

Meat refrigeration

S. J. James and C. James



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Part 1

Refrigeration and meat quality

1

Microbiology of refrigerated meat

There are many pertinent texts on the microbiology of meats. The purpose of this chapter is to examine briefly the types of micro-organisms and conditions that are of interest in relation to the refrigeration of meat and meat products.

In a perfect world, meat would be completely free of pathogenic (food poisoning) micro-organisms when produced. However, under normal methods the production of pathogen-free meat cannot be guaranteed. The internal musculature of a healthy animal is essentially sterile after slaughter (Gill, 1979, 1980). However, all meat animals carry large numbers of different micro-organisms on the outer surfaces of the body and in the alimentary tract. Only a few types of bacteria directly affect the safety and quality of the finished carcass. Of particular concern are foodborne pathogens such as *Campylobacter* spp., *Clostridium perfringens*, pathogenic serotypes of *Escherichia coli*, *Salmonella* spp., and *Yersinia enterocolitica*.

In general, the presence of small numbers of pathogens is not a problem because meat is normally cooked before consumption. Adequate cooking will substantially reduce the numbers, if not completely eliminate all of the pathogenic organisms present on the meat. Most meat-based food poisoning is associated with inadequate cooking or subsequent contamination after cooking. The purpose of refrigeration is to reduce or eliminate the growth of pathogens so that they do not reach levels that could cause problems.

Normally the growths of spoilage organisms limit the shelf-life of meat. The spoilage bacteria of meats stored in air under chill conditions include species of *Pseudomonas*, *Brochothrix* and *Acinetobacter/Moraxella*. In general, there is little difference in the microbial spoilage of beef, lamb, pork and other meat derived from mammals (Varnam and Sutherland, 1995).

Meat is considered spoiled by bacteria when the products of their metabolic activities make the food offensive to the senses of the consumer (Gill, 1983). Therefore, the perception of a state of spoilage is essentially a subjective evaluation that will vary with consumer expectations. Few, however, would not acknowledge that the appearance of slime, gross discoloration and strong odours constitute spoilage.

‘Off’ odours are due to an accumulation of malodorous metabolic products, such as esters and thiols. Several estimations have been made of the number of bacteria on meat at the point at which odour or slime becomes evident and the mean is about $3 \times 10^7 \text{ cm}^{-2}$ (Shaw, 1972). When active growth occurs, the number of bacteria increases exponentially with time. Therefore, a convenient measure of the growth rate is the time required for doubling of numbers, often called the generation time. If this, for example, were one hour, the number would increase two-fold in 1 h, four-fold in 2 h, eight-fold in 3 h, and so on.

The bacterial safety and rate of spoilage depends upon the numbers and types of micro-organisms initially present, the rate of growth of those micro-organisms, the conditions of storage (temperature and gaseous atmosphere) and characteristics (pH, water activity a_w) of the meat. Of these factors, temperature is by far the most important.

1.1 Factors affecting the refrigerated shelf-life of meat

1.1.1 Initial microbial levels

1.1.1.1 Tissue sterility

For many years microbiologists believed that the tissues of healthy animals normally contained bacteria (Reith, 1926; Ingram, 1972). These ‘intrinsic’ bacteria were the cause of phenomena such as ‘bone taint’. The cause of bone taint is still questioned and will be discussed later. The prevailing view of the majority of textbooks (Banwart, 1989; Varnam and Sutherland, 1995), based in part on the work of Gill (Gill, 1979, 1980) is that the meat of a healthy animal is essentially sterile. Low numbers of specific micro-organisms, which have reached the tissues during the life of the animal, may occur in the viscera and associated lymph nodes from time to time (Gill, 1979; Roberts and Mead, 1986). These are often pathogenic species, such as *Salmonella*, and clostridia spores. The absence of bacteria appears to be due to the continued functioning of the immune system in slaughtered animals. Experiments with guinea pigs showed that the antibacterial defences of live animals persisted for an hour or more after death and could inactivate bacteria introduced during slaughter (Gill and Penney, 1979). Clearly, if bacteria are thus inactivated there can be no multiplication, in deep tissue, during carcass chilling irrespective of cooling rates.

1.1.1.2 *Rigor mortis*

The way in which animals are handled before slaughter will effect the biochemical processes that occur before and during rigor mortis. The resulting metabolites influence the growth of micro-organisms on meat.

During the onset of rigor mortis, which may take up to 24h, oxygen stored in the muscle is depleted and the redox potential falls from above +250mV to -150mV. Such a low redox value combined with the initial muscle temperature of 38°C provides ideal growth conditions for mesophilic micro-organisms. Stress and excitement caused to the animal before slaughter will cause the redox potential to fall rapidly, possibly allowing proliferation of such micro-organisms before cooling (Dainty, 1971).

Concurrent with the fall in redox potential is a fall in pH from an initial value in life of around 7 to a stable value around 5.5, the 'ultimate pH'. This is due to the breakdown of glycogen, a polysaccharide, to lactic acid in the muscle tissue. Lactic acid cannot be removed by the circulation nor oxidised, so it accumulates and the pH falls until the glycogen is all used or the breakdown stops. The pH has an important role in the growth of micro-organisms, the nearer the pH is to the ultimate value, the more growth is inhibited (Dainty, 1971). Stress or exercise before slaughter can deplete an animal's glycogen reserves, consequently producing meat with less lactic acid and a relatively high ultimate pH, this gives the meat a dark, firm, dry (DFD) appearance. Alternative terms are 'dark cutting' and 'high-pH meat'. The condition occurs in pork, beef and mutton, but is of little economic importance in the latter (Newton and Gill, 1981). DFD meat provides conditions that are more favourable for microbial growth than in normal meat. The microbiology of DFD meat has been comprehensively reviewed by Newton and Gill (1981).

Glucose is the preferred substrate for growth of pseudomonads, the dominant bacteria in meat stored in air at refrigerated temperatures. Only when glucose is exhausted do they break down amino acids, producing the ammonia and sulphur compounds that are detectable as spoilage odours and flavours. In meat containing no glucose, as is the case with some DFD meat, amino acids are broken down immediately and spoilage becomes evident at cell densities of $6 \log_{10} \text{cfu cm}^{-2}$ (colony forming units per centimetre squared). This is lower than in normal meat, where spoilage becomes apparent when numbers reach *ca.* $8 \log_{10} \text{cfu cm}^{-2}$. Thus, given the same storage conditions, DFD meat spoils more rapidly than normal-pH meat. There is no evidence that the spoilage of pale, soft, exuding (PSE) meat is any different to that of normal meat (Gill, 1982). There is little significant difference in pH or chemical composition between PSE and normal meat.

1.1.1.3 *Surface contamination*

Initial numbers of spoilage bacteria on carcasses significantly affect shelf-life. With higher numbers, fewer doublings are required to reach a spoilage

level of $ca. 10^8$ organisms cm^{-2} . For example, starting with one organism cm^{-2} , 27 doublings would be needed; for 10^3 organisms cm^{-2} initially, the number of doublings is reduced to 17.

Contamination of carcasses may occur at virtually every stage of slaughtering and processing, particularly during flaying and evisceration of red-meat animals and scalding, and mainly affects the surface of the carcass. Sources of contamination have been reviewed by James *et al.* (1999). Hygienic handling practices should ensure that total viable counts on the finished carcass are consistently 10^3 – 10^4 organisms cm^{-2} or lower for red meats. Bad practices can cause counts to exceed 10^6 organisms cm^{-2} .

With red meats, carcasses of good microbial quality are obtained by

- 1 preventing contamination from the hide;
- 2 avoiding gut breakage;
- 3 the adoption of good production practices that include more humane practices throughout the slaughtering system.

The effectiveness of chemical and physical decontamination systems for meat carcasses has been reviewed by James and James, (1997) and James *et al.* (1997). Commercial systems using steam have been introduced into the USA and are claimed to reduce the number of bacteria on the surface of beef carcasses to below $1 \log_{10} cfu cm^{-2}$ (Phebus *et al.*, 1997).

1.1.2 Temperature

Micro-organisms are broadly classified into three arbitrary groups (psychrophiles, mesophiles and thermophiles) according to the range of temperatures within which they may grow. Each group is characterised by three values: the minimum, optimum and maximum temperatures of growth. Reduction in temperature below the optimum causes an increase in generation time, i.e. the time required for a doubling in number. It is an accepted crude approximation that bacterial growth rates can be expected to double with every $10^\circ C$ rise in temperature (Gill, 1986). Below $10^\circ C$, however, this effect is more pronounced and chilled storage life is halved for each 2 – $3^\circ C$ rise in temperature. Thus the generation time for a pseudomonad (a common form of spoilage bacteria) might be 1 h at $20^\circ C$, 2.5 h at $10^\circ C$, 5 h at $5^\circ C$, 8 h at $2^\circ C$ or 11 h at $0^\circ C$. In the usual temperature range for chilled meat, -1.5 – $+5^\circ C$, there can be as much as an eight-fold increase in growth rate between the lower and upper temperature. Storage of chilled meat at $-1.5 \pm 0.5^\circ C$ would attain the maximum storage life without any surface freezing.

Meat stored above its freezing point, $ca. -2^\circ C$, will inevitably be spoiled by bacteria. Obviously, the nearer the storage temperature of meat approaches the optimum for bacterial growth (20 – $40^\circ C$ for most bacteria) the more rapidly the meat will spoil. Work of Ayres (1960) compared the rate of increase in bacterial number on sliced beef stored at 0, 5, 10, 15, 20 and

25°C. The meat developed an off odour by the third day at 20°C, the tenth day at 5°C and the 20th day at 0°C. Similar data has been reported by other workers. They clearly demonstrate the effectiveness of refrigeration in reducing the rate of increase in bacterial numbers and extending shelf-life.

As bacteria generally grow more rapidly than fungi, mould spoilage of meat is thought to develop only when competing bacteria are inhibited. Temperature is usually assumed to be the critical factor, mould spoilage being typically associated with frozen meat. It has been generally accepted that moulds can develop on meat at temperatures as low as -10 or -12°C. There is some evidence that this is an exaggeration and that for practical purposes the minimum temperature for mould growth on meat should be taken to be *ca.* -5°C (Lowry and Gill, 1984). It is further thought that surface desiccation, rather than temperature, is the factor that inhibits bacterial growth. If this is the case then mould growth on frozen meats is indicative of particularly poor temperature control.

Many factors influence the growth and survival of micro-organisms in meat during freezing and frozen storage. However, the main factor affecting the growth of micro-organisms during freezing is the availability of water. Until the temperature is reduced below the minimum temperature for growth, some micro-organisms have the potential to multiply. While most of the water in meat is turned to ice during freezing, there is always some free liquid water available, 26% at -5°C, 18% at -10°C, 14% at -18°C, 10% at -40°C (Rosset, 1982). The transformation of water into ice significantly modifies the growth environment for micro-organisms, since solutes become concentrated in the remaining free water to the level that microbial growth is inhibited. Below the freezing point of the meat, the water activity is progressively reduced preventing microbial growth (Fig.

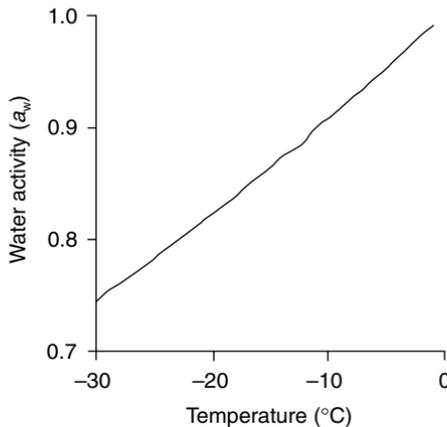


Fig. 1.1 Water activities (a_w) of meat at various sub-freezing temperatures (source: Leistner and Rödel, 1976).

Table 1.1 Minimum and optimum growth temperatures for pathogens associated with red meats

| | Minimum temperature (°C) | Optimum temperature (°C) |
|--|-----------------------------|-----------------------------|
| <i>Campylobacter</i> spp. | 30 | 42–43 |
| <i>Clostridia perfringens</i> | 12 | 43–47 |
| Pathogenic <i>Escherichia coli</i> strains | 7 | 35–40 |
| <i>Salmonella</i> spp. | 5 | 35–43 |
| <i>Listeria monocytogenes</i> | 0 | 30–37 |
| <i>Yersinia enterocolitica</i> | –2 | 28–29 |

Source: Mead and Hinton, 1996.

1.1). The greatest reduction in the microbial load occurs during, or shortly after, freezing itself. During frozen storage, the numbers are gradually reduced further.

1.1.2.1 Pathogenic organisms

A number of bacterial pathogens capable of causing food poisoning in humans are known to contaminate red meat. Those of most importance are *Campylobacter* spp., *Clostridium perfringens*, pathogenic serotypes of *Escherichia coli* (principally *E. coli* O157:H7), *Salmonella* spp. and *Yersinia enterocolitica* (Nottingham, 1982; Anon, 1993; Mead and Hinton, 1996). *Listeria monocytogenes* is commonly associated with meat, but its public health significance in relation to raw meat is unclear (Mead and Hinton, 1996). The essential characteristics of pathogenic micro-organisms can be found in numerous texts.

Minimum and optimum growth temperatures for pathogens commonly associated with red meat are shown in Table 1.1. Some pathogens, such as *L. monocytogenes*, are capable of growth at chill temperatures below 5°C. These are often cited as being of particular concern in relation to refrigerated meats since refrigeration can not be relied on to prevent growth (Doyle, 1987). On the other hand, psychrotrophic pathogens are not particularly heat resistant and adequate cooking should be sufficient to destroy any such pathogens. Illnesses caused by *L. monocytogenes* and *E. coli* are often due to inadequate cooking before ingestion.

1.1.2.2 Spoilage organisms

The number of types of micro-organisms capable of causing food spoilage is very large and it is not possible to discuss them in any detail in this text. Depending on the initial microflora and the growth environment, only a few species of the genera *Pseudomonas*, *Acinetobacter*, *Moraxella*, *Lactobacillus*, *Brochothrix* and *Alteromonas*, and of the family

Enterobacteriaceae are significantly represented in most spoilage microflora of chilled meats (Bell and Gill, 1986).

The micro-organisms that usually spoil meat are psychrotrophs, i.e. they are capable of growth close to 0°C. Only a small proportion of the initial microflora on meat will be psychrotrophs; the majority of micro-organisms present are incapable of growth at low temperatures. As storage temperature rises the number of species capable of growth will increase.

1.1.2.2.1 Spoilage of chilled meat

The spoilage of chilled meat stored in air is dominated by Gram-negative, psychrotrophic, aerobic rod-shaped bacteria. Although a wide range of genera are present on meat, only *Pseudomonas*, *Acinetobacter* and *Psychrobacter* species are normally of importance (Dainty and Mackey, 1992). Of these, species of *Pseudomonas* are of greatest importance (Gill, 1986). *Pseudomonas* spp. typically account for >50% of the flora and sometimes up to 90% (Dainty and Mackey, 1992).

Other bacteria are present in small numbers and may occasionally form a significant part of the microflora. *Brochothrix thermosphacta* appears to be of more importance on pork and lamb than on beef especially on fat where the pH value is generally higher, and at temperatures above 5°C (Gill, 1983; Varnam and Sutherland, 1995).

Species of both *Micrococcus* and *Staphylococcus* are present on meat stored in air but their significance is generally considered limited under refrigerated storage. Psychrotrophic members of the Enterobacteriaceae, including *Serratia liquefaciens*, *Enterobacter agglomerans* and *Hafnia alvei* are also common at low levels (Dainty and Mackey, 1992). These organisms become of greater importance at temperatures of 6–10°C, but *Pseudomonas* spp. usually remain dominant (Varnam and Sutherland, 1995).

Yeasts and moulds are considered by many to be of limited importance in modern practice (Varnam and Sutherland, 1995). Moulds were of historic importance on carcass meat stored for extended periods at temperatures just above freezing.

1.1.2.2.2 Spoilage of chilled packaged meat

Large vacuum packs usually contain *ca.* 1% O₂ that in theory will support the growth of pseudomonads (Varnam and Sutherland, 1995). Continuing respiration, however, by the meat rapidly depletes oxygen (O₂) and increases the carbon dioxide (CO₂) concentration to *ca.* 20%. *Pseudomonas* spp. are usually unable to grow under such conditions. In general conditions vacuum packs favour lactic acid bacteria (LAB), although there may also be significant growth of *Br. thermosphacta*, '*Shewanella putrefaciens*' (formally *Altermonas putrefaciens*) and the Enterobacteriaceae. Under anaerobic conditions LAB have a considerable advantage in growth rate over competing species of facultative anaerobes (Fig. 1.2). The predominant LAB are homofermentative species of *Lactobacillus*, *Carnobacterium* and

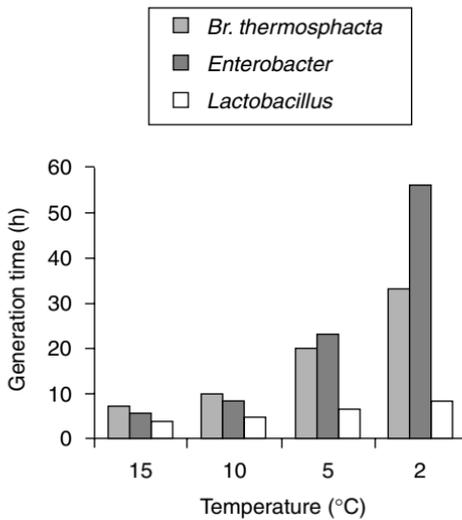


Fig. 1.2 Effect of temperature on the rates of anaerobic growth of bacteria on meat slices (source: Newton and Gill, 1978).

Leuconostoc, *Lactococcus* spp. are much less common. LAB are able to grow at low temperatures and low O_2 tensions and tolerate CO_2 . Psychrophilic species of *Clostridium* have been recognised as a significant potential problem (Varnam and Sutherland, 1995).

Both *Br. thermosphacta* and *Sh. putrefaciens* are favoured by high pH values. *Sh. putrefaciens* is unable to grow below pH 6.0 during storage at low temperatures, whereas *Br. thermosphacta* is unable to grow anaerobically below pH 5.8 (Gill, 1983). At temperatures below 5°C, Enterobacteriaceae are inhibited in vacuum packs by CO_2 , low pH and lactic acid. At higher temperatures and pH values, CO_2 is markedly less inhibitory and growth is possible, in particular by *Serratia liquefaciens* and *Providencia* spp. (Varnam and Sutherland, 1995).

The predominant type of spoilage in vacuum-packed chilled meat is souring (Sofos, 1994; Varnam and Sutherland, 1995). This is not normally detectable until bacterial numbers reach $8 \log_{10} \text{cfu cm}^{-2}$ or greater. The exact cause of such spoilage is unknown, but is assumed to result from lactic acid and other end-products of fermentation by dominant LAB. High-pH (DFD) vacuum-packed meat spoils rapidly and involves the production of large quantities of hydrogen sulphide (H_2S) by *Sh. putrefaciens* and Enterobacteriaceae (Gill, 1982; Varnam and Sutherland, 1995). Characteristic 'greening' occurs owing to H_2S combining with the muscle pigment to give green sulphmyoglobin; the meat also develops putrid spoilage odours (Gill, 1982).

Packaging in various gaseous atmospheres has been used as an alternative to vacuum packing. The intention has been to preserve the fresh meat colour and to prevent anaerobic spoilage by using high concentrations of

oxygen (50–100%) along with 15–50% carbon dioxide to restrict the growth of *Pseudomonas* and related species (Nottingham, 1982). The microflora of meat stored in commercially used modified atmosphere packs (MAP) is in general similar to that of vacuum packs (Varnam and Sutherland, 1995). At temperatures below 2°C, LAB are dominant, *Leuconostoc* spp. being the most important. *Br. thermosphacta*, *Pseudomonas* spp. and Enterobacteriaceae are more prevalent in MAP (modified atmosphere packs) than vacuum packs at storage temperatures *ca.* 5°C, rather than 1°C. *Br. thermosphacta* is relatively CO₂ tolerant and the presence of O₂ permits growth of this bacterium at pH values below 5.8. Prior conditioning in air favours the growth of these bacteria, they are also more prevalent in pork than other meats (Dainty and Mackey, 1992). The spoilage of meat in MAP may involve souring similar to that in vacuum-packed meat. Other characteristics include ‘rancid’ and ‘cheesy’ odours. Chemical rancidity does not appear to be primarily involved and souring is probably caused by the metabolites of LAB or *Br. thermosphacta* (Varnam and Sutherland, 1995).

1.1.2.2.3 Spoilage of frozen meat

Micro-organisms do not grow below *ca.* –10°C, thus spoilage is only normally relevant to handling before freezing or during thawing. In these contexts, frozen meats behave like their unfrozen counterparts, although growth rates may be faster after thawing, owing to drip.

Although *Salmonella*, *Staphylococci*, and other potential pathogens can survive freezing and frozen storage, the saprophytic flora (spoilage bacteria) tend to inhibit their growth (Varnam and Sutherland, 1995). During freezing and thawing of food, the temperature favours the growth of psychrophilic organisms, most of which are spoilage organisms. Hence, in nearly all cases, if a frozen product is mishandled, spoilage is apparent before the food becomes a health hazard.

In the past, carcass meats were imported at temperatures of –5 to –10°C. At these temperatures there were problems with the growth of psychrotrophic moulds such as strains of *Cladosporium*, *Geotrichum*, *Mucor*, *Penicillium*, *Rhizopus* and *Thamnidium*, causing ‘whiskers’ or ‘spots’ of various colours depending on the species. Since little meat is now stored at these temperatures mould spoilage is largely of historic importance. Despite this, many meat microbiology textbooks continue to discuss this subject in great detail.

1.1.3 Relative humidity

Historically low relative humidities (RH) have been recommended to extend shelf-life. Schmid (1931) recommended a storage temperature for meat of 0°C and an RH of 90%. Haines and Smith (1933) later demonstrated that lowering the RH is more effective in controlling bacterial growth on fatty or connective tissue than on lean meat. This was due to a slower rate of diffusion of water to the surface. Low RH was more

effective, therefore, in reducing microbial spoilage of carcass meat than of small lean joints.

Micro-organisms normally grow in foods in the equivalent of a nutrient solution and the availability of water in this solution is one of the factors normally controlling growth. The term used for physiologically available water is 'water activity' (a_w). By definition

$$a_w = P/P_0$$

Where P and P_0 are the vapour pressures of the solution and of the pure solvent, respectively. The above equation also defines the relative humidity (RH) of the vapour phase in equilibrium with the solution. The RH (%) of an atmosphere in equilibrium with a food would be 100 times the a_w of the food.

If the RH of the atmosphere corresponds to an a_w lower than that of meat then the meat surface will lose water to the atmosphere and the a_w will fall. In practice, the a_w of the surface of meat will not fall to the corresponding RH value of the atmosphere, because water lost from the surface is partially replaced by diffusion of water from the interior. However, the basis of the efficacy of low relative humidities in extending shelf-life is the reduction of the a_w of the meat surface to a level inhibiting the growth of psychrophilic bacteria.

The a_w of lean meat is of the order of 0.993 (Scott, 1936) and offers ideal growth conditions for micro-organisms. Scott (1936) and Scott and Vickery (1939) established that the important meat spoilage bacteria are unable to grow on meat at temperatures below 4°C if the a_w is less than 0.96. This occurs when the water content has fallen from about 300 to about 85 g of water/100 g of dry matter. They recommended that in chilled storage the maximum values of the mean RH at air speeds of 0.15, 0.45, 0.70 and 0.90 m s⁻¹ should be approximately 72, 85, 88 and 90%, respectively. These conditions would maintain the water content at the surface of the meat at or near inhibitory levels for bacteria. If conditions during the cooling stage were unsatisfactory, they recommended that for any given air speed the relative humidity would need to be lower to prevent bacterial growth.

These recommendations were made for long-term storage during shipment from Australia to the UK. Higher relative humidities may be used if only short-term storage is the aim. This work remains the basis for the usual recommendation to operate meat chillers between 85–95%. The actual RH used will depend, of course, upon the air speed, the type of meat, the length of storage required and the temperature of storage.

1.2 Other considerations

Legislation and recommendations for cooling of meat are believed to be based on clear microbiological criteria. However, there are a lack of data

to support recommendations on the avoidance of bone taint, and on chilling rates for hot and cold boning.

1.2.1 Bone taint

It has been said (Moran and Smith, 1929) that 'possibly the strongest argument for the rapid cooling of beef immediately after death is that it reduces the possibility of bone taint'. Twenty years earlier in the USA, Richardson and Scherubel (1909) had concluded that, to control the condition, the carcass should be cooled to 4°C or below at the centre of the round (hindquarter) within 48 h of slaughter.

Bone taint has long been regarded as evidence for the presence of intrinsic bacteria. This view is diminishing, but the exact nature of what constitutes bone taint remains undefined (Nottingham, 1982; Shaw *et al.*, 1986). A wide range of bacteria has been implicated in the past. Varnam and Sutherland (1995) in their book on meat report that halophilic *Vibrio* species and *Providencia* are now most commonly attributed to this condition, while work by De Lacy *et al.* (1998) demonstrated that some strains of psychrotrophic *Clostridium* spp. have the potential to cause bone taint.

Bone taint in beef is usually localised in the region of the hip joint and is manifested by a 'typical sewage type odour' or 'putrefactive sulphide-type odours'. This is referred to as 'souring' in the American literature, which is only detected when the hindquarter is divided (Thornton, 1951). Taints in pork products appear to differ from bone taint in beef, occurring most often after processing into cured hams or gammons (Jensen and Hess, 1941; Haines, 1941).

The aetiology of bone taint remains obscure. The bacteria associated with bone taint are supposed to have their origin in the bloodstream at death and the infection starts in the blood vessels of the marrow of the femur (Callow and Ingram, 1955). How they get into the blood supply is not established. One possibility is that unusually large numbers of bacteria are introduced at slaughter, for example, by the use of slaughter instruments contaminated with faeces (Jensen and Hess, 1941; Mackey and Derrick, 1979). Such massive contamination might be sufficient to overwhelm the immune system leading to survival of a few cells (Gill and Penney, 1979). Alternatively, bacteria may originate from undetected infection, for example of joints. The lymph nodes have also been implicated as centres of infection (Lepovetsky *et al.*, 1953; Cosnett *et al.*, 1956; Nottingham, 1960).

Surprisingly, in view of the early recognition of the importance of temperature, there are apparently no definitive data on the cooling rate required to assure freedom from bone taint in the various species of meat animal. In all examples studied in cattle and sheep (i.e. ruminants) it is agreed that bone taint will only manifest itself if cooling of the carcass post-mortem is insufficiently rapid (Kitchell, 1972). Some conditions under which bone taint has occurred are given in Table 1.2. With pigs, on the other

Table 1.2 Cooling conditions under which bone-taint in beef has been reported

| Reference | Deep muscle temperature (°C) | Time post-mortem (h) |
|------------------------------|---------------------------------|-------------------------|
| Moran and Smith (1929) | 22 17 | 24 48 |
| Haines and Scott (1940) | >18 | 40 or longer |
| De Lacy <i>et al.</i> (1998) | 20 | 20 |

hand, Jensen and Hess (1941) reported that, even under optimum cooling conditions, 6–7.5% of several thousand hams exhibited various forms of ‘souring’. Unfortunately, the cooling data furnished in support of this statement include no temperatures measured at the hip joint.

From time to time bone taint of carcasses is still reported within the industry. The rarity of bone taint may reflect a requirement for coincident circumstances, each of which is uncommon. Microbial survival and growth would be favoured by very high levels of contamination, possible weakening of the antimicrobial defences (as can occur in haemorrhagic shock), high muscle pH and slow cooling. To allow for the infrequent occurrence of bacteria in deep tissues it is thus prudent to cool carcasses promptly after slaughter. The temperature of the deep leg should be brought below 15°C within 24 h.

1.2.2 Cold deboning

Council Directives of the EU (Council Directive No. 64/433/ECC, 1964; Council Directive No. 83/90/ECC, 1983) stipulate that carcass meat must be chilled immediately after post-mortem inspection. Chilling must continue to an internal temperature of 7°C before cutting or transportation can take place. This requirement, aimed at preventing growth of salmonellas, has caused problems in the meat industry. To allow deboning 24 h post-mortem, the outer portions of the carcass may have to be cooled at a rate causing toughening due to ‘cold shortening’ and surface fat may become very hard and difficult to handle. The 1964 Council Directive also stipulated a maximum cutting room temperature of 10°C, which was increased to 12°C in the 1983 amendments to that Directive.

To judge the need for such a stringent regulation the effect of temperature on the growth of salmonellas on meat has been defined. Mackey *et al.* (1980) used observed generation times of salmonellas on beef surfaces maintained at high RH values to calculate the maximum extent of growth during storage for different times at temperatures between 10 and 15°C. Smith (1985) produced tables of lag and generation times which can be used to determine the length of time raw chilled meat can be held at temperatures between 10 and 40°C without an increase in salmonella numbers.

Because of their studies, Mackey *et al.* (1980) concluded that under practical conditions of cutting and packaging that takes only 2–3 h, a meat temperature of 10°C would be entirely adequate to ensure no significant multiplication of salmonella. Smith (1985) concluded that cutting rooms could be maintained above 10°C provided carcasses are processed promptly and meat is not allowed to accumulate in the cutting room.

1.2.3 Hot deboning

Hot deboning has received much attention in recent years because of its potential to streamline butchery, packaging and chilling. As the name implies the carcass is deboned while hot and the meat is chilled in vacuum packs or cartons. In principle, this could increase the risk of microbial growth because there is no surface drying, and some contaminated surfaces are deep in the meat where they will cool more slowly.

The possible microbiological effects of hot deboning have been investigated either by monitoring growth following natural contamination or by prediction of growth based on data obtained following inoculation. Natural contamination experiments have shown that it is possible to produce hot deboned meat of the same microbiological quality as cold deboned meat in terms of total counts and numbers of mesophilic pathogenic bacteria (Taylor *et al.*, 1980). Based on natural contamination experiments, Fung *et al.* (1981) recommended chilling to 21°C within 3–9 h after packaging with continuous chilling to below 10°C within 24 h. The validity of using natural contamination to monitor the growth of pathogens on hot deboned meat has, however, been questioned (Grau, 1983) because initial numbers are very low, often undetectable, and heterogeneous in distribution. As an alternative, prediction of growth at different cooling rates can be calculated from an equation derived from observations on the growth of the organism on meat following inoculation (Herbert and Smith, 1980). Cooling rates recommended on this basis are more rapid (e.g. cool to 8°C from an initial 30°C within 6 h of the commencement of boning) than those based on natural contamination experiments.

Microbiologists have yet to agree whether the observational (natural contamination) or predictive approach is more appropriate in defining the effect of different cooling rates on the extent of microbial growth. Prediction using mathematical models based on data from inoculation experiments avoids the need to perform time-consuming tests on each cooling rate in question. In some instances, where factors affecting growth are fully understood, it may even be possible to predict growth with reasonable precision from growth rate data obtained in laboratory media, as demonstrated by Gill (1984) for *E. coli* in tub-packed livers. The accuracy of all predictive models must, however, be confirmed as far as is possible by comparison with observed growth at a selection of cooling rates following natural contamination, as performed by Gill (1984).

1.3 Conclusions

- 1 The muscle tissue of live, healthy animals is sterile. The source of microbial contamination is usually the hide and to a lesser extent the gut and occurs during slaughter and handling. Post-process handling is the usual source of microbial contamination on cooked products, provided adequate processing has taken place.
- 2 The rate of spoilage depends upon the numbers and types of organisms initially present, the conditions of storage (temperature and gaseous atmosphere) and characteristics (pH, a_w) of the meat.
- 3 Spoilage is characterised by off-odours, slime formation and discolouration. The pattern of spoilage is defined by the type of micro-organisms present. The dominance and thus type of spoilage is dependent on the storage conditions.
- 4 Those bacteria responsible for the spoilage of carcass meat grow most rapidly above 20 °C. Any reduction below this temperature will extend the storage life. Broadly speaking bacterial growth will be half as fast at 5 °C as at 10 °C and half as fast again at 0 °C, i.e. meat should keep roughly four times longer at 0 °C than at 10 °C.
- 5 The precise reasons for bone taint are still not fully understood. However, the carcass should be chilled as rapidly as possible to an internal temperature below 15 °C and, finally, to below 5 °C within 48 h if the condition is to be avoided.
- 6 In evaluating the microbiological consequences of hot deboning there is a disconcerting difference between recommended 'safe' cooling rates proposed from experiments using naturally contaminated meat and those using artificially inoculated meat.

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2

Drip production in meat refrigeration

The quality of fresh meat exposed for retail sale is initially judged on its appearance. The presence of exudate or 'drip', which accumulates in the container of prepackaged meat or in trays or dishes of unwrapped meat, substantially reduces its sales appeal (Malton and James, 1983). Drip can be referred to by a number of different names including 'purge loss', 'press loss' and 'thaw loss' depending on the method of measurement and when it is measured.

In general, beef tends to lose proportionately more drip than pork or lamb. Since most of the exudate comes from the cut ends of muscle fibres, small pieces of meat drip more than large intact carcasses. The protein concentration of drip is about 140mgml^{-1} , about 70% of that of meat itself. The proteins in drip are the intracellular, soluble proteins of the muscle cells. The red colour is due to the protein myoglobin, the main pigment of meat.

The problem of drip loss is not however confined to retail packs. The meat industry uses large boneless primal cuts, which are packed in plastic bags, for distribution throughout the trade. These may be stored under refrigeration for many weeks before use and during this time a considerable volume of drip may accumulate in the bag. Not only does this exudate look unattractive, but it also represents an appreciable weight loss to the user when the meat is subsequently removed from its container.

Excessive drip could have a small effect on the eating quality of meat. Perceived juiciness is one of the important sensory attributes of meat. Dryness is associated with a decrease in the other palatability attributes, especially with lack of flavour and increased toughness (Pearson, 1994). However, moisture losses during cooking are typically an order of

magnitude higher than most drip losses during refrigeration. Consequently, small differences in drip loss will have little effect on eating quality.

The potential for drip loss is inherent in fresh meat and is influenced by many factors. These may include breed, diet and physiological history, all of which affect the condition of the animal before it is slaughtered. After slaughter, factors such as the rate of chilling, storage temperatures, freezing and thawing can all influence the drip produced.

The mechanism of drip formation has been well described by Taylor (1972), Bendall (1974) and Penny (1974) and form the basis of this chapter. To understand how drip occurs, it is useful to have a basic understanding of the biochemistry of meat. This includes the structure of muscle, the changes that take place after death and where water is held in the muscle. The factors affecting drip production through the refrigerated cold chain can then be quantified.

