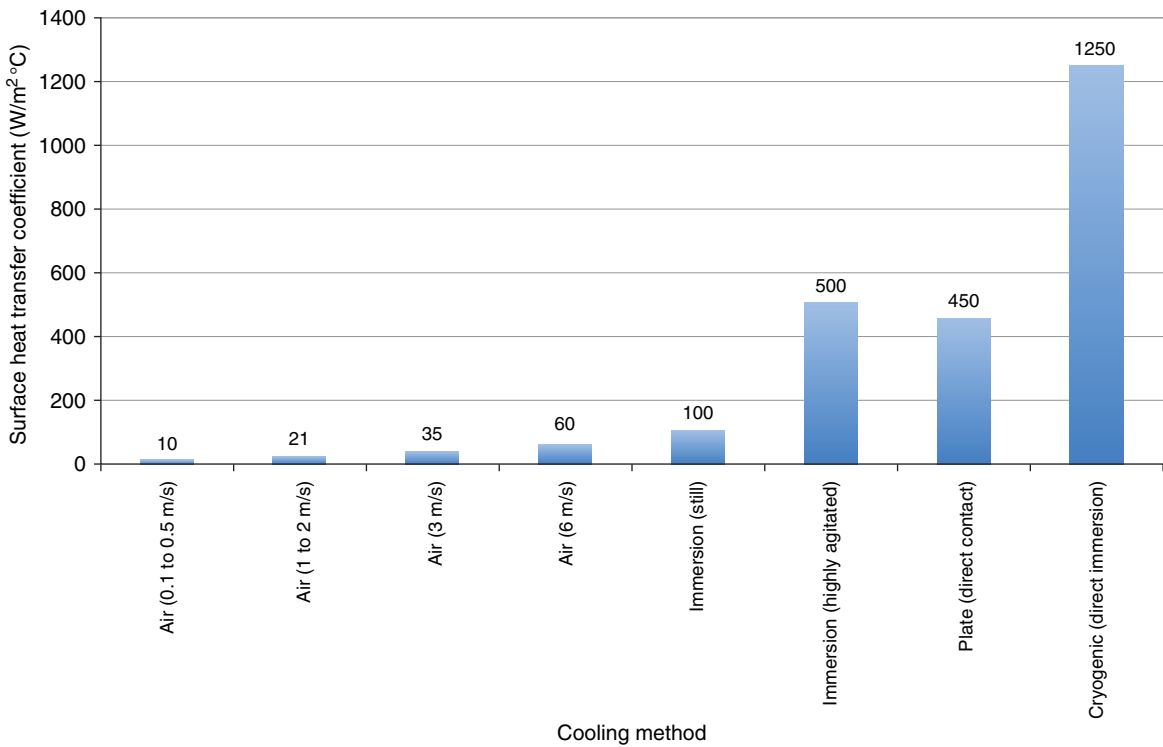


Figure 5.4 Typical heat transfer coefficients in cooling situations.

air-cooled systems. The big advantages of air systems are their lower cost and versatility compared to immersion, contact and cryogenics, especially when there is a requirement to cool a variety of irregularly shaped products.

In general, relatively low rates of heat transfer (see Figure 5.1) are attained from product surfaces in air-cooled systems. In standard systems, air speeds are seldom faster than 6 ms^{-1} , but far higher air speeds (up to 30 ms^{-1}) are achievable in impingement systems, and thus surface heat transfer rates are far higher in impingement chillers. Impingement systems are best suited for products with high surface area to weight ratios (for example, products with one small dimension such as hamburger patties, pizzas, etc.). Testing has shown that products with a thickness less than 20 mm chill/freeze most effectively in an impingement heat transfer environment.

Fluidized bed freezing is a modification of air-blast freezing. The principle behind fluidization is that fairly uniform particles are subjected to an upward air stream. At a certain velocity, the particles will float in the air stream, each separated from the other, surrounded by air and free to move. In this state, the particles act in a similar fashion to a fluid, thus the term “fluidized.” Products are fed into the higher end of a sloping tunnel, where they are simultaneously conveyed and frozen by the same air. Fluidized bed freezers can also be combined with a conveyorized system. Additional agitation, in the form of a movable base, may be required for some irregular products such as French fries (International Institute of Refrigeration, 2006).

Fluidized bed freezers are used to produce free-flowing products, most notably vegetables (such as peas, sliced carrots, green beans, etc.) and fruit, but can also be used for peeled cooked shrimps, diced meats, etc. (Hodgins, 1990; Persson & Löndahl, 1993). Products frozen by this method, as well as in other in-line blast freezers, are commonly referred to as individually quick frozen (IQF).

Higher air speeds are not suited for thick products where heat transfer within the product is the rate-limiting factor rather than that between the heat transfer medium and the product. For example, while increasing the air velocity during chilling of beef sides substantially reduces chilling times at low air velocity, the effect is smaller at higher velocities. Also, the power required by the fans to move the air within a chill room increases with the cube of the velocity. Thus, while a four-fold increase in air velocity from 0.5 to 2 ms^{-1} will result in a 4.4 h (18%) reduction in chilling time for a 140 kg side, it requires a 64-fold increase in fan power. In most practical situations, where large items are being cooled it is doubtful whether an air velocity greater than 1 ms^{-1} can be justified.

One of the principal disadvantages of air-cooling systems is their tendency to dehydrate unwrapped products. One solution to this problem is to saturate the air with water. Wet-air cooling systems recirculate air over ice-cold water so that the air leaving the cooler is cold ($0\text{--}1^\circ\text{C}$) and virtually saturated with water vapor (100% relative humidity, RH). An ice-bank chiller uses a refrigeration plant with an evaporator (plate or coil) immersed in a tank of water that chills the water to 0°C . During times of low load, and overnight use of off-peak electricity, a store of ice is built up on the evaporator, which subsequently melts to maintain temperatures during times of high load.

5.6.2 Contact systems

Contact refrigeration methods are based on heat transfer by contact between products and metal surfaces, which in turn are cooled by either primary or secondary refrigerants. Contact cooling offers several advantages over air cooling, such as much better heat transfer (Figure 5.4) and significant energy savings. Contact cooling systems include plate coolers, jacketed heat exchangers, belt coolers, and falling film systems. Vertical plate freezers (Figure 5.5) are commonly used to freeze fish at sea, while horizontal systems are commonly used for meat blocks and ready meals.