2.1 Biochemistry of meat

2.1.1 Structure of muscle

The structure of muscle has been well described by Voyle (1974) and forms the basis of this section. Meat consists mainly of skeletal muscles which all have a similar structure. Figures 2.1–2.4 show in diagrammatic form the levels of organisation of the components which together form a muscle. The gross levels of organisation can be resolved with the unaided eye, and it may be observed that each muscle is separated from its neighbour by a sheet of white connective tissue – the fascia. This gives support to the functional components of the muscle and connects it to the skeleton through tendinous insertions. The connective tissue consists mainly of collagen and in some muscles includes elastic fibres.

In cross-section (Fig. 2.1) a muscle appears to be subdivided into tissue bundles surrounded by thin layers of connective tissues. These bundles consist of a number of very long, multinucleated cells or fibres each surrounded by a thin layer of connective tissue. Each fibre is about as thick as a hair of a young child and may be several centimetres in length. Fibres are normally elliptical in cross-section and have blunt tapered ends (Fig. 2.2). Fibre thickness varies between muscles within an animal as well as between species. It is also dependent on age, sex and nutritional status. As an example, the fibres of the eye muscle (*M. longissimus dorsi*) of an 18-month-old steer are about 40 μm in diameter.

Each fibre is surrounded by a typical lipoprotein membrane, the sarcolemma, which in its native state is highly selective in its permeability to solutes. The space within the sarcolemma is mostly occupied by smaller longitudinal elements, or myofibrils, each about 1 μm in diameter. Figure 2.3 shows part of a single myofibril in longitudinal section. Figure 2.4 repre-

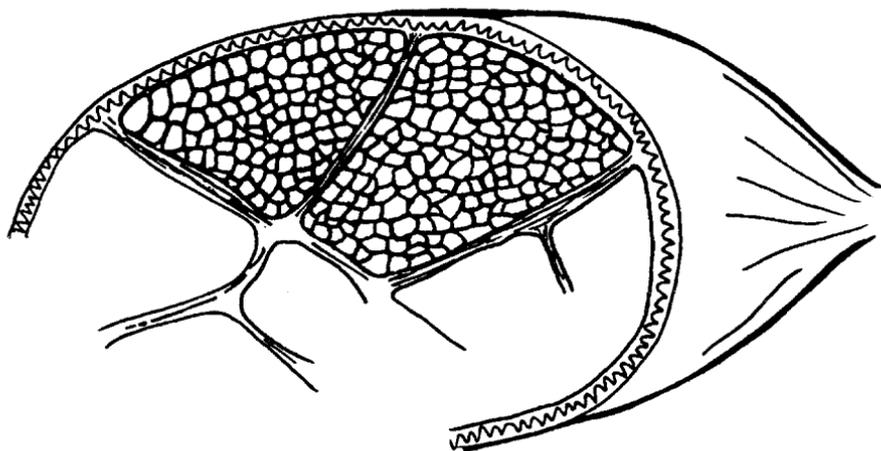


Fig. 2.1 Diagrammatic representation of cut surface of muscle to show bundles of fibres (source: Voyle, 1974).



Fig. 2.2 Single muscle fibre. Diagrammatic representation of morphology as seen by direct microscopy (source: Voyle, 1974).

sents a single muscle fibre in cross-section, showing myofibrils and associated structures that are referred to below.

Each myofibril is enwrapped in a thin vesicular structure the sarcoplasmic reticulum, which is involved in the transmission of the nervous impulse to the contractile elements. The characteristic striated appearance of each muscle fibre, represented in Fig. 2.2, may be observed by direct microscopy. The finer details of structure, represented in Figs 2.3–2.4, can only be resolved by electron microscopy.

Between the myofibrils are small particles, the mitochondria, which provide the energy for contraction via oxidative processes. The myofibrils are bathed in a fluid, the sarcoplasm, which contains many soluble enzymes. These are mostly concerned with the process of glycolysis by which lactic acid is produced in the oxygen-free post-mortem muscle. The myofibrils occupy about 74% of the total fibre volume.

The myofibrils are packed with contractile microfilaments of actin and myosin which, in cross-section, may be seen to be arranged in a hexagonal lattice. The interdigitating sliding action of these filaments when stimulated to contract is suggested by the longitudinal view represented in Fig. 2.3. A fibril contains about 16% contractile protein and about 84% water in which are dissolved small solutes such as adenosine triphosphate (ATP),

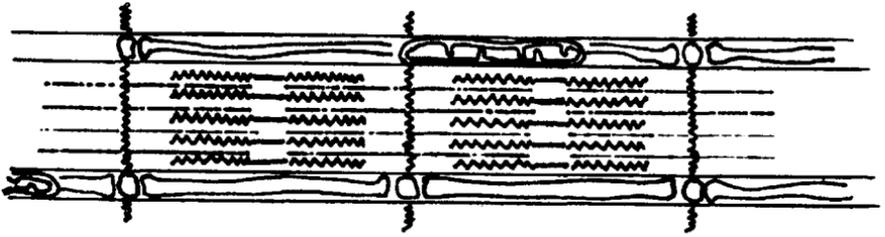


Fig. 2.3 Part of myofibril. Diagrammatic representation to show filament-array in longitudinal section with adjacent structures (source: Voyle, 1974).

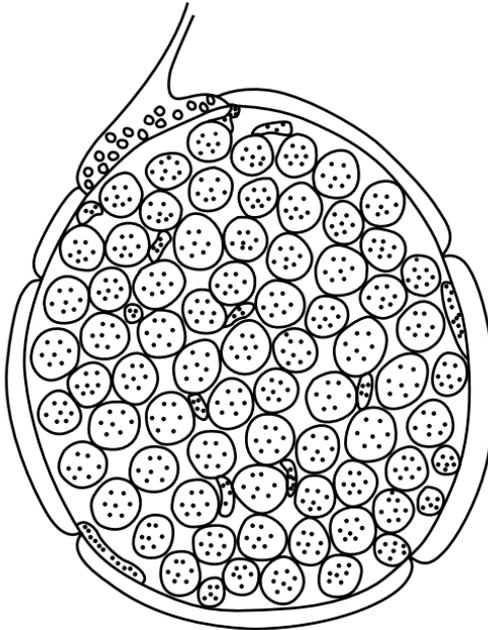


Fig. 2.4 Cross-section of single fibre, showing myofibrils and other structures (source: Voyle, 1974).

the fuel for contraction, but from which the larger enzyme molecules are excluded.

The fluid within the fibrils is distributed between the microfilaments of the hexagonal lattice. After rigor in a muscle at rest length the filament lattice volume decreases and releases fluid into the spaces between the myofibrils, i.e. into the sarcoplasm. The permeability of the sarcolemma also changes after rigor, and fluid, generally referred to as 'drip', escapes into the extracellular space. The extent to which this happens depends upon the ultimate level of pH attained by the post-rigor muscle.

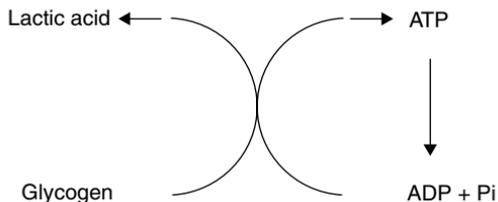


Fig. 2.5 Reaction of ATP in muscle (source: Bendall, 1972).

2.1.2 Changes after slaughter

Muscles of freshly killed mammals are relaxed, soft, extensible and flexible. However, after a short time they become stiff, rigid and contracted. This state is called rigor mortis.

Muscles obtain the energy they need for contraction by taking up glucose from the blood and storing it in a polymeric form called glycogen. The chemical fuel the muscle cells use is adenosine triphosphate (ATP), which as well as providing the energy required to shorten muscle fibres, acts as a lubricant during contraction preventing cross-linking. Muscles power contraction by hydrolysing this ATP to the diphosphate (ADP) and inorganic phosphate (Pi) but there is only enough ATP in muscle cells to fuel a contraction for three seconds. For a sustained contraction, the ATP has to be resynthesised from ADP and Pi by coupling this energetically unfavourable reaction to the energetically favourable breakdown of glycogen to lactic acid (Fig. 2.5).

In muscle after death, the rate of breakdown of ATP is low but still appreciable and the muscle draws slowly on its glycogen stores. These are not replenished because there is no longer a blood supply. The lactic acid accumulates and the pH falls from an initial value of about 7 to a final value of about 5.5 to 6.0.

When the breakdown of glycogen comes to a halt, the ATP concentration falls to zero and the force-generating machinery of the muscle stops in mid-cycle causing the muscle to become rigid and inextensible. It is then said to be in the state of rigor mortis (rigor for short).

The most important structural change in muscle tissue during the onset of rigor is the formation of actomyosin complex caused by the cross-linking of actin and myosin filaments and muscle contraction brought about by the breakdown of ATP. Breakdown of ATP also contributes to the temperature rise (0.2–2.0°C) which is sometimes observed in the deep musculature of pigs and beef animals during the first hour or so after slaughter, as described by Bendall (1972) and measured by Morley in 1974.

Normal rigor sets in before glycolysis ends, i.e. before reaching the final pH value. The time that rigor takes to develop (Table 2.1) is dependent on muscle type, its posture on the carcass, rate of cooling and so on (Offer *et al.*, 1988). Temperature is particularly significant. Between 10 and 37°C

Table 2.1 Typical time for rigor onset

| Type of meat | Development time for rigor (h) | Range (h) |
|--------------|--------------------------------|-----------|
| Beef | 18 | 8–30 |
| Lamb | 12 | 10–20 |
| Pork | 3 | 0.6–8 |

Source: Offer *et al.*, 1988.

the rate of rigor development increases with temperature, like many other metabolic processes. The rate increases three to four times for each 10°C rise in this range.

As a result of this fall in pH a number of enzymes change their activity. Some lose it by changing their three-dimensional structure and some enhance their activity, i.e. especially liposomal enzymes which are necessary for the conditioning process (Honikel, 1990). In the course of the breakdown of energy-rich compounds (shortly before they get used up) the onset of rigor occurs which increases the rigidity of the meat, i.e. the meat toughens. Conditioning reduces the toughness as the number of rigid longitudinal and transversal cross-links in the myofibres are reduced by enzymic action (Honikel, 1990).

The conditions for the onset and development of rigor have a profound influence on the tenderness, juiciness and water-holding capacity of meats. While factors such as species, breed, age, nature of muscle, ante- and post-mortem treatments, and so on all have an influence, temperature is probably the most important.

Conditions of exhaustion or stress before slaughter can cause changes in the degree of glycolysis producing detrimental effects to the meat. Animals subjected to severe exhaustion shortly before slaughter use up their glycogen reserves thus less lactic acid is formed producing high pH (6.0–6.5) dark meat, often described as dark, firm and dry (DFD) meat. DFD problems can occur in pork, mutton, veal and beef. By convention all pork above pH 6.0/6.2 is classified as DFD meat (Honikel, 1990). Drip losses from DFD meat are less than from normal meat (Offer *et al.*, 1988).

A second cause of shrinkage is protein denaturation. In life, muscle proteins are stable for many days at 37°C and pH 7. However, after death the musculature, especially in the interior of the carcass, cools relatively slowly and becomes acidic. Under this combination of high temperature and low pH, some proteins especially myosin, the principal protein of muscle, slowly denature. If sufficient myosin is denatured, the myofibrils shrink about twice as much as usual and the meat is pale, soft and exudes drip more quickly and in greater amounts than usual. Consumers react unfavourably against the unattractive paleness of this pale, soft and exuding (PSE) meat.

With beef and lamb, provided the chilling regime is adequate, only a little myosin denaturation occurs probably because the carcass is chilled sufficiently before a low pH is reached. PSE meat is therefore not usually a problem with these species, except sometimes in the deep muscle if the carcass has been chilled slowly (Offer *et al.*, 1988).

With pork, however, the pH fall is faster, especially in carcasses of stress-susceptible animals. In these carcasses, the pH falls to below 6.0 within 45 min of slaughter when the carcass temperature is above 35°C. Myosin denaturation may then be extensive and pig carcasses are vulnerable to the PSE state. As well as stress, this condition may be genetically predetermined (Honikel, 1990).

PSE is not an all-or-none phenomenon and the drip loss depends on the extent of myosin denaturation. The drip loss can therefore be controlled to some extent by the chilling regime. Frozen PSE meat exhibits excessive drip loss on thawing (Honikel, 1990).

2.1.3 Water relationships in meat

In living muscle, 85–95% of the total water is held within the fibres in dynamic equilibrium with the remaining 5–15% (plasma water) outside the fibre walls. Within the fibre, the water is held both by the contractile, myofibrillar, filament proteins, myosin and actin, and by the soluble, sarcoplasmic proteins which include myoglobin and the glycolytic enzymes. The water balance is such that it allows movement of the proteins within the fibre and exchange of metabolites in and out of the fibre, without altering the overall amount of water held. Therefore, when a force is applied to a pre-rigor muscle, excised immediately after the death of an animal, very little fluid can be squeezed out. The distribution of space in muscle is shown in Table 2.2.

Calculations can be made of the diameters of the capillary-like spaces between the filaments of the myofibril and between sarcoplasmic proteins from which the number of water molecules between nearest-neighbour structures can be deduced. The results are shown in Table 2.3.

Table 2.2 Approximate distribution of the spaces in excised muscle

| Structure | Volume as % total vol. | |
|----------------------|------------------------|--------------------|
| | pre-rigor | post-rigor |
| Extrafibre space | <12 | 100 |
| Intrafibre space | 88–95 | |
| Extrafibrillar space | 22–24 | 30–32.5 |
| Intrafibrillar space | 66–71 | 58–62 ^a |

^a Assuming a 12% reduction in filament lattice volume post rigor.
Source: Penny, 1974.

Table 2.3 Diameters of the 'cylindrical' capillary spaces between nearest-neighbour elements of the fibre and the number of water molecules accommodated between surfaces of nearest-neighbour protein molecules

| Elements | Diameter of capillary (nm) | Number of molecules of water |
|------------------------------------|----------------------------|------------------------------|
| Actin-myosin overlap | 21.5 | 42 |
| Myosin-myosin (H-zone) | 38.4 | 120 |
| Actin-actin (I-zone) | 45.3 | 67 |
| Sarcoplasmic proteins ^a | 15.3 | 30 |

^a Assuming the average molecular weight (MW) = 120 000 Da and a mean diameter of 6.52 nm.

Source: Penny, 1974.

These show the capillary spaces between the elements are very small so that it seems reasonable that much of the water would be held by surface tension forces. In addition, quite a large proportion of the water should be immobilised by surface charges on the proteins.

When a muscle goes into rigor a number of important changes take place, which affect the water balance. As a result of the loss of ATP, the actin and myosin filaments become bonded together and tend to squeeze water out of the filament lattice into the sarcoplasmic space, and possibly also into the spaces between fibres. This squeezing effect is increased as the pH falls from 7.2 in pre-rigor muscle to 5.5–5.8 in post-rigor muscle. This is because the proteins are then much nearer the mean isoelectric point of 5.0–5.2 at which their hydration is at a minimum and their packing density maximal (Rome, 1968). This, no doubt, explains Hegarty's (1969) finding that muscle fibre diameter decreases during rigor, which also suggests that the fibre wall has become leaky and allowed fluid to escape. Table 2.2 gives the approximate change in the distribution of space which would occur if the myofibrillar lattice volume was reduced by 12% (Rome, 1968).

The loss of water binding by the proteins also depends on the amount of denaturation that has taken place in the post-mortem period. Denaturation is an irreversible alteration to the structure and properties of the proteins. Denaturation leads to extra loss of water binding and to closer packing of the fibrillar proteins. It is a function of the post-mortem rate of cooling and the rate of pH fall, and increases dramatically at low rates of cooling and high rates of pH fall.

As a result of all these post-mortem changes, a considerable amount of previously immobilised water is released by the proteins and redistributed from filament spaces to sarcoplasmic spaces within the fibres, and also into the spaces outside the fibres. This released water makes up most of the fluid (drip) which can then be squeezed out of the meat.

2.1.4 Ice formation in muscle tissues

In general, freezing and thawing exacerbate drip loss through damage of the muscle structure. It is necessary to differentiate between the effects of freezing in pre-rigor and post-rigor muscle. For most practical purposes, meat is in the latter condition but there has been considerable interest in the rapid freezing of 'hot', i.e. pre-rigor meat.

2.1.4.1 Pre-rigor muscle

The freezing of meat immediately after slaughter appears at first sight to be an excellent method of overcoming many of the chilling, hygiene and storage problems of conventional production methods. However, there are two problems, 'cold shortening' and 'thaw rigor', that result in very tough meat and that have to be overcome to make such a process viable. Thaw rigor, or 'thaw contractor' as it is sometimes called, also significantly increases drip loss after thawing.

If the meat temperature falls below 10°C before the supply of fuel for contraction, i.e. ATP, is used up, but freezing has not occurred, the muscle will contract. This phenomenon called 'cold shortening' was first described by Locker and Haggard (1963) and is discussed in Chapter 3 of this book. The protein denaturation that results from cold shortening produces a large amount of drip (Offer *et al.*, 1988).

If very high rates of heat extraction can be achieved, then the meat can be frozen fast enough to stop cold shortening. However, in this case, a more severe shortening, thaw rigor, will occur during thawing. In unrestrained muscle up to 25% of the muscle weight will be lost in the form of drip during thawing (Bendall, 1974). Bendall stated that the problems associated with thaw rigor could be overcome by holding the frozen meat at -3 to -5°C for at least 48h. However, such a process is not used commercially.

2.1.4.2 Post-rigor muscle

Chemical changes after slaughter cause the acidity of the tissue to increase and the pH falls to a level which is normally in the range of 5.5-5.7. This compares with a pH of about 7.0-7.2 in the living tissue. One of the consequences of this fall in pH is a change in the permeability of the sarcolemma which now permits sarcoplasmic proteins and water to pass more readily out of the cell (Voyle, 1974). When the tissue is slowly cooled below its freezing point, this protein-containing fluid is extracted from the cell to contribute to the growth of extracellular ice crystals. Loss of fluid from the cell results in an increase in the intracellular salt concentration. This in turn causes some denaturation of those proteins remaining within the cell. A more rapid rate of freezing will cause the intracellular water, including that in the actin-myosin lattice, to crystallise.

2.2 Measurement of drip

Many methods have been used to measure drip loss from meat. Data obtained using different methods can be used to determine trends but the values obtained are not directly comparable.

The most important factor that affects the measurement of drip is the ratio of cut surface to weight or volume. It is clear that the free water has to move to the surface before it can drip from the meat and therefore the more cut surface to volume there is, the less distance the water has to travel. In 1956, Howard and Lawrie reported that drip from beef quarters, domestic joints and small samples in the laboratory ranged from 0.3 to 1, 1.2 to 2, and 4 to 10% of weight, respectively. Howard (1956) showed that pieces with the same cross-section but 1 and 3 cm thick lost 8 and 6% as drip, respectively. The drip is also reduced if the pieces are cut along the direction of the fibres rather than across it. Pressure applied to slices or blocks of meat increases the amount of drip and so does an absorbent material placed on the cut surfaces because of the increase in hydrostatic pressure.

It is therefore important that an appropriate method is used in order to obtain data that are directly applicable to a commercial situation. Weighing unwrapped samples of meat provides information on total weight loss. However, some of the loss is due to evaporation from the surface, not drip. One simple method is to hang the preweighed meat, using a nylon mesh to support it. A polythene bag is then placed round the sample but not in contact with it to prevent evaporation. The system is then kept in a controlled environment and the sample reweighed after a set time.

For experimental purposes more information and better reproducibility can usually be obtained from methods where force is applied rather than the simple method of measuring 'free' drip (Penny, 1974). These include the press method of Grau and Hamm (1953) or methods depending on centrifugation.

2.3 Factors affecting the amount of drip

Some factors that affect the amount of drip are inherent in the animal and include the breed of the animal and the position of the meat within the animal. Treatment of the animal before slaughter, especially in the case of pork, can influence drip production by producing DFD or PSE meat. The conditions in and the length of the refrigerated cold chain will further influence the resulting drip.

2.3.1 Animal factors

2.3.1.1 Breed

In pigs especially, there are large differences in drip loss from meat from different breeds. Taylor (1972) measured drip loss from leg joints from four

Table 2.4 Drip loss after two days storage at 0°C from leg joints from different breeds of pig cooled at different rates

| Breed | Drip loss (% by wt.) | |
|----------------------|----------------------|-------|
| | Slow | Quick |
| Landrace | 0.47 | 0.24 |
| Large White | 0.73 | 0.42 |
| Wessex X Large White | 0.97 | 0.61 |
| Pietrain | 1.14 | 0.62 |

Source: Taylor, 1972.

Table 2.5 Drip loss after 2 days storage at 0°C from four muscles from two breeds cooled at different rates

| Cooling rate | Drip (as % muscle weight) | | | | | Combined (four muscles) |
|-------------------------|---------------------------|------------------|----------|----------------|------|-------------------------|
| | Semi-tendinosus | Semi-membranosus | Adductor | Biceps femoris | | |
| Pietrain (13 pigs) | Quick | 2.82 | 4.40 | 5.52 | 2.69 | 3.86 |
| | Slow | 3.99 | 6.47 | 6.61 | 4.11 | 5.30 |
| Large White (6 pigs) | Quick | 1.69 | 2.01 | 2.92 | 1.04 | 1.92 |
| | Slow | 1.95 | 3.50 | 5.07 | 2.32 | 3.21 |

Source: Taylor, 1972.

different breeds subjected to two different chilling regimes. Drip loss was estimated by suspending pieces of meat in sealed polythene bags and weighing the amount of free liquid that accumulated in the bag during storage at 0°C. Since most of the drip was lost during the first two days of storage, drip was always expressed as the weight of exudate after 2 days at 0°C. Analysis of the mean values for each breed (Table 2.4) showed that there was a substantial difference, up to 2.5-fold, in drip loss between breeds.

In a further comparison, four major leg muscles were excised 24h post-slaughter from sides of Large White and Pietrain pigs. The average levels of drip loss from the four muscles varied by 1.65-fold for slow cooled and just over two-fold for the quick cooled between the breeds (Table 2.5).

The rate of pH fall after slaughter was shown to be a major factor where pig meat was concerned. Pigs with pH values below 6.1 (30 min after slaughter) tended to give meat with high drip loss, while values above 6.1 were associated with low loss. The incidence of rapid pH change varies to some extent with breed and the excessive drip from the Pietrain samples was

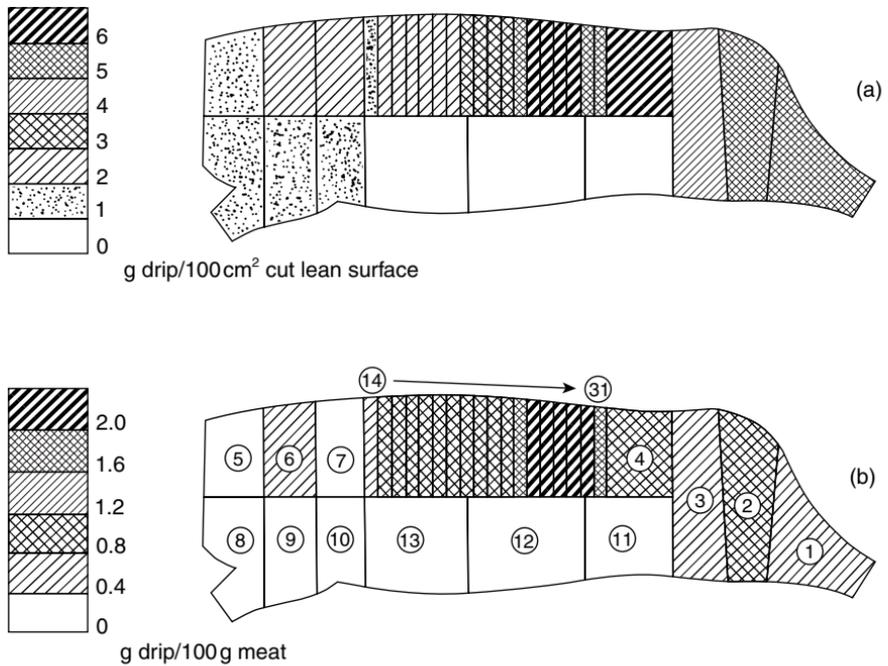


Fig. 2.6 Distribution of drip in pig carcasses expressed on basis of (a) area of cut lean surface and (b) of weight of joint. Numbers refer to standard jointing system (source: Taylor, 1972).

undoubtedly a consequence of their rapid pH fall (Lister, 1970; MacDougall and Disney, 1967). The average pH_{30} for Pietrains in the experiment comparing drip from muscles was 6.04 (range 6.80–5.60), while that for Large Whites was 6.52 (range 6.75–6.35).

The range of ultimate pH in these experiments was very narrow (5.5–5.7), a result of using animals which had been well rested overnight before slaughter. It is only when pre-slaughter conditions cause an abnormally high ultimate pH, that the water-holding capacity of the meat is markedly improved and drip reduced.

2.3.1.2 Muscle type

Different muscle groups show different degrees of drip. Taylor (1972) showed there to be a significant anatomical distribution of drip loss in pig carcasses that was not changed by either breed, carcass weight or rate of cooling. This general pattern is illustrated in Fig. 2.6. Three breeds of pig, Large White, Landrace and Pietrain were used, with carcass weights ranging from 40 to 60 kg. Twenty-two sides were chilled at a variety of cooling rates until carcass temperature was uniformly at 0°C after 24 h. The cooled sides were then jointed in a chill room at 0°C and drip estimations carried out using the method detailed in the previous section.

Table 2.6 Drip loss from wholesale groups of joints, after 2 days at 0°C

| Joint | Joint weight (kg) | % of carcass weight | Drip loss from joint (g) | g drip/100 g |
|------------|-------------------|---------------------|--------------------------|--------------|
| Leg | 5.608 | 24.8 | 43.4 | 0.77 |
| Loin | 6.500 | 28.7 | 82.0 | 1.26 |
| Fore-end | 7.044 | 31.1 | 21.8 | 0.31 |
| Belly | 3.482 | 15.4 | 2.1 | 0.06 |
| Side total | 22.634 | — | 149.3 | 0.66 |

Source: Taylor, 1972.

The joints with the greatest drip loss were the commercially valuable chops, chump and leg joints. Table 2.6 shows that 84% of the gross drip loss came from these joints which made up only 54% of the total weight of meat on the carcass.

In beef the topside and rump regions are particularly bad in respect to drip, in comparison with the l. dorsi (Taylor, 1972). However, the difference between muscles may not apply to all animal species. Dawood (1995) found that average drip losses after thawing Najdi Camel steaks from chuck, ribeye and leg were all in a similar range, 9.77–12.34%, and unaffected by the age (8–26 months) of the animal.

2.3.2 Refrigeration factors

The rate of change of temperature during chilling and the temperature at which meat is stored during the cold chain influence drip loss. Freezing and subsequent thawing substantially increase drip loss from meat.

2.3.2.1 Chilling

Rapid cooling of meat immediately after slaughter will reduce drip loss after subsequent cutting operations. The potential for drip loss is established in the first period of cooling, the temperature range conducive to drip is down to about 30°C or perhaps a little lower.

There are a number of publications showing that rapid cooling can reduce drip production. Taylor (1972) compared two cooling treatments for pig carcasses (Table 2.7).

In 38 out of 40 paired legs, the drip loss was less after the quicker cooling. The difference varied between breed (Table 2.4) and ranged from approximately 1.6- to two-fold. In other studies the two cooling rates again gave highly significant differences in drip loss from four muscles (Table 2.5).

Similar experiments were also carried out on beef using four cooling procedures:

- 1 23 h at 0°C (air at 1–2 m s⁻¹) + 24 h at 0°C (still air)
- 2 47 h at 0°C (still air)

Table 2.7 Temperatures in pig carcasses during cooling quickly and slowly

| Time after slaughter (h) | Temperature (°C) | | | |
|--------------------------|------------------|-------|-------------------|-------|
| | Deep leg | | Longissimus dorsi | |
| | Slow | Quick | Slow | Quick |
| 5 | 30 | 19 | 24 | 7 |
| 10 | 14 | 5 | 6 | 0 |
| 15 | 3 | 0 | 0 | 0 |

Source: Taylor, 1972.

Table 2.8 Drip loss after 43 h at 0°C from longissimus dorsi samples removed from slowly and quickly cooled beef sides

| Cooling method | | Range drip (% by wt) | | Ratio drip, slow/quick |
|----------------|-------|----------------------|---------|------------------------|
| Slow | Quick | Slow | Quick | |
| 3 | 1 | 0.2–3.2 | 0.1–2.0 | 2.2 |
| 4 | 2 | 0.8–4.1 | 0.6–1.8 | 2.4 |
| 4 | 1 | 3.6–4.4 | 0.9–2.1 | 2.9 |

Source: Taylor, 1972.

- 3 6 h at 15°C + 41 h at 0°C (still air)
- 4 23 h at 15°C + 24 h at 0°C (still air).

Opposite sides of the same animal were used for comparison and drip was measured in four 25.4 mm thick slices of l. dorsi cut between the 9th and 10th ribs and stored at 0°C for 43 h. The saving in drip gained by cooling quickly after slaughter was clearly shown (Table 2.8). The mean loss from the samples taken from sides cooled quickly by method 2 was 1.1%, while that from sides cooled at the slowest rate, method 4, was 2.7%. Other subsequent studies have shown that rapid chilling, as long as freezing of the muscle or cold shortening is avoided, will substantially reduce drip loss.

Gigiel *et al.* (1985) removed cylindrical samples of muscle from freshly slaughtered beef. The curved surface and one end of the cylinder were surrounded by insulation and the free end placed in contact with solid carbon dioxide (CO₂). Since heat was only extracted from one end this produced a wide range of cooling rates through the length of the cylinder. After cooling and equalisation, the cylinder was cut into discs and the drip potential of each disc measured using a centrifuge technique described by Taylor (1982). The resulting plot of drip loss against cooling rate is shown in (Fig. 2.7). Close to the surface in contact with the CO₂ the rate of cooling was

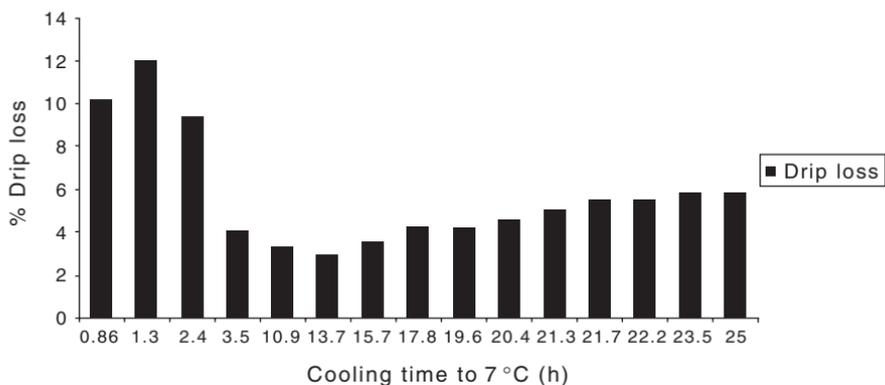


Fig. 2.7 Percentage drip loss from beef sample as function of cooling time at 7°C (source: Gigiel *et al.*, 1985).

Table 2.9 Effect of hot versus cold boning on drip loss from pork muscles, stored at 0–3°C for 7 days post mortem

| Expt. | No. of samples | Muscle | Drip loss (%) | | |
|-------|----------------|-----------------|------------------------|-------------------------|------------|
| | | | Hot boned ^a | Cold boned ^b | Difference |
| 1 | 19 | L. dorsi | 9.5 (±2.4) | 11.8 (±3.1) | 2.3 |
| | 19 | L. dorsi | 9.9 (±1.5) | 11.65 (±2.7) | 1.75 |
| | 19 | Semimembranosus | 6.95 (±2.9) | 7.05 (±3.1) | 0.1 |
| 2 | 22 | L. dorsi | 6.95 (±2.4) | 7.25 (±2.75) | 0.3 |
| | 22 | L. dorsi | 7.0 (±2.4) | 7.6 (±3.1) | 0.6 |
| | 22 | Semimembranosus | 7.65 (±2.6) | 6.6 (±2.6) | -1.05 |

^a Hot boned within 45 min post-mortem and chilled uniformly; in experiment 1, 7°C within 10 h, 2°C at 24 h post-mortem; in experiment 2, 7°C within 6 h, 2°C at 14 h post-mortem. ^b Cold boned after chilling carcass less uniformly to 12°C within 15 h; then deboned and chilled rapidly to 2°C.

Source: Honikel, 1990.

highest but freezing occurred and the drip was high. Minimum drip potential was measured in the next region where high cooling rates were achieved without freezing. Drip then increased as cooling time to 7°C increased.

Hot boning, i.e. removing the meat from the carcass immediately after slaughter, has been shown to reduce drip in pork provided chilling is strictly controlled. Honikel (1990) showed that preventing cold shortening is the key to reducing drip. The two muscles studied, l. dorsi and semimembranosus, exhibit different pH fall rates, with semimembranosus having a slower pH fall than l. dorsi. Consequently under the chilling conditions used, even with the slower rate in the first experiment (Table 2.9), the hot boned semimembranosus exhibited some shortening, thus the difference

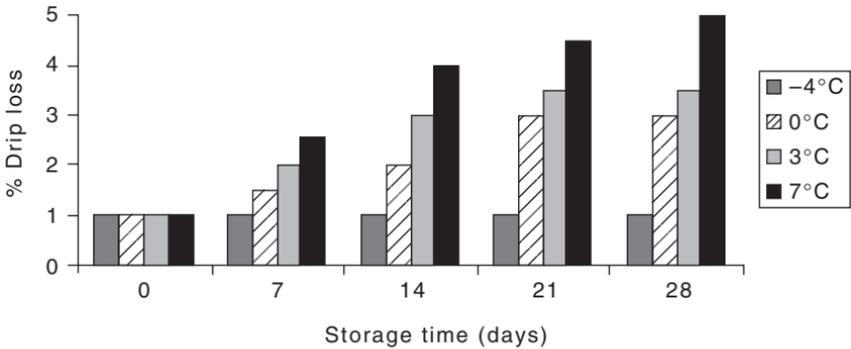


Fig. 2.8 Drip loss from vacuum-packed cubes of pork stored at -4 , 0 , 3 and 7°C (source: Lee *et al.*, 1985).

between hot and cold boning is small. The faster chilling rate in the second experiment induced even more shortening in the hot boned semimembranosus increasing drip further. Under the conditions used in the first experiment neither cold- nor rigor-shortening occurred in the l. dorsi.