Good heat transfer is dependent on product thickness, good contact, and the conductivity of the product. Plate freezers are often limited to a maximum thickness of 50–70 mm (Ciobanu, 1976c; International Institute of Refrigeration, 2006; Persson & Löndahl, 1993). Good contact is a prime requirement. Air spaces in packaging and fouling of the plates can have a significant effect on cooling time; for example, a water droplet frozen on the plate can lengthen the freezing time in the concerned tray by as much as 30–60% (Ciobanu, 1976c).

5.6.3 Immersion/spray systems

Immersion/spray systems involve dipping products into a cold liquid or spraying a cold liquid onto the food. Cooling using ice or direct contact with a cryogenic substance is essentially an immersion/spray process. These systems range in size from 2–3 m^3 tanks used to cool small batches of cooked products to large, continuous chilling systems capable of cooling 10,000 poultry carcasses per hour. This produces high rates of heat transfer due to the intimate



Figure 5.5 Vertical plate freezer.



Figure 5.6 Ice/water immersion cooling of whole fish.

contact between product and cooling medium. Both immersion and spray methods offer several inherent advantages over air cooling in terms of reduced dehydration and coil frosting problems (Robertson et al., 1976). Clearly, if the food is unwrapped, the liquid has to be a substance that is safe to ingest. The freezing point of the cooling medium used dictates its use for chilling or freezing. Obviously, any immersion/spray-freezing process must employ a medium at a temperature substantially

below 0°C. This necessitates the use of non-toxic salt, sugar or alcohol solutions in water, or the use of cryogenes.

5.6.3.1 Ice systems

Chilling with crushed ice, or an ice/water mixture, is simple, effective and commonly used for the cooling of fish (Figure 5.6), turkeys (Figure 5.7), and some fruits and vegetables. Cooling is more attributable to the contact



Figure 5.7 Immersion cooling of turkey carcasses.

between the fish and the cold melt water percolating through it (i.e. hydrocooling) than with the ice itself. The individual fish are packed in boxes between layers of crushed ice, which extract heat from the fish and consequently melt. Ice has the advantage of being able to deliver a large amount of refrigeration in a short time as well as maintaining a very constant temperature, 0°C to -0.5°C (where sea water is present).

5.6.3.2 Cryogenic systems

Direct spraying of liquid nitrogen onto a food product whilst it is conveyed through an insulated tunnel is one of the most commonly used methods of applying cryogenics. The method of cooling is essentially similar to water-based evaporative cooling, the essential difference being the temperature required for boiling. As well as using the latent heat absorbed by the boiling liquid, sensible heat is absorbed by the resulting cold gas. Due to very low operating temperatures and high surface heat transfer coefficients between product and medium, cooling rates of cryogenic systems are often substantially

higher than other refrigeration systems. For example, an individual 1 cm thick beefburger takes less than 3 min to freeze in a cryogen system compared with up to 100 min in a cold store.

5.6.4 Vacuum systems

Food products having a large surface area to volume ratio (such as leafy vegetables) and an ability to readily release internal water are amenable to vacuum cooling. The products are placed in a vacuum chamber (typically operating at $530\text{--}670\text{ N}\cdot\text{m}^{-2}$), and the resultant evaporative cooling removes heat from the food. Evaporative cooling is quite significant; the amount of heat released through the evaporation of 1 g of water is equivalent to that released in cooling 548 g of water by 1°C . Suitable products, such as lettuce, can be vacuum cooled in less than 1 h. In general terms, a 5°C reduction in product temperature is achieved for every 1% of water evaporated. Since vacuum cooling requires the removal of water from the product, prewetting is commonly applied to prevent the removal of water from the tissue of the product.

Traditionally, this method of cooling has been relatively common for removing “field heat” of leafy vegetables immediately after harvest, but it is also suitable for many other foods, such as baked products, sauces, soups, particulate foods, and meat joints (James & James, 2002; Zheng & Sun, 2005). It is particularly useful for cooked fillings, stews, sauces and casseroles since pressure cooking and vacuum cooling can be combined in the same vessel, reducing both cooking and cooling times and saving space.

5.6.5 Scraped surface freezers

Scraped surface, or cylindrical, freezers are designed for freezing liquid products on either the inner or the outer surface of a cooled cylinder. The layer of frozen product formed on the surface of the cylinder is continuously scraped from the cylinder surface, thus achieving high heat transfer and a rapid freezing rate (Ciobanu, 1976c; International Institute of Refrigeration, 2006). Scraped surface freezers are used for manufacturing ice creams and similar products.

5.6.6 High-pressure freezing systems

High-pressure freezing, and in particular “pressure shift” freezing, is attracting considerable scientific interest (Otero & Sanz, 2012). The food is cooled under high

pressure to sub-zero temperatures but does not undergo a phase change and freeze until the pressure is released. Rapid nucleation yields small homogeneous ice crystals. However, studies on pork and beef have failed to show any real commercial quality advantages (Fernandez-Martin et al., 2006).

5.7 Chilled and frozen storage systems

A typical United Kingdom cold store usually has 75,000 m³ of storage space and is fitted with 10–14 m long mobile racks. A typical European system is almost three times as large (200,000 m³) and has 32–38 m long automated racks. The size of a cold store has an effect on the overall heat load through the insulation. A 2830 m³ cold store uses 124 kWh per m³ per year, whereas a 85,000 m³ store uses 99 kWh/ m³. Large refrigerated (chilled and frozen) distribution centers (Figure 5.8) are increasingly used by large food retailers and serve the dual purpose of a food store and a marshaling yard. At the other end of the cold chain, many millions (over 500,000 in the UK alone) of refrigerated commercial service cabinets are used to store food and/or drink in commercial catering facilities. The majority of the market is for chilled or frozen upright cabinets with one or two doors (between 400 and 600 L for single-door cabinets and 1300 L for double-door cabinets) or undercounter units with up to four doors (150–800 L).

There are clear differences between the environmental conditions required for cooling (chilling or freezing), which is a heat removal/temperature reduction process, and those required for storage, where the aim is to maintain a set product temperature. Three factors during storage, the storage temperature, the degree of fluctuation in the storage temperature and the type of wrapping/packaging in which the food is stored, are commonly believed to have the main influence on storage life.

Publications such as the International Institute of Refrigeration (IIR) *Recommendations for the Chilled Storage of Perishable Produce* (2000) provide data on the storage life of many foods at different temperatures. The storage life of most chilled foods is limited by the growth of spoilage microorganisms. However, with unwrapped food, dehydration of the surface layers may lead to unacceptable color changes. Poor temperature control can also lead to color problems. Rosenvold and Wiklund (2011) stated that “an increase in the storage temperature from the ideal temperature of -1.5°C to 2°C significantly decreased the color stability of lamb loins. Even one week at 2°C at the end of the storage period had a substantial negative impact on the retail color display life.”

Although freezing inhibits some enzymes, a considerable number, such as invertases, lipases, lipoxidases, catalases, peroxidases, etc., remain active (Ciobanu, 1976a). Because frozen foods are stored for relatively long periods, these enzymic reactions, although slow (reactions that take 45 min at 37°C will take over a week at -29°C),



Figure 5.8 Refrigerated distribution store serving retail shops.

can cause significant problems. For example, lipases, responsible for breaking down fats, remain active at very low temperatures. The storage life of many frozen foods is limited by these changes, for example rancidity development in the fat of meat. Publications such as the *IIR Recommendations for the Processing and Handling of Frozen Foods* (2006) provide data on the storage life of many foods at different temperatures. Storage lives for frozen food can be as short as 3–4 months for individually quick-frozen, polybag-packed shrimps at -18°C . On the other hand, lamb stored at -25°C can be kept for over 2.5 years.

Frozen foods are often stored at or near -18°C ; the reason for the use of this temperature is mainly historic since it is 0°F . There is an assumption that a low storage temperature is always beneficial to storage life. This is seen to be an oversimplification by some (Jul, 1982), and is not always so. There is a growing realization that storage lives of several foods can be less dependent on temperature than previously thought. Some products such as cured meats often have “reverse stability,” i.e. sliced bacon may keep longer at -12°C than at -20 or -30°C . While other products may benefit from temperatures as low as -30°C , storage below such temperatures may not have a substantial effect on storage life. Since research has shown that many food products, such as red meats, often produce non-linear time-temperature curves, there is probably an optimum storage temperature for a particular food product. Improved packing and preservation of products can also increase storage life and may allow higher storage temperatures to be used.

5.8 Chilled and frozen transport systems

Over a million refrigerated road vehicles, 400,000 refrigerated containers and many thousands of other forms of refrigerated transport systems are used to distribute refrigerated foods throughout the world (Gac, 2002). All these transportation systems are expected to maintain the temperature of the food within close limits to ensure its optimum safety and high-quality shelf life. Developments in temperature-controlled transportation systems for chilled products have led to the rapid expansion of the chilled food market.

It is particularly important that the food is at the correct temperature before loading since the refrigeration systems used in most transport containers are not designed to extract heat from the load but to maintain its temperature. Irrespective of the type of refrigeration equipment used,

the product will not be maintained at its desired temperature during transportation unless it is surrounded by air or surfaces at or below the maximum transportation temperature. This is usually achieved by a system that circulates air, either forced or by gravity, around the load. Inadequate air distribution is a major cause of product deterioration and loss of shelf life during transport. If products have been cooled to the correct temperature before loading and do not generate heat then they only have to be isolated from external heat ingress. Surrounding them with a blanket of cooled air achieves this purpose. Care has to be taken during loading to prevent any product from touching the inner surfaces of the vehicle because this would allow heat ingress by conduction during transport.

In the large containers used for long-distance transportation, food temperatures can be kept within $\pm 0.5^{\circ}\text{C}$ of the set point. With this degree of temperature control, transportation times of 8–14 weeks (for vacuum-packed meats stored at -1.5°C) are possible while still retaining a sufficient chilled storage life for retail display. Products such as fruits and vegetables that produce heat by respiration, or products that have to be cooled during transit, also require circulation of air through the product. This can be achieved by directing the supply air through ducts to channels at floor level or in the floor itself. In general, it is not advisable to rely on product cooling during transportation.

5.8.1 Sea transport

Recent developments in temperature control, packaging, and controlled atmospheres have substantially increased the range of foods that can be transported around the world in a chilled condition. Control of the oxygen and carbon dioxide levels in shipboard containers has allowed fruits and vegetables, such as apples, pears, avocados, melons, mangos, nectarines, blueberries and asparagus, to be shipped (typically 40 days in the container) from Australia and New Zealand to markets in the USA, Europe, Middle East, and Japan (Adams, 1988). If the correct varieties are selected and rapidly cooled immediately after harvest, the product arrives in good condition and has a long subsequent shelf life. With conventional vacuum packaging, it is difficult to achieve a shelf life in excess of 12 weeks with beef and 8 weeks for lamb (Gill, 1984). However, a shelf life of up to 23 weeks at -2°C can be achieved in cuts of lamb individually packed in evacuated bags of linear polyethylene, and then placed in gas-flushed foil laminate bags filled with a volume of



Figure 5.9 Refrigerated container, or reefer, showing refrigeration unit (courtesy of Sarah Klinge, Klinge Corporation).

CO₂ approximately equal to that of the meat (Gill & Penney, 1986). Similar storage lives are currently being achieved with beef primals transported from Australia and South Africa to the European Union (EU).

Most International Standard Organization (ISO) containers are either “refrigerated” or “insulated.” The refrigerated containers (reefers) have refrigeration units built into their structure (Figure 5.9). The units operate electrically, either from an external power supply on board the ship or dock or from a generator on a road vehicle. Insulated containers either utilize the plug-type refrigeration units already described or may be connected directly to an air-handling system in a ship’s hold or at the docks. Close temperature control is most easily achieved in insulated containers that are placed in insulated holds and connected to the ship’s refrigeration system. However, suitable refrigeration facilities must be available for any overland sections of the journey. When the containers are fully loaded and the cooled air is forced uniformly through the spaces between cartons, the maximum difference between delivery and return air can be less than 0.8°C (Heap, 1986). The entire product in a container can be maintained to within $\pm 1.0^{\circ}\text{C}$ of the set point.

Refrigerated containers are easier to transport overland than the insulated types, but have to be carried on deck when shipped because of problems in operating refrigeration units within closed holds. Therefore, on board ship they are subjected to much higher ambient temperatures, and consequently larger heat gains, than containers held

below deck, which makes it far more difficult to control product temperatures.