2.3.3 Chilled storage

In meat, drip loss increases with length and temperature of chilled storage (Fig. 2.8). Drip loss from pork cubes increased substantially during 21 days of storage at 0 , 3 and 7°C . The rate of increase was greater at the higher temperatures. In storage at 0 and 3°C no increase in drip loss with time was measured after 21 days. At 7°C drip was still increasing between 21 and 28 days. At -4°C the samples remained frozen and no drip was observed until the samples were thawed.

In beef, Boakye and Mittal (1993) reported a different relationship between the length of time longissimus was conditioned (aged) and drip loss. There was small, but not significant, increase in drip over the first 8 days of ageing. A marked increase in drip was measured on day 12 followed by a marked decrease on day 16.

The importance of effective secondary cooling after cutting is shown by the data of Löndahl and Eek (1986). The amount of drip loss from pork rib after cutting when held at 10°C was twice that of meat chilled and held at 2.5°C (Table 2.10).

Drip from offal also increases with length of storage but is very variable. Strange (1987) cut pigs liver into 1.25 cm thick strips on the day of slaughter, stored them at 5°C and measured the drip loss during chilled storage. On the day of slaughter the average drip was 0.72% (range 0–2.27%), after 2 days storage it averaged 2.61% (range 0.9–4.52%), and after 4 days it was 2.9% (range 1.01–5.07%).

Table 2.10 Drip loss (%) from pork ribs after cutting when held at 10 or 2.5 °C

| Storage temperature (°C) | Storage time (h) | | | |
|-----------------------------|------------------|-----|-----|-----|
| | 20 | 45 | 70 | 90 |
| 10 | 1.3 | 2.2 | 2.9 | 3.2 |
| 2.5 | 0.5 | 1.0 | 1.4 | 1.7 |

Source: Löndahl and Eek, 1986.

2.3.3.1 Freezing

The above considerations apply to fresh meat, where the decrease in the water-holding capacity is determined by the post-mortem conditions. Freezing, apart from one case reported by Deatherage and Hamm (1960), always tends to decrease water-holding capacity and hence increase drip. When meat is frozen quickly, the water released by the fibrils as the meat has gone into rigor, and the water which is still held are both frozen simultaneously. Consequently, there is no change in their relative positions or amounts. At slower freezing rates, however, the water balance is altered, the extracellular water freezing first. As freezing continues, the existing ice crystals grow at the expense of water from the intrafibrillar space. This can result in salt crystallisation and pH changes (van den Berg, 1964; 1966) which potentially cause protein denaturation. This has been well documented for frozen fish (e.g. Love, 1966) which is much more susceptible to freezing damage than meat.

A number of scientific investigations, which can be compared to commercial practice, have defined the effect of freezing rate on drip production. Petrovic *et al.* (1993) stated that the optimal conditions for freezing portioned meat are those that achieve freezing rates between 2 and 5 cm h⁻¹ to -7 °C. Grujic *et al.* (1993) suggest even tighter limits of 3.33–3.95 cm h⁻¹. They found that ‘slow freezing’ up to 0.39 cm h⁻¹ resulted in decreased solubility of myofibrillar proteins, increase in weight loss during freezing, thawing and cooking, lower water-binding capacity and tougher cooked meat. ‘Very quickly frozen’ meat (>4.9 cm h⁻¹) had a lower solubility of myofibrillar proteins, lower water-binding capacity and tougher and drier meat. The samples were thawed after storage times of 2–3 days at -20 °C so the relationship between freezing rates and storage life was not investigated. Sacks *et al.*, (1993) found that after 2.5 months, drip loss from mutton samples frozen using cryogenics was >2% less than in those using air freezing (Table 2.11).

These results are scientifically very interesting, however, in industrial practice most meat is air frozen in the form of large individual pieces or cartons of smaller portions. In commercial situations freezing rates of 0.5 cm h⁻¹ in the deeper sections would be considered ‘fast’ and there would

Table 2.11 Drip loss (%) from 77.6 g samples of *Mm longissimus lumborum et thoracis* frozen under different methods and thawed at 4 °C

| Freezing conditions | Freezing time to -2.2 °C | Freezing rate (cm h ⁻¹) | Storage time at -20 °C | |
|-------------------------|-----------------------------|--|---------------------------|--------------------|
| | | | 48 h | 2.5 months |
| Cryogenic -90 °C | 15 month | 6.4 | 3.34 ^a | 9.49 ^a |
| Cryogenic -65 °C | 22 month | 4.4 | 4.70 ^{ab} | 9.72 ^a |
| Blast freezer -21 °C | 1.83 h | 0.55 | 5.53 ^b | 12.74 ^b |
| Walk-in-freezer -21 °C | 1.88 h | 0.53 | 4.71 ^{ab} | 13.18 ^b |
| Domestic freezer -25 °C | 1.96 h | 0.51 | 5.26 ^b | 11.72 ^b |

Values given in the 'storage time' columns that have the same superscripts (a or b) are not statistically different ($P > 0.05$).

Source: Sacks *et al.*, 1993.

be considerable variation in freezing time within the meat. The samples frozen by Sacks *et al.* (1993) were much smaller (77.6 g in weight) than most commercial products. Even with such small samples there was no significant difference in drip after 48 h between cryogenic freezing at -90 °C and a walk-in freezer operating at -21 °C.

Sakata *et al.* (1995) investigated the freezing of samples similar in size to a domestic joint. They found no significant difference in drip loss from 700 g samples of pork l. dorsi frozen in air at -20 or -80 °C. At -20 °C samples required *ca.* 6 h to pass from -1 to -6 °C compared with half this time at -80 °C. Average drip losses were 3.7% at -20 °C and 5.2 at -80 °C. As described in Chapter 9, in commercial situations freezing times typically range from tens of hours to a few days. Freezing rates are therefore outside the values that influence drip potential.

In a number of operations, meat is 'tempered', i.e. partially frozen to aid cutting, dicing, slicing and so on. This process will increase drip loss though not to the same extent as full freezing. Irie and Swatland (1993) found that drip loss from 3 mm thick slices of pork that had been 'lightly frozen' before slicing averaged $8.0 \pm 4.2\%$ over a 4-day-period. Drip losses from samples that had been kept in a freezer at -10 °C for 6 days had a higher drip loss of $14.0 \pm 4.3\%$. Drip was measured by hanging 7 slices in a bag in a refrigerator at 5 °C.

In other cases, partial freezing during a chilling operation may increase drip. James *et al.* (1983) found that partial freezing of pork during ultra-rapid chilling produced a four-fold increase in drip.

2.3.3.2 Frozen storage

Storage temperature has a marked effect on the behaviour of ice crystals that could be detrimental to the ultimate quality of the meat. It has been demonstrated that frozen tissue stored for 180 days at -20 °C has small ice

crystal formations of irregular shape in the extracellular spaces. Storage for the same period at -3°C results in the development of large rounded ice formations with a concomitant compression of the muscle fibres (Moran, 1932). These changes are also reflected in the increased amount of drip, which is released from frozen tissue stored at the higher temperature. It is thus desirable that frozen meat should be stored at a sufficiently low temperature to prevent growth of ice crystals in the extracellular spaces. Such growth occurs if the temperature of the frozen tissue is allowed to rise above its eutectic point. However, quoted values for the eutectic point of meat range from 'probably just below -20°C ' (Moran, 1934) to -52°C (Riedel, 1961).

Drip loss in frozen storage has also been shown to increase with storage time. Calvelo (1986) states that in general, drip production increases as time and frozen storage temperature increase. After approximately 42 and 63 days, drip from beef stored at -10 or -15°C had reached 80% and 90%, respectively of its maximum. At -25°C it required over 120 days to reach the 80% value.

Storage times of 48 h and 2.5 months were used during investigations of the effect of different freezing systems and rates on drip production from small samples of mutton muscle (Sacks *et al.*, 1993). In all cases drip loss after 2.5 months was at least double the percentage measured after 48 h (Table 2.11).

Drip loss during thawing from ground beef patties was also found to increase with the length of time the patties had been in frozen storage (Bhattacharya *et al.*, 1988). For higher fat content samples, drip loss increased from 1.8% in fresh samples to 12.5% after 20 weeks in storage. Higher drip losses in thawing were obtained from samples stored at -12.2°C than those stored at lower temperatures. However, there was no difference between storage temperatures of -23.3 and -34.4°C .

2.3.3.3 Thawing

When meat is thawed the reverse of the freezing process occurs. Water which has been frozen is released and has to re-establish equilibrium with the muscle proteins and salts. Obviously if the muscle proteins have been denatured they will reabsorb less water. Since the fibres have been squeezed and distorted by ice formation, this non-reabsorbed water will lie in wider channels within the meat structure, thus increasing the potential drip. If cell walls have also been damaged by freezing, even less water will be reabsorbed and will exude as drip.

Experiments with pig liver (Strange *et al.*, 1985; Strange, 1987) showed that repeated freeze-thaw cycles produced increased drip. Strips of liver were frozen and held at -20°C for 70 h (Strange *et al.*, 1985) or 7 days (Strange, 1987) then subjected to cycles of thawing at 5°C for 24 h followed by freezing at -20°C for 24 h. In the 1985 investigations the drip loss was compared to chilled liver held at 5°C for sequential 24-h-periods

Table 2.12 Drip loss (%) and standard deviation in () from liver subjected to repeated freeze–thaw cycles or stored at 5°C

| | Fresh | Cycle 1 | Cycle 2 | Cycle 4 | Cycle 5 | Cycle 6 |
|-------------|-------|-----------|-----------|-----------|------------|------------|
| Freeze/thaw | 0 | 3.1 (2.1) | 5.5 (3.6) | 8.9 (2.4) | 11.4 (5.3) | 10.5 (4.8) |
| Chilled | 0 | 1.9 (0.9) | 2.7 (2.7) | 3.4 (3.7) | 5.9 (4.6) | 5.7 (5.6) |

Source: Strange *et al.*, 1985.

(Table 2.12). Average drip loss was higher after each freeze–thaw cycle. However, there was considerable variability between samples and whilst freeze–thaw cycling always produced more drip than the chilled material, the difference was not statistically different.

After the first, second and third thawings respectively in the 1987 work the average drip losses were 5.8% (range 1.7–10.4%), 8.3% (range 3.29–13.4%) and 11.2% (range 4.3–15.8%). Drip loss from fresh liver before freezing was <1%.

2.4 Conclusions

The amount of drip which is exuded from meat depends on its intrinsic characteristics, post-mortem treatment and the pH of the meat. It also depends on the conditions of chilling/freezing, the temperature and time of storage, the size of the pieces of meat when thawed and the conditions of thawing.

In general:

- 1 Although, the potential for drip loss is predetermined to a large extent by breed and conditions before slaughter, the realisation of this potential is influenced by the temperature/time history in the cold chain.
- 2 Rapid cooling substantially reduces drip production, especially over the critical range from 40°C to just below 30°C.
- 3 During chilled storage, transport and display, drip loss increases with time.
- 4 The lower the storage temperature the lower the amount of drip produced.
- 5 Pre- and post-rigor muscles differ in their initial reaction to cooling down to freezing temperature.
- 6 Freezing will substantially increase the amount of drip.
- 7 During frozen storage, drip potential increases with time of storage.
- 8 Within the normal commercial range the rate at which meat is frozen or thawed has little influence on drip.
- 9 In commercial situations the amount of drip that appears is greatly influenced by the cut surface area to sample volume ratio.

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3

Effect of refrigeration on texture of meat

Whilst a number of characteristics affect the overall quality and acceptability of both fresh and frozen meats, tenderness is the major characteristic of eating quality because it determines the ease with which meat can be chewed and swallowed. The tenderness of meat is affected by both chilling/freezing and storage. Under the proper conditions, tenderness is well maintained throughout the chilled/frozen storage life, but improper chilling/freezing can produce severe toughening and meat of poor eating quality.

Some of the factors that influence the toughness of meat are inherent in the live animal. It is now well established that it is the properties of the connective tissue proteins, and not the total amount of collagen in meat, that largely determine whether meat is tough or tender (Church and Wood, 1992). As the animal grows older the number of immature reducible cross-links decreases. The mature cross-links result in a toughening of the collagen and this in turn can produce tough meat. Increasing connective tissue toughness is probably not commercially significant until a beast is about four-years-old (Husband and Johnson, 1985).

Although there is common belief that in beef, breed has a major effect, CSIRO (1992) state 'although there are small differences in tenderness due to breed, they are slight and currently of no commercial significance to Australian consumers.' However, there are substantial differences in the proportion of acceptable tender meat and toughness between *Bos indicus* and *Bos taurus* cattle. The proportion of acceptable tender meat decreased from 100% in Hereford Angus crosses to 96% in Tarentaise, 93% in Pinzgauer, 86% in Brahman and only 80% in Tsahiwal (Koch *et al.*, 1982). Toughness of meat increases as the proportion of *Bos indicus* increases (Crouse *et al.*, 1989).

There can also be significant differences within a breed. Longissimus dorsi shear force values for double muscled Belgium Blue bulls were significantly higher than those of the same breed with normal conformation (Uytterhaegen *et al.*, 1994). Calpain I levels at 1 h and 24 h post-mortem were also much lower. It was suggested that the lower background toughness in the double muscled was compensated for by reduced post-mortem proteolytic tenderisation.

Again, castration appears to have little influence on tenderness. Huff and Parrish (1993) compared the tenderness of meat from 14-month-old bulls and steers. Strip loins were removed from carcasses *ca.* 24 h post-mortem, vacuum packed and held at 2°C for up to 28 days. No differences were found between the tenderness of bulls and steers.

Experiments designed to determine the effect of treatments immediately before or at the point of slaughter appear to show that they have little effect on meat texture. Exercising pigs before slaughter has been shown to have no effect on texture parameters, *i.e.* muscle shortening and shear force (Ivensen *et al.*, 1995). The use of different stunning methods (both electrical and carbon dioxide) does not seem to have a significant effect on the quality of pork (Garrido *et al.*, 1994).

Consumers' surroundings influence their appreciation of tenderness (Miller *et al.*, 1995). Consumers were more critical of the tenderness of beef steaks cooked in the home than those cooked in restaurants. The Warner-Bratzler force transition level for acceptable steak tenderness was between 4.6 and 5.0 kg in the home and between 4.3 and 5.2 kg in restaurants. Warner-Bratzler tests are probably the most uniformly used method of texture measurement. However, there are many other methods of determining the mechanical properties of meat (Lepetit and Culioli, 1994). In cooked meat it is suggested that applying mechanical tests in different strain directions is likely to produce information that can be more readily related to perceived texture.

End-point temperature after cooking is crucial to tenderness. Davey and Gilbert (1974) showed that there was a three- to four-fold toughening occurring between 40 and 50°C and a further doubling between 65 and 70°C.

Refrigeration has two critical roles in meat tenderness. One is in the prevention of muscle shortening in the period immediately following slaughter. The second is in the conditioning of the meat so that the desired degree of tenderness is obtained.

3.1 Muscle shortening

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 meat pH has fallen below about 6.2 (Bendall, 1972). In this state the muscles contain

sufficient amounts of the contractile fuel, adenosine triphosphate (ATP), for forcible shortening to set in as the temperature falls below 11°C, the most severe effect occurring at about 3°C. 'Cold-shortening' first became apparent in New Zealand, when tough lamb began to be produced routinely by the improved refrigeration techniques which were introduced after the Second World War (Locker, 1985). The shortening phenomenon was first observed scientifically by Locker and Hagyard (1963) and the resulting extremely tough meat after cooking by Marsh and Leet (1966). The mechanism of cold shortening has been well described by Bendall (1974) and Jeacocke (1986) and forms the basis of the next sections of this chapter.

3.1.1 Mechanism of shortening

The characteristic pattern of post-mortem chemical change, found in all the skeletal muscles of the mammals so far investigated, is shown in Fig. 3.1. The figure has an arbitrary timescale, because although the pattern is virtually constant its duration is highly temperature dependent. Relative time scales can be interpolated from the temperature data in Fig. 3.2.

It can be seen in Fig. 3.1 that the supply of contractile fuel (ATP) remains constant and high for some time. It is kept topped up by two resynthetic processes that counteract its slow wastage in the resting muscle. The first of

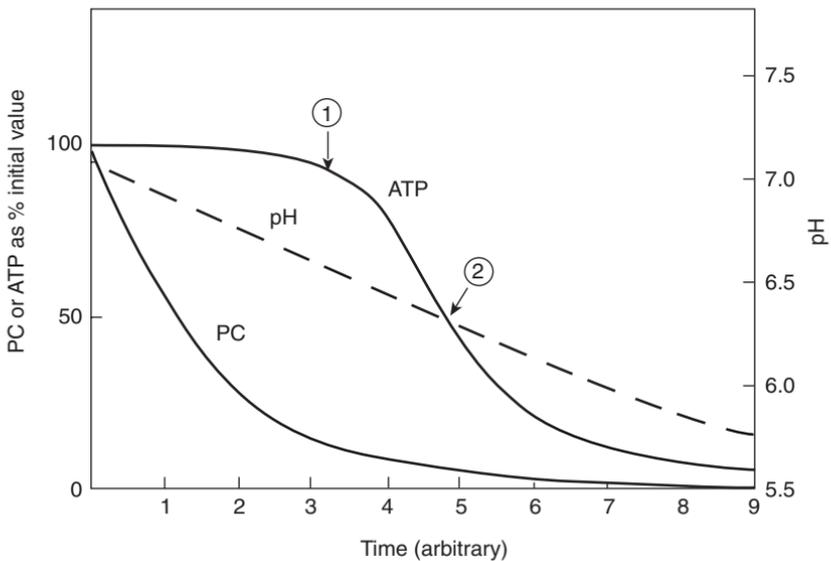


Fig. 3.1 Biochemical changes during the course of rigor mortis. Arrow 1 indicates onset of rapid decline of ATP, and arrow 2 the time for half-change of ATP. The time scale is arbitrary and highly temperature dependent (see Fig. 3.2) (source: Bendall, 1974).

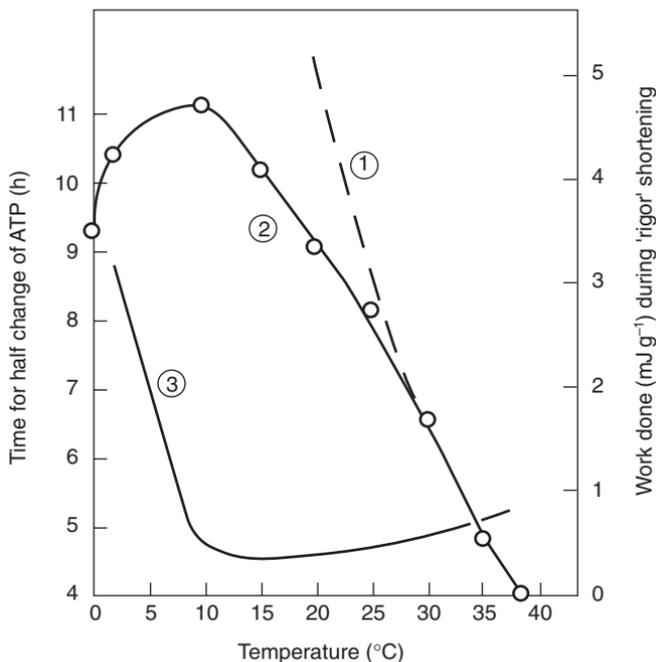


Fig. 3.2 Time for half-change of ATP during rigor in beef LD muscle, plotted against temperature. Initial pH = 7.0 in all cases. Curve 1: times for an initial reaction. Curve 2: observed times. Curve 3: work done during shortening (source: Bendall, 1974).

these processes is the creatine kinase reaction, which resynthesises ATP from its breakdown product, ADP, and phosphocreatine (PC). The second is the complex process of glycolysis in which the energy for resynthesis comes from the breakdown of glycogen to lactate, with concomitant acidification and fall of muscle pH. The ATP supply remains constant only while PC is still available, but begins to fall as soon as glycolysis is left on its own as the sole source of resynthesis. This phase of declining ATP supply is known as the rapid phase of rigor, because it is then that the stiffening (rigor) of the muscle sets in. It is shown by the first arrow in Fig. 3.1.

At temperatures above 12°C the post-mortem muscle remains in a passive, relaxed state until the ATP supply begins to dwindle at the onset of the rapid phase of rigor. It then begins to shorten actively. At body temperature (38°C) the shortening can reach 40% or more of the muscle length if unopposed by the force of a load. This so-called 'rigor shortening' can be overcome by quite small loads and is incapable of doing much work, even at 38°C (see Fig. 3.2).

The effect of temperature on the duration of the chemical changes during rigor is shown in Fig. 3.2, using the time for half-change of ATP as

the criterion (see second arrow in Fig. 3.1). From 38°C down to 25°C the duration increases in the manner for a normal chemical reaction (cf. curves 1 and 2). Below this point, however, the experimental points diverge more and more from the predicted line; in other words, the processes take place more quickly. At about 10°C the experimental curve actually inverts, so that the rate of chemical change at 2°C is greater than at 15°C. Such anomalous temperature dependence can only mean that new reactions are occurring with increasing intensity as the temperature is reduced.

The clue to the nature of the new reactions is given by curve 3, which represents the total work the muscle does during shortening. From 16°C up to 38°C the total work increases about 2.5-fold, but even so it is very small. By contrast, it increases by a similar amount by going only from 16 to 9°C and eight-fold by going to 2°C. Quite clearly, therefore, the new reactions intervening below 9–10°C are somehow concerned with the increased muscle shortening.

The shortening occurring below 10°C is usually described as ‘cold shortening’ or ‘cold contracture’. In some muscles, it can develop a force of between 1 and 2 N cm⁻², which is between 4 and 8% of the total force developed in a fully stimulated contraction of living muscle. It is supposed to set in because the trigger for contraction is itself highly temperature sensitive and fires spontaneously to an increasing extent as the temperature is reduced below 10°C.

This trigger has been shown to be the release of calcium ions, Ca²⁺, from the sarcoplasmic reticulum (Bendall, 1974; Jeacocke, 1986; Offer *et al.*, 1988). During use, muscle cells are triggered to contract by calcium ions (Ca²⁺) liberated from internal stores within the muscle cell. Although the early stages of activation in muscle contraction in life and cold shortening in a carcass differ, the final stage, the release of calcium ions, is the same.

In resting muscle, the intrafibrillar level of free Ca²⁺ is very low. Most of the total store of intracellular calcium (about 10⁻³ Mole) is locked up in highly specialised structures which enwrap each of the 1000 or so fibrils within a muscle fibre (see Fig. 3.3). These structures which are part of the so-called sarcoplasmic reticulum (SR) have transverse connections (SR(T)) with the outer membrane or sarcolemma (S) of the fibre, so that when a nervous impulse from the motor nerve (MN) arrives at the motor end-plate (EP) it travels in both directions along the sarcolemma and invades the muscle fibre itself via the myriads of these transverse tubules. These tubules are in contact with the longitudinal elements (SR(L)) of the SR which enwrap each fibril (see upper fibril in Fig. 3.3). The contact is made via the triad junctions (TJ) where two dense structures, the so-called lateral cisternae, are closely opposed to the transverse tubules (SR(T)). It is thought that the lateral cisternae are the storehouse for Ca²⁺ in the resting muscle. In many muscles there are pairs of cisternae at the level of the Z-discs (Z) of each sarcomere, so that in a fibril that is 10 cm in length there are about 40000 transverse connections and pairs of cisternae.

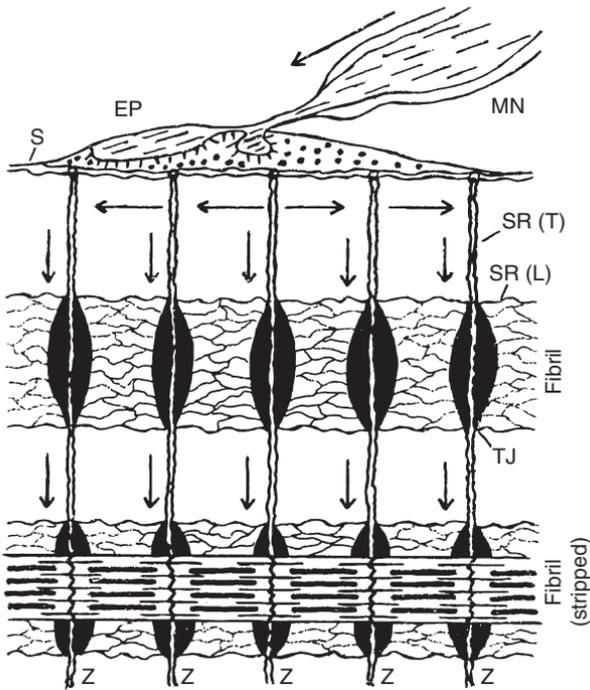


Fig. 3.3 Diagram of part of a muscle fibre in longitudinal section to demonstrate the effect of a nervous impulse. For abbreviations see text (source: Bendall, 1974).

The effect of an impulse invading the muscle fibres is to cause release of Ca^{2+} from the cisternae of each fibril. The Ca^{2+} then diffuses down its electrochemical gradient, finally reaching the microfilaments of actin (thin) and myosin (thick) shown in the lower, stripped fibril in Fig. 3.3. Here the Ca^{2+} is temporarily absorbed and thereby triggers the contractile explosion. This consists first of the rapid splitting of ATP to ADP and Pi (inorganic phosphate) at active centres on the myosin filaments. Then there is transduction of some of the free energy released into relative movement of the two sorts of interdigitating filaments. The process is not unlike the explosion of the petrol/air mixture in a car cylinder, when the sparking plug fires. For a crude analogy, the cylinder can be likened to the myosin filaments and the piston to the actin filaments. However, it is the upstroke which resembles a contraction and not the downstroke (i.e. the piston is actively pulled or pushed into the cylinder).

Relaxation is the opposite process during which the status quo at the sarcolemma is restored, thereby enabling the lateral cisternae of the SR to re-accumulate the Ca^{2+} released during the contraction. They do this by an active pumping process, using the energy of ATP-splitting to push Ca^{2+} up the now adverse electrochemical gradient. Meanwhile fresh ATP has

flooded the microfilaments, thus separating them from each other once more and enabling them to slide freely over each other in response to any externally applied force.

Two features of the calcium-pumping mechanism are of special importance in the present context. First, it is likely that the calcium storage vesicles are somewhat leaky, even in resting muscle, so that the calcium pump has to operate continuously, albeit slowly, to keep the intrafibrillar Ca^{2+} concentration at its low resting level. Second, the calcium pump has an extremely high temperature coefficient, so that at 10°C it works at 1/200th and at 2°C at only 1/1000th of the rate at the body temperature of about 38°C (Bendall, 1974). Passive diffusion (leakage) out of the pump would only be reduced at 10°C to about half the value at 38°C . Thus, there is an increasing chance of net Ca^{2+} leakage into the myofilaments as the temperature falls, the effect becoming dramatic below 10°C . Such leakage stimulates the contractile ATP-ase, bringing about the shortening characteristic of cold shortening and increasing the production of ADP. The latter in its turn would then stimulate the reactions of ATP synthesis mentioned earlier, so that the timescale in Fig. 3.1 would become shorter and shorter the lower the temperature. This explains the anomalous temperature dependence of the time for half change of ATP, shown in Fig. 3.2.

The contracture, which occurs when a rapidly frozen muscle is thawed, resembles cold contracture in that it sets in while the level of contractile fuel (ATP) is still high. However, it differs because the amount of work done and force developed are much higher. With 'thaw shortening' the temperature is raised through the 'calcium release' danger zone from 0 to 10°C , whereas in cold shortening it is reduced through this zone. The rate of contracture depends entirely on the rate of thawing. Rapid thawing of a freely suspended, unloaded muscle strip causes very dramatic shortening, often to less than 40% of the 'frozen' length.

3.1.2 Preventing shortening

Rapid chilling has many practical advantages but increases the danger of cold shortening. As discussed in Chapter 2 the breakdown of glycogen to lactic acid occurs at different speeds in different species. In lamb and beef, the rate is low and the pH falls slowly. Hence, it is only too easy to cool carcasses of these animals, at least on the surface, below 10°C when the pH is above 6.2 and such carcasses are extremely vulnerable to cold shortening.

In pork, the rate of breakdown of glycogen is more rapid and under moderate chilling regimes, cold shortening will not occur. However, pig muscle can cold shorten, and with fast chilling, for example using sub-zero air temperatures, cold shortening has been clearly demonstrated.

Another point that should be made is that at an early stage, the surface of the carcass will reach the same temperature as that of the air. Since the air temperature used in chilling is commonly below 10°C , there exists the

possibility that cold shortening may occur at the surface, even if it does not occur in the bulk of the meat. Whether or not cold shortening occurs on the surface will often depend on the amount of fat cover over the carcass.

This leads to the question of whether shortening can be eliminated whilst retaining high cooling rates? This can be done in two ways: (1) by preventing the underlying cold contraction or (2) by restraining the muscle sufficiently to prevent the deleterious shortening. The second solution has been developed with considerable success and has generally involved adopting novel methods of hanging the carcass, such as from the hip (Taylor, 1996).

The alternative avenue, of prevention, has found favour with the widespread application of electrical stimulation (ES) of the carcass immediately after death. This procedure greatly accelerates post-mortem metabolism by stimulating the muscles to contract and relax at a very fast rate, which quickly depletes glycogen and ATP and thus accelerates rigor. ES of the carcass after slaughter can allow rapid chilling without much of the toughening effect of cold shortening. Taylor (1987) and Taylor (1996) provide details of optimum ES treatments. ES has also been shown to be effective in reducing cold shortening in deer meat (Chrystall and Devine, 1983; Drew *et al.*, 1988).

Although chilling or freezing pre-rigor produces tough meat caused by cold shortening or thaw rigor it still has good functional properties (Xiong and Blanchard, 1993). It is therefore feasible to manufacture good quality comminuted meat products from hot boned pre-rigor refrigerated beef. Abu-Bakar *et al.* (1989) found no differences in eating quality between Wieners manufactured from either hot boned beef chilled rapidly using CO₂ or brine, or conventionally chilled cold boned beef.

As a 'rule of thumb', cooling to temperatures not below 10°C in 10 h for beef and lamb (Offer *et al.*, 1988) and in 5 h for pork (Honikel, 1986) can avoid cold shortening.

3.2 Development of conditioning (ageing)

The terms 'conditioning', 'ageing', 'ripening', 'maturing' and 'the resolution of rigor' have all been applied to the practice of storing meat for periods beyond the normal time taken for cooling and setting, to improve its tenderness after cooking. Conditioning imposes a severe limitation on processing conditions because it is a slow process.

The deficiencies in the commercial conditioning of meat were clearly illustrated by replies to a questionnaire to sections of the trade in the UK in 1977/8 (Dransfield, 1986). At the time a period of storage for wholesale meat was often not specified by retailers. When specified the duration of storage had much to do with distribution and turnover of meat and could often be shortened by commercial pressures. At retail, beef was kept for 1–4 days and most beef was sold 3–6 days after slaughter (Palmer, 1978).

The majority of beef therefore had been only partially conditioned and tenderness would have been improved if the beef had been stored for a further week. Many retailers nowadays condition beef for longer periods, but economic factors often still dictate the time of conditioning.

3.2.1 Mechanism of ageing

The major change, which takes place in meat during ageing, occurs in the muscle fibre. Little or no change which can be related to tenderness improvement takes place in the structures which hold the fibres together (the connective tissue, collagen) (Herring *et al.*, 1967).

Conditioning is caused by the presence of proteolytic enzymes in the muscle which slowly catalyse the breakdown of some of the muscle proteins. This causes weakening of the muscle so that the meat is more readily pulled apart in the mouth and is therefore tenderer. Two groups of enzymes are thought mainly responsible: calpains, which are active at neutral pH shortly after slaughter, and cathepsins, which are active at acid pH after rigor (Offer *et al.*, 1988).

Dransfield (1994) states that it is generally accepted that tenderisation results from proteolysis by endogenous enzymes. The major problem in identifying the specific enzymes has been that the enzyme activities cannot be measured in meat since they depend on local *in situ* concentrations of cofactors and inhibitors. However, modelling the activation of calpains shows how tenderness develops and points to methods of optimising its development. Calpain I is activated first, at low calcium ion concentrations, and then calpain II is activated as the concentration of calcium ions rises further. There are enough free calcium ions to activate all of calpain I but only about 30% of calpain II. Tenderisation therefore begins when calpain I starts to be activated, normally at about pH 6.3 or about 6h after slaughter in beef, and rapidly increases as more calpain is activated. After about 16h in beef, calpain II becomes activated and causes a further tenderisation.

The calpain-tenderness model shows that in beef longissimus dorsi, most of the tenderisation is caused by calpain I. Approximately 50% of the tenderisation occurs in the first 24h, after which the rate is exponential.

The model clearly shows that the ultimate tenderness of the meat will depend on (1) the tenderisation that occurs during chilling and (2) further tenderisation during storage. In extreme cases, for example dark, firm and dry (DFD) beef, all the tenderisation will occur in stage 1 and none during ageing. The incidence of DFD beef is markedly dependent on the sex of the animal. It occurs in about 1–5% of steers and heifers, 6–10% of cows and 11–15% of young bulls (Tarrant and Sherington, 1981). Rigor development is very rapid in DFD beef and during normal cooling to an ultimate pH of 7.0, all of the tenderisation occurs before 24h and no ageing occurs (Dransfield, 1994).

3.2.2 Prediction of tenderness

There is great interest in the development of any measurement method that can be applied soon after slaughter, which will predict the tenderness of meat. Many laboratory techniques (Dransfield, 1986; Dransfield, 1996) have been used to detect changes in the muscle down to the molecular level. However, there is no routine test which can indicate how much of the tenderising has occurred or, more usefully, how much longer a piece of meat must be stored.

In 1988 Marsh *et al.* proposed that the pH in the longissimus dorsi at 3 h post-mortem may have a use as a predictor of tenderness. However, subsequent studies involving large numbers of animals (Marshall and Tatum, 1991; Shackelford *et al.*, 1994) found that it was not highly correlated with tenderness. Thus it is not a reliable method of identifying potentially tough or tender meat.