5.8.2 Air transport

Airfreighting is increasingly being used for high-value perishable products, such as strawberries, asparagus, and live lobsters (Sharp, 1988; Stera, 1999). However, foods do not necessarily have to fall into this category to make air transportation viable since it has been shown that “the intrinsic value of an item has little to do with whether or not it can benefit from air shipment, the deciding factor is not price but mark-up and profit” (ASHRAE, 2006). Perishables account for approximately 14–18% of the total worldwide air cargo traffic. Although airfreighting of foods offers a rapid method of serving distant markets, there are many problems because the product is unprotected by refrigeration for much of its journey. Up to 80% of the total journey time is made up of waiting on the tarmac and transport to and from the airport. During flight, the hold is normally between 15°C and 20°C. Perishable cargo is usually carried in standard containers, sometimes with an insulating lining and/or ice or dry ice, but is often unprotected on aircraft pallets (Sharp, 1988). Thus it is important that:

- the product be transported in insulated containers to reduce heat gain
- the product be precooled and held at the required temperature until loading
- containers be filled to capacity
- a thermograph should accompany each consignment.

5.8.3 Land transport

Overland transportation systems range from 12 m refrigerated containers for long-distance road or rail movement of bulk chilled or frozen products, to small uninsulated vans supplying food to local retail outlets or even directly to the consumer. Most current road transport vehicles for refrigerated foods are refrigerated using mechanical, eutectic plates or solid carbon dioxide or liquid nitrogen cooling systems.

Many advantages are claimed for liquid nitrogen transport systems, including minimal maintenance requirements, uniform cargo temperatures, silent operation, low capital costs, environmental acceptability, rapid temperature reduction, and increased shelf life due to the modified atmosphere (Smith, 1986). Some studies have claimed costs to be comparable with mechanical

systems (Smith, 1986), whilst others have reported costs to be up to 2.2 times higher (Nieboer, 1988).

In eutectic refrigeration systems, a freezing mixture (such as a salt solution) with a known freezing point (its eutectic point) is contained in plates that are typically fitted to the ceiling of the container or vehicle. Power is used to freeze the eutectic whilst the vehicle is in a static situation, such as overnight. During the vehicle's working day, no power is required, nor noise created, as the frozen solid gradually thaws until reaching its eutectic point. At this stage, large amounts of heat are absorbed as the mixture begins to change its state whilst remaining at a constant temperature.

Large retailers supply their stores in a single load, using large vehicles with variable temperature (ambient, chilled, and frozen) compartments, from central distribution depots. However, many small retail stores, garage outlets, etc. are supplied by sales vans. These are small to medium size refrigerated vehicles that are loaded with products in the morning and travel around to a series of retail outlets selling to each in turn. They therefore have a large number of stops when the doors are opened and food is removed from the van. Sometimes, food that has passed its sell-by date and empty trays are returned from the shops to the vans. The insulation, door protection, and refrigeration plant fitted to the vans have sometimes proved inadequate to maintain food temperature as cold as required. It is a problem for operators of the vans to know in advance whether a particular van, on a particular round, under given ambient conditions,

will be able to deliver food at the correct temperature. The rise in supermarket home delivery services, where there are requirements for mixed loads of products that may each require different storage temperatures, is introducing a new complexity to local land delivery (Cairns, 1996).

5.9 Refrigerated retail display systems

Refrigeration systems that include display fixtures in the sales area and systems serving the cold rooms are the major energy-consuming equipment in supermarkets. Refrigerated display equipment in supermarkets and other smaller food retail outlets (Figure 5.10) can be classified as "integral," where all the refrigeration components are housed within the stand-alone fixture, or "remote," where the evaporator or cooling coils within the display fixtures are served by refrigeration equipment located remotely in a plant room. The main advantages of integral units are the flexibility they offer in merchandizing, their relatively low cost and their relatively low refrigerant inventory and much lower potential leak rate compared to centralized systems. Their main disadvantage is the low efficiency of the compressors compared to large centralized compressors, noise and heat ejection in the store, which increases cooling requirements in the summer. Although small food retail outlets invariably use "integral" refrigeration equipment, larger food retail stores predominantly use centralized equipment of much more



Figure 5.10 Typical serve-over refrigerated retail cabinet display.

sophisticated technology plus a small number of integrals for spot merchandizing.

Centralized systems provide the flexibility of installing the compressors and condensers in a centralized plant area, usually at the back of the store or on a mezzanine floor or roof. The evaporators in the refrigerated display fixtures and cold rooms are fed with refrigerant from the central plant through distribution pipework installed under the floor or along the ceiling of the sales area. In the plant room, multiple refrigeration compressors, using common suction and discharge manifolds, are mounted on bases or racks normally known as compressor “packs” or “racks,” which also contain all the necessary piping, valves, and electrical components needed for the operation and control of the compressors. Air-cooled or evaporative-cooling condensers used in conjunction with the multiple compressor systems are installed remotely from the compressors, usually on the roof of the plant room. A schematic diagram of the direct expansion (DX) centralized system is shown in Figure 5.11. Separate compressor packs are used for chilled and frozen food applications. Most large supermarkets will have at least two packs to serve the chilled

food cabinets and one or two packs to serve the frozen food cabinets.

A major disadvantage of the centralized DX system is the large quantity of refrigerant required, 4–5 kg/kW refrigeration capacity and the large annual leakage rates of between 10% and 30% of total refrigerant charge. One way of significantly reducing the refrigerant charge in supermarket refrigeration systems is to use a secondary or indirect system arrangement. With this arrangement, shown schematically in Figure 5.12, a primary system can be located in a plant room or the roof and can use natural refrigerants such as hydrocarbons or ammonia to cool a secondary fluid, which is circulated to the coils in the display cabinets and cold rooms. Separate refrigeration systems and brine loops are used for the medium- and low-temperature display cabinets and other refrigerated fixtures.

The temperature of individual consumer packs, small individual items and especially thin sliced products responds very quickly to small amounts of added heat. All these products are commonly found in retail display cabinets and marketing constraints require that they have maximum visibility. Maintaining the temperature

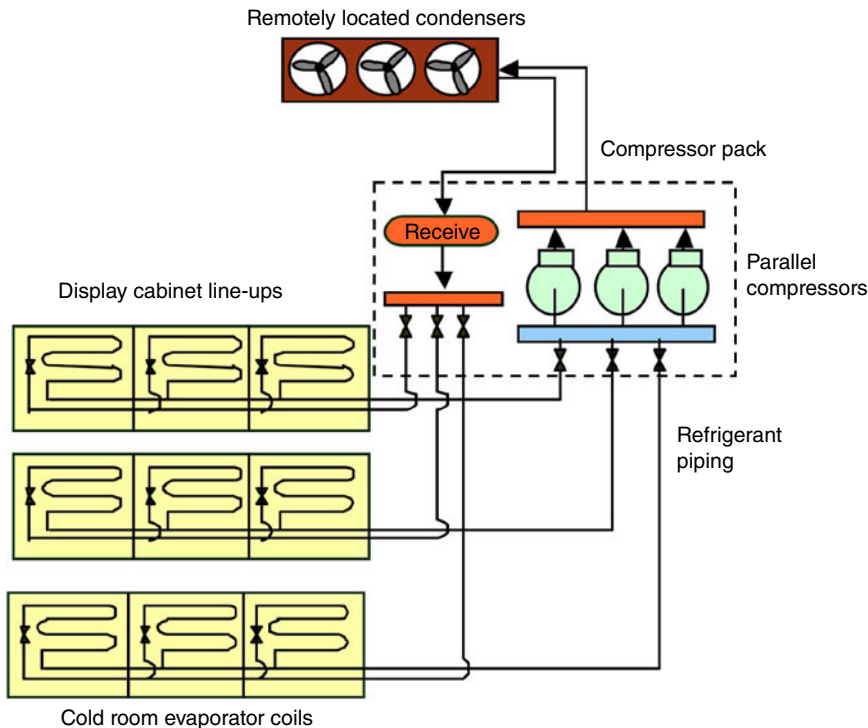


Figure 5.11 Schematic of refrigeration layout in retail store.

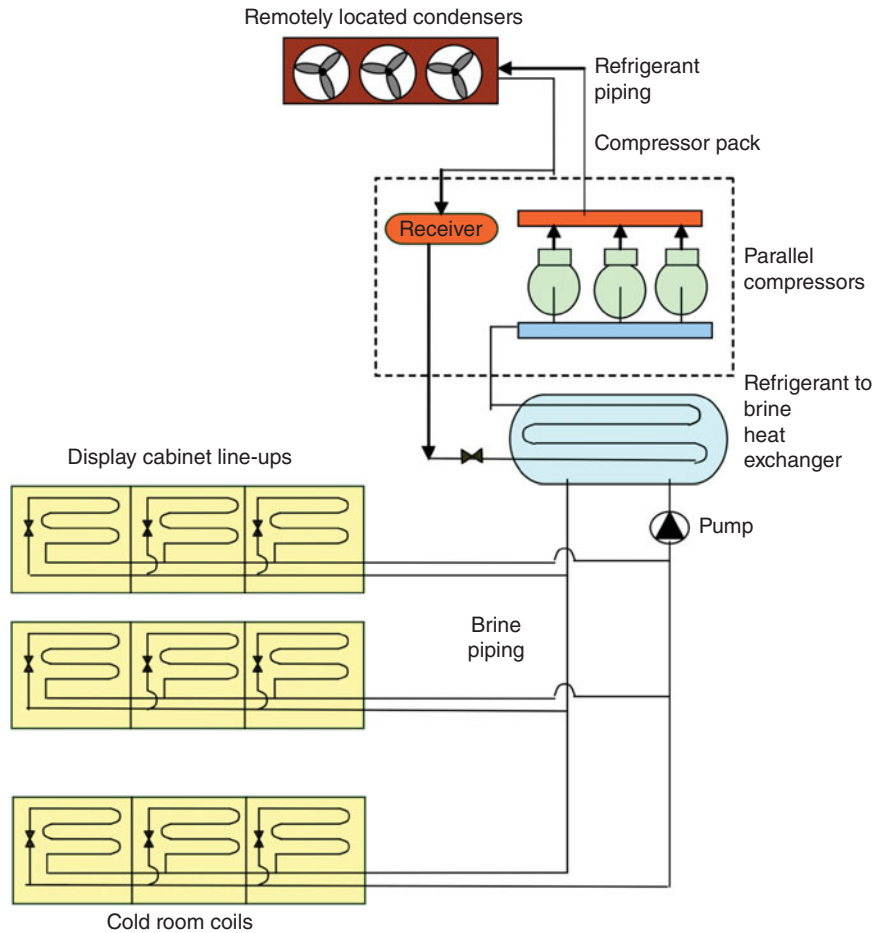


Figure 5.12 Schematic diagram of a secondary refrigeration system.

of products below set limits while they are on open display in a heated store will always be a difficult task. Attempts to improve the maintenance of food temperature include the use of phase change materials and heat pipes in the display shelves (Lu et al., 2010). These improve temperature distribution throughout the cabinet. The use of a heat pipe shelf is claimed to reduce food temperature by between 3.0°C and 5.5°C (Lu et al., 2010).

Average air temperatures in chilled displays can vary considerably from cabinet to cabinet, with inlet and outlet values ranging from -6.7°C to +6.0°C and -0.3°C to +7.8°C, respectively, in one survey (Lyons & Drew, 1985), while other studies reported temperatures ranging from -1.2°C to 19.2°C in refrigerated displays for fruit and vegetables (Nunes et al., 2009). A recent survey (Morelli et al., 2012) of 20 Parisian food retail shops

reported that 70% of the time-temperature profiles obtained exceeded 7°C. Evans et al. (2007) carried out an analysis of the performance of well freezers, chest freezers, frozen and chilled door cabinets (solid or glass door), and open-fronted chilled cabinets under EN441 standard test conditions. This revealed that maximum air and product temperatures in cabinets were generally in the most exposed (to ambient) areas and that minimum temperatures were located in the least exposed areas.

The temperature performance of an individual display cabinet does not only depend on its design. Its position within a store and the way the products are positioned within the display area significantly influence product temperatures. In non-integral (remote) cabinets (i.e. those without built-in refrigeration systems), the design and

performance of the central refrigeration system are also critical to effective temperature control.