Cross and Belk reviewed, in 1994, all the non-invasive technologies capable of objectively determining yield or the eating quality of the lean meat in live animals or carcasses in commercial situations. Technologies included X-ray, nuclear magnetic resonance, electrical conductivity analysis, near-infrared reflectance, video image analysis, optical fat/lean probes, optical connective tissue probes, bioelectrical impedance analysis, velocity of sound and elastography. Elastography, which measures the internal displacement of small tissue elements in response to externally applied stress using ultrasonic pulses, was thought to have the best potential in the future. It may be capable of depicting muscle structure at the muscle bundle level, and of detecting differences in elasticity of muscle bundles, connective tissue amounts and the quality of intramuscular fat.

3.2.3 Consumer appreciation of ageing

Consumer assessments of unaged beef are variable, ranging from 'moderately tough' to 'moderately tender' whilst beef conditioned for 9 days at 1°C receives largely favourable reactions, being scored 'moderately' to 'very' tender (Dransfield, 1985). Consumer panels, however, have rarely been used to assess the factors affecting conditioning. They have usually been measured by laboratory taste panels and mechanical tests. A type of 'shear' test is frequently used on cooked meat and the measurements are usually well related to sensory assessments (Dransfield, 1986).

The results of Dransfield (1986) illustrate the effect of conditioning on a taste panel's assessment of texture of 3 beef joints. Tenderness increased in all 3 joints (Table 3.1) and these changes were reflected in increases in the overall acceptability.

In further work roasted sirloin joints from a six-year-old cow were compared with an 18-month-old heifer at storage times of 2–15 days at 2°C. By 8 days, the heifer joint showed significant improvement in tenderness (Table 3.2). By 15 days both joints showed significant improvements.

Table 3.1 Average taste panel scores for roasted joints from a 30-month steer carcass aged between 4 and 22 days at 2 °C

| Joint | Unaged | | | | Aged | | | |
|------------|------------|---------|---------|-----------------------|------------|---------|---------|-----------------------|
| | Day tasted | Texture | Flavour | Overall acceptability | Day tasted | Texture | Flavour | Overall acceptability |
| Sirloin | 4 | -2.2 | 2.5 | 2.5 | 22 | 0.8 | 3.6 | 3.2 |
| Silverside | 4 | -3.0 | 2.4 | 1.8 | 15 | 1.0 | 4.2 | 4.0 |
| Topside | 4 | -3.4 | 2.5 | 1.9 | 15 | 1.4 | 2.4 | 2.6 |

Texture: an eight-point scale from extremely tough (-4) to extremely tender (+4). Flavour and overall acceptability: a five-point scale from not acceptable (1) to extremely good (5).

Source: Dransfield, 1986.

Table 3.2 Average taste panel texture scores for roasted loin joints of 6-year-old cow compared with 18-month-old heifer aged between 2 and 15 days at 2 °C

| Day tasted | Cow | Heifer |
|------------|------|--------|
| 2 | -3.7 | -3.0 |
| 4 | -3.2 | -2.4 |
| 8 | -1.8 | -0.4 |
| 15 | +0.4 | +3.2 |

Eight-point scale from extremely tough (-4) to extremely tender (+4).

Source: Dransfield, 1986.

3.2.4 Preslaughter factors

Rates of conditioning differ widely between species. The tenderness of meat improves approximately as the logarithm of the storage time. Most of the improvement in tenderness therefore takes place in the initial storage period and tenderness eventually reaches a maximum. Table 3.3 shows the first order rate constants derived from the exponential decay of toughness of cooked muscles with time (Dransfield, 1986). Beef, veal and rabbit have a rate constant of 0.17 per day, which means that 80% of the tenderising that is theoretically possible occurred in 10 days at 1 °C. Although beef and veal condition at the same rate, veal is tenderer and therefore can reach an acceptable tenderness in 5 days at 1 °C. Lamb conditions slightly faster than beef, and pig meat about twice as fast as beef.

There is little information on the influence of breed on the rate of conditioning. Purchas (1972) observed that Friesian Brahman cross bull beef improves more in tenderness than Friesian bull beef from 5 to 14 days post-mortem at 4 °C.

There appears to be little difference in rate of conditioning between different muscles. Semlek and Riley (1974) reported that in 18 Hereford bulls, the longissimus muscle conditioned more during storage at 2 °C than did

Table 3.3 Variation in rate of conditioning among species

| | Rate (day ⁻¹) | Time for 50% tenderising (days) | Time for 80% tenderising (days) |
|--------|------------------------------|---------------------------------------|---------------------------------------|
| Beef | 0.16 (0.04) | 4.3 | 10.0 |
| Veal | 0.17 (0.03) | 4.1 | 9.5 |
| Rabbit | 0.17 (0.06) | 4.1 | 9.5 |
| Lamb | 0.21 (0.05) | 3.3 | 7.7 |
| Pork | 0.38 (0.11) | 1.8 | 4.2 |

Longissimus muscles from four species were stored at 1–4 °C (cf. Dransfield *et al.*, 1980b) and rates calculated (cf. Dransfield *et al.*, 1980a). Values are the rate of tenderising with standard errors and the time taken after stunning for 80% of the complete tenderising to occur.

Source: Dransfield, 1986.

biceps, semitendinosus or triceps. However, it is not clear whether this represents different rates or whether it was caused by different amounts of ‘background’ toughness. More comprehensive data on beef muscles was obtained at Texas A and M on 125 choice beef carcasses (Dransfield, 1986), the normalised data are shown in Table 3.4. The rate of conditioning did not differ significantly between the 17 muscles and averaged 0.25 per day at 1 °C. In pork, the semitendinosus muscle conditions at a similar rate to that of longissimus (Dransfield *et al.*, 1980b).

There appears to be an interaction between carcass grade, marbling and animal age in the development of tenderness. Doty and Pierce (1961) found that unaged meat from ‘Prime’ grade carcasses was tenderer than from ‘Good’ grade, but when the meat was aged the difference in tenderness was not so pronounced. Tuma *et al.* (1962, 1963) found that meat from 18-month-old animals was influenced little by conditioning for 14 days whereas older animals improved in tenderness. They also found that marbling influenced the development of tenderness in older animals but not in animals of 18 months. Other studies found that the rate of conditioning was not dependent on the level of finish or marbling in steers, bulls and heifers (Martin *et al.*, 1971) nor on the weight of steers (Purchas, 1972).

In reviewing the research on marbling and eating quality Rhodes (1971) concluded that, at the slaughter ages then commonly used in beef production, marbling did not affect tenderness and consequently was of no importance in tenderness development during conditioning.

3.2.5 Pre-rigor factors

Over 30 years ago, tenderness of beef was promoted by holding freshly killed and dressed carcasses at 37 °C for 4–5 h prior to normal chilling

Table 3.4 Conditioning in different beef muscles

| Muscle | Conditioning | | |
|----------------------------|--------------|-------------------|---------------------------------|
| | Cut | Rate ^a | Ultimate toughness ^b |
| Longissimus | Chuck | 0.2 (0.3) | 5.0 |
| Spinalis dorsi | Chuck | 0.3 (0.1) | 3.1 |
| Rhomboideus | Chuck | 0.1 (0.1) | 4.6 |
| Latissimus dorsi | Chuck | 1.3 (5.0) | 4.6 |
| Serratus ventralis (steak) | Chuck | 0.2 (0.2) | 2.4 |
| Infraspinatus (steak) | Chuck | 0.1 (0.1) | 2.5 |
| Serratus ventralis (roast) | Chuck | 0.1 (0.0) | 2.5 |
| Infraspinatus (roast) | Chuck | 0.1 (0.1) | 1.5 |
| Complexus | Chuck | 0.3 (0.2) | 3.2 |
| Extensor carpi radialis | Shin | 0.4 (0.3) | 5.0 |
| Triceps brachii | Shoulder | 0.3 (0.1) | 4.3 |
| Deep pectoral | Brisket | 0.1 (0.1) | 4.6 |
| Superficial pectoral | Brisket | 0.3 (0.1) | 4.8 |
| Longissimus | Rib | 0.3 (0.1) | 3.4 |
| Semimembranosus | Topside | 0.2 (0.2) | 4.1 |
| Semitendinosus | Silverside | 0.2 (0.1) | 4.6 |
| Biceps femoris | Silverside | 0.3 (0.4) | 4.4 |
| Rectus femoris | Thick flank | 0.1 (0.2) | 3.7 |
| Vastus lateralis | Thick flank | 0.2 (0.1) | 4.1 |

Muscles from US choice beef carcasses were stored at $1 \pm 1^\circ\text{C}$, $87 \pm 7\%$ RH for up to 28 days. Parameters for tenderising were calculated from shear values determined instrumentally.

^a day⁻¹, with standard errors in parenthesis; ^b Toughness in kg force predicted at infinite storage time.

Source: Dransfield, 1986.

(Lochner *et al.*, 1980). More recent work (Martin *et al.*, 1983) has confirmed that toughness decreases in direct relation to the holding temperature over the range 10–42°C but a complex mechanism involving muscle shortening and conditioning appears to take place. The tenderising process also occurs in the absence of cold shortening (Lochner *et al.*, 1980) but a full explanation of the mechanism has not been made.

The rapid glycolysis produced by these high temperatures can also be induced by pre-rigor electrical stimulation of carcasses. Electrical stimulation also tenderises meat in the absence of cold shortening (Martin *et al.*, 1983; George *et al.*, 1980). George *et al.* (1980) found, however, that the tenderising effect decreases with storage, and at completion of conditioning, stimulated and control meats were equally tender.

To investigate how much of the tenderising effect was due to advancement of conditioning, three factors were needed: (1) the temperature coefficient for conditioning, (2) the time of the start of conditioning and (3) the temperature profile after the start of conditioning.

Calculations were performed assuming that conditioning started at 90–95% of rigor development although at that time there was little evidence for this. Later evidence suggested that this was correct (Locker and Wild, 1982) and their conclusion was valid in that most, if not all, of the tenderising was due to advancement of the start of conditioning at slightly higher temperatures. Later work (Takahashi *et al.*, 1984) suggests that the tenderising may have been caused by fracture of fibres brought about by tetanic contractions induced by high voltage stimulation. It showed that, sometimes (not always) low frequency (2 Hz) stimulation, which caused less fracture, made meat less tender than high frequency (50 Hz). However, it has not been shown how fibre fracture relates to tenderness, and also, if fracturing affects tenderness, why there is no permanent tenderising. Rapid glycolysis, with or without electrical stimulation, also causes tenderising (Martin *et al.*, 1983). It seems then that the tenderising effect of electrical stimulation in the absence of cold shortening is due to the advancement of the start of conditioning and acceleration of its rate at higher temperatures. The extent of tenderising would therefore depend upon the rate of glycolysis, the temperature at the start of conditioning (full rigor), the subsequent time/temperature profile and the time when tenderness was measured. In five beef muscles, stimulated and held at 15 °C for 7 h and then at 1 °C, the tenderness of control non-stimulated muscles at 10 days was achieved in 7 days following low voltage (85 V). Only 3 days were required when high voltage (700 V) stimulation was used (Taylor *et al.*, 1984).

3.2.6 At chill temperatures

The bulk of investigations to determine the time required for the tenderising changes to take place in beef have been carried out in North America. Deatherage and Harsham (1947) investigated the changes in beef at 0.5–2 °C and found that the tenderness of cooked sirloin (longissimus dorsi) increased up to 17 days storage with some additional improvement up to 31 days. They concluded that unless beef is to be aged beyond 4 weeks, it need be aged only 2.5 weeks. Doty and Pierce (1961) also showed that conditioning for 2 weeks at 0.5–2 °C improved texture and caused very substantial reductions in the shear strength of cooked meat, but much less change occurred during the next two weeks.

Most studies have shown that the major improvement in tenderness occurs in less than 14 days. Larmond *et al.* (1969) compared beef aged at 1 °C for 2, 9 and 16 days. They found that samples stored for 9 days were tenderer than those stored for 2 days, but samples stored for 16 days were not more tender than those stored for 9 days. Steinhilf and Weniger (1966) showed that the transformations in the muscle necessary to give meat its highest eating quality were achieved by storing at 2–4 °C for 8–14 days, no significant improvement taking place between 12 and 19 days. In a study by Martin *et al.* (1971) in which more than 500 animals were examined, it was

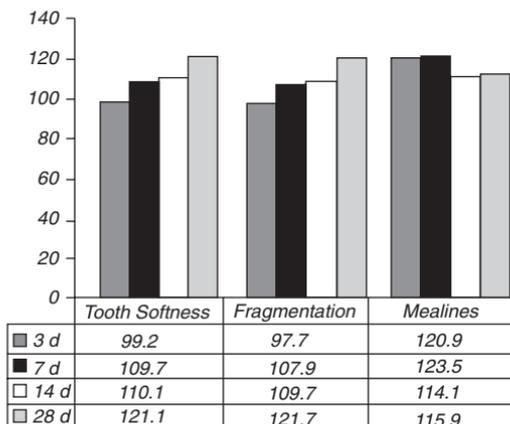


Fig. 3.4 Mean sensory scores for loin steaks after different ageing periods (source: Huff and Parrish, 1993).

concluded that for beef carcasses, a period of 6 days is sufficient for a consumer product of satisfactory tenderness. Buchter (1970) also showed that no significant increase in tenderness occurs after 4–5 days for calves and 8–10 days for young bulls at 4°C.

However, a more recent study by Huff and Parish (1993) shows a different pattern. Strip loins were removed from carcasses *ca.* 24h post-mortem, vacuum packed and held at 2°C for up to 28 days. Samples were removed after 3, 7, 14 and 28 days. Sensory scores for tooth softness and fibre fragmentation showed little difference between 7 and 14 days of ageing (Fig. 3.4). However, there were substantial differences between 3 and 7 days and between 14 and 28 days. Average Warner–Bratzler shear force values decreased with length of ageing with the biggest decrease from 2.8 to 2.3 kg cm⁻² occurring between 14 and 28 days.

3.2.7 At frozen temperatures

Increasing the delay period before freezing enhances tenderness because meat ages at chill temperatures but not at normal freezer temperatures. Meat which has been conditioned prior to freezing is more tender than that frozen within 1 or 2 days and the difference is maintained throughout frozen storage for 9 months (Table 3.5).

Freezing rate affects the rate of tenderising after thawing (Table 3.6) but not the ultimate tenderness. Freezing at -10°C more than doubles the rate; freezing in liquid nitrogen almost trebles the rate. Freezing is known to cause structural damage by ice crystal formation. It seems likely that ice crystals, particularly small intracellular ice crystals formed by very fast freezing rates, enhance the rate of conditioning probably by release of

Table 3.5 Effect of conditioning time on the tenderness of beef

| Conditioning time (days) prior to freezing | Period of frozen storage (months) | | | |
|---|-----------------------------------|-----|---------------------------------|-----|
| | 1 | 9 | 1 | 9 |
| | Cooked after thawing | | Cooked from the frozen state | |
| 4 | 5.6 | 4.3 | 5.7 | 4.6 |
| 14 | 6.8 | 6.7 | 6.9 | 6.7 |

Note: Sections of eye muscle (*M. longissimus dorsi*) were aged at 3 °C, frozen at -20 °C and thawed at 10 °C. Numbers are the mean taste panel scores (scale: 1, extremely tough to 9, extremely tender).

Source: Jakobsson and Bengtsson, 1973.

Table 3.6 Effect of rate of freezing on the conditioning rate at 1 and 15 °C after thawing

| Treatment | Freezing time (min) from -1 to -7 °C | Conditioning temperature | |
|---------------------------------|---|--------------------------|-------------|
| | | 1 °C | 15 °C |
| Not frozen | | 0.14 (0.03) | 1.01 (0.13) |
| Frozen at -10 °C | 45 | 0.16 (0.04) | 2.59 (0.61) |
| Frozen in liquid N ₂ | 0.2 | 0.39 (0.07) | 2.99 (1.40) |

24 hours after slaughter, slices of beef *M. semitendinosus* were frozen in air at -10 °C and in liquid nitrogen, stored for 2 h at -10 °C and then thawed in air at 15 °C for 60 min. Thawed meat was conditioned for up to 25 days at 1 °C or 7 days at 15 °C. Values are rate constants (day⁻¹) with standard errors.

Source: Dransfield, 1986.

enzymes (Dransfield, 1986). Repeated freeze-thaw cycles using relatively low freezing rates do not seem to cause any enhanced tenderising (Locker and Daines, 1973). This enhancement of conditioning resolves the apparent anomaly, reported by Hiner *et al.* (1945), that freezing did not affect tenderness of aged beef but increased it in unaged or partially aged beef.

3.2.8 At higher temperatures

After the onset of rigor, the muscle temperature has the largest effect on the rate of conditioning. From zero up to 40 °C the rate increases about 2.5-fold for every 10 °C rise in temperature (Ewell, 1940; Dransfield *et al.*, 1980a; Davey and Gilbert, 1976). Above 60 °C the rate drops rapidly due to enzyme denaturation (Davey and Gilbert, 1976). In beef therefore which achieves 80% of the tenderising in 10 days at 0 °C, 4 days would be required at 10 °C and only 1.5 days at 20 °C.

3.3 Influence of chilling on texture

3.3.1 Lamb

The small size of a lamb carcass makes very rapid chilling possible in modern refrigerated installations.

In a study by Bailey (Taylor *et al.*, 1972) two cooling regimes were compared; in the rapid condition the centre of rib-eye muscle and of the leg muscle reached 10°C in 3 and 5 h, respectively, and in the slow condition after 27 and 28 h. Meat from these treatments was cooked and judged in direct comparison by a trained taste panel using eight-point scales, four degrees of tender and four degrees of tough, and the mechanical strength of the cooked meat was measured on a shearing device. The results showed that a drastic increase in the toughness of the meat resulted from the rapid cooling. The difference between the rapid and slow treatments was found directly after chilling and was maintained after 5 days ageing at 0°C. The lamb treated normally (slow cool, conditioned) was judged to be close to 'very tender' by the panel, whereas the rapidly cooled meat was two whole scale divisions lower at 'slightly tender'. Before ageing, descriptions were at 'moderately tender' and 'slightly tough', respectively. Since the meat came from young English lambs, a texture score of 'very tender' would be expected, and 'slightly tender' would be regarded as the lower desirable limit. The mean score of 'slightly tough' would indicate a high proportion of definitely unacceptable carcasses. The mean shear values showed a close correspondence with the panel results.

These results show that chilling of lamb carcasses without freezing can be sufficiently rapid to produce toughness in the rib-eye muscle. They show too that such toughening can be considerable, especially if rapidly cooled carcasses were to be distributed quickly to reach consumers without a conditioning period after processing.

3.3.2 Pork

Although pork carcasses are not much larger than lamb, the problem of cold shortening is not so acute in this species. First, the rate of fall in pH in pig muscle is much more rapid than in lamb hence the critical conditions for cold shortening are less onerous. Second, the pig generally has a much thicker layer of subcutaneous fat and the retention of this with the skin on the carcass slows the rate of cooling. Finally, the scalding and scraping manipulations extend the processing time and delay the start of cooling. It appeared in the 1970s that little danger could arise in the normal handling of pork carcasses (Rhodes, 1972). However, studies in the 1980s (James *et al.*, 1983; Gigiél and James, 1984) clearly showed that rapid chilling could produce tougher pork.

In pork muscles, cold shortening is observed if temperatures between 3 and 5°C are reached before the onset of rigor, which in normal glycolysing

Table 3.7 Comparison of weight losses and organoleptic parameters from pig sides electrically stimulated or not chilled under different regimes

| Treatment | ES | Sarcomere length (μm) | Panel toughness |
|---------------|-----|------------------------------------|-----------------|
| Rapid cooling | Yes | 1.85 | 4.30 |
| | No | 1.89 | 3.8 |
| Conventional | Yes | 1.92 | 4.57 |
| | No | 1.99 | 4.47 |

Source: Taylor *et al.*, 1995b.

pork muscle lasts 3–8 h depending on the muscle and the breed (Honikel, 1990). Taylor *et al.* (1995a) showed that rapid cooling of pork sides (-20°C , $1\text{--}1.5\text{ m s}^{-1}$ for 2–3 h followed by 1°C , 0.5 m s^{-1}) produced tougher pork than conventionally cooled meat (Table 3.7).

ES, hip suspension and conditioning have been found to alleviate the toughening affect of rapid chilling of pork. Dransfield *et al.* (1991) found that stimulation improved tenderness but increased drip and paleness, but both effects were reversed by rapid chilling. Pelvic suspension reduced drip and improved tenderness to the same magnitude as stimulation. Taylor and Tantikov (1992) found ES (700 V peak at 12.5 Hz for 90 s) 20 min post-slaughter improved the tenderness of the l. dorsi and to a lesser extent the semimembranosus of rapidly chilled pig sides. This advantage was gained without producing PSE pork as shown by the lower drip losses from the ES sides.

Taylor *et al.* (1995b) showed that even under conventional chilling conditions a form of toughening that can be avoided by electrical stimulation occurs. Their data also clearly show that pork can benefit from up to 12 days of conditioning.

There are potential problems in hot boning of pork. Møller and Jensen (1993) reported that pork loins excised 1 hour post-mortem and then cooled in air at $2\text{--}4^{\circ}\text{C}$, 0.2 m s^{-1} had a similar texture to conventionally cold boned loins. Loins excised at the same time but cooled in iced water showed signs of cold shortening. These results are not surprising since the conventional cooling treatment used air at -18°C , 3.0 m s^{-1} for 65 min before transfer to a room at $2\text{--}4^{\circ}\text{C}$, 0.2 m s^{-1} . A temperature of 10°C was reached in the control loins in *ca.* 3 h compared with 7 h in the hot-boned loins (cooled at $2\text{--}4^{\circ}\text{C}$) and 2.5 h for those in iced water. Similarly, Ivensen *et al.* (1995) showed that hot boning pork carcasses, 1 h post-stunning, and cooling in iced water produces significant toughening. After 7 days of conditioning at 2°C the tenderness was still not acceptable. Boning at 6 h post-stunning and conditioning produced an acceptable product.

Table 3.8 Cooling rates of beef sides in moving air at 0°C. Temperature measured at centre of rib-eye muscle

| Air speed (m s ⁻¹) | Number of sides | Mean wt of sides (kg) | Time for rib-eye to reach 10°C (h) |
|--------------------------------|-----------------|-----------------------|------------------------------------|
| 0.5 | 12 | 141 | 10.7 |
| 1.0 | 17 | 146 | 10.1 |
| 2.0 | 13 | 146 | 8.3 |
| 3.0 | 13 | 143 | 7.3 |

Source: Rhodes, 1972.

3.3.3 Beef

As in lamb, cold shortening can be readily induced in all muscles of a beef carcass by rapid cooling before rigor, and the critical conditions of 10h to 10°C apply equally (Rhodes, 1972). The cooling of the larger carcass can not be so rapid, however this is offset by splitting into sides.

When considering the possibility of cold shortening in beef sides it is important to know the thickness of the layer of tissue below the surface which has been cooled to 10°C in 10h (or less). The thickness of this layer will, of course, vary over the carcass; it will be thinner where there is a bulk of underlying tissue, for example on the round, and thicker at the flank. The presence of interstitial fat layers will also exert a considerable influence.

Measurements made at the centre of the rib-eye muscle have shown that at an air temperature of 0°C and air speeds of 2.0 and 3.0 m s⁻¹, the cooling rate is sufficient to expose the whole muscle to cold shortening. Such air speeds are greater than that usually achieved on average in commercial practice, which is more closely reflected in the results at 0.5 and 1.0 m s⁻¹ (Table 3.8). These results showed that the time taken for the centre of the eye muscle to reach 10°C was just outside the critical limit for cold shortening. However, this infers that the remainder of the muscle, which will cool more rapidly than the centre, was adversely affected, the outer layer most certainly.

3.4 Influence of freezing on texture

Other sections in this chapter have dealt with the biochemistry of rigor and the excessive shortening which may occur in meat frozen pre-rigor which causes toughening. In this section the main concerns are:

1. whether freezing of carcasses can be rapid enough to reduce the eating quality;
2. the freezing conditions which are required to maintain good eating quality.

Table 3.9 Effect of delay in the time before freezing on the toughness of lamb

| Cuts | Muscles | Delay time (h) | | | | |
|------------|----------------|--------------------------------|------|------|------|------|
| | | 0 | 5 | 10 | 16 | 24 |
| | | Toughness values (0–120 units) | | | | |
| Loin | LD | 73.4 | 70.3 | 56.1 | 41.3 | 25.5 |
| Leg/fillet | BF, SM, ST, GM | 54.1 | 44.0 | 46.5 | 28.0 | 21.4 |
| Shoulder | IS, SS, TB | 17.8 | 14.8 | 16.3 | 13.6 | 13.8 |

Sides from 60 carcasses were delayed at 18 °C for up to 24 h before freezing at about -18 °C with air velocity 500 ft min⁻¹. Cuts were roasted directly from the frozen state, dissected into LD, *M. longissimus dorsi*; BF, *M. biceps femoris*; SM, *M. semimembranosus*; ST, *M. semitendinosus*; GM, *M. gluteus medius*; IS, *M. infraspinatus*; SS, *M. supraspinatus*; TB, *M. triceps brachii* muscles and the average toughness was calculated for each of the cuts.

Source: McCrae *et al.*, 1971.

3.4.1 Lamb

Smith *et al.* (1968) found that lamb frozen at about -20 °C had tougher loin chops and leg roasts but more tender rib chops than unfrozen lamb. No difference in the palatability of lamb loin, leg and liver has been found when frozen slowly or rapidly (Lampitt and Moran, 1933; Brady *et al.*, 1942).

Modern freezing plants can freeze the entire lamb carcass in 6 h thus freezing all the meat in a pre-rigor state. The effect of rapid freezing on the toughness of the cooked meat can be seen from the results of work carried out by McCrae *et al.* (1971) (Table 3.9). Two points are evident: first that early freezing toughened some parts of the carcass more than others and second, that the induced toughness decreased as the delay in the time before freezing was increased. A toughness value of 40 units was stated to be the minimum acceptable level. It was therefore evident that some parts of the carcass would be made unacceptable by freezing within 24 h after death if cooked directly from the frozen state.

The effect of storage condition on the toughness of lamb loins cooked after thawing was investigated at the MRI (Dransfield, 1974). Lamb carcasses were frozen soon after slaughter and the loins stored at -30 °C or -3 °C. The former temperature was chosen to prevent the progress of rigor compared with the latter. Meat held at -30 °C was tough (Table 3.10). When held at -3 °C for 6 days before thawing, the loins became acceptably tender but were still slightly tougher than control unfrozen loins (Table 3.10). Thus toughening caused by thaw rigor was avoided by a holding period just below 0 °C. Such a storage temperature is not used in normal commercial handling of frozen meat. However, a sufficient period for rigor resolution may be attained unwittingly by temperature rises during transportation and handling, and the major toughness caused by thaw rigor would be avoided.

Table 3.10 Effect of storage temperature on the toughness of lamb eye muscle

| | Pre-rigor cooling | | |
|--------------------------|-------------------|-----------|---------------|
| | Rapid freezing | | Slow chilling |
| Storage temperature (°C) | -30 | -3 | +1 |
| Toughness (kgf) mean | 6.26 | 3.37 | 2.13 |
| range | 5.12-9.04 | 1.76-4.78 | 1.65-3.13 |

One side of each of four carcasses was frozen at -40°C with air velocity 5 m s^{-1} . After 24 h, the loins were halved and stored for a further 6 days at -30°C or -3°C . Each of the other sides were slowly chilled and stored for the same period at 1°C . The sections were thawed at room temperature before cooking and the toughness determined on seven replicate samples taken from the *M. longissimus dorsi*. Only the meat with toughness values of 4 kgf or less was acceptable to all panellists.

Source: Dransfield, 1974.

3.4.2 Pork

The larger pork carcass, with its greater insulation of fat, cools more slowly than lamb and this, in combination with the faster onset of rigor, means that the meat is unlikely to be frozen pre-rigor. Toughness caused by thaw shortening (which produces tough lamb) is not encountered in pork. However, exposure to freezing temperatures would cool the carcass rapidly and produce cold shortening and equally tough meat after cooking. Unlike meat frozen pre-rigor, the toughness due to cold shortening cannot be adequately removed by subsequent storage conditions.

3.4.3 Beef

DuBois *et al.* (1940) showed that freezing times (from 0 to -10°C in the centre of 1.4 kg cuts of meat) of greater than 8 h toughened the meat, whilst shorter freezing times down to 1 hour improved the tenderness. However, in all these studies, the material used was of good quality and the freezing rate accounted for only 16% of the variation in tenderness (Hankins and Hiner, 1940). At about the same time, Lampitt and Moran (1933), Brady *et al.* (1942) and others found no differences in the palatability of beef frozen slowly or rapidly. Similar results were obtained for beef slices frozen at 0.04 , 2 and 13 cm h^{-1} which corresponded to freezing times of about 19 h, 23 min and 4 min, respectively (Jakobsson and Bengtsson, 1973). The latter authors noted that the slowest rate tended to cause toughening (Table 3.11). It has also been reported that the tenderising effect of faster freezing rates disappeared after storage for 6 months (Nicholas *et al.*, 1947; Hankins and Hiner, 1941).

It is generally agreed that there is a progressive toughening of meat during frozen storage. The cause of this toughening is uncertain but its development is unaffected by the freezing rate and is retarded at lower

Table 3.11 Effect of freezing rate, frozen storage and thawing conditions on beef tenderness

| Treatment | | Tenderness scores within treatments | |
|--------------------------------------|------|-------------------------------------|------------------------------|
| | | Cooked after thawing | Cooked from the frozen state |
| Freezing rate (cm h^{-1}) | 13 | 6.0 | 6.0 |
| | 2 | 6.0 | 6.2 |
| | 0.04 | 5.6 | 5.8 |
| Storage time (months) | 1 | 6.2 | 6.3 |
| | 9 | 5.5 | 5.7 |

Sections of eye muscle (*M. longissimus dorsi*) were frozen at -20°C and thawed at 10°C . Tenderness scale: 1, extremely tough to 9, extremely tender.

Source: Jakobsson and Bengtsson, 1973.

temperatures, such that, at -20°C , beef cuts are still tender after storage for 9 months (Table 3.11).

3.5 Influence of thawing on texture

It might be expected that slow thawing, like slow freezing, would have a detrimental effect on eating quality by increasing the time spent at the thawing temperature, but such an effect has only been demonstrated with very long thawing times. Beef frozen post-rigor and thawed before cooking has similar tenderness to that thawed rapidly by cooking directly from the frozen state (Table 3.5 and Table 3.11). This has been found with beef, pork and lamb steaks (Brady *et al.* 1942). A similar study with beef, pork and lamb patties Causey *et al.* (1950) found only small differences attributable to the thawing method. It was noted that judges tended to prefer pork and lamb patties that were cooked directly from the frozen state. Although cooking directly from the frozen state may be convenient for steaks, to produce adequate cooking in larger pieces of meat, cooking times may have to be increased by 50%. Repeated freeze-thaw cycles of freezing and thawing are unlikely to affect the subsequent rate of tenderisation (Dransfield, 1994). The process of freezing and slow thawing has been found to improve the tenderness of deer meat (Drew *et al.*, 1988) by 10–40% when compared with unfrozen.

3.6 Conclusions

- 1 The rate of cooling, the length of time and the temperature during conditioning are the most important refrigeration factors controlling the texture of meat.

- 2 Rates of conditioning vary widely among species. The time for 80% of the tenderising at 1 °C for beef is 10 days, lamb 7.7 days and pork 4.2 days. Since the time for distribution is typically only 3 days, a time should be deliberately allocated to complete the conditioning process in beef, lamb and pork.
- 3 It seems, at least for beef, that there are only small, if any, differences in the rate of conditioning between muscles. Therefore no cut can be stored for shorter periods and obtain the same proportion of conditioning.
- 4 The extent of tenderising varies with muscle length. In cold shortened meat little or no tenderising occurs. Cold shortening toughness therefore cannot be reversed by even prolonged storage.
- 5 Over the range of 0–40 °C, the rate of conditioning increases about 2.5-fold for every 10 °C rise in temperature. Above 60 °C the rate drops rapidly due to enzyme denaturation and is therefore arrested during cooking.
- 6 Cold shortening sets in during the chilling of lamb and beef muscles if the conditions are such that the temperature has fallen below 11 °C before the pH has fallen below 6.2. In pork cold shortening occurs if temperatures between 3 and 5 °C are reached before the onset of rigor (normally 3–8h).
- 7 To allow a safety margin and taking into account the fact that some carcasses will show high initial pH values in the eye muscle, it is recommended that lamb or beef carcasses should not be chilled below 10 °C until at least 10h after slaughter. Only under these conditions can optimal tenderness be ensured.
- 8 The severity of cold shortening is highly pH dependent, being much greater at pH 6.8 (i.e. exceptionally rapid chilling) than at pH 6.2 (i.e. at an easily attainable commercial rate of chilling).
- 9 Cold shortened muscle is tougher after cooking than unshortened muscle, the toughness increasing with the degree of shortening (up to a limit of about 40% of the initial length).
- 10 Freezing merely delays conditioning. Conditioning stops on freezing, continuing on thawing. Freezing lamb, pork or beef carcasses shortly after slaughter can produce very tough meat after cooking. Normal commercial handling of frozen meats cannot reliably make such meat acceptable to the consumer.
- 11 Storing chilled carcasses or cuts of meat for more than one day before freezing enhances the tenderness. The maximum tenderness is obtained by conditioning beef for 10 days and lamb for 4 or 5 days prior to freezing.
- 12 Freezing cuts of meat over a wide range of conditions has little effect on the eating quality.

3.7 References

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4

Colour changes in chilling, freezing and storage of meat

The appearance of meat at its point of sale is the most important quality attribute governing its purchase. The ratio of fat to lean and the amount of marbled fat are important appearance factors and another is the colour of the meat. The changes in colour of the muscle and blood pigments (myoglobin and haemoglobin, respectively) determine the attractiveness of fresh red meat, which in turn influences the consumers acceptance of meat products (Pearson, 1994). Consumers prefer bright-red fresh meats, brown or grey-coloured cooked meats and pink cured meats (Cornforth, 1994).

Reviews of the affect of chilling and freezing on the colour of meat were carried out by MacDougall in 1972 and 1974, respectively. The principle factors governing colour changes from those reviews have been included in this chapter.

4.1 Meat colour

Objects appear coloured when some wavelengths of light are selectively absorbed. Meat looks red because it absorbs all other colours other than red, which is reflected. When meat is examined in reflected light its colour will depend on (1) the nature of the illuminating light, and (2) changes taking place during reflection. Light sources contain a varying spectrum of intensities and wavelengths and meat viewed in tungsten light, for example, will appear redder because of the abundance of red light produced by the source. The physical structure of the meat and the chemical changes to the pigment govern the changes taking place during reflection.

Table 4.1 Main form of pigment found in uncured meat

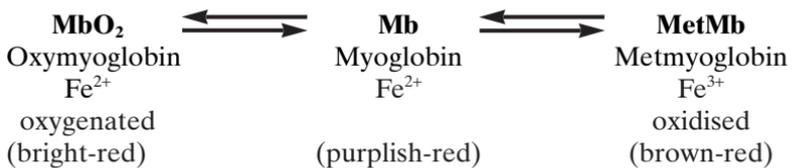
| Pigment | Colour |
|------------------------------|------------|
| Reduced myoglobin | Purple |
| Oxymyoglobin | Bright red |
| Metmyoglobin | Brown |
| Denatured globin haemichrome | Brown |

Source: MacDougall, 1972.

Instrumental measurements of meat colour are usually expressed in terms of 'lightness', 'hue' and 'saturation'. 'Hue' is the psychological appreciation of colour describing purple to red to orange to yellow, and so on and 'saturation' is the lack of greyness or increase in purity (MacDougall, 1972). The principles of colour measurement for food are described by MacDougall (1993) and instrumental measurement of meat colour is reviewed by Warriss (1996).

Myoglobin is the primary meat pigment and exists as bright-red oxymyoglobin (MbO_2), purple-red deoxymyoglobin (Mb), or brown metmyoglobin (MetMb). Haemoglobin which is responsible for the colour of blood plays only a small role in the colour of red meat, although it may be more significant in paler meat (Bendall, 1974). For example, in back bacon, about 40% of the colour intensity is attributable to haemoglobin and 60% to myoglobin. In most beef muscles myoglobin is by far the more dominant pigment, whereas in the calf 20–40% of the total is haemoglobin. The main forms of the pigments found in uncured meat are given in Table 4.1.

The purple colour of freshly cut meat is due to the deoxymyoglobin. On exposure to air, it is converted to the bright red pigment oxymyoglobin, which gives fresh meat its normal desirable appearance. The brown colour of cooked meat is due to denatured globin haemichrome. In extreme conditions the pigment can decompose and green choleglobin and colourless bile pigments are formed.



The depth of the oxymyoglobin layer is controlled by several factors, the more important of which are the duration of exposure (Brooks, 1929), the temperature (Urbin and Wilson, 1958) and the oxygen tension (Brooks, 1929; Landrock and Wallace, 1955; Rikert *et al.*, 1957). Other important factors are the diffusion of the oxygen through the tissue (Brooks, 1929), and its utilisation.

tion in the tissue (Watts *et al.*, 1966). At low partial pressures of oxygen, oxidation to brown metmyoglobin occurs (George and Stratmann, 1952) and the desirable red colour is lost. Such conditions occur, for example, at the limit of oxygen penetration in meat at the oxymyoglobin myoglobin boundary. Metmyoglobin can be converted back to myoglobin (Stewart *et al.*, 1965; Watts *et al.*, 1966) by the products of enzymic activity, if present (Saleh and Watts, 1968). The pigment status, therefore, depends on the balance between enzymic activity, oxygen tension and oxidation.

4.2 Factors affecting the colour of meat

4.2.1 Live animal

The pigment concentration in meat is affected by many factors affecting the live animal. These include:

- 1 Species – beef for example contains substantially more myoglobin than pork.
- 2 Breed.
- 3 Age – pigment concentration increases with age.
- 4 Sex – meat from male animals usually contains more pigment than that from female animals.
- 5 Muscle – muscles that do more work contain more myoglobin.

There are also two specific meat defects, dark, firm, dry (DFD) and pale, soft, exudative (PSE) associated with the live animal that result in poor meat colour. DFD meat has a high ultimate pH and oxygen penetration is low. Consequently, the oxymyoglobin layer is thin, the purple myoglobin layer shows through and the meat appears dark. In PSE meat the pH falls while the muscle is still warm and partial denaturation of the proteins occur. An increased amount of light is scattered and part of the pigment oxidised so that the meat appears pale.

4.2.2 Chilling

Red colour is more stable at lower temperatures because the rate of oxidation of the pigment decreases. At low temperatures, the solubility of oxygen is greater and oxygen-consuming reactions are slowed down. There is a greater penetration of oxygen into the meat and the meat is redder than at high temperatures.

Changes in colour have been reported resulting from chilling treatment. Taylor *et al.* (1995) found that electrical stimulation of pork produced higher lightness (L), i.e. paler, values than those measured in non-stimulated sides. Spray chilling of pork has some effect on its colour during the initial chilling period (Feldhusen *et al.*, 1995a). After 4 h of chilling, the musculature of sprayed ham becomes lighter and red and yellow values

decrease. However, after 20 h there is no significant difference in the colour values. The surface of the skin becomes lighter after spray chilling.

4.2.3 Conditioning

Newly cut conditioned meat is known to show a brighter surface after a short exposure to air than unconditioned meat (Doty and Pierce, 1961; Tuma *et al.*, 1962; 1963). MacDougall (1972) studied the effects of conditioning on colour and on subsequent storage in packages of high oxygen permeability typical of those used for display and in vacuum packages of low oxygen permeability. The average colour values for the selection of muscles are given in Table 4.2 along with the statistical significance of the colour differences. Meat, when cut and exposed to air, changed from dull purple red to a bright cherry red, which is measured as an increase in 'lightness', a 'hue' change towards red and an increase in 'saturation'. The magnitude of the change on blooming for conditioning meat as compared with unaged was the same size for 'lightness' but was two-fold greater for 'hue' and three-fold greater for 'saturation'. Conditioned meat, when freshly cut, was lighter but more purple than the unconditioned. After 1 h exposure to air, conditioned meat had a redder 'hue' which was considerably more saturated and intense than the unconditioned samples. These changes in lightness, hue and saturation produced by conditioning result in a brighter, more attractive appearance. The overall colour improvement was of a similar magnitude to that which occurred on blooming.

Conditioned meat is superior to unconditioned because of its eating quality and bloomed colour. However, this improved colour is not maintained on subsequent packaging for retail display. Both the improvements in the colour of conditioned meat when freshly cut and the faster accumulation of metmyoglobin can be accounted for by the diminution of the meat's enzymic activity which occurs during the conditioning process:

First, a thick layer of oxymyoglobin forms in conditioned meat because of the lowering of the rate of oxygen consumption and oxygen therefore penetrates faster and further into the tissue. Second, metmyoglobin formed

Table 4.2 Effect of conditioning for up to 22 days on meat colour when cut and after 1 h exposure to air at 2 °C

| Colour when freshly cut | Lightness | Hue | Saturation |
|----------------------------|-----------|------|------------|
| Unaged | 28.1 | 22.9 | 15.6 |
| Conditioned | 29.7 | 18.0 | 16.0 |
| Colour after bloom for 1 h | | | |
| Unaged | 28.8 | 24.2 | 17.3 |
| Conditioned | 30.3 | 21.4 | 21.4 |

Source: MacDougall, 1972.

in the region of low oxygen tension is no longer converted back to myoglobin. The band of metmyoglobin below the surface is established sooner and any advantage in appearance conditioned meat could have over unconditioned is soon lost as the brown band displaces and dilutes the surface oxymyoglobin layer.

The difference in the mechanism of brown discolouration in packages of high and low oxygen permeability, is that in the former metmyoglobin is formed several millimetres below the surface, while in the latter it appears on the surface.

Boakye and Mittal (1996) observed that the lightness of longissimus dorsi muscle increases with the length of conditioning. The change was greatest over the first 2 days and then became almost linear with time at a decreased rate. Similar effects were observed in total colour difference, brightness difference and hue difference. Yellowness decreased between 2 and 4 days of conditioning and then increased.

4.2.4 Chilled storage

The muscle surface of fresh meat undergoes extensive oxygen penetration and oxygenation of myoglobin after short periods of exposure to air. The length of time meat is kept in chilled storage has an effect on the rate of colour change during retail display. Feldhusen *et al.* (1995b) showed that there were clear colour changes after exposure in beef longissimus dorsi muscle stored for up to 5 days at 5°C. The degree of lightness (L), percentage of red (a) and percentage of yellow (b) all increased by 3–4 units. The colour of meat stored for longer periods showed less intense colour changes during 5 h of exposure.

Bacterial activity is another factor in pigment changes in fresh meat (Faustman *et al.*, 1990). The primary role of bacteria in meat discolouration is the reduction of oxygen tension in the surface tissue (Walker, 1980). Initial oxygen concentrations in packaging over approximately 0.15% will seriously compromise the colour stability of both beef and lamb (Penney and Bell, 1993). Pork appears able to tolerate oxygen concentrations above 1% without obvious detrimental effect during short-term storage at chilled temperatures.

Gill and McGinnis (1995) have shown clearly that control of both storage temperature and oxygen content are required to stop colour deterioration in controlled atmosphere storage of beef. Samples were packaged in either N₂ or CO₂ containing oxygen at concentrations between 100 and 1000 ppm. The colour of samples of longissimus dorsi, which has a high colour stability, had deteriorated after 4 h at either 5 or 1°C. Samples stored at -1.5°C with oxygen concentrations ≤400 ppm had not deteriorated after 48 h. At 0°C samples deteriorated after 24 h at >200 ppm and 48 h at 100 ppm O₂. Beef muscles with low colour stability discoloured under all conditions.

4.2.5 Freezing

The colour of frozen meat varies with the rate of freezing. Taylor (1930, 1931) reported that as the speed of freezing diminished, the appearance of the product changes and at very low rates there is a marked development of translucence. Later experiments have demonstrated a direct relationship between freezing rate and muscle lightness; the faster the rate the lighter the product. Guenther and Henrickson (1962) found that 2.5 cm thick steaks frozen at -9°C were dark. Those frozen at -34 to -40°C had the most desirable colour and those frozen at -73 to -87°C tended to be pale. Jakobsson and Bengtsson (1969, 1973) obtained similar results; very rapid freezing in liquid nitrogen spray at a freezing rate of about 13 cm h^{-1} produced meat which was unnaturally pale. Air blast freezing at 2 cm h^{-1} gave the best frozen appearance while very slow freezing at 0.04 cm h^{-1} resulted in a darker colour and the formation of ice on the product surface. Zaritzky *et al.* (1983) reported that the surface of liver frozen at high rates was lighter in colour. These differences in frozen meat lightness result from the dependence of ice crystal growth on the freezing rate. Small crystals formed by fast freezing scatter more light than large crystals formed by slow freezing and hence fast frozen meat is opaque and pale and slow frozen meat is translucent and dark.

Meat frozen at -55°C or lower need not be pale (Tuma, 1971). If exposure time to liquid nitrogen is based on thickness of the product its appearance at an equilibrated temperature of -18°C can be assured (Bernholdt, 1971).

Studies have been carried out using freezing times, from -1 to -7°C , of 1–37 minutes which are believed to represent the range of times found at the surface in normal blast freezing operations (Lanari *et al.*, 1989). No effect of freezing rate on colour within this range was found. These results were similar to those of Jul (1984) who stated that the colour of beef was not affected by variations in freezing rate between 0.2 cm h^{-1} (still air freezing) and 5 cm h^{-1} (quick frozen).

In addition to the rate of freezing, the duration of exposure to air prior to freezing is important. Lentz (1971) found that blast freezing at -30°C produced a frozen product similar in appearance to fresh beef if exposed to air for 30 min before packaging and freezing. Freezing before or after the development of optimum 'bloom' affected the appearance of the frozen material adversely. Tuma (1971) also bloomed meat for 30 min before packaging, but suggested that 5–10 min might be adequate.

4.2.6 Frozen storage

'Freezer burn' is the main appearance problem that traditionally affected the appearance of meat in frozen storage. Desiccation from the surface tissues produces a dry, spongy layer that is unattractive and does not recover after thawing. This is commonly called 'freezer-burn'. It occurs in

unwrapped or poorly wrapped meat. The problem is accentuated in areas exposed to low humidity air at high velocities, and by poor temperature control. Since most meat is now wrapped and temperature control much improved this is less of a problem than it once was commercially. Provided problems of freezer burn can be eliminated, the major appearance problem that affects frozen meat arises from oxidation of oxymyoglobin to metmyoglobin.

Both temperature and illumination level affect the rate of discolouration during frozen storage, but light is by far the more serious factor. Townsend and Bratzler (1958) found that frozen beef steaks stored under fluorescent light (60 dekalux) discoloured in 2–3 days at -18°C . Lane and Bratzler (1962) found that metmyoglobin formation in frozen extracts of meat was similar to the pattern seen in frozen steaks and was increased by exposure to fluorescent illumination. Tuma (1971) showed that the acceptable storage life of *M. longissimus dorsi* beef steaks was 3–4 weeks at -26°C under fluorescent illumination (110 dekalux) although colour changes could be seen within 7 days. *M. psoas major* steaks were unacceptable under these conditions within 7 days.

Lentz (1971) reported the progress of discolouration in the light (160–220 dekalux) and in the dark for frozen beef stored at a range of temperatures in terms of the Munsell colour notation. The prefreezing colour of most samples in the study was 7.5R 4/8. Based on the notation, this means that the hue was 7.5 Red, which is an intermediate step between Red and Yellow-Red. The lightness was 4 on a scale where 10 is white and 0 is black, and the chroma or saturation was 8 on a scale which ranges from 0 (neutral or grey) to about 12 (intense or strong). During frozen storage the chroma decreased and the hue became more yellow, producing a brown appearance. A chroma of 6 at a hue of 7.5–10R is no longer an attractive meat colour but is greyish red to reddish brown. The time from freezing to reach a chroma of 6 is shown in Table 4.3 where the effect of temperature and

Table 4.3 Effect of storage temperature and light on the colour stability of frozen beef

| Temperature ($^{\circ}\text{C}$) | Time after freezing to reach Munsell Chroma 6 (days) | |
|------------------------------------|--|-----------------|
| | No light | 160–220 dekalux |
| -7 | 3 | 1 |
| -18 | 60–90 | 3 |
| -29 | 60 | 7 |
| -40 | 90 | 7 |

Munsell Chroma immediately after freezing was 8 to 10.
Source: MacDougall, 1974 after Lentz, 1971.

light on colour stability is clearly seen. At -18°C , a temperature typical of good commercial display, the colour remained attractive for 3 months in the dark but only 3 days in the light.

The relationship between frozen storage temperature and oxidation rate was studied by Zachariah and Satterlee (1973) for purified bovine, ovine and porcine myoglobins. When the rates were measured between -5°C and -27°C , it was found that they were highest at -11 to -12°C and lowest below -18°C . The autoxidation of porcine myoglobin was faster than ovine or bovine myoglobin. Porcine myoglobin is precipitated by freezing which leads to the conclusion that the more rapid rate for this protein is due to a combination of autoxidation and precipitation. The results indicate that the red colour in frozen beef, pork and lamb can best be preserved if the temperature is less than -18°C . Ledward and MacFarlane (1971) showed that metmyoglobin formation and lipid oxidation both depend upon the treatment meat receives prior to and during frozen storage. Meat frozen promptly was most stable while meat that had been subjected to cyclic thawing was least stable. Thus, it is desirable during prolonged aerobic frozen storage to avoid both delay in freezing and any subsequent thawing and refreezing of the surface.

Lanari *et al.* (1994) have shown that dietary vitamin E supplementation improved pigment and lipid stability of frozen beef stored under illumination and in the dark at -20°C . These results complemented their earlier publication (Lanari *et al.*, 1993) which showed that the colour of control samples of longissimus lumborum deteriorated in 1 day compared with 11 days for treated samples stored in the dark. Under an illumination of 1614 lux the treated samples deteriorated after 38 days. The advantages of using vitamin E supplementation in the extension of chilled and frozen storage life was reviewed by Liu *et al.* (1995).

Vacuum packaging of frozen beef increases colour stability maintaining metmyoglobin levels lower than those found in just frozen samples wrapped in polyethylene (Lanari *et al.*, 1989).

The storage life of precooked frozen meat, for example sliced roast beef and pork, can be extended if the slices are covered with gravy prior to freezing (Jul, 1969). The gravy acts as a barrier to oxygen and protects against surface changes and oxidation.

4.2.7 Thawing

Although the freezing rate has a marked effect on the colour of the frozen product it does not affect the lightness of the meat when thawed, with the exception of meat which has been very slowly frozen. Jakobsson and Bengtsson (1969, 1973) found that slowly frozen beef, which also darkened on freezing, showed considerable loss of redness after thawing. In contrast, meat frozen in liquid nitrogen and then defrosted was a light bright red. Little difference was also found between thawed beef steaks which were

frozen at 15 cm h^{-1} in liquid nitrogen spray and those which were blast frozen at 4 cm h^{-1} (Pap, 1972). In both cases, they were frozen to the same final temperature of -30°C . However, the bloomed meat before freezing was redder than the same material after thawing.

In thawed meat, the rate of pigment oxidation is increased (Cutting, 1970) and therefore the colour will be less stable than when fresh. On prolonged frozen storage, a dark brown layer of metmyoglobin may form 1–2 mm beneath the surface so that on thawing the surface colour will rapidly deteriorate. Meat which has lost its attractiveness during frozen storage because of oxidation of oxymyoglobin on the surface will remain brown after thawing.

Unwrapped meat thawed in high humidity air, water or in steam under vacuum appears very white and milky after thawing. However, if then stored in a chill room for 10–24 h it will be almost indistinguishable from fresh meat. Unwrapped meat thawed in air at high temperatures and low humidities will take on a dark, dry, tired appearance. It will not recover its appearance during chilled storage and will often require extensive trimming before sale.

4.2.8 Retail display

4.2.8.1 Chilled

During refrigerated display, oxymyoglobin oxidises to brownish green metmyoglobin (MacDougall, 1993). Twenty per cent dilution of surface oxymyoglobin with metmyoglobin causes the product to be rejected at retail because of its faded colour (Hood and Riordan, 1973).

The colour stability of fresh meat is influenced to a very marked degree by the temperature of display. Landrock and Wallace (1955) showed that meat held at 2°C in packaging films whose oxygen permeability is greater than $5000\text{ ml m}^{-2}\text{ atm}^{-1}\text{ day}^{-1}$ will remain attractive for 4 days. In practice, commercial display cabinets are not controlled to maintain their contents at near freezing temperatures; meat temperatures during display at times may exceed 10°C (Malton, 1971, 1972). Heiss and Eichner (1969) showed that the rate of discolouration is roughly doubled for a 5°C rise in temperature, while Buck and Peters (1970) demonstrated that the rate of colour deterioration is dependent upon the temperature of the meat, which in turn is dependent upon location within the showcase. Similarly, MacDougall and Malton (1972) also found that the rate of colour change is influenced by position in the showcase and temperature differences of the order of 5°C have a large effect on the rate of colour change. For example, a change in redness, which takes 72–168 h at 0°C , will occur in 24–48 h at 5°C .

The discolouration rate is also different for different muscles. MacDougall and Malton (1972) found, for example, that the fillet discoloured faster than the loin. Similar observations were made by

Table 4.4 Relationship between evaporative weight loss and appearance of sliced beef topside after 6h display

| Evaporative loss (g cm ⁻²) | Change in appearance |
|---|---|
| up to 0.01 | Red, attractive and still wet; may lose some brightness |
| 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 |

Source: Swain and James, 1986.

Hood (1971) who showed that the rate of metmyoglobin formation on the surface of these muscles was different. The increase in the rate of discolouration with an increase in temperature is explained by the lowering of the solubility of oxygen in the meat (Urbin and Wilson, 1958) and the faster formation of metmyoglobin (George and Stratmann, 1952) nearer the surface.

Changes in appearance are normally the criteria which limit display of unwrapped products, rather than microbiological considerations. Deterioration in the appearance of unwrapped meats has been related to the degree of dehydration (Table 4.4) which makes the product unattractive to consumers.

4.2.8.2 *Frozen*

The major problem in retail marketing of frozen meat is its appearance. The freezing process causes changes in the structure and colour of the muscle, and the deterioration in appearance during frozen storage and display ultimately leads to rejection of the product by the consumer. Storage temperature, light intensity on the display area and method of packaging all affect the rate of deterioration. The appearance of fresh meat is a primary factor in acceptability at retail level and the same criteria of attractiveness will apply to frozen meat, retailed either frozen or after thawing. The poor colour of the frozen product and the drip associated with it when it thaws, have in the past both contributed to consumer resistance.

The problem of light-catalysed pigment oxidation remains the largest single problem in the display of frozen meat. It can be overcome by opaque packaging in cartons, but the trade and consumer have to develop a very high level of mutual trust for it to be accepted. Where it has been tried in the past (Trieb, 1971) sales of meat packed in cartons were less than those in transparent film.

Frozen imported carcass meat has been an item of commerce in the United Kingdom for almost a century and its retail marketing is an established part of the meat trade. Consumer satisfaction is evident by the

demand and acceptance of New Zealand lamb although the colour of the product in the frozen state is different from that when fresh. Frozen beef similarly differs from fresh and is often extremely unattractive when displayed for sale in the frozen state. However, if it is allowed to partly thaw and bloom during display its attractiveness improves. Undoubtedly the price differential between frozen and fresh meat is an important factor in the acceptance of the frozen product by the consumer.

The appearance of frozen meat is markedly improved if retail sized portions are first packed in film to exclude air between the meat surface and the film and then rapidly frozen. With this product, however, the price differential between fresh and frozen would necessarily be small and the consumer would have to be persuaded by the trade that such frozen meat was in no way inferior to fresh.

4.3 Conclusions

- 1 Consumers prefer bright-red fresh meats, brown or grey-coloured cooked meats and pink cured meats.
- 2 Myoglobin is the primary meat pigment and exists as bright-red oxymyoglobin (MbO_2), purple-red deoxymyoglobin (Mb), or brown metmyoglobin (MetMb).
- 3 Red colour (oxymyoglobin) is more stable at lower temperatures because the rate of oxidation of the pigment decreases. At low temperatures, the solubility of oxygen is greater and oxygen-consuming reactions are slowed down. There is a greater penetration of oxygen into the meat and the meat is redder than at high temperatures.
- 4 Conditioned meat is a brighter and more attractive red than unconditioned meat but its colour stability becomes progressively poorer the longer it is conditioned.
- 5 Commercial refrigerated display temperatures require close control if maximum shelf-life is to be obtained. Meat display temperatures of -1°C would be ideal, but the higher temperatures commonly found limit shelf-life to 2 days or less.
- 6 Very fast freezing rates can potentially affect the colour of meat. However, the range of rates available commercially are unlikely to have a significant effect on colour.
- 7 Provided problems of freezer burn can be eliminated, the major appearance problem that affects frozen meat arises from oxidation of oxymyoglobin to metmyoglobin. Both temperature and illumination level affect the rate of discolouration during frozen storage, but light is by far the more serious factor.
- 8 Surface condensation during thawing results in a milky appearance which disappears during chilled storage.
- 9 Drying during thawing results in a darkening from which the meat does not recover.

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5

Influence of refrigeration on evaporative weight loss from meat

From the moment an animal is slaughtered the meat produced begins to lose weight by evaporation. Under typical commercial distribution conditions, it has been estimated that lamb and beef lose from 5.5 to 7% by evaporation between slaughter and retail sale (Malton, 1984). Weight losses from pork are probably of the same magnitude. In addition to the direct loss in saleable meat there are also secondary losses. Excessive evaporation during initial chilling and chilled storage produces a dark unattractive surface on the meat. Either this has to be removed by trimming, or the meat is down-graded and sold at a reduced price.

Freezing does not stop weight loss. After meat is frozen, sublimation of ice from the surface occurs. If the degree of sublimation is excessive, the surface of the meat becomes dry and spongy, a phenomenon called 'freezer burn'. In the United States, weight loss resulting from a combination of direct evaporative loss and freezer burn in pork bellies stored for one month before curing was estimated to be 500 000 kg (Ashby and James, 1974). Since that report, developments in the use of moisture imperious packaging materials have significantly reduced sublimation in frozen meat.

Over 4 000 000 tonnes of meat and meat products are sold in the UK per year (MAFF, 2000). A very conservative estimate is that the use of existing technology in the field of refrigeration could reduce evaporative loss by at least 1%. This would result in a minimum saving to the UK meat industry of £60 000 000 (€96m) per annum.

In this chapter the theoretical factors that govern evaporative loss are briefly discussed. Comparisons are then made between weight losses in commercial practice and those resulting from the use of more closely controlled refrigeration techniques throughout the cold chain. The data for this

comparison have been obtained from the available literature, and from an unpublished survey and experimental information gathered by the MRI (Meat Research Institute at the Institute of Food Research, Bristol Laboratory (IFR-BL)). In the concluding section, areas and systems that require further investigations are discussed.

5.1 Theoretical considerations

The rate at which a piece of meat loses weight through its surface depends upon two related processes: evaporation and diffusion. Evaporation is the process that transfers moisture from the surface of the meat to the surrounding air. Diffusion transfers water from within the meat to its surface.

The rate of evaporation (M_e) from the surface of a food is given by Dalton's law:

$$M_e = mA(P_m - P_a) \quad [5.1]$$

where m is the mass transfer coefficient, A the effective area and P_m and P_a the vapour pressure at the surface of the meat and in the surrounding air, respectively.

If each term in the right-hand side of the equation is examined in turn, the difficulty of predicting the rate of mass transfer from a meat carcass or joint becomes apparent. In most systems a value for the mass transfer coefficient is not obtained directly, but by analogy with the overall surface heat transfer coefficient (h). Some work has been carried out to measure m and h simultaneously (Kondjoyan *et al.*, 1993). The surface heat transfer coefficient itself is a function of the shape of the body and the properties of the medium flowing over it. It can be calculated for simple shapes, but must be obtained experimentally for irregular bodies such as meat joints and carcasses. Arce and Sweat (1980) carried out one of the most comprehensive reviews of publishing values of h for foodstuffs. However, only 4 references relate to meat and these cover a very limited range of refrigeration conditions. It is well established for forced air conduction systems that h becomes larger as air velocity increases. Therefore, all other factors being equal, weight loss will increase as air velocity increases.

The effective area A can be difficult to measure, for example, the surface area of an irregular shape such as a meat carcass. In many commercial situations joints and/or carcasses are packed tightly together making an estimate of the 'effective' area even more problematic. Even meat blocks contain a number of irregularly shaped pieces of meat and do not normally present flat continuous surfaces to the air stream. Only in limited applications such as plate freezing or thawing can an accurate estimate be made of the effective surface area.

P_a is a function of both air humidity and temperature and values are readily available in standard text books. P_m is dependent upon the rate of diffusion and thus difficult to determine. After slaughter and flaying, free

water is present on the surface of a carcass and the P_m can be assumed to equal that of saturated vapour at the same temperature as the surface. As the surface cools, water evaporates and this assumption only remains true if the rate of diffusion is high enough to maintain free water at the surface. Investigations in South Africa (Hodgson, 1970) reported that during chilling of a beef side only a part of the surface remained saturated throughout the operation. After flaying, the surface apparently dried, reaching maximum dehydration after *ca.* 10h when only 70% of the surface was wet. Diffusion then gradually restored free water to the surface until, after 20h under the test conditions, 90% of the surface was wet. There was no definition of 'wet' in the paper but we interpret the statement to mean that after 10h the rate of evaporative loss was 70% of that from a saturated surface at the same temperature. No other published work relating to carcasses has been located, but Australian experiments (Lovett *et al.*, 1976) on small samples produced a similar pattern. There is a short initial phase, when the rate of evaporation is the same as that from free water. This is followed by a decreased rate of evaporation below the value expected from a water surface and a final phase where the surface is progressively rewetted. However, Daudin and Kuitche (1995), predicted weight loss from pork carcasses assuming a fully wetted surface to a stated accuracy of 0.1%.

A simple examination of Fick's law gives an indication of the problems in calculating the rate at which diffusion can occur through meat. It states that:

$$M_d = KA\delta C \quad [5.2]$$

Where M_d is the rate diffusion of water, K is the diffusion coefficient and δC is the concentration gradient.

Meat is a non-homogeneous material consisting of fat, lean and bone and even these three elements are heterogeneous within themselves. Lean, commercially the most important component, is the muscle tissue of the live animal and consists of fibre bundles and connective tissue. The fibres have a preferred orientation, and diffusion coefficients and concentration gradients vary with this orientation and the presence of barriers of different permeability within and between muscles. The rate of diffusion cannot therefore be predicted with any great degree of accuracy.

5.2 Weight loss in practice

In this section the unit operations present in a meat distribution chain, chilling, chilled storage and display, freezing and frozen storage, are considered from the point of view of weight loss. Since the majority of the loss tends to occur during chilling, it is given greater consideration than the other processes.

5.2.1 Chilling

Immediately after slaughter the surface of the carcass is hot (*ca.* 30 °C) and wet so the rate of evaporation is high. Pork carcasses lose 0.4% moisture between 0.5 and 1.0 h post-mortem when held at approximately 15 °C (Cooper, 1970). Spray-washed lamb carcasses show an even greater rate of weight change, *ca.* 1.0%, during this time (James, unpublished work). Consequently, the time at which initial hot weight is obtained is crucial in all weight loss measurements. The majority of carcasses in the UK are chilled in a single stage system, pork at a nominal temperature of 4 °C, air velocity of 0.4 m s⁻¹, 85–90% relative humidity (RH), lamb and beef at 0 °C, 0.5 m s⁻¹, 85–90% RH. In practice the majority of chill rooms have under-powered refrigeration plants and are overloaded, so the rooms take several hours to reach their designed operating conditions. Typical weight losses in these single stage systems for beef are 2–3.5%, for lamb 2–2.8%, and for pork 1.8–3.5%.

In a single stage chilling process, the factors in equation [5.1] that can be controlled by the refrigeration designer are P_a and m , since both are a function of air humidity and temperature. Humidity is controlled by the temperature difference (ΔT) across the evaporator coil. There are two ways of designing a coil to extract the same amount of heat: it can either have a very large surface area and a small ΔT , or a small area and a large ΔT . The former is expensive but produces air at a high humidity, whilst the latter is cheap but dries the air. If we assume that in the initial stages of chilling the surface of a carcass is saturated and is above 30 °C, then in air at 0 °C, 90% RH, $P_m - P_a = 0.054$ bar, and at 70% RH, $P_m - P_a = 0.055$ bar. The initial effect of RH on weight loss is therefore small, but as cooling proceeds, P_m reduces and RH becomes increasingly important. Hodgson (1970) in South Africa showed that beef sides cooled for 20 h in air at a temperature of 1.7 °C, and velocity of 0.75 m s⁻¹ lost 2.75% in weight at 90% RH, and 3.4% at 70% RH, i.e. a 0.65% difference. Hodgson also stated that the maximum return on investment was achieved using a large coil with a ΔT of 5 °C. Since that time the price of beef has risen faster than the capital and the running costs of refrigeration equipment, and it is probable that the ΔT for a maximum return is now even smaller.

The lower the air temperature the faster the rate of fall of the surface temperature, which controls the maximum value of P_m . Lower air temperatures should therefore reduce weight loss during chilling. Beef sides of average UK weight (140 kg) lost 1.2% in air at 4 °C, 0.5 m s⁻¹, 90% RH and 0.2% less at 0 °C, 0.5 m s⁻¹, 90% RH when cooled to a maximum centre temperature of 10 °C (Bailey and Cox, 1976). The initial weight was recorded *ca.* 2 h after slaughter.

Since air velocity is directly related (via h), to the mass transfer coefficient it would seem from equation [5.1] that increasing the air velocity during chilling would produce a greater weight loss. However, higher air velocities also increase the rate of fall of surface temperature and hence

Table 5.1 Percentage weight loss from $15 \times 15 \times 2$ cm thick samples of lean mutton cooled from one side in air at $1-2^\circ\text{C}$, for a set time, at different air velocities

| Air velocity (m s^{-1}) | Cooling time (h) | |
|------------------------------------|------------------|------|
| | 4 | 22 |
| 3.7 | 1.64 | 4.11 |
| 1.4 | 1.60 | 3.25 |
| 0.56 | 1.67 | 3.03 |

Source: Lovett *et al.*, 1976.

Table 5.2 Percentage weight loss from $15 \times 15 \times 2$ cm thick samples of lean mutton cooled from one side in air at $1-2^\circ\text{C}$, to a set maximum temperature, at different air velocities

| Air velocity (m s^{-1}) | Final temperature ($^\circ\text{C}$) | | |
|------------------------------------|--|------|------|
| | 13 | 7 | 4 |
| 3.7 | 0.95 | 1.14 | 1.27 |
| 1.4 | 1.09 | 1.32 | 1.48 |
| 0.56 | 1.20 | 1.49 | 1.69 |

Source: Lovett *et al.*, 1976.

decrease ($P_m - P_a$), so the overall effect is not obvious. The results of experiments carried out on samples ($15 \times 15 \times 2$ cm thick) removed from freshly killed sheep (Lovett *et al.*, 1976), show that the effect depends upon the definition of the completion of chilling, either within a set time (Table 5.1), or to a given maximum temperature (Table 5.2).

Independent experiments using beef sides confirmed these findings. When chilling time was defined as that required to a set temperature (10°C in the deep leg), increasing air velocity from 0.5 to 1.0 m s^{-1} reduced weight loss by 0.15% (Cooper, 1970). When chilling for a set time (20 h), increasing the air velocity from 0.75 to 3 m s^{-1} increased weight loss from 2.75 to 3.3% (Hodgson, 1970).

Minimal weight loss during chilling is therefore attained by using the lowest temperature and highest humidity that are practically feasible, and the minimum air velocity needed to meet the temperature/time requirements. In single stage chilling the lowest temperature that can be used is -1°C to avoid freezing at the surface of the meat. Toughening resulting from rapid chilling ('cold shortening') limits the use of such methods with lamb and beef. To avoid cold shortening a number of systems have been introduced that involve an initial holding period at a high temperature, consequently increasing weight loss.

The same restrictions do not apply to pork since the presence of insulating fat layers and the more rapid rate of glycolysis minimises the likelihood of toughening. Harsher pork chilling treatments are quite common and in Denmark (Hermanson, personal communication) a two-stage system has been used in which the carcass is conveyed for 80 min through a tunnel, operating at -15°C , 3 ms^{-1} , then equalised for 12 h in a chill room at 4°C , 0.5 ms^{-1} with a very high RH. After the first stage the surface temperature of the carcass is below 0°C and moisture therefore condenses onto it in the initial part of the second stage. The average weight loss from 70 kg carcasses in such systems is claimed to be as low as 0.8% over the 14 h period.