The desired chilled display life for wrapped meat, fish, vegetables, and processed foods ranges from a few days to weeks and is primarily limited by microbiological considerations. Retailers of unwrapped fish, meat, and delicatessen products normally require a display life of one working day, which is often restricted by appearance changes. Frozen food can potentially be displayed for many weeks.

Reducing energy consumption in a chilled multideck cabinet is substantially different from reducing it in a frozen well cabinet (James et al., 2009). Improvements have been made in insulation, fans, and energy-efficient lighting but only 10% of the heat load on a chilled multideck comes from these sources, compared with 30% on the frozen well. Research efforts are concentrating on minimizing infiltration through the open front of multideck chill cabinets, by the optimization of air curtains and airflows (Gaspar et al., 2011), since this is the source of 80% of the heat load. Another effective method of reducing the refrigeration load is to fit doors to the cabinets. In frozen well cabinets, reducing heat radiation onto the surface of the food, accounting for over 40% of the heat load, is a major challenge.

5.9.1 Unwrapped products

Display cabinets for delicatessen products (see Figure 5.10) are available with gravity or forced convection coils and the glass fronts may be nearly vertical or angled up to 20°. In the gravity cabinet, cooled air from the raised rear-mounted evaporator coil descends into the display well by natural convection and the warm air rises back to the evaporator. In forced circulation cabinets, air is drawn through an evaporator coil by a fan and then ducted into the rear of the display, returning to the coil after passing directly over the products, or forming an air curtain, via a slot in the front of the cabinet and a duct under the display shelf.

Changes in product appearance are normally the criteria that limit the display life of unwrapped foods, with consumers selecting newly loaded product in preference to that displayed for some time. Deterioration in appearance has been related to degree of dehydration in red meat (Table 5.4) and is likely to occur similarly in other foods. Apart from any relationship to appearance, weight loss is of considerable importance in its own right. Relative humidity in delicatessen retail cabinets has been shown to have more effect on weight loss from displayed

Table 5.4 Relationship between weight loss and change in appearance of beef topside

Loss ($\text{g} \cdot \text{cm}^{-2}$)	Change in appearance
<0.01	Red, attractive and still wet, some brightness loss
0.015–0.025	Surface becoming drier, still attractive but darker
0.025–0.035	Distinct obvious darkening, becoming dry and leathery
0.05	Dry blackening
0.05–0.10	Black

products than air speed or temperature. Reducing the RH from 95% to 40% increases weight loss over a 6 h display period by a factor of between 14 and 18 (James & Swain, 1986).

There is a conflict between the need to make the display attractive and convenient to increase sales appeal and the optimum display conditions for the product. High lighting levels increase the heat load and the consequent temperature rise dehumidifies the refrigerated air. The introduction of humidification systems can significantly improve display life of unwrapped products (Brown et al., 2005) and studies have been carried out to optimize the humidification process (Moureh et al., 2009).

5.9.2 Wrapped products

To achieve the display life of days to weeks required for wrapped chilled foods, the product should be maintained at a temperature as close to its initial freezing point as possible to prevent microbial spoilage. In some cases, e.g. particular cheeses, dairy products and tropical fruits, quality problems may limit the minimum temperature that can be used, but for the majority of meat, fish and processed foods, the range -1°C to 0°C is desirable.

Air movement and relative humidity have little effect on the display life of a wrapped product, but the degree of temperature control can be important, especially with transparent, controlled atmosphere packs. Large temperature cycles will cause water loss from the product and this water vapor will condense on the inner surface of the pack, consequently reducing consumer appeal. Although cabinets of the type described for delicatessen products can be used for wrapped foods, most are sold from multideck cabinets with single or twin air curtain

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

To maintain product temperatures close to 0°C, the air off the evaporator coil must typically be -4°C and any ingress of humid air from within the store will quickly cause the coil to ice up. Frequent defrosts are often required and even in a well-maintained unit, the cabinet temperature may rise to 10–12°C and the product by at least 3°C (Brooks, 1986). External factors such as the store ambient temperature, the position of the cabinet and poor pretreatment and placement of products substantially affect cabinet performance. Warm and humid ambient air, and loading with insufficiently cooled products, can also overload the refrigeration system. Even if the food is at its correct temperature, uneven loading or too much product can disturb the airflow patterns and destroy the insulating layer of cooled air surrounding the product. An in-store survey of 299 prepackaged meat products in chilled retail displays found product temperatures in the range -8.0°C to 14.0°C, with a mean of 5.3°C and 18% above 9°C (Rose, 1986). Other surveys (Bøgh-Sørensen, 1980; Malton, 1971) have shown that temperatures of packs from the top of stacks were appreciably higher than those from below due to radiant heat pick-up from store and cabinet lighting. It has also been stated that products in transparent film overwrapped packs can achieve temperatures above that of the surrounding refrigerated air due to radiant heat trapped in the package by the “greenhouse” effect. However, specific investigations have failed to demonstrate this effect (Gill, 1988).

5.9.3 Frozen foods

No frozen food, with the possible exception of ice cream, should be unwrapped when in a retail display cabinet. Traditionally, frozen foods were displayed in a “well-type” cabinet with only the top faces of food packs being exposed. In many cases the cabinets were fitted with a see-through insulated lid to further reduce heat infiltration. Increasingly, there is marketing pressure to display more frozen food in open multideck display cabinets. The rate of heat gain in a multideck cabinet, and consequently the energy consumption, is much higher than in a well cabinet.

Maintaining the temperature of frozen products below set limits while they are on open display in a heated store will always be a difficult task. Radiant heat gain on the surfaces of exposed packs can result in the food thawing in extreme cases. During display, temperature, temperature fluctuations and packaging are the main parameters that control quality.

Temperature fluctuations can increase the rate of weight loss from wrapped meat. Higher rates of dehydration have been measured in a retail cabinet operating at -15°C than another cabinet operating at -8°C. Fluctuations in air temperature in the -15°C cabinet ranged from -5°C to -21°C compared with $\pm 1.5^\circ\text{C}$ in the -8°C cabinet. Successive evaporation and condensation (as frost) caused by wide temperature differentials resulted in exaggerated in-package dehydration (Cutting & Malton, 1972).