Work at the MRI produced a single stage 3 h system for 70 kg pork carcasses using air at -30°C , 1 ms^{-1} (James *et al.*, 1983; Giegel and James, 1983). After chilling the average meat temperature is 0°C and the carcass can be band sawn into primal joints and vacuum packed for distribution. The overall weight loss at 5 days post-mortem was just over 1%. The principle advantage of such a system is that the chilling can be conveyorised. Since the overall process time can be reduced from 14 to 4 h, a three-fold increase in throughput can be achieved without a corresponding increase in chiller space.

Commercial trials of a similar system for beef sides using electrical stimulation to minimise cold shortening, then air at -15°C , 3 ms^{-1} for 6 h, showed an overall chilling loss of 0.8%. However, its application in the production of chilled meat is limited since a proportion of the muscle is frozen. A number of large abattoirs in the USSR (Sheffer and Rutov, 1970) used a two-stage chilling system for beef sides, 4–8 h in air at -10 to -15°C , 1 – 2 ms^{-1} followed by 6–8 h at -1°C and a moderate air velocity. Special jets were used to increase the air velocity over the thickest sections of the sides during the first stage and the overall weight loss was reported to be *ca.* 1%.

5.2.2 Chilled storage

Equation [5.1] also governs weight loss in chilled storage. Since there is no further requirement to extract heat from the product, the relative importance of the factors change and the air velocity should now be the minimum required to maintain a stable uniform temperature around the meat. Any increase in velocity will increase the rate of weight loss.

Since there will normally only be a small temperature difference between the meat and the air, it is clear from equation [5.1] that the effect of any change in RH will be marked. If both the air and the surface are at 0°C , and the surface is assumed to be saturated, a 10% change in RH will produce an equivalent change in the rate of evaporative loss.

In commercial storage, -1°C , 90% RH and 0.3 ms^{-1} represent near ideal conditions for minimal weight loss. Lower temperatures produce a risk of surface freezing, while a higher RH may reduce shelf-life because of faster

Table 5.3 Weight loss (% per day) from beef, lamb and pork carcasses stored at different relative humidities and temperatures

| | Temperature (°C) | % RH | % Loss |
|------|------------------|------|---------|
| Beef | 2 | 90 | 0.1–0.3 |
| | | 80 | 0.5 |
| Lamb | –1 | 90 | 0.5 |
| | | 94 | 0.2 |
| Pork | –1 | 95 | 0.2 |
| | | 85 | 0.5 |
| | | 75 | 0.8 |
| | 5 | 95 | 0.3 |
| | | 85 | 0.6 |
| | | 75 | 1.0 |

Malton and James, 1984.

Table 5.4 Percentage loss from stockinet-wrapped meat during freezing

| Freezing conditions | | |
|------------------------------|------------------|----------|
| Velocity (ms ⁻¹) | Temperature (°C) | Loss (%) |
| 0.3 | –30 | 0.7–1.2 |
| | –20 | 1.4–1.6 |
| | –12 | 1.2–2.6 |
| 1.5 | –28 | 0.6 |

Malton and James, 1984.

growth of micro-organisms in moist conditions. Table 5.3 shows the effects of different storage conditions upon weight loss from carcasses.

A direct consequence of equation [5.1] is that poor temperature control during chilled storage should increase weight loss, for example poorly designed automatic defrosting systems in storage rooms lead to periodic cycles of condensation and drying on meat (Malton, 1984). These cycles harden and darken the surface of the meat and necessitate extra trimming before sale. Overall losses from beef joints can be as much as 5% per day.

5.2.3 Freezing and frozen storage

The rate of sublimation of ice from a frozen surface is considerably slower than the rate of evaporation from a moist surface, and the ability of air to hold water rapidly diminishes as its temperature falls below 0°C. The consequent advantage of fast freezing and using low temperatures is shown in the survey summarised in Table 5.4.

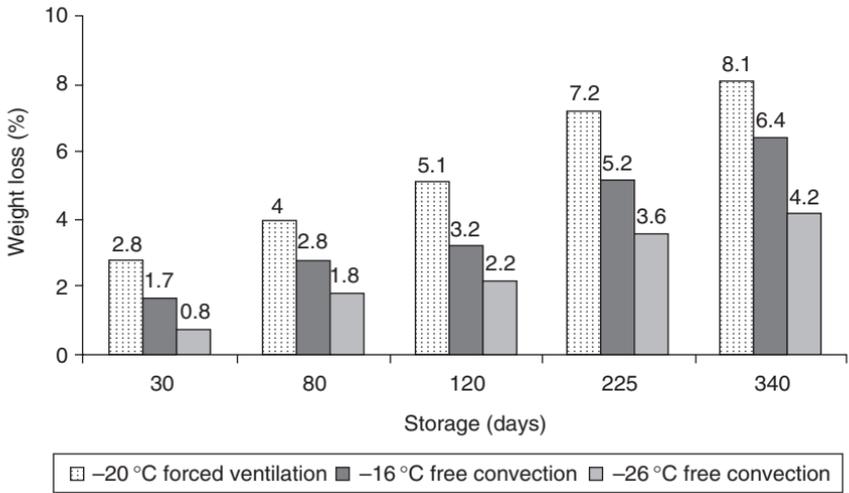


Fig. 5.1 Weight loss from unwrapped hams in frozen storage (source: Malton and James, 1984).

More meat is now wrapped in impervious material before freezing, but, despite popular belief to the contrary, such packaging does not completely eliminate weight loss. Evaporative losses from polyethylene-wrapped carcass meat frozen at -30°C are negligible, but losses of up to 0.5% have been recorded at -10°C . The slower freezing time allowed water to migrate from the meat to the inner surface of the polyethylene.

No published information has been located of the effect of RH on weight loss during frozen storage presumably because of the difficulty of measuring RH at temperatures below 0°C . Figure 5.1 shows clearly the detrimental effect of both air movement and high storage temperatures on weight loss. Although weight losses per day in frozen storage are small, storage times can be long with consequent overall losses as high as 10% (Roussel and Sarrazin, 1970). The importance of temperature control as well as actual temperature is supported by French experiments (Gac *et al.*, 1970). Lean beef stored in cartons at -11°C lost 20mgcm^{-2} when the temperature was controlled to $\pm 1^{\circ}\text{C}$, but the losses increased by over three-fold to 72mgcm^{-2} when the temperature fluctuated by $\pm 6^{\circ}\text{C}$. Both losses were measured over 220 days.

5.2.4 Retail display

During retail display meat is particularly vulnerable to evaporative losses. The surface of meat displayed (without refrigeration) either hanging from rails or on shelves rapidly warms, and then quickly loses weight in dry ambient conditions. The problem of rapid weight loss is exacerbated by fluctuations in temperatures and by draughts from doorways or fans.

Table 5.5 Percentage weight loss from unwrapped meat during display for 6 h

| | | Unrefrigerated | Refrigerated |
|------|--------|----------------|--------------|
| Lamb | Joints | 1.0 | 0.7 |
| Pork | Chops | 1.5 | 1.1 |
| Beef | Joints | 0.4 | 0.4 |
| | Slices | 1.5 | 1.2 |
| | Cubes | 1.9 | 1.5 |
| | Mince | 2.8 | 2.1 |

Source: Malton and James, 1984.

Although refrigerated display lowers weight loss (Table 5.5), the design of many cabinets has paid little or no attention to product evaporation. Improved designs should take greater account of the factors that control evaporation and could significantly reduce losses at this stage of distribution. For example, the importance of continuous refrigeration was shown in work where lambs cut into retail portions and displayed for 7 h under refrigeration lost 0.3% when refrigerated before cutting and 0.8% when not.

5.3 Overall

The previous sections have shown the importance of refrigeration and its control in minimising weight loss at various stages in the distribution chain. Table 5.6 estimates the total evaporative loss during cooling and distribution using information gathered from industry and published data. It shows clearly the importance of 'good' refrigeration design at all stages of the chilled distribution chain. However, it must be viewed with some caution since there is very little published information to indicate whether low initial weight loss could lead to higher weight loss at a later stage. Work in New Zealand (MIRINZ, 1983) shows a complicated relationship. Maximum freezing losses on lamb carcasses occurred when the previous chilling loss had been *ca.* 1%. Chilling losses both above and below this value resulted in lower losses during freezing. The minimum overall loss occurred in lambs that had experienced the minimum chilling loss.

Following the path of weight loss through total distribution chains requires further investigation. Limited data have been gathered for chilled lamb. Refrigerated carcasses lost 2.2% during a 24h chilling process increasing to a total of 3.4% after 3 days subsequent refrigerated distribution. Similar carcasses lost 3.1% during ambient cooling for 24h rising to 4.8% after a further 3 days of refrigerated distribution. This indicates that initial weight savings are maintained.

Table 5.6 Estimates of total evaporative losses (%) in cooling and distribution

| | Cooling | Storage | Transport | Shop store | | | Total |
|-----------------------|---------|---------|-----------|------------|-----|---------|-------|
| | | | | Carcass | Cut | Display | |
| Lamb | | | | | | | |
| Ideal refrigeration | | | | | | | |
| Days | 0.5 | 3 | 0.25 | 1 | 1 | 0.25 | 6 |
| Loss (%) | 1.2 | 0.6 | 0.1 | 0.2 | 0.5 | 0.3 | 2.9 |
| Typical refrigeration | | | | | | | |
| Days | 0.5 | 3 | 0.25 | 1 | 1 | 0.25 | 6 |
| Loss (%) | 2.0 | 1.5 | 0.1 | 0.5 | 0.9 | 0.6 | 5.6 |
| Unrefrigerated | | | | | | | |
| Days | 1 | 1 | 0.25 | 1 | 0.2 | 0.25 | 3.7 |
| Loss (%) | 3.7 | 3 | 0.2 | 2.0 | 1.5 | 1.5 | 9.2 |
| Beef | | | | | | | |
| Ideal refrigeration | | | | | | | |
| Days | 1 | 3 | 0.25 | 3 | 1 | 0.25 | 8.5 |
| Loss (%) | 1.4 | 0.3 | 0.1 | 0.3 | 1.0 | 0.6 | 3.7 |
| Typical refrigeration | | | | | | | |
| Days | 2 | 2 | 0.25 | 3 | 1 | 0.25 | 8.5 |
| Loss (%) | 2.5 | 0.6 | 0.1 | 0.9 | 1.5 | 1.5 | 7.1 |
| Unrefrigerated | | | | | | | |
| Days | 2 | 2 | 0.25 | 2.5 | 0.5 | 0.25 | 7.5 |
| Loss (%) | 3.8 | 4.0 | 0.2 | 4.0 | 1.5 | 2.0 | 15.5 |

Source: Malton and James, 1984.

5.4 Conclusions

- 1 Meat distributed without refrigeration loses twice as much weight as commercially refrigerated meat.
- 2 The best refrigeration systems found in industry produce a further two-fold reduction in weight loss when compared with the average.
- 3 Application of the best current established technology could probably save a further 1% weight loss.
- 4 In an industry where profits are low, typically 1–2% of the value of the throughput at the wholesale stage, the relative effect on profitability would be large.
- 5 Low temperatures and high relative humidity will minimise weight loss from unwrapped meat.
- 6 To minimise weight loss in chilling, the air velocity should be just sufficient to attain the desired chilling time.
- 7 A better understanding of water diffusion through meat and mass transfer from the surface are required before we can optimise refrigeration systems.

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Part 2

The cold chain from carcass to consumer

6

Primary chilling of red meat

6.1 Introduction

The increased application of temperature legislation in many countries, coupled with economic requirements to maximise throughput, minimise weight loss and operate refrigeration systems in the most efficient manner, has created a very large demand for process design data on all aspects of carcass chilling. Concurrently there has been a growing realisation of the importance of chilling rate on meat saleability, in terms of drip potential (see Chapter 2), appearance (see Chapter 4), and eating quality, particularly texture (see Chapter 3).

EU temperature legislation governs the chilling of beef, pork and lamb for the majority of abattoirs within the community. The only derogations are for very small abattoirs and for retail shops cutting meat for direct sale to the final consumer. The EC legislation does not define a chilling time, only a maximum final meat temperature of 7°C before transport or cutting.

Abattoir management and refrigeration contractors require reliable design data, relating processing variables to chilling time and weight loss, so that they can specify and design carcass cooling systems to meet differing requirements. To optimise fully such systems, knowledge is also required of the product heat load, and its variation with time, so that the refrigeration machinery can be sized to achieve the required throughput.

It is also important that the industry is made aware of a growing number of alternatives to conventional batch air chilling systems. Many of the alternative systems offer significant advantages in terms of increased throughput, lower costs and increased product quality.

6.2 Conventional chilling

The majority of carcass meat is chilled in conventional chill rooms nominally operating at one or sometimes two conditions during the chilling cycle. Most of the factors that control the chilling process are common to all species and are covered in the following section on beef. Specific considerations for sheepmeat, pork and offal are outlined in their respective sections.

6.2.1 Beef

This section brings together design data on many aspects of the chilling of beef sides. Effects of environmental, carcass and operational variables on the rate of chilling and evaporative weight loss in single stage air chilling systems are described in detail. Data are also presented on the rate of heat release from sides that are encountered in these cooling operations. Using conventional single stage chilling regimes it is evident that only relatively light (<105 kg), lean beef sides can be cooled to 7°C in the deep leg during a 24h operating cycle, whilst evaporative losses are of the order of 2%.

Despite the general absence of specific regulations for chilling time, the time required to cool a side to a specified maximum temperature is the most important commercial factor determining the cost and operation of a cooling system. If sides cannot be chilled within 18h, which is the time available in one day, making allowance for loading, unloading and cleaning, they will probably remain in chill for a further 24h. Chilling facilities will then have to be twice as large, with considerably increased capital investment and running costs. Some investigations on the continuous chilling of beef (Drumm *et al.*, 1992a,b) have been carried out but such systems are not widely used.

Increasing attention is now being paid to the reduction in energy consumption, but it has been shown that in commercial chilling operations the cost of evaporative weight loss in beef sides (Collett and Gigiél, 1986) are at least an order of magnitude higher than the energy costs.

Major investigations to provide such data have been carried out at Food Refrigeration and Process Engineering Research Centre (FRPERC), Langford (formerly the Meat Research Institute) (Bailey and Cox, 1976; Cox and Bailey, 1978) and at the National Mechanical Engineering Research Institute, Pretoria (Kerens and Visser, 1978; Kerens, 1981). Published information from these investigations and others has been brought together in this section together with some unpublished material.

6.2.1.1 Effect of environmental and carcass variables on cooling rate

Air temperature, air velocity, and to a limited extent, relative humidity, are the environmental factors that affect the cooling time of beef sides. Cooling rate will also be a function of the weight and fat cover of a given side.

6.2.1.1.1 Air temperature

The results of the programme on beef chilling carried out at Langford clearly show the importance of air temperature on cooling time (Bailey and Cox, 1976). For ease of use the results of the investigations have been presented as four plots of the logarithm of temperature against time covering a wide range of side weights (100–220 kg) and air velocities (0.5–3.0 ms^{-1}). Data for the slowest cooling area of the side, which was located by inserting a probe into the centre of the thickest section of the leg, are shown in Fig. 6.1 and can therefore be used to determine the environmental conditions required to attain a desired cooling time when a maximum final temperature has been specified. Potential surface freezing problems can then be evaluated from the surface temperature plots (Figs. 6.2 and 6.3). These in conjunction with the deep M. longissimus dorsi data (Fig. 6.4) also identify toughening problems and the possible requirement for electrical stimulation.

Cooling in air at a constant 4°C, compared with 0°C, at 3 ms^{-1} will increase the time to reach 7°C in the deep leg of a 100 kg side from 20.3 to 27.7 h (a 36% increase). At 0.5 ms^{-1} , the time for a 220 kg side to reach 7°C will increase from 45.9 to 68.3 h (a 49% increase). In systems designed to produce fully chilled sides, with average meat temperatures of 2–4°C, the requirement for low air temperatures becomes even more important because of the small meat/air temperature difference at the end of the process.

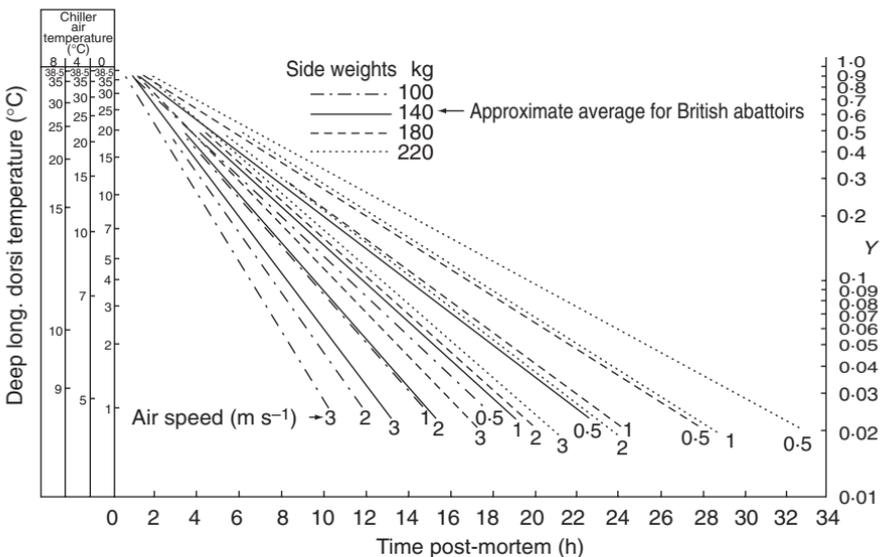


Fig. 6.1 Relationship between deep longissimus dorsi temperature and cooling time for beef sides (source: Bailey and Cox, 1976).

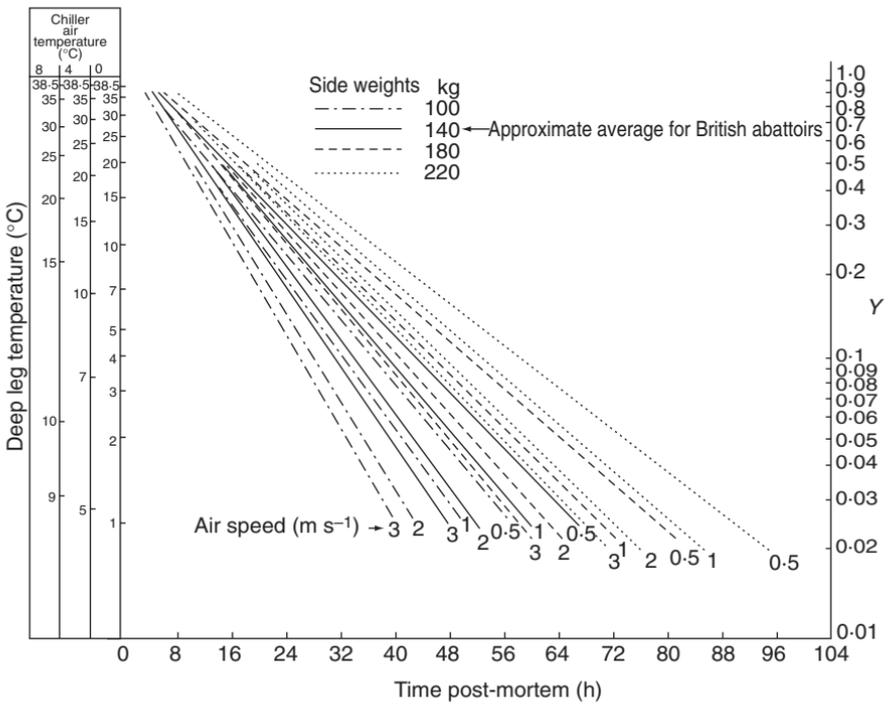


Fig. 6.2 Relationship between deep leg temperature and cooling time for beef sides (source: Bailey and Cox, 1976).

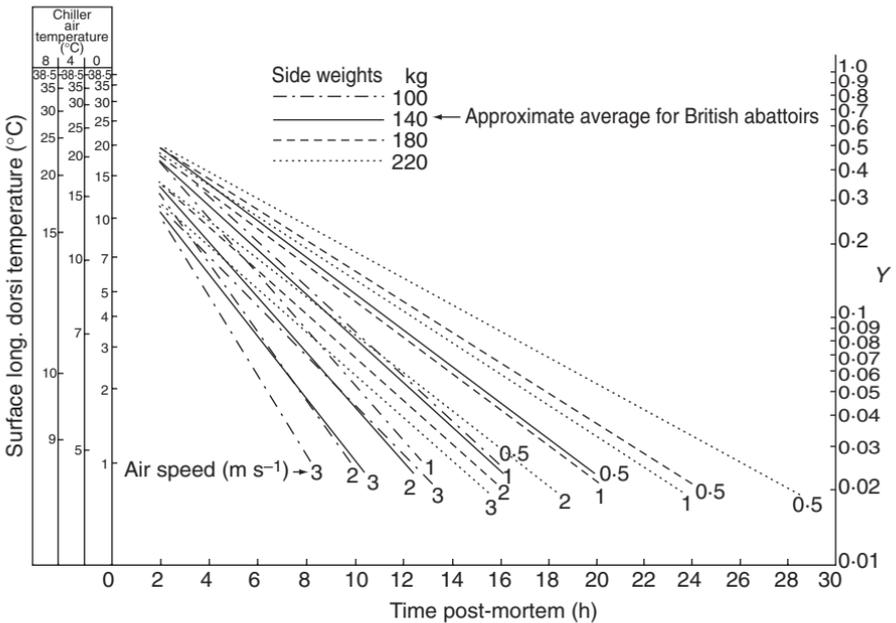


Fig. 6.3 Relationship between surface longissimus dorsi temperature and cooling time for beef sides (source: Bailey and Cox, 1976).

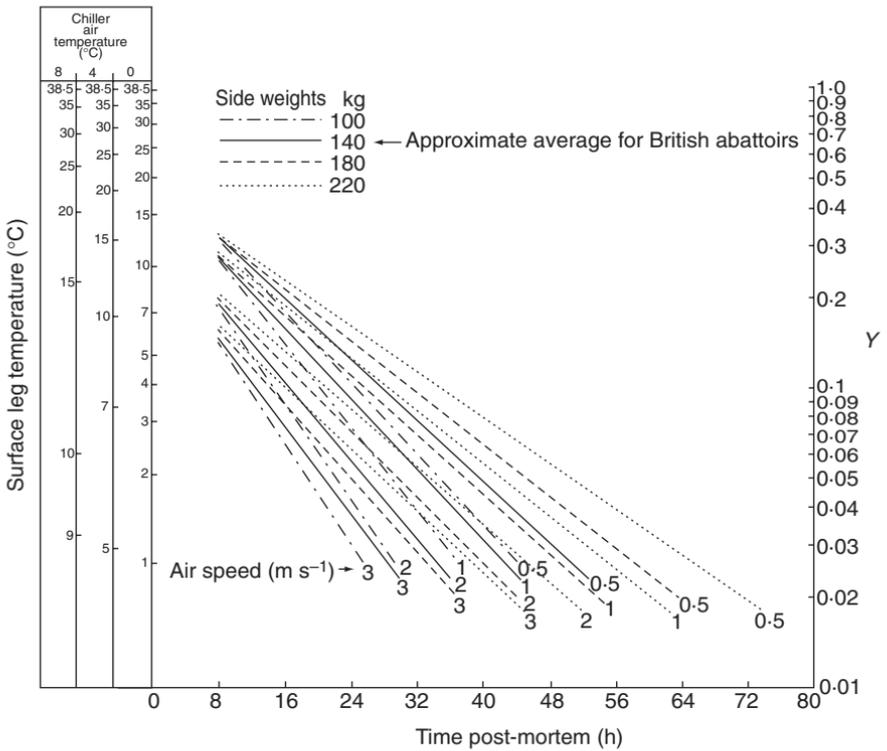


Fig. 6.4 Relationship between surface leg temperature and cooling time for beef sides (source: Bailey and Cox, 1976).

Provided air temperatures are chosen to avoid substantial surface freezing it is quite feasible to determine the cooling time for any other air temperature using Figs. 6.1 to 6.4. The fractional unaccomplished temperature on the Y axis can be replaced by the meat temperature calculated by:

$$Y = (t - t_f) / (t_i - t_f) \quad [6.1]$$

where t is the meat temperature, t_i is the initial meat temperature and t_f is the air temperature.

The experimental data used to produce the figures were obtained in powerful refrigeration systems where the initial temperature pull down period was minimal. Commercial systems with long pull down periods take considerably longer to cool because initial air temperatures are higher than the required design figure.

6.2.1.1.2 Air velocity

Increasing the air velocity during chilling produces a substantial reduction in chilling times at low air velocity but similar increases at higher velocities have a much smaller effect (Table 6.1).

Table 6.1. Chilling time (in h) to a deep bone temperature of 10°C in beef sides of 105 and 140 kg in air at 0°C, 95% relative humidity at air velocities from 0.5 to 3.0 m s⁻¹

| Reference | Side weight (kg) | Air velocity (m s ⁻¹) | | | | |
|-----------------------------|------------------|-----------------------------------|------|------|------|------|
| | | 0.5 | 0.75 | 1.0 | 2.0 | 3.0 |
| Kerens and Visser (1978) | 105 | 19.5 | 18.5 | 18.0 | 16.0 | 14.8 |
| Kerens and Visser (1978) | 140 | 24.1 | 22.8 | 21.8 | 19.7 | 18.5 |
| Bailey and Cox (1976) | 140 | 27.2 | – | 25.0 | 22.1 | 20.0 |

The power required by the fans to move the air increases with the cube of the velocity. A four-fold increase in air velocity from 0.5 to 2 m s⁻¹ results in a 4–7 h reduction in chilling time for a 140 kg side weight, but requires a 64-fold increase in fan power. Further increasing air velocity to 3 m s⁻¹ only achieves an extra 6–8% reduction in chilling time. In most practical situations it is doubtful whether an air velocity greater than 1 m s⁻¹ can be justified.

6.2.1.1.3 Relative humidity

A small number of investigations (Kerens and Visser, 1978) have shown that decreased relative humidity (RH) results in slight reduction in chilling time, apparently caused by increased evaporative cooling from the carcass surface. However, unless water is added to the surface of the carcass, any increase in the rate of evaporation will be directly reflected in a larger weight loss. It is therefore difficult to envisage a commercial situation where the installation of small, high temperature difference (TD) evaporators with attendant lower relative humidities would be economically viable.

6.2.1.1.4 Side weight

The marked effect of side weight on chilling time (Table 6.2) is a clear problem in chill room design and operation. In most practical situations it is impossible to load chilling systems with batches of matched weight sides or to remove sides in a weight-based order. A compromise must therefore be made between overcooling the light-weight sides and undercooling heavy sides. Overcooling can lead to excessive weight loss while undercooling can shorten shelf-life and overload the refrigeration systems of transport vehicles. Subsequent slow cooling in transport vehicles results in a further reduction in shelf-life.

6.2.1.1.5 Fat cover

It is difficult to separate the effect of fat cover from that of carcass weight. Experimental investigations are hampered because light animals tend to be

Table 6.2 Chilling time (in h) to 7°C in the deep leg of 50–220 kg beef sides in air at 0°C, 0.75 m s⁻¹ (source: Kerens and Visser, 1978) or 0°C, 1.0 m s⁻¹

| Conditions | Side weight (kg) | | | | | |
|-----------------------------|------------------|------|------|------|------|------|
| | 50 | 75 | 100 | 140 | 180 | 220 |
| 0°C, 0.75 m s ⁻¹ | 13.0 | 17.6 | 21.6 | 27.4 | – | – |
| 0°C, 1.0 m s ⁻¹ | – | – | 25.6 | 30.9 | 36.0 | 42.1 |

Source: Bailey and Cox, 1976.

lean and heavy animals fat. Comparisons can thus only be made over a limited weight range. In the Langford work (Bailey and Cox, 1976) using 140 kg sides in air at 0°C, 0.5 m s⁻¹, cooling times of the fattest carcasses were as much as 20% above the average and the leanest 20% below. In South Africa (Kerens and Visser, 1978) cooling times at 0°C, 0.75 m s⁻¹ for fat and lean sides of 100 kg were 24.5 and 19.0 h, respectively, and for 125 kg, 27 and 22 h, respectively.

6.2.1.2 Effect of environmental and carcass variables on weight loss

Weight loss is governed by the same variables that affect cooling rate but with different relative importance.

6.2.1.2.1 Air temperature

The effect of air temperature on evaporative weight loss during chilling is dependent upon the criteria used to define the end of the chilling process (Fig. 6.5). When chilling for a set time (18 h) weight loss increases as temperature decreases. The opposite effect is found when chilling to a set temperature (10°C in deep leg) with weight loss decreasing as the air temperature is lowered. However, the magnitude of the effect of air temperature on weight loss is small, as a reduction in air temperature from 4 to 0°C produces a change of <0.1% (Fig. 6.5) under either criteria.

6.2.1.2.2 Air velocity

The effect of air velocity is similar to that of air temperature. An increase from 0.5 to 3.0 m s⁻¹ made <0.1% difference to losses when sides were chilled to a deep leg temperature of 10°C. Increasing the air velocity from 0.75 to 3 m s⁻¹ raised weight losses by up to 0.2% when measured over an 18 h chilling period (Fig. 6.5). In a longer chilling cycle, the effect would be even more severe. Hence, there are considerable economic advantages to be gained in systems where the air velocity is reduced after the majority of the heat has been extracted from the carcasses (Gigiél and Peck, 1984). From this time on, the rate of cooling is then determined by thermal conductivity of the meat and not by the heat transfer coefficient at its surface. In Australia, the Meat Research Corporation (1995) recommends the use of infrared thermometry to automate this process. If the room is also

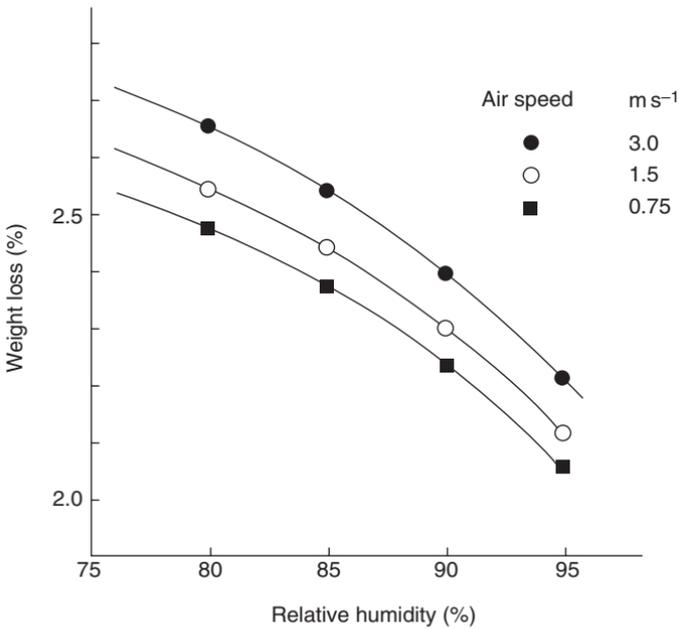


Fig. 6.5 Weight loss during 18h chilling at an air temperature of 0°C at different velocities and relative humidities (source: James and Bailey, 1990).

operated as a storage chill, for example over weekends, the need to operate at low air velocities to reduce weight loss and subsequent surface discolouration is even more important.

6.2.1.2.3 Relative humidity

Relative humidity has a greater effect on weight loss than either air temperature (see previously) or velocity (Fig. 6.5). Reducing relative humidity from 95 to 80% increased evaporative weight loss over an 18h chilling cycle at 0°C by nearly 0.5%.

6.2.1.2.4 Side weight

Percentage evaporative weight loss decreases as side weight increases (Table 6.3), the effect being marked at very low side weights (<100kg), but far less so at and above the average side weight for the UK (135kg).

6.2.1.2.5 Fat cover

It is clear from Fig. 6.5 that fat cover has a substantial effect on evaporative weight loss during an 18h chilling period. In the worst circumstances a very lean side with little or no fat cover can lose almost 1% more than sides of similar weight with a thick even covering of fat.

Table 6.3 Effect of side weight on evaporative weight loss (%) after cooling for 18 and 42 h at 0°C, 0.75 m s⁻¹ and 95% relative humidity

| Chilling time (h) | Side weight (kg) | | | | |
|----------------------|------------------|-----|-----|-----|-----|
| | 50 | 110 | 130 | 150 | 170 |
| 18 | 2.7 | 2.0 | 1.9 | 1.8 | 1.7 |
| 42 | 3.6 | 2.5 | 2.4 | 2.2 | 2.1 |

Source: Bailey and Cox, 1976.

6.2.1.2.6 Operational factors

Investigations have been carried out in a commercial chiller that was designed to operate in either (1) a slow chilling mode to avoid cold shortening or (2) a rapid chilling mode for a quick turnover and reduced weight loss. The work showed that operational factors are as important as technical specifications with respect to total weight loss (Gigiel *et al.*, 1989b). Over 50% of the variance in weight loss was accounted for by the difference in time that elapsed between death and hot weighing, whilst a further 11.8% was related to the time that elapsed between hot weighing and loading the beef side into the chiller.

6.2.1.3 Product loads

If specified cooling schedules are to be attained, refrigeration machinery must be designed to meet the required heat extraction rate at all times during the chilling cycle. Heat enters a beef chill room via open doors, via personnel, through the insulation, from lights and cooling fans, and from the cooling carcasses or sides. The product load is the major component of the total heat to be extracted from a fully loaded chill room (Collett and Gigiel, 1986).

The rate of heat release from a single side varies with time. It is at a peak immediately after loading and then falls rapidly. The peak value is primarily a function of the environmental conditions during chilling and is not substantially affected by side weights in the region of 120–140 kg (Kerens, 1981). In commercial systems, the peak load imposed on the refrigeration plant is also a function of the rate at which hot sides are introduced into the chill room. Increasing air velocity, decreasing air temperature or shortening loading time increases the peak heat load. There is a four-fold difference in peak load between a chill room operating at 8°C, 0.5 m s⁻¹ loaded over 8 h and the same room operating at 0°C, 3 m s⁻¹ and loaded over 2 h.

The average product load can easily be calculated by dividing the total enthalpy change during chilling by the chilling time. The ratios of peak to average (Table 6.4) and actual to average heat loads (Table 6.5) can be used both to determine compressor size and ascertain the heat loads during the later stages of chilling, when compressor off-loading might be required.

Table 6.4 Ratio of the peak to the average rate of heat release from 140 kg beef sides, for chiller cycle time of 24 h from 1 h post-mortem

| Chiller conditions | | Peak to average ratio Air speed (m s^{-1}) | | | |
|---------------------------------------|-----------------------|--|-----|-----|-----|
| Temperature ($^{\circ}\text{C}$) | Loading period (h) | 0.5 | 1.0 | 2.0 | 3.0 |
| 0 | 2 | 3.4 | 3.3 | 4.3 | 4.0 |
| 4 | 2 | 4.1 | 3.7 | 4.3 | 4.3 |
| 0 | 4 | 2.9 | 2.8 | 3.0 | 3.0 |
| 4 | 4 | 3.1 | 2.7 | 3.2 | 3.1 |
| 0 | 6 | 2.5 | 2.5 | 2.5 | 2.6 |
| 4 | 6 | 2.7 | 2.3 | 2.8 | 2.7 |
| 0 | 8 | 2.3 | 2.5 | 2.3 | 2.4 |
| 4 | 8 | 2.6 | 2.3 | 2.4 | 2.5 |

Source: Cox and Bailey, 1978.

Table 6.5 Ratio of actual to average heat load ratios for 140 kg beef side in air at 0°C , 1.0 m s^{-1} , for a chiller cycle time of 24 h from 1 h post-mortem

| Time after start of chill (h) | Heat load ratios at end of period shown | Time after start of chill (h) | Heat load ratios at end of period shown |
|----------------------------------|--|----------------------------------|--|
| 2 | 3.3 | 14 | 0.6 |
| 4 | 2.3 | 16 | 0.4 |
| 6 | 1.5 | 18 | 0.4 |
| 8 | 1.2 | 20 | 0.4 |
| 10 | 0.8 | 22 | 0.3 |
| 12 | 0.7 | | |

Source: Cox and Bailey, 1978.

Peak load data charts have also been produced in South Africa (Kerens, 1981) for two air temperatures (0 and 7°C), an air velocity of 0.75 m s^{-1} and 95% relative humidity. They are expressed in terms of peak heat loss rate against a loading rate in cattle units per hour. A cattle unit is defined as a whole carcass and the average whole carcass weight is 210 kg. In a typical South African situation a plant operating at 0°C , 0.75 m s^{-1} would be loaded over a 3 h period at a rate of 200 cattle units h^{-1} . The peak heat loss rate from the 600 carcasses would be 550 kW. It is stated that using three chill rooms, each with a capacity of 200 carcasses (400 sides), the fan power required would be 60 kW and the heat infiltration 105 kW, of which 90 kW infiltrates through the doors. Thus, the total peak load on the refrigeration plant would be 715 kW.

6.2.1.4 Cost of chilling operation

Data were obtained from a survey of 14 commercial beef chilling systems (Gigiel and Collett, 1990). They ranged in capacity from 18 000 to 93 000 kg

Table 6.6 Average ambient air temperature over survey. The energy used per kilogram of beef produced divided into the base demand and the product demand, and *the total energy consumption per kg adjusted to allow for a full chiller

| Chiller system identity number | Ambient air temperature (°C) | Base demand (kJ kg ⁻¹) | First 24h (kJ kg ⁻¹) | Second 24h (kJ kg ⁻¹) | *First 24h (kJ kg ⁻¹) | *For 48h (kJ kg ⁻¹) |
|--------------------------------|------------------------------|------------------------------------|----------------------------------|-----------------------------------|-----------------------------------|---------------------------------|
| 1 | 4.0 | 0.0 | 63.0 | 5.8 | 63.0 | 68.8 |
| 2 | 14.0 | 35.0 | 43.0 | 15.0 | 78.0 | 128.0 |
| 3 | 7.5 | 26.0 | 62.6 | – | 86.0 | – |
| 4 | 0.0 | 15.0 | 48.0 | 3.0 | 63.0 | 81.0 |
| 5 | 14.0 | 38.0 | 42.0 | 36.0 | 80.0 | 154.0 |
| 6 | 19.0 | 33.0 | 62.3 | 5.3 | 86.0 | 115.0 |
| 7 | 21.0 | 56.7 | 22.6 | 5.6 | 67.0 | 116.0 |
| 8 | 11.0 | 44.0 | 42.0 | 9.0 | 86.0 | 139.0 |
| 9 | 0.0 | 32.0 | 30.0 | 14.0 | 62.0 | 108.0 |
| 10 | 4.0 | 26.0 | 31.8 | 7.9 | 52.0 | 80.0 |
| 11 | 18.0 | 40.0 | 62.8 | 45.8 | 102.0 | 187.0 |
| 12 | 10.5 | 24.0 | 53.0 | – | 77.0 | – |
| 13 | 14.0 | 40.0 | 47.7 | 18.8 | 86.0 | 143.0 |
| 14 | 18.0 | 44.0 | 53.0 | 9.0 | 97.0 | 150.0 |
| Means | | 32.4 | 47.4 | 14.6 | 77.5 | 122.5 |

Source: Gigiel and Collett, 1990.

(mean 30625 kg) of beef in carcass form and in size from 216 to 1124 m³. The energy data were broken down into a base demand and a product demand (Table 6.6). Base demand is the energy required to maintain the chiller at the desired temperature with the doors closed. Product demand is the additional energy needed to reduce the temperature of the meat. When carcasses are loaded into a chilling system the infiltration of warm air through the open doors further adds to the load on the refrigeration plant and this is included in the product load values.

The base demand will depend on the average ambient air temperature, the level of insulation, the fan power and the control system used. Plant 1 achieved a zero-base demand in the winter because the control system cut out the fans and compressor when the desired room temperature was reached. The other plants were controlled such that all the evaporator fans ran continuously, except during defrosts, resulting in considerable base demands. To aid comparison, where chillers were not fully loaded, specific energy consumption for full loading was calculated by multiplying product demand per kilogram for a partially loaded chiller by its total capacity and adding this to the base demand.

Approximately 48h were required in the commercial chillers to meet the EC requirement of a maximum carcass temperature of 7°C (Table 6.7) and side temperatures of up to 17.0°C were measured on dispatch from one of

Table 6.7 Average weight of sides, average air velocity over deep leg, average chiller temperature over and at end of 24 h, deep leg temperature after 24 h and when removed from chiller, time of removal from chiller and percentage weight loss

| Chiller number | Average side weight (kg) | Air velocity (m s^{-1}) | Chiller temperature | | Side temperature | | Time of removal (h) | Weight loss | |
|----------------|--------------------------|------------------------------------|---------------------|------|------------------|---------|---------------------|-------------|-------|
| | | | mean | end | after | on | | after | after |
| | | | 24 h | 24 h | 24 h | removal | | 24 h | 48 h |
| | | | (°C) | (°C) | (°C) | (°C) | | (%) | (%) |
| 1 | 128 | 0.49 | 3.0 | 0.0 | 10.8 | 5.8 | 44.0 | 1.18 | 1.45 |
| 2 | 138 | 0.27 | 4.0 | 2.0 | 10.8 | 10.8 | 24.0 | 1.75 | – |
| 3 | 148 | 0.90 | 1.5 | 0.0 | 11.9 | 9.0 | 26.5 | 1.36 | – |
| 4 | 178 | 0.60 | 3.0 | 6.0 | 14.5 | 8.0 | 48.0 | 1.46 | 1.66 |
| 5 | 152 | 0.66 | 8.0 | 4.0 | 15.0 | 12.0 | 26.0 | 1.79 | – |
| 6.1 | 145 | 0.08 | 3.0 | 1.0 | 15.6 | 3.9 | 50.0 | 1.82 | – |
| 6.2 | 137 | 0.08 | 3.0 | 1.0 | – | – | – | – | 2.31 |
| 7 | 129 | 0.75 | 12.5 | 3.0 | 17.0 | 17.0 | 24.0 | 1.61 | – |
| 8 | 130 | 0.40 | 5.5 | 1.0 | 17.5 | 7.0 | 48.0 | 1.66 | – |
| 9 | 163 | 0.34 | 9.0 | 5.0 | 18.5 | 8.6 | 48.0 | 1.67 | – |
| 10 | – | 0.20 | 6.0 | 2.0 | 19.0 | 9.0 | 44.0 | 1.12 | – |
| 11 | 152 | 0.41 | 16.5 | 7.0 | 19.8 | 4.4 | 48.0 | 1.89 | – |
| 12 | 154 | 0.90 | 7.0 | 2.0 | 20.0 | 14.5 | 32.0 | 1.43 | – |
| 13 | 142 | 0.33 | 6.0 | 4.0 | – | – | – | 2.06 | 2.3 |
| 14 | – | 0.75 | 10.0 | 3.0 | – | – | – | – | – |
| Means | 146 | 0.48 | 6.5 | 2.7 | 15.9 | 9.2 | 38.5 | 1.6 | 1.93 |

Source: Giegel and Collett, 1990.

the chillers. Specific energy consumption for the first 24 h of chilling varied from 57.8 to 78 kJ kg⁻¹ in the winter to 78 to 102.8 kJ kg⁻¹ in the summer. Substantially less energy was required in the subsequent 24 h ranging from 3.0 to 45.8 kJ kg⁻¹ (average 14.1 kJ kg⁻¹).

Weight losses ranged from 1.18 to 2.06% for the first day of chilling and from 1.45 to 2.31% for 2 days. The cost of this loss was on average 20 times the energy cost and therefore of greater economic importance. Plant 1 had the lowest weight loss and energy consumption and achieved a maximum meat temperature of 5.8°C after 44 h. It can therefore be used as a target for chill room design and operation. This target would require a maximum energy consumption over 48 h of 44 kJ kg⁻¹ in winter, 140 kJ kg⁻¹ in summer and a maximum weight loss of 1.5%.

6.2.2 Lamb, mutton and goat chilling

Many conventional chilling systems for lamb carcasses fail to produce optimal textural qualities or minimum weight losses. No publications have been found on large scale systematic investigations of lamb chilling that are similar to those that have been carried out on beef.

In beef sides the heat capacity and thickness of the carcasses makes it very difficult to reduce the internal temperature of the meat, to a value suitable for cutting or transportation, within a 24h cooling cycle. Lamb and mutton carcasses are much smaller and rapid cooling rates can be achieved. However, it has been known for many years that reducing the temperature of the muscles in either beef or lamb to below 10°C within 10h post-mortem is likely to increase the toughness of the meat when cooked owing to a phenomenon called ‘cold shortening’ (see Chapter 3). Many experimental investigations have been carried out to determine the extent of toughening under different cooling conditions and ways of alleviating the condition by either a delay period (Anon, 1975) or electrical stimulation (Crystal, 1978). In commercial operation, a chilling system needs to be designed and operated to chill efficiently while maintaining meat quality. In order to achieve this objective, the designer must have information about the environmental conditions that are necessary to meet any given meat temperature specification, and the effect of these conditions on the cooling rate, weight loss, microbiology, appearance and acceptability of the product.

Most lamb carcasses chilled in the EU have to have a maximum internal temperature of 7°C, before cutting or transport. Some abattoirs would like to dispatch lamb on the day of slaughter and to meet this requirement, chilling has to be complete in 8–10h. For others overnight chilling in 14–16h is normally desired.

6.2.2.1 *Effect of environmental and carcass variables on cooling rate*

The temperature of the air and its velocity over the surface of the carcass are the two main environmental factors governing the rate that heat can be extracted from a sheep carcass. Carcass weight and fat cover control the amount of heat that has to be extracted and its rate of conduction to the surface.

Published data from a number of sources on chilling time is presented in Table 6.8 and Table 6.9 and discussed in the following sections.

6.2.2.1.1 *Air temperature and velocity*

Earle and Fleming (1967) found that reducing the air temperature used during chilling from 4 to 0°C results in approximately a 25% reduction in chilling time to 7°C in the deep leg of carcasses ranging in weight from 12 to 33kg.

No data have been located that examine the effect of air velocity on the chilling rate of lamb or mutton carcasses, but those produced for goats of 20kg (Gigiel and Creed, 1987), which have a comparable chilling time, show a large effect. In air at 0°C, increasing the air velocity from 0.5 to 1 ms⁻¹ reduces the chilling time to 7°C in the deep leg from 10 to 8h and further increasing the velocity to 3 ms⁻¹ results in a time of 5h.

Chilling in air at 0°C, 1.0ms⁻¹ will achieve a chilling time to 7°C of 10h for carcasses up to 30kg in weight, which will allow for dispatch on the same

Table 6.8 Environmental conditions, carcass weight and cooling times (h) in different parts of carcass

| Air conditions | | Weight (kg) | Position | Temp | Time | Position | Temp | Time |
|------------------|---------------------------|-------------|-----------|------|------|------------|------|------|
| Temp °C | speed (ms ⁻¹) | | | | | | | |
| 0 | 0.15 | 12 | Deep leg | 7 | 6.5 | Deep leg | 2 | 10.0 |
| | | | | 7 | 7.2 | | | 12.0 |
| | | | | 7 | 8.4 | | | 14.0 |
| | | | | 7 | 10.4 | | | 17.0 |
| | | | | 7 | 15.0 | | | 23.0 |
| 4 | 0.15 | 12 | Deep leg | 7 | 8.6 | | | |
| | | | | 7 | 10.0 | | | |
| | | | | 7 | 12.0 | | | |
| | | | | 7 | 14.3 | | | |
| | | | | 7 | 20.0 | | | |
| 1 | 0.5 | 30 | Deep leg | 7 | 10.0 | Deep loin | 7 | 7.0 |
| | | | Surf. leg | 7 | 7.0 | Surf. loin | 7 | 5.0 |
| 6 h at 15 then 1 | 0.1 | 30 | Deep leg | 7 | 13.0 | Deep loin | 7 | 10.0 |
| | 0.5 | | | 7 | 9.0 | | | |
| 7 h at -2 then 0 | 3.0 | 15 to 17.5 | Deep leg | 10 | 4.2 | Deep loin | 10 | 2.5 |
| | 0.1 | | Deep leg | 7 | 6.0 | Deep loin | 7 | 3.5 |

Source: Swain and James, 1988.

Table 6.9 Cooling time to 7°C and 1°C in deep M. longissimus dorsi in air at 1 ± 1°C for lamb carcasses of different average weights and fat covers

| | | | |
|-----------------------------|------|------|------|
| Carcass weight (kg) | 26.8 | 21.5 | 16.8 |
| Fat thickness 12th rib (mm) | 7.1 | 3.3 | 1.1 |
| Cooling time to 7°C (h) | 4.3 | 3.1 | 1.9 |
| Cooling time to 1°C (h) | 8.1 | 5.9 | 5.6 |

Source: Smith & Carpenter, 1973.

day as slaughter in many abattoirs. Reducing the initial temperature to -2°C, and increasing the air velocity to 3.0ms⁻¹ resulted in a 6h chilling time with lighter 15–17.5kg lamb carcasses without any surface freezing.

Neglecting other constraints, imposed by eating quality considerations, severe environmental conditions are not required to produce chilling times that allow cutting or transport on the same day as slaughter. Air temperatures of, or slightly less than the desired final meat temperature in the range 0–4°C, and a low air velocity 0.2–0.5ms⁻¹ will achieve overnight chilling in 14–16h.

6.2.2.1.2 Carcass weight and fat cover

As with beef, it is difficult to separate the effect of carcass weight from fat cover on chilling time. Little difference was observed in the cooling times

in the deep longissimus muscles of 29.6–30.3 kg ram carcasses with high and low fat thicknesses (Kadim *et al.*, 1993). The ram carcasses were initially held for 100 ± 5 min at 15–20°C then cooled in air at 1–3°C. When the fat was completely stripped from the muscle, the cooling time to 7°C was reduced from 10 to 8h.

However, the chilling time to 7°C in the *M. longissimus dorsi* of lean light (16.8kg) lambs can be under half that of 26.8kg lambs with a much thicker fat covering (Table 6.9). It would not be unusual for a chilling system to contain lamb carcasses covering this range of weights and fat covers. The design and operation of such a system must therefore be a compromise between overlong chilling periods for the smaller carcasses and undercooling of the larger carcasses.

6.2.2.2 *Effect of environmental and carcass variables on weight loss*

Experiments carried out at Langford showed that a lamb carcass has lost *ca.* 2.5% of its hot weight at 24h post-mortem after chilling and the initial phase of storage and after a further 5 days in the chill room this loss has risen to over 4%. Losses of this magnitude are therefore of considerable economic consequence to a meat wholesaler. The environmental and carcass factors that affect weight loss include those that affect chilling time with the addition of the relative humidity of the air.

6.2.2.2.1 *Air temperature, velocity and relative humidity*

The rate of loss of moisture from a saturated surface into an air stream passing over it is a function of the surface area, mass transfer coefficient and the vapour pressure difference between the surface and the air. Any decrease in relative humidity increases the total weight loss, and within the temperature range (0–10°C) found in commercial chill rooms, a 20% reduction in relative humidity will increase weight loss by at least 0.2%.

Weight loss increases as chilling temperature decreases. However, this fact must be considered in context with the data already presented on chilling time. After 6h in air at 0°C, a 15kg lamb carcass would be substantially cooled and after a few more hours it could be either cut or dispatched. At 25°C, less than 40% of the required heat would have been extracted and a substantial further time at a lower temperature would be required before the carcass could be further processed. During this time the carcass would continue to lose weight.

A similar complication occurs with the effect of air velocity on weight loss (Table 6.10). If the carcass is to be removed from the chilling system immediately after a maximum internal temperature has been achieved, then increasing the air velocity will result in a lower weight loss. However, if a set time is allowed for the chilling process then the minimum weight loss is likely to be achieved by using the minimum air velocity that will result in the desired amount of heat being extracted in the time available.

Table 6.10 Percentage weight loss from $15 \times 15 \times 2$ cm thick samples of lean mutton cooled from one side in air at $1-2^\circ\text{C}$, for a set time or to a set maximum internal temperature, at different air velocities

| Air velocity (ms^{-1}) | Cooling time (h) | | Final temperature ($^\circ\text{C}$) | | |
|-----------------------------------|------------------|------|--|------|------|
| | 4 | 22 | 13 | 7 | 4 |
| 3.7 | 1.64 | 4.11 | 0.95 | 1.14 | 1.27 |
| 1.4 | 1.60 | 3.25 | 1.09 | 1.32 | 1.48 |
| 0.6 | 1.67 | 3.03 | 1.20 | 1.49 | 1.69 |

Source: Lovett *et al.*, 1976.

Table 6.11 Percentage weight loss from lamb carcasses in different weight ranges chilled and stored in air at $2 \pm 1^\circ\text{C}$, 90% relative humidity for 72 h

| Carcass weight range (kg) | No of carcasses | Weight loss after 72 h (%) |
|---------------------------|-----------------|----------------------------|
| <22.4 | 32 | 3.14 |
| 22.5-24.7 | 87 | 3.08 |
| 24.8-26.9 | 74 | 2.99 |
| 27.0-29.2 | 55 | 3.10 |
| >29.3 | 52 | 2.95 |

Source: Smith & Carpenter, 1973.

In all cases, the air humidity should be maintained at the highest level that can be economically justified.

6.2.2.2.2 Carcass weight and fat cover

The rate of weight loss is proportional to surface area and the surface area to volume ratio becomes less as the weight of a carcass increases. Percentage weight loss should therefore decrease as carcass weight increases. In a test using 300 carcasses in the same chilling system (Smith and Carpenter, 1973) the lightest carcasses lost 3.14% and the heaviest 2.95% over 72 h (Table 6.11) but the difference was not significant ($P > 0.05$).

In the same tests, a maximum increase in weight loss of 0.26%, over 72 h chilling and storage, was found between lambs with low areas of fat cover and those with almost complete fat cover. Further investigations involving almost 700 carcasses in three chill rooms showed that increasing fat thickness reduced weight loss by up to 1.12% over 72 h.

6.2.2.3 Quality considerations

Toughening caused by cold shortening (see Chapter 3) will occur in lamb if the meat falls below 10°C within 10 h post-mortem (Rhodes, 1972). As the rate of temperature reduction increases, the amount of cold shortening increases. The longer the delay between slaughter and the reduction of any

part of the musculature on the carcass to below 10°C, the less the degree of shortening that will occur. All the musculature of a 30kg lamb carcass that is chilled sufficiently to meet the EEC legislation and to be dispatched on the same day as slaughter will be cold shortened.

Delaying cooling by hanging the carcass at a temperature of *ca.* 15°C for 6h and then chilling at 1°C, 0.5 m s⁻¹, will avoid the risk of cold shortening in the major parts of the leg and loin (Taylor *et al.*, 1972). The process will achieve a total chilling time to 7°C of 13h. Recommendations from New Zealand (MIRINZ, 1985) state that meat held at 10°C for 16–24h (conditioned) and then rapidly chilled and frozen is only moderately tender. Holding the carcass, after conditioning, in a chilled state for three days will increase the percentage of acceptably tender meat in the loin from 64 to 90%. Nearly the same degree of tenderness can be achieved using high voltage electrical stimulation in an accelerated conditioning and ageing process. The carcass is either stimulated at less than 5 min post-mortem (predressing) for 45s or for 90s at less than 30min post-mortem (post-dressing). It is then held at a temperature above 6°C for at least 8h before being chilled to 0–2°C for cutting or transportation.

6.2.3 Pork

Conventional pig chilling systems aim to reduce the mean temperature of the side or carcass to *ca.* 4°C, a temperature considered suitable for cutting or curing. Most producers despatch, cut or commence further processing of the chilled carcass on the day after slaughter, allowing a period of 14–16h for the chilling operation. Different markets for pig carcasses are defined in terms of weight ranges (Table 6.12).

Many pig slaughterhouses concentrate on a limited range of weights, some specialising in pigs for one type of further processing such as bacon production, while only a few handle the total weight range. Experimental studies at Langford investigated the relationship between air temperature and velocity and rates of cooling in pig carcasses covering a weight range from 40 to 150kg.

Table 6.12 Market weight ranges for pig carcasses

| Group | Carcass weight (kg) |
|---------------|---------------------|
| Porkers | <50 |
| Cutters | 50–67.5 |
| Baconers | 58.5–76.5 |
| Heavy cutters | 68–81 |
| Heavy hogs | >81.5 |

Source: Kempster *et al.*, 1981.

6.2.3.1 Effect of environmental and carcass variables on cooling rate

6.2.3.1.1 Air temperature and velocity

Mean cooling curves, together with 95% confidence limits, for 40, 60, 80, 100 and 150 kg carcass weights in air at 0, 4 and 6 °C have been produced for various air velocities such as 0.5 ms⁻¹, 1.0 ms⁻¹ and 3.0 ms⁻¹ (Brown and James, 1992). A deep leg temperature of 7 °C is required by EC regulations before the transport or cutting of meat for export. A 40 kg carcass would require *ca.* 13 h in air at 4 °C and 0.5 ms⁻¹. A 4 °C reduction in air temperature to 0 °C will decrease the cooling time by 3 h to slightly under 10 h. To achieve the same reduction whilst maintaining the air temperature at 4 °C the air velocity would have to be increased from 0.5 to 3.0 ms⁻¹.

6.2.3.1.2 Carcass weight

Table 6.13 gives the heaviest pig carcasses that can be cooled to a deep leg temperature of 7 °C by 16 h post-mortem. In the experimental situation the carcasses were placed in the cooling chamber at 50 min post-mortem, the temperature pull-down period was minimal (less than 30 min) and the air velocity was maintained over all the surfaces of the carcasses. Few if any of these conditions would be achieved in commercial practice and the weights should therefore be taken as a theoretical upper limit to the weights that could be cooled.

6.2.3.2 Product loads

The thermal load released by a pig carcass during a conventional chill has been measured for a particular set of chilling conditions (Lang, 1972). The rate of heat release will depend not only on carcass and environmen-

Table 6.13 Maximum weight of pig carcass that can be cooled to 7 °C in deep leg within 16 h at different combinations of air temperature and velocity

| Chill room air | | Heaviest carcass cooled to 7 °C in deep leg in 16 h (kg) |
|---------------------|---------------------------------|--|
| Temperature (°C) | Velocity (ms ⁻¹) | |
| 0 | 0.5 | 100 |
| | 1.0 | 105* |
| | 3.0 | 110* |
| 4 | 0.5 | 60 |
| | 1.0 | 80 |
| | 3.0 | 95* |
| 6 | 0.5 | <40 |
| | 1.0 | 40 |
| | 3.0 | 60 |

*Interpolated values

Source: Brown and James, 1992.

tal factors but also the loading pattern for the chiller. Data are provided on the decline in product load from peak to average and below. It is expressed in the form of % of heat released per h of chilling.

The total heat released (Q) can be calculated by:

$$Q = mC_p\Delta T \quad (\text{kJ}) \quad [6.2]$$

where m = mass of carcass in kg, C_p = specific heat in $\text{kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$ and ΔT = temperature reduction of carcass in $^\circ\text{C}$. The way in which this heat is released can then be determined using the percentages for each pig entering the chillroom.

6.2.3.3 Cost of chilling operation

A survey of five pig chilling operations in the United Kingdom highlighted some of the problems inherent in conventional chilling systems (Gigiel, 1984; Collett and Gigiel, 1986). See Table 6.14 and 6.15. All the plants

Table 6.14 Environmental conditions and loading in five commercial pork chilling systems

| Plant no. | Hot weight of pigs | | Total pigs in room (no.) | Chill room capacity (no.) | Air velocity | | | Air temp at end of chilling ($^\circ\text{C}$) |
|--------------|--------------------|------------|--------------------------|---------------------------|---------------------------|----------------------------|------|--|
| | average (kg) | total (kg) | | | av. (m s^{-1}) | max. (m s^{-1}) | min. | |
| 1 | 42.7 | 3 245 | 76 | 200 | 1.5 | 2.2 | 0.2 | 6 |
| 2 | 63.9 | 29 713 | 465 | 465 | 0.5 | 1.3 | 0.2 | 1 |
| 3 | 64.8 | 14 714 | 227 | 270 | 0.5 | 1.0 | 0.3 | 2 |
| 4 | 67.0 | 21 440 | 320 | 500 | 0.2 | 0.5 | 0.2 | 5 |
| 5 | 64.1 | 22 249 | 375 | 780 | 0.8 | 4.4 | 0.5 | |
| Second stage | | | | 500 | 0.7 | 1.8 | 0.2 | 3 |

Source: Collett and Gigiel, 1986.

Table 6.15 Energy demand, consumption and product weight loss during commercial chilling

| Plant no | Base demand (MJ) | Product demand in full room (MJ) | Total energy consumption in full room (kJ kg^{-1}) | Weight loss (%) |
|----------|------------------|----------------------------------|---|-----------------|
| 1 | 778 | 378 | 208 | 3.50 |
| 2 | 1728 | 1624 | 112 | 2.60 |
| 3 | 781 | 648 | 89 | 2.17 |
| 4 | 1332 | 1206 | 96 | 1.85 |
| 5 | 3658 | 2371 | 258 | 2.06 |
| Mean | 1655 | 1245 | 153 | 2.44 |

Source: Collett and Gigiel, 1986.

surveyed used an overnight chilling operation so that the pork carcasses were ready for cutting or dispatch on the day after slaughter. The air temperature in the four single stage systems rose substantially to a maximum of 19°C in plant 1, after they were loaded with freshly slaughtered carcasses, and still ranged from 1 to 6°C at the end of the chilling process. During loading the energy consumption of the refrigeration plant was typically over 2.5 times the average consumption throughout chilling. The plant operated at full capacity for 4h until the peak rate of heat release had been overcome and it was able to start reducing the air temperature to its designed level.

Air velocities over the surface of the hind legs of carcasses varied considerably both within (<0.2–2.2 m s⁻¹) and between chill rooms (<0.2–1.5 m s⁻¹).

In normal operation the base energy demand, i.e. the amount of energy required to run the empty closed chill room at its design temperature, was 57% of the total energy consumption during the chilling operation. The energy cost of the chilling operation per kilogram of pork chilled was therefore dependent on the utilisation of the chill room. The average cost of the evaporative weight loss during the chilling period was a factor of 15 higher than the energy costs.

The data gathered in this survey revealed large variations in the performance of commercial chilling plants and a lack of complete chilling in a number of situations. Variation in weight loss was substantial, although the mean agreed well with the national average of 2.27% (Kempster *et al.*, 1981). Chiller number 4 produced the lowest overall cost and since it had no novel features, provides a target of 96 kJ kg⁻¹ for energy consumption and a 1.85% weight loss for a fully loaded chill room against which all pork chill rooms can be compared. The survey did not provide any direct process design data to aid in the specification of new chilling systems.

6.2.4 Chilling of offal

There appears to be little published data on the chilling of offal. Stiffler *et al.* (1985) and Vanderzant *et al.* (1985) investigated the effect of five chilling treatments on weight loss and bacterial and sensory changes after storage and transportation. The five regimes used: (1) air at 2°C for 24h, (2) air at 2°C for 4–6h, (3) air at -20°C for 2h, (4) air at -20°C for 0.5–1h and (5) slush ice for 2h. Significant differences in weight loss were measured after chilling with the faster treatments using air at -20°C or immersion tending to produce the lowest losses (Table 6.16). After storage and transportation, there was usually no significant difference in weight losses between treatments or with the non-prechilled control. Bacterial counts after transport were usually lower on samples that had been prechilled before packaging. However, off-odour scores of non-prechilled vacuum packed samples of beef livers, pork tongues, lamb livers and lamb tongues were lower than comparable samples that had received an initial chilling treatment.

Table 6.16 Percentage weight loss after different chilling treatments and after storage and transportation

| Treatment | % Weight loss | | | | | Control |
|-----------------------------|---------------|------|------|------|-------|---------|
| | 1 | 2 | 3 | 4 | 5 | |
| After chilling | | | | | | |
| <i>Beef</i> | | | | | | |
| Liver | 2.51 | 1.49 | 1.13 | 1.12 | – | – |
| Heart | 1.56 | 1.39 | 1.35 | 0.69 | – | – |
| Tongues | 1.53 | 1.25 | 1.05 | 0.42 | – | – |
| Kidneys | 1.59 | 1.37 | 1.33 | 0.63 | – | – |
| <i>Pork</i> | | | | | | |
| Liver | 1.72 | – | 0.97 | – | –0.98 | – |
| Heart | 1.93 | – | 1.11 | – | –1.99 | – |
| Tongues | 0.62 | – | 0.00 | – | –1.89 | – |
| Kidney | 0.69 | – | 0.63 | – | – | – |
| After storage and transport | | | | | | |
| <i>Beef</i> | | | | | | |
| Liver | 5.48 | 5.36 | 6.65 | 5.35 | – | 3.97 |
| Heart | 3.87 | 2.47 | 3.55 | 2.74 | – | 5.07 |
| Tongues | 1.46 | 1.29 | 1.21 | 0.92 | – | 0.23 |
| Kidneys | 1.65 | 1.63 | 1.56 | 1.46 | – | 0.11 |
| <i>Pork</i> | | | | | | |
| Liver | 3.33 | – | 4.79 | – | 2.59 | 2.45 |
| Heart | 5.79 | – | 5.66 | – | 3.64 | 6.11 |
| Tongues | 4.00 | – | 2.89 | – | 1.37 | 2.13 |
| Kidney | 1.87 | – | 1.78 | – | – | 1.03 |

Source: Stiffler *et al.*, 1985.

6.3 Novel systems with future potential

The previous section has outlined a number of obvious problems with conventional chilling operations. These include long chilling times, variable chilling, batch operation, uneven product loads and high weight losses. Many alternative systems have been investigated to overcome some if not all of these problems.

6.3.1 Accelerated chilling systems

6.3.1.1 Beef

Using conventional single stage chilling regimes it is evident that only relatively light, lean beef sides can be cooled to 7°C in the deep tissue during a 24h operating cycle, whilst evaporative losses are of the order of 2%. There is considerable interest in methods of shortening cooling times and reducing evaporative weight loss. All accelerated cooling systems are likely

to be more expensive to install and operate than conventional plants. Therefore, to be cost effective they must offer substantial savings in terms of increased throughput and/or higher yields of saleable meat.

Attempts have been made to reduce cooling times by increasing the surface heat transfer coefficient, for example, by using radiative plates in conjunction with blast air (Gerosimov and Malevany, 1968; Gerosimov and Rumyanstev, 1972). However, most accelerated chilling systems rely on the maintenance of very low temperatures (-15 to -70°C) during the initial stages of the chilling process. This can be achieved either by powerful mechanical refrigeration plant (Kerens, 1983; Watt and Herring, 1974; Sheffer and Rutov, 1970; Union International Consultants, 1984) or by cryogenic liquids (Kerens, 1983; Watt and Herring, 1974; Bowling *et al.*, 1987). The factors governing the evaporative loss from sides chilled at sub-zero temperatures are the same as those from meat chilled in conventional systems. The rapid drop in surface temperature of the side when chilling at very low temperatures not only limits evaporation from the surface but also leads to crust freezing. This frozen crust acts as a vapour barrier inhibiting further evaporation.

Any substantial freezing would produce increased drip loss on final cutting (Gigiel *et al.*, 1985). To avoid this, accelerated systems only maintain very low temperatures during the first few hours of the chilling process. One or more successive stages at progressively higher temperatures are employed, with the final stage at or above 0°C either to remove the last of the heat or to allow for temperature equalisation. However, in one report (Anon, 1985), where chilling was carried out at -70°C for 5 h and the interior of the loin had reached 0 to -2°C at the end of this period, a substantial amount of freezing must have occurred.

Data on cooling times, environmental conditions, weight losses or savings in weight loss where comparisons have been made with conventional carcass chilling systems are given in Table 6.17. All the accelerated chilling systems offer substantial increases in yield, 0.4–1.37% and the majority cool all but the heaviest sides to below 7°C in under 18 h, to achieve a 24 h processing cycle. Little information is provided on the amount of crust freezing that occurred during the chilling operations or any textural problems caused by the rapid rates of temperature fall. Considerable surface freezing occurred in all the experiments carried out at Langford (Union International, 1984; James; unpublished). All of those carcasses had been subjected to high voltage electrical stimulation before chilling to avoid cold shortening, and instrumental tests failed to reveal any significant difference in texture between rapidly chilled and control sides.

Despite the considerable number of trials that have taken place and the cost advantages shown in feasibility studies (Union International Consultants, 1984; Bowater, 2001), no commercial plants are believed to have resulted from the work, with the possible exception of some systems in the former Soviet Union.