The extent of temperature fluctuations will be dependent upon the air temperature over the product, the product packaging, and the level of radiant heat. Retail display packs have a relatively small thermal mass and respond relatively quickly to external temperature changes. These can be from store and display lighting, defrost cycles, and heat infiltration from the store environment. In products where air gaps exist between the packaging and the meat, sublimation of ice within the product leads to condensation on the inside of the packaging, resulting in a build-up of frost. This dehydration causes small fissures in the surface of the food, allowing the ingress of any packaging gases into the food. This can aid the acceleration of oxidative rancidity within the product. Minor product temperature fluctuations are generally considered to be unimportant, especially if the product is stored below -18°C and fluctuations do not exceed 2°C.

5.10 Recommended temperatures

Publications such as the IIR *Recommendations for the Chilled Storage of Perishable Produce* (2000) and *Recommendations for the Processing and Handling of Frozen Foods* (2006) provide data on the storage life of many foods at different temperatures. The Agreement on the International Carriage of Perishable Foodstuffs (ATP Agreement; United Nations, 2012) specifies maxima temperatures for the transportation of chilled and frozen foods (Table 5.5). These temperatures are also a good guideline to follow during storage and retail display of such foods.

Table 5.5 Maxima temperatures for the transportation of chilled and frozen foods specified in the Agreement on the International Carriage of Perishable Foodstuffs (ATP Agreement)

	Maximum temperature (°C)	Description
Chilled foods	7	Red meat and large game (other than red offal)
	6	Raw milk
	6*	Meat products, pasteurized milk, fresh dairy products (yoghurt, kefir, cream, fresh cheese), ready-cooked foodstuffs (meat, fish, vegetables), ready-to-eat (RTE) prepared raw vegetables and vegetable products, concentrated fruit juice and fish products not listed
	4	Poultry, game (other than large game), rabbits
	3	Red offal
	2*	Minced meat
	0**	Untreated fish, molluscs, and crustaceans
Frozen foods	-20	Ice cream
	-18	Frozen or quick (deep)-frozen fish, fish products, molluscs and crustaceans and all other quick (deep)-frozen foodstuffs
	-12	All other frozen foods (except butter)
	-10	Butter

* Or at temperature indicated on the label and/or on the transport documents; ** at temperature of melting ice.

5.11 Refrigeration and the environment

The dominant types of refrigerant used in the food industry in the last 60 years have belonged to a group of chemicals known as halogenated hydrocarbons. Members of this group, which includes the chlorofluorocarbons (CFCs) and the hydrochlorofluorocarbons (HCFCs), have excellent properties, such as low toxicity, compatibility with lubricants, high stability, good thermodynamic performance, and relatively low cost, which make them excellent refrigerants for industrial, commercial, and domestic use. However, their high chemical stability leads to environmental problems when they are released and rise into the stratosphere. Scientific evidence clearly shows that emissions of CFCs have been damaging the ozone layer and contributing significantly to global warming. With the removal of CFCs from aerosols, foam blowing and solvents, the largest single application sector in the world is refrigeration, which accounts for almost 30% of total consumption.

Until recently, R12 (dichlorodifluoromethane), R22 (chlorodifluoromethane) and R502 (a mixture of R22 and R115 chloropentafluoroethane) were the three most common refrigerants used in the food industry. R12 and R502 have significant ozone depletion potential (ODP) and global warming potential (GWP); although R22 has less ODP and GWP than the other refrigerants,

it is still considered to have a significant impact in the long term. Two international agreements, the Montreal and the Kyoto Protocols, have had substantial effects. The Montreal Protocol was originally signed in 1987, and substantially amended in 1990 and 1992; it banned CFCs, halons, carbon tetrachloride, and methyl chloroform by 2000 (2005 for methyl chloroform). The Kyoto Protocol was negotiated by 160 nations in December 1997 and reduced net emissions of certain greenhouse gases, primarily CO₂ (plus methane, nitrous oxide, HFCs, perfluorocarbons, sulfur hexafluoride). Consequently, as a result of these international agreements, pure CFCs (e.g. R12, R502) have been completely banned. Pure HCFCs (mainly R22) are banned in new industrial plant and are being phased out completely in existing plant. HCFC blends and HFC blends originally introduced as CFC replacements are covered by the F-Gas regulations that limit leak rates.

The aim of the F-Gas regulations is to help the EU to meet its Kyoto Protocol target of reducing emissions of greenhouse gases by 8% from baseline levels by 2008–12. They contain requirements to minimize emissions of fluorinated greenhouse gases and for handlers of F-gases to be qualified and for monitoring of plant and gases (containment, training, labeling, reporting). Chemical companies are making large investments in terms of both time and money in developing new refrigerants that have reduced or negligible environmental

effects. Other researchers are looking at the many non-CFC alternatives, including ammonia, propane, butane, carbon dioxide, water, and air, that have been used in the past.

Ammonia is increasingly a common refrigerant in large industrial food cooling and storage plants. It is a cheap, efficient refrigerant whose pungent odor aids leak detection well before toxic exposure or flammable concentrations are reached. The renewed interest in this refrigerant has led to the development of compact, low-charge (i.e. small amounts of ammonia) systems that significantly reduce the possible hazards in the event of leakage. It is expected that ammonia will meet increasing use in large industrial food refrigeration systems. Carbon dioxide is being advocated for retail display cabinets and hydrocarbons, particularly propane and butane or mixtures of both, for domestic refrigerators.

As well as the direct affect of refrigerants on the environment, energy efficiency is increasingly of concern to the food industry. Worldwide, it is estimated that 40% of all food requires refrigeration and 15% of the electricity consumed worldwide is used for refrigeration (Mattarolo, 1990). In the UK, 11% of electricity is consumed by the food industry (DBERR, 2005). However, detailed estimates of what proportion of this is used for refrigeration processes are less clear and often contradictory (James et al., 2009). On the best available data, the energy-saving potential in the top five refrigeration operations (retail, catering, transport, storage, and primary chilling), in terms of the potential to reduce energy consumed, lies between 4300 and 8500 GWh/y in the UK (James et al., 2009).

It is clear that maintenance of food refrigeration systems will reduce energy consumption (James et al., 2009). Repairing door seals and door curtains, ensuring that doors can be closed and cleaning condensers produce significant reductions in energy consumption. In large cold storage sites, it has been shown that energy can be substantially reduced if door protection is improved, pedestrian doors fitted, liquid pressure amplification pumps fitted, defrosts optimized, suction liquid heat exchangers fitted, and other minor issues corrected (James et al., 2009).

In the retail environment, the majority of the refrigeration energy is consumed in chilled and frozen retail display cabinets (James et al., 2009). Laboratory trials have revealed large, up to six-fold, differences in the energy consumption of frozen food display cabinets of similar display areas. In chilled retail display, which accounts for a larger share of the market, similar large differences,

up to five-fold, were measured. A substantial energy saving can therefore be achieved by simply informing and encouraging retailers to replace energy-inefficient cabinets by the best currently available.

New/alternative refrigeration systems/cycles, such as trigeneration, air cycle, sorption-adsorption systems, thermoelectric, Stirling cycle, thermoacoustic and magnetic refrigeration, have the potential to save energy in the future if applied to food refrigeration (Tassou et al., 2009). However, none appears likely to produce a step change reduction in refrigeration energy consumption in the food industry within the next decade.

5.12 Specifying, designing, and commissioning refrigeration systems

In the author's experience, the poor performance of new refrigeration systems used to maintain the cold chain can often be linked to a poor, non-existent, or ambiguous process specification. In older systems, poor performance is often due to a change in use that was not considered in the original specification. There are three stages in obtaining a refrigeration system that works.

1. Determining the process specification, i.e. specifying exactly the condition of the product(s) when they enter and exit the system, and the amounts that have to be processed.
2. Drawing up the engineering specification, i.e. turning processing conditions into terms that a refrigeration engineer can understand, independent of the food process.
3. The procurement and commissioning of the total system, including any services or utilities.

The first task in designing a system is the preparation of a clear specification by the user of how the facility will be used at present and in the foreseeable future. In preparing this specification, the user should consult with all parties concerned; these may be officials enforcing legislation, customers, other departments within the company and engineering consultants or contractors, but the ultimate decisions taken in forming this specification are the user's alone.

The process specification must include, as a minimum, data on the food(s) to be refrigerated, in terms of size, shape, and throughput. The maximum capacity must be catered for and the refrigeration system should also be specified to operate adequately and economically at all other throughputs. The range of temperature requirements for each product must also be clearly stated. If it

is intended to minimize loss, it is useful to quantify at an early stage how much extra money can be spent to save a given amount of weight. All the information collected so far, and the decisions taken, will be on existing production. Another question that needs to be asked is, "Will there be any changes in the use of the system in the future?"

The refrigeration system chiller, freezer, storeroom, etc. is one operation in a sequence of operations. It influences the whole production process and interacts with it. An idea must be obtained of how the system will be loaded, unloaded and cleaned, and these operations must always be intimately involved with those of the rest of the production process. There is often a conflict of interest in the usage of a chiller or freezer. In practice, a chiller/freezer can often be used as a marshaling yard for sorting orders, and as a place for storing product not sold. If it is intended that either of these operations is to take place in the chiller/freezer, the design must be made much more flexible in order to cover the conditions needed in a marshaling area or a refrigerated store. In the case of a batch or semi-continuous operation, holding areas may be required at the beginning and end of the process in order to even out flows of material from adjacent processes. The time available for the process will be in part dictated by the space that is available; a slow process will take more space than a fast process, for a given throughput.

Other refrigeration loads, in addition to that caused by the input of heat from the product, also need to be specified. Many of these, such as infiltration through openings, the use of lights, machinery, and people working in the refrigerated space, are all under the control of the user and must be specified so that the heat load given off by them can be incorporated in the final design. Ideally, all the loads should then be summed together on a time basis to produce a load profile. If the refrigeration process is to be incorporated with all other processes within a plant, in order to achieve an economic solution, then the load profile is important. The ambient design conditions, e.g. the temperatures adjacent to the refrigerated equipment and the temperatures of the ambient to which heat will ultimately be rejected, must be specified. If the process is to be integrated with heat reclamation then the temperature of the heat sinks must be specified. Finally, the defrost regime should also be specified. There are times in any process where it is critical that coil defrosting and its accompanying temperature rise do not take place, and that the coil is cleared of frost before commencing the specified part of the process.

Although it is common practice throughout the food industry to leave much of this specification to

refrigeration contractors or engineering specialists, the end user should specify all the above requirements. The refrigeration contractors or engineering specialists can give good advice on this. However, since all the above are outside their control, the end user, using their knowledge of how well they can control their overall process, should always take the final decision.

The aim of drawing up an engineering specification is to turn the user requirements into a specification that any refrigeration engineer can then use to design a system. The first step in this process is iterative. A full range of time, temperature, and air velocity options must be assembled for each cooling specification covering the complete range of each product. Each option must then be evaluated against the user requirements. If they are not a fit then another option is selected and the process repeated. If there are no more options available, there are only two alternatives: either standards must be lowered (recognizing in do so that cooling specifications will not be met) or the factory operation must be altered.

A full engineering specification will typically include: the environmental conditions within the refrigerated enclosure, air temperature, air velocity, and humidity; the way the air will move within the refrigerated enclosure; the size of the equipment; the refrigeration load profile; the ambient design conditions; and the defrost requirements. The final phase of the engineering specification should include a schedule for testing the engineering specification prior to handing over the equipment to the owner/operator. This test will be in engineering and not product terms. The specification produced should be the document that forms the basis for quotations and finally the contract between the user and his or her contractor and must be stated in terms that are objectively measurable once the chiller/freezer is completed. Arguments often ensue between contractors and their clients arising from an unclear, ambiguous or unenforceable specification. Such lack of clarity is often expensive to all parties and should be avoided.

5.13 Conclusion

Chilling and freezing are two of the most common methods for preserving foods. Carried out correctly, they can provide a high-quality, nutritious, and safe product for consumption with a long storage life.

The principal factor controlling the safety and quality of a refrigerated (chilled or frozen) food is its temperature. The principle of the refrigerated preservation of foods is

to reduce, and maintain, the temperature of the food such that it stops, or significantly reduces, the rate at which detrimental changes occur in the food. In many cases, the time taken to reach the desired temperature is also important. To provide safe, high-quality refrigerated food products, attention must be paid to every aspect of the cold chain from initial chilling or freezing of the raw ingredients, through storage and transport, to retail display.

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