Table 6.17 Beef side weights, time to reach a maximum meat temperature of 7°C, total cooling time, weight loss and savings over conventional chilling systems, and conditions used in accelerated chilling systems

| Conditions | Side weight (kg) | Time (h) | | Weight loss (%) | |
|------------|---------------------|----------|-------|-------------------|-------|
| | | to 7°C | Total | Savings | Total |
| 1 | 50 | 11 | 18 | 0.78 | 1.47 |
| | 100 | 18 | 18 | average 3 weights | |
| | 150 | 24 | — | | |
| 2 | 123 | 15 | 20 | — | 0.88 |
| 3 | 119 | 14 | 21 | — | 1.03 |
| 4 | 118 | 13 | 21 | 1.03 | 1.12 |
| 5 | — | — | — | 0.4–0.5 | — |
| 6 | — | — | 10–16 | 1.0 | 1.0 |
| 7 | — | 14 | 21 | 0.66 | 1.28 |
| 8 | 125 | — | 21 | 1.37 | 1.36 |
| 9 | 120 | 20 | 21 | 0.44 | 1.08 |
| 10 | — | — | 24 | 0.90 | 0.43 |

The chilling conditions are:

(1) 3 h at -30°C with liquid nitrogen injection then gradually rising to 0°C over 4 h and remaining at 0°C.

(2) 3 h at -19°C, 1.2 m s⁻¹ followed by 17 h at 0.6°C, 0.75 m s⁻¹.

(3) 3 h at -19°C, 1.2 m s⁻¹ then air gradually rising to 0.7°C over 7 h with air at 0.75 m s⁻¹ and remaining at same conditions.

(4) 2.5 h at -19.5°C, 1.2 m s⁻¹; 3 h at -9.5°C, 0.75 m s⁻¹ then rising to 0°C.

(5) 4 h at -29°C with liquid air.

(6) 4–8 h at -15 to -10°C, 1–2 m s⁻¹ then 6–8 h at -1°C, 0.1–0.2 m s⁻¹.

(7) 6 h at -15°C, 0.5–1.5 m s⁻¹, then air gradually rising to 4°C over 12 h.

(8) 1 h at 15°C, 2 m s⁻¹; 3 h at -12°C, 2 m s⁻¹ then 17 h at 4°C.

(9) 6 h at -15°C, 2.3 m s⁻¹, then 15 h at 0°C, 0.5 m s⁻¹.

(10) 5 h at -70°C, then 16°C for 4 h and then at 1°C for 15 h.

Source: James and Bailey, 1990.

6.3.1.2 Lamb

The New Zealand specification for lamb carcasses requires a holding time of 90 min after stimulation before being subjected to temperatures below 6°C. Some processors would like to chill their carcasses much more rapidly with the aim of reducing the need for cooling floor space or to firm the carcass prior to cutting. Research by Davey and Gilbert (1973) and Davey and Garnett (1980) suggested that rapid chilling of lamb was possible in certain circumstances without cold shortening. MIRINZ (1986/87) have carried out investigations on the possibility of using very low temperatures (-25 or -30°C) for a short period of 30 min followed by an equalisation period at 0°C until the deep leg temperature reaches 7°C. The treatment produced a 4 h process from slaughter to deep temperature of 7°C. The products, which are then fast frozen, are claimed to be moderately tender.

Sheridan (1990) reported that meat from lambs chilled at -20°C , 1.5ms^{-1} for 3.5h was as tender after 7 days ageing as that from lambs conventionally chilled at 4°C . After 24h the very rapidly chilled carcasses had lost 0.8–0.9% less in weight.

6.3.1.3 Pork

Chilling in two stages, with the first stage consisting of a conveyerised air blast tunnel is quite common (Cooper, 1972; Wernburg, 1972). The prechiller serves two requirements in that it rapidly lowers the surface temperature, reducing the rate of evaporative weight loss, and has the capacity to absorb the initial peak heat load. Studies (James *et al.*, 1983; Gigieli and James, 1984) have shown that all the required heat can be extracted from a pig carcass or side in a single short blast chilling operation. Immediately after chilling, the carcass can be band sawn into primals and stored or transported on the same day as slaughter.

After a 4h chilling process at -30°C , 1.0ms^{-1} , the average temperature in the primal joints from sides ranged from -1.9°C in the loin to 1.2°C in the shoulder and in whole carcasses from -2.1°C in the belly to 3.0°C in the shoulder. The average maximum temperatures, recorded at the end of the 4h process in the 3 most commercially important joints, were for sides and whole carcasses respectively, shoulder 10.7 and 18.6°C , loin -1.9 and 2.0°C and leg 14.6 and 14.6°C .

Evaporative loss was reduced to 1.13% for sides and 1.10% for whole carcasses, almost half that in the controls (Table 6.18). No extra drip was measured from the primal joints but the chops from the sides that had been partially frozen during the process recorded higher drip levels.

Instrumental measurements of texture carried out on loin chops from ultra-rapidly chilled pork stored for 2 days showed that the meat was tougher than that of the controls (Table 6.18). There was less increase in toughness in sides subjected to ultra-rapid chilling than whole carcasses. After chilling, cutting and 2 days storage in vacuum packs there was no significant difference between counts from ultra-rapid chilled material and the controls.

Table 6.18 Mean evaporative and drip losses from ultra-rapid and conventionally chilled pork, and work done in shearing cooked samples

| | Side | Whole carcass |
|--------------------------------|-------------------------------|-------------------------------|
| Evaporative loss (%) | 1.13 (-0.85) [†] | 1.10 (-1.01) [†] |
| Drip in vacuum pack (%) | 0.20 (0.00) | 0.20 (0.00) |
| Drip in retail packs (%) | 2.31 ($+1.32$) [†] | 0.86 ($+0.20$) |
| Work done shearing samples (J) | 0.18 ($+0.02$)* | 0.21 ($+0.05$) [†] |

Difference significant at [†] $P < 0.001$, * $P < 0.05$.

Figures in brackets are differences between treatment and control.

Source: James *et al.*, 1983.

6.3.2 Spray chilling

6.3.2.1 Beef

An alternative system in the USA that seems to be rapidly gaining commercial acceptance for beef, is spray chilling (Anon, 1985; Heitter, 1975; Allen *et al.*, 1987; Johnson *et al.*, 1988). Practical spray chilling systems have used a combination of air and sprays for the initial part of the chilling period and then air only for the rest of the chilling cycle. The sprays are not applied continuously but in short bursts, 90 s at 15 min intervals for the first 8 h in one system (Allen *et al.*, 1987) and 30 s at 30 min intervals for the first 12 h in another (Hamby *et al.*, 1987). Cooled water at 2–3 °C is used in the sprays and in the latter a total of 11 litres was delivered from 11 nozzles over the 30 s period (Hamby *et al.*, 1987). Studies carried out in Canada (Jones and Robertson, 1988) used 1 min sprays every 15 min for either 4, 8 or 12 h with shrouded sides or 8 h with unshrouded sides. Further studies concentrated on 1 min sprays every 15 min for 10 h with shrouded sides (Greer *et al.*, 1990).

The main advantage claimed for the system is a reduced weight loss measured over 24 h that can range from *ca.* 0.5 to 1.5% (Table 6.19). After 6 days, small but industrially significant reductions in weight loss were reported for shrouded sides sprayed for 12 h and the unshrouded sides (Jones and Robertson, 1988). After 7 days the weight loss from the 10 h shrouded treatment was 0.41% less than that from controls (Greer *et al.*, 1990). Cooling rates were faster in the spray cooling systems with deep temperatures typically 1–2 °C lower than controls. This was caused by the higher rates of heat transfer and the heat extracted to evaporate the added water.

Surface drying is often considered an important factor in limiting microbial growth. If the surface remains wet there may be microbial problems that shorten shelf-life. The addition of lactic or acetic acid has been found

Table 6.19 Weight loss (%) and saving over conventional chilling produced by different spray cooling systems

| Reference | Treatment | Weight loss (24 h) | Saving (%) |
|----------------------------|-------------------------------------|--------------------|------------|
| Allen <i>et al.</i> , 1987 | 90 s at 0.25 h for 8 h | 0.32 | 1.16 |
| Jones & Robertson, 1988 | 60 s at 0.25 h for 4 h (shrouded) | 1.15 | 0.48 |
| Jones & Robertson, 1988 | 60 s at 0.25 h for 8 h (shrouded) | 0.60 | 0.69 |
| Jones & Robertson, 1988 | 60 s at 0.25 h for 12 h (shrouded) | 1.15 | 0.48 |
| Jones & Robertson, 1988 | 60 s at 0.25 h for 8 h (unshrouded) | 0.35 | 1.43 |
| Greer <i>et al.</i> , 1990 | 60 s at 0.25 h for 10 h (shrouded) | 0.28 | 1.05 |
| Lee <i>et al.</i> , 1990 | 60 s at 0.25 h for 8 h (shrouded) | 0.53 | 0.72 |
| Lee <i>et al.</i> , 1990 | 60 s at 0.25 h for 8 h (unshrouded) | 0.44 | 1.29 |

to reduce bacterial contamination (Hamby *et al.*, 1987). However, no differences in bacterial numbers were found on sides after 7 days ageing or on vacuum packed meat after 70 days in storage (Greer *et al.*, 1990).

There is little evidence that spray chilling has any adverse effects on meat quality. In some spray cooled sides fat colour was significantly lighter than in controls (Hamby *et al.*, 1987), but Greer *et al.* (1990) found no differences in colour. Lee *et al.* (1990) found no differences in tenderness or juiciness of meat from spray or conventionally chilled carcasses.

6.3.2.2 Pork

Work carried out in the UK (Dransfield and Lockyer, 1985) and Denmark (Moller and Vestergaard, 1987) has shown that a short delay period before the start of chilling improves the texture of pork. However, during this period the rate of weight loss is highest so yield is likely to suffer. With spray cooling, the surface remains wet giving maximum mass transfer and evaporative cooling effect, with no penalty in increased weight loss. Consequently, combining a spray system with the delay period offers a way of producing high quality pork without excessive weight loss.

Spray chilling was examined experimentally (Gigiel *et al.*, 1989a) as a two-stage process (air at 10°C, 98% RH and 0.7 m s⁻¹ for 2 h followed by air at 4°C, 97% RH and 0.3 m s⁻¹ for 21 h) using sprays of 250 ml of water every 20 min for the first 6 h of chilling. Controls were chilled in air at 4°C, 92% RH and 0.3 m s⁻¹ for 23 h. Achieving the same time to 7°C, the spray treatment reduced weight loss by 1.22% (Table 6.20).

Both the chilling regimes reduced the total viable counts of bacteria and there were very small (less than 1 log cycle) but statistically significant differences between some treatments in counts measured on the medial surface of carcasses. There were no significant differences in drip loss between treatments. Jeremiah and Jones (1989) found that spray chilled pork had to be stored in vacuum packs for 42 days before they measured any difference in drip between the samples and conventionally chilled controls. They noted a non-statistically significant trend for spray cooled pork to have a shorter display life.

Commercial spray chilling plants for pork have now been installed in France and the Netherlands but none currently operate in the UK.

Table 6.20 Spray chilling results

| Treatment | Weight loss (%) | Drip (%) | Cooling time to 7°C (h) | Texture (J) |
|---------------|-------------------|----------|-------------------------|-------------|
| Delay + spray | 0.95 ^a | 0.97 | 17.7 | 0.196 |
| Conventional | 2.17 ^b | 1.55 | 17.7 | 0.214 |

Values within columns with different superscripts a and b are significantly different ($P < 0.05$). Source: Gigiel *et al.*, 1989a.

Table 6.21 Mean weight losses and standard deviations () from conventional and spray-chilled lamb carcasses

| Treatment | Weight loss (%) | | |
|----------------|---------------------------|--------------------------|--------------------------|
| | 8 h | 24 h | 5 days |
| Conventional | 1.16 ^a (0.25) | 2.20 ^a (0.24) | 3.97 ^a (0.55) |
| Multiple spray | -0.01 ^b (0.25) | 0.86 ^b (0.15) | 2.97 ^b (0.27) |
| Double spray | 0.78 ^c (0.21) | 1.20 ^c (0.28) | 3.19 ^b (0.42) |

Values within columns with different superscripts are significantly different ($P < 0.05$).

Source: Brown *et al.*, 1993.

6.3.2.3 Lamb

Heitter (1975) showed that chlorinated water sprayed on the carcass during chilling produced lower bacterial counts (reductions of 94.5–99.5% in viable counts), lower evaporative weight loss (up to 1.25%) and quicker cooling rates.

Brown *et al.* (1993) developed two spray chilling treatments to improve appearance and reduce weight loss during lamb chilling. The first treatment was an intermittent spray, 8 sprays of 250 ml at 10°C at 20 min intervals, during the first 3 h of chilling. The second consisted of 2 sprays, one at 2 h and the second at 10 h post-mortem. These treatments were compared to a conventional two-stage process, with air at 10°C, 1 m s⁻¹ for the first 10 h, followed by air at 0°C, 1 m s⁻¹ for 14 h.

Both treatments significantly reduced weight loss after chilling and this advantage was retained during 4 further days of storage (Table 6.21).

There were small (<1 h) but significant reductions in the cooling rates of spray-chilled loins and legs owing to sustained evaporative cooling of the wetted surfaces. No effects on texture or drip loss and only slight effects on surface lean and fat colour were found.

No significant differences in bacterial numbers were found between treatments after chilling and storage. There were small but significant increases (<1 log cycle) on all diaphragms and on the breasts of double-sprayed carcasses (Table 6.22).

6.3.3 Immersion chilling

6.3.3.1 Pork

All frozen poultry is initially chilled by being immersed in chilled water or an ice water mixture. The procedure is very rapid and the birds actually gain weight during the process. Whole carcasses or even sides of pork are too big to handle in this way. It is possible, however, to hot joint the pork into primal cuts, vacuum pack the primals and then chill them by immersion in

Table 6.22 Mean values and standard deviation () from conventionally and spray-chilled lamb carcasses

| Treatment | Site | Total viable count (log 10) | |
|----------------|-----------|-----------------------------|--------------------------|
| | | Before chilling | After storage |
| Conventional | Leg | 3.44 (0.44) | 3.42 (0.66) |
| | Breast | 3.89 (0.67) | 4.05 (0.60) |
| | Diaphragm | 2.81 ^{ax} (0.35) | 3.17 ^y (0.41) |
| Multiple spray | Leg | 3.80 (0.71) | 3.85 (0.48) |
| | Breast | 4.05 (0.58) | 4.32 (0.55) |
| | Diaphragm | 3.11 ^{bx} (0.19) | 3.47 ^y (0.35) |
| Double spray | Leg | 3.45 (0.36) | 3.39 (0.26) |
| | Breast | 3.91 ^x (0.38) | 4.32 ^y (0.38) |
| | Diaphragm | 2.81 ^{ax} (0.26) | 3.40 ^y (0.52) |

Values for each site within columns with different superscripts (a,b) and between rows (x,y) are significantly different ($P < 0.05$).

Source: Brown *et al.*, 1993.

Table 6.23 Mean evaporative and drip losses from immersion and conventionally chilled pork, and work done in shearing cooked samples

| | Immersion | Control | Difference |
|--------------------------|-----------|---------|--------------------|
| Evaporative loss (%) | 0.32 | 2.40 | -2.08 [†] |
| Drip in vacuum pack (%) | 0.36 | 0.25 | +0.11 |
| Drip in retail packs (%) | 1.52 | 1.52 | 0.00 |
| Work done (J) | | | |
| 1 day conditioning | 0.30 | 0.25 | +0.05* |
| 14 days conditioning | 0.23 | 0.20 | +0.03 |

Difference significant at [†] $P < 0.001$, * $P < 0.05$.

Source: Brown *et al.*, 1988.

iced water or brine. The vacuum packaging prevents water pick up and overcomes any possibility of cross contamination, both of which are considered a problem in the poultry system.

In immersion chilling trials (Brown *et al.*, 1988), pigs were slaughtered, dressed and split into sides. Sides were then cut into primals (shoulder, leg, loin and belly), vacuum packed and immersed in a tank of refrigerated agitated brine at 0°C. The primals were then placed in a chill room operating at 0°C.

The average temperature of the loin and belly primals was reduced to 7°C within a 2–3h period and legs and shoulders in 6h in the immersion system. Evaporative weight loss was reduced by over 2% in the immersion chilling system (Table 6.23) and this yield advantage was still maintained after 14 days further storage.

Table 6.24 Times for deep leg temperatures to fall to 7°C and average weight losses for the ice bank and control regimes

| Treatment | Time to 7°C (h) | Percentage weight loss at post-mortem | | |
|-----------|---------------------|--|-------------------|--------------------|
| | | 24 h | 48 h | 72 h |
| 1 | 11.90 ^{ac} | 1.94 ^a | 2.02 ^a | 1.92 ^a |
| 2 | 9.60 ^b | 2.37 ^b | 2.79 ^b | 3.31 ^b |
| 3 | 11.70 ^{ab} | 1.80 ^a | 1.94 ^a | 1.88 ^a |
| 4 | 10.40 ^{ab} | 1.83 ^a | 2.00 ^a | 2.03 ^{ac} |
| 5 | 11.30 ^{ab} | 2.07 ^c | 2.20 ^a | 2.17 ^c |

Means within columns with different superscripts are significantly different ($P < 0.05$).

Source: Gigiel and Badran, 1988.

6.3.4 Ice bank chilling

6.3.4.1 Pork

Another possible way of reducing weight loss is to increase the humidity of the air in the chilling system. In the early stages of chilling when the surface of the carcass is still much warmer than the air in the room, humidity has little effect. However, during the later stages of cooling and in subsequent storage its effect can be substantial.

Ice bank refrigeration systems produce high humidity air at a steady temperature close to 0°C and have proven advantages in storage of fruit and vegetables. Such systems use refrigeration coils or plates to cool tanks of water and then build up 'banks' of ice. The chilled water is then used to cool and humidify air, by direct contact, which is in turn used to cool the product. The ice bank is energy and cost effective because it uses smaller compressors operating at full power and hence high efficiency. It can also be run overnight on off-peak electricity to build up the bank of ice for use the next day. This bank can then be used to overcome the high heat loads that are initially produced when the hot pigs are loaded into the chill room.

In studies (Gigiel and Badran, 1988) during the first 24 h, the carcasses in the ice bank room lost 0.4% less weight than those chilled in the conventional chill room (Table 6.24). Over the subsequent 2 days in storage, the pigs in the ice bank room lost little additional weight, while those in the conventional chill room lost 0.9%. The use of a prechilling stage before the ice bank did not further reduce weight loss.

In all treatments the majority of the heat was removed from the carcasses in less than 12 h. After this time the deep leg temperature was less than 7°C and the surface of the leg, the highest surface temperature on the carcass, was below 5°C. The average temperature of the carcass would be approximately 4°C.

The only problem encountered experimentally was that of surface texture, experienced butchers subjectively judging that the ice bank chilled carcasses were less firm and more slippery than those chilled conventionally. In commercial use, ice banks would also require more space than conventional chilling systems. To reduce 250 pig carcasses of 63 kg average weight from 35 to 7°C would require 5000 kg (5.4 m³) of ice.

6.3.5 Combined systems

A number of investigations have been carried out into the use of different chilling systems in combination.

6.3.5.1 Pork

Neel *et al.* (1987) investigated the combination of electrical stimulation followed by a short initial spray chill using iced water, then immersion chilling. Pork carcasses, average market weight 98.6 kg, were either stimulated (550 V for 30 s, 2 s on 1 s off) or unstimulated. Sides were then chilled for 20 min using an ice water shower system (30 l s⁻¹ at 2°C) for 20 min. Loin primals were then cut from the sides, vacuum packed and chilled for 2.5 h in brine at -2.2°C. Controls were chilled for 24 h in air at 2°C before cutting and immersion chilling for 30 min.

After immersion chilling, temperatures were very similar under the two systems, ranging from 0 to 5°C in the spray chilled and 2–6°C in the control loins. After storage for 21 days at 0°C drip loss was highest, 1.27% from the stimulated and 1.09% from the unstimulated, spray chilled meat compared with 0.71 and 0.78% from the conventionally chilled. Pork from all treatments was rated tender by the taste panel and ratings for overall desirability did not differ significantly. All the pork was evaluated as acceptable or highly acceptable so the authors concluded that the accelerated system could considerably reduce processing time, space and energy while maintaining quality.

Long and Tarrant (1990) looked at the effect of combining a preslaughter shower with post-slaughter rapid chilling on temperature, weight losses and eating quality of pork meat. Showering caused a reduction in deep loin temperature at 40 min post-mortem and there was a strong indication of reduced drip from winter showering. The treatments had no effect on cooking loss or toughness of longissimus dorsi muscle.

The effect of immersing pork sides for 3 min in liquid nitrogen before conventional chilling was investigated by Jones *et al.* (1991). The main effect of the treatment was to reduce evaporative loss by 1.6% over the first 24 h of chilling. No significant differences were found in any of the other parameters measured, which included colour, texture, drip and bacterial survival. However, laboratory trials with strips of chilled pork showed that immersion in liquid nitrogen was effective in reducing inoculated populations of aerobic spoilage pseudomonads.

6.3.6 Protective coatings

6.3.6.1 Lamb

Popov and Vostrikova (1985) and Lazarus *et al.* (1976) have investigated the use of a protective coating, applied prior to chilling, to reduce weight loss. In the method, an edible animal fat and starch emulsion or a calcium alginate film (Flavor-*Tex*) was sprayed over the entire carcass straight after dressing. Savings in weight loss of up to 1.20% for the Flavor-*Tex* treated and 1.14% for the fat emulsion treated after 24 h post-mortem were found. Wrapping the carcass in a plastic film (low moisture and high oxygen transfer) resulted in savings in weight loss of up to 1.5% after 24 h chilling when compared with non-wrapped controls. The results of these studies showed that evaporative weight loss can be reduced by the use of either protective coating. However, considerations of the carcass cooling rate and microbial growth favoured the edible coating since it cools slightly quicker and produces lower microbial counts than the plastic wrap.

6.3.7 Hot boning

6.3.7.1 Beef

An obvious way of overcoming many of the problems associated with carcass chilling is to bone the carcass whilst hot and cool the resulting primal joints (Cuthbertson, 1977, Taylor *et al.*, 1980/81; Williams, 1978). However, the hot wet cut surfaces are easily contaminated and subject to a very high rate of evaporative weight loss unless wrapped. The potential hygiene problem has resulted in the Australian Department of Primary Industry specifying maximum cooling times (see Table 6.25) (Herbert and Smith, 1980).

The cooling times are difficult, if not impossible, to meet using conventional refrigeration systems and many consider them unreasonably strict. However, the importance of good hygiene and fast cooling of hot-boned meat is generally accepted. The majority of hot-boned beef is chilled inside 580 × 380 × 150 mm fibreboard cartons containing *ca.* 25 kg of primal cuts.

Table 6.25 Maximum cooling times to 8°C for hot-boned meat with different initial temperatures

| Initial meat temperature (°C) | Time to 8°C (h) |
|-------------------------------|-----------------|
| 40 | 4.0 |
| 35 | 5.0 |
| 30 | 6.0 |
| 25 | 7.5 |
| 20 | 9.5 |

Source: Herbert and Smith, 1980.

The most severe conditions that can be used in practice without partial freezing (air -1°C , 5 m s^{-1}), will achieve complete chilling from 40 to 2°C in 24 h . This time is more than doubled to 54 h using still air at the same temperature. The poor conductivity of the fibreboard, the layer of entrapped air, and the thickness of the meat, prevent even plate cooling systems (which produce high surface heat transfer coefficients) from achieving cooling times below 17 h .

These cooling times are too long to make conveyerised chilling systems economic unless very high throughputs are required; consequently, most hot-boned meat is chilled in batch systems. Careful design and operation of these systems are required to achieve acceptable air flows over the top and bottom faces of the cartons. Air gaps of at least 5 cm between layers of cartons are required which considerably reduces packing density in the chiller and necessitates double handling if the meat is to be stored and transported on pallets. The batch systems also suffer from the same peak load problems as carcass chillers.

Bell *et al.* (1996) studied hot-boning of bull beef and chilling in either vacuum or CO_2 packs. Cooling times to 7°C were *ca.* 13 and 20 h , respectively. The authors stated that the process could produce high quality beef for catering use with a storage life of 70 days at *ca.* 0°C .

Attempts have been made to compensate for the poor conductivity of the packaging material by introducing a quantity of liquid nitrogen into the carton before the lid is applied (Herbert, personal communication). This was partially successful in reducing the peak load on the refrigeration system and increasing the cooling rate, but substantial surface freezing occurred and nitrogen spillage produced a safety hazard in the cutting rooms. Greater success has been achieved by packing the meat in cartons and then adding 20% by weight of carbon dioxide pellets (Gigiel, 1985). Meat with an initial temperature of 30°C cooled to an average temperature of 0°C after 22 h without any further refrigeration being required. Consequently, the cartons could be assembled into pallets and/or transported directly after carbon dioxide addition. Very little refrigeration would subsequently be required to protect the meat from environmental heat gains. After 7 days storage the yield from the hot-boned carbon dioxide chilled meat was 3% more than that from conventionally chilled cold-boned controls. In this particular application the saving in weight loss more than offset the extra cost of solid carbon dioxide over conventional refrigeration. Further work showed that increased drip caused by partial freezing of a thin surface layer in contact with the solid carbon dioxide was balanced by reduced drip from the rapidly chilled but not frozen inner regions (Gigiel *et al.*, 1985).

Computer predictions indicated that the CSIRO cooling requirements could be attained in primals chilled in 158 mm deep aluminium moulds in a plate freezer operating with plate temperatures of -35°C (Visser, 1986). Cooling times of 5 h from 40 to 2°C would allow for a continuous opera-

tion. An automatic plate freezer cooling and subsequently freezing 800 cartons of hot-boned beef per day is now in operation in Australia (Anon, 1986). The system as designed would not be suitable for chilled meat production. Computer predictions show that if surface freezing is to be avoided, meat thickness would have to be reduced to below 8 cm before the CSIRO requirements could be achieved in a plate or immersion chilling system (James, 1988).

6.3.7.2 *Pork*

A whole range of technologies exists to overcome some, if not all, of the problems already identified, dependent to some extent upon the degree of further processing applied. As early as the 1950s, several progressive sausage manufacturers in the USA, who were also engaged in pig slaughtering, deboned hot (less than 1 h post-mortem) sow carcasses (Kauffman, 1987). The resulting prerigor muscles were treated with salt or sometimes polyphosphates and this procedure improved the water-holding capacity for the production of frankfurters. Today, the majority of sows and some boars, 15% of the total pork production, are hotboned and nearly all the musculature transformed immediately into sausages. This is the most extreme example of accelerated processing currently in commercial operation, from pig to sausage in less than 2 h. The ATP present in prerigor pork acts as a natural glue in the production of restructured products and with the trend towards additive-free food, such processing prerigor bears reexamination.

The rate of diffusion of salt through muscle becomes faster as muscle temperature rises. Also, the still intact arterial system of the pig immediately after slaughter provides a good distribution network for curing brine. Systems have been developed to hot cure bacon by arterially pumping cold brine into the carcass prerigor. This has the added advantage of partially cooling the meat, before immersion chilling in a refrigerated brine.

Neel *et al.* (1987) investigated a system where loins were removed 30 min post-mortem, vacuum packed, held in a water bath at 11 °C for 5 h then brine chilled. Drip loss after storage for 21 days at 0 °C was less (0.55%) than the control and other rapidly chilled treatments. Other sensory parameters were similar.

Warm processing where loins were removed from carcasses either 1, 3 or 5 h post-stunning was investigated by Frye *et al.* in 1985. Three rapid cooling treatments: immersion in brine at -23 °C; CO₂ chilling at -94 °C or packing in CO₂ at -68 °C, were used in the trials. These produced loin temperatures of -2 °C after 1.5–2 h of chilling with no significant difference between treatments. The crust frozen loins were then tempered and mechanically portioned. Pork chilled at 1 h post-stunning resulted in high shear force values and short sarcomere length. For a delay time of 3 h or more there were no major differences in muscle colour, pH, sarcomere lengths, drip or taste panel determinations between treatments and a conventionally (0–2 °C chiller) chilled control.

Warm boning as practised in Denmark is another technology that allows same day processing and distribution (Hermansen, 1987). Immediately after dressing, chilling in air at -25 to -30°C for *ca.* 80 min is commenced. This brings the surface temperature down to about -2°C . It is therefore necessary to equilibrate the carcass for one or two hours before cutting and boning take place. The total chilling loss is about 0.6%. After boning the meat is either vacuum packed for storage and ageing, wrapped, boxed and frozen, or cured and tumbled. Not all the heat is extracted during the short initial blast chilling operation and further cooling is required after cutting. Van Laack and Smulders (1989) showed that there were no differences in the microbial and sensory qualities of the 'warm' processed pork compared with cold boned controls. Overall yield was 0.8% higher than that from the controls.

6.4 Conclusions

- 1 The factors that control the cooling of a side of meat are the rates at which heat can be conducted from the innermost tissues to the surface and from the surface to the circulating air in the chill room. The former is rate controlling because of the very poor conductivity and considerable thickness of the beef hindquarter, although this fact is still not appreciated by many of those engaged in refrigeration design. Attempts by contractors to meet continuing commercial pressures for increased rates of cooling are therefore confined to changing the parameters that affect surface heat transfer, i.e. temperature, air velocity and humidity.
- 2 The optimisation of a carcass chilling system will depend upon the market being supplied. If eating quality is of prime importance, then cold shortening has to be avoided. For beef and lamb this will be achieved by specifying a minimum air temperature of 10°C for the first 10 h of chilling or by the application of electrical stimulation. A high air velocity during this stage will increase the rate of chilling and reduce the drip loss on cutting.
- 3 If cost is of prime importance then the minimum weight loss and fastest throughputs are required. This necessitates low air temperatures, high air velocities and high relative humidities. Even under these conditions, it is difficult if not impossible to attain a temperature of 7°C in a true 24 h cycle with beef and alternative chilling methods should be considered.

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7

Freezing of meat

Meat for industrial processing is usually frozen in the form of carcasses, quarters or boned out primals in 25 kg cartons. Most bulk meat, consumer portions and meat products are frozen in air blast freezers. Some small individual items, for example beefburgers, may be frozen in cryogenic tunnels and a small amount of offal and other meat is frozen in plate freezers. It is not unusual for meat to be frozen twice before it reaches the consumer. During industrial processing frozen raw material is often thawed or tempered before being turned into meat-based products, i.e. pies, convenience meals, burgers, etc or consumer portions, fillets, steaks, and so on. These consumer-sized portions are often refrozen before storage, distribution and sale.

7.1 Freezing rate

There are little data in the literature to suggest that, in general, the method of freezing or the rate of freezing has any substantial influence on a meat's subsequent storage life, its quality characteristics or final eating quality. There is some disagreement in the literature about whether fast or slow freezing is advantageous. Slightly superior chemical and sensory attributes have been found in food cryogenically frozen in a few trials (Sebranek *et al.*, 1978; Dobryski *et al.*, 1977; Sebranek, 1980) but other trials did not show any appreciable advantage (Lampitt and Moran, 1933) especially during short term storage (Hill and Glew, 1973). Jakobsson and Bengtson (1973) indicated that there is an interaction between freezing rate and cooking method. Meat that had been cooked from frozen was found to

show a favourable effect from faster freezing rates. Mittal and Barbut (1991) showed that freezing rate affected the modulus of rigidity of meat after cooking. Similar values to fresh meat were produced in meat frozen in liquid nitrogen. The value of the modulus increased as the rate of freezing decreased.

In 1980 Añón and Calvelo reported a relationship between the rate of freezing and drip loss, drip loss reaching a maximum when the freezing time from -1 to -7°C was *ca.* 17 min. Mascheroni (1985) used this relationship to produce a method for determining the rate at which frozen meat had been frozen. However, attempts to replicate the work at Langford (James *et al.*, 1983) were unsuccessful because of the variability in drip loss from meat before freezing. Studies using differential scanning calorimetry (DSC) on fresh and frozen bovine muscle at different freezing rates show a decrease of denaturation enthalpies; the slower the freezing rate the greater the loss (Wagner and Añón, 1985). Investigations covered freezing times from 5 to 60 min.

Experiments with pork *M. longissimus dorsi* found no difference in drip loss between samples frozen at -20°C or -80°C (Sakata *et al.*, 1995). At -20 and -80°C samples took 6 and 3 h, respectively to pass from -1°C to *ca.* -6°C . In the -20°C samples inter- and intracellular ice were seen but only intracellular ice was seen at -80°C .

Methods of freezing clearly affect the ultrastructure of muscle. Slow freezing ($1\text{--}2\text{ mm h}^{-1}$ for example (Buchmuller, 1986) tends to produce large ice crystals extracellularly, whilst quick freezing (e.g. 50 mm h^{-1}) gives smaller crystals in and outside cells (Buchmuller, 1986; Bevilacqua *et al.*, 1979). Obviously a temperature gradient will occur in large pieces of meat and result in a non-uniform ice morphology (Bevilacqua *et al.*, 1979).

Petrovic *et al.* (1993) found that slowly frozen meat, 0.22 and 0.39 cm h^{-1} , lost more weight during freezing, thawing and cooking than that frozen at $3.95\text{--}5.66\text{ cm h}^{-1}$ (Table 7.1). However, higher weight losses during thawing were measured at an intermediate freezing rate of 3.33 cm h^{-1} . Meat frozen at rates of 3.33 cm h^{-1} and faster was rated as more tender and juicier after cooking than unfrozen controls and slow frozen samples (Table 7.2). Petrovic *et al.* stated that the optimal conditions for freezing portioned meat are those that achieve freezing rates between 2 and 5 cm h^{-1} to -7°C . Grujic *et al.* (1993) suggest even tighter limits, $3.33\text{--}3.95\text{ cm h}^{-1}$. Slow freezing at up to 0.39 cm h^{-1} resulted in decreased solubility of myofibrillar proteins, increase in weight loss during freezing, thawing and cooking, lower water-binding capacity and tougher cooked meat. Very quickly frozen meat ($>4.9\text{ cm h}^{-1}$) had a somewhat lower solubility of myofibrillar proteins, lower water-binding capacity and somewhat tougher and drier meat. The samples were thawed after storage times of 2–3 days at -20°C so the relationship between freezing rates and storage life was not investigated.

Storage times of 48 h and 2.5 months were used during investigations of the effect of different freezing systems and rates on drip production from

Table 7.1 Relationship between freezing rate of beef M. longissimus dorsi and weight loss during freezing, thawing and cooking

| Freezing rate (cm h ⁻¹) | % Weight loss during | | |
|-------------------------------------|----------------------|---------|---------|
| | Freezing | Thawing | Cooking |
| Control | – | – | 36.32 |
| 0.22 | 2.83 | 0.78 | 38.41 |
| 0.39 | 2.58 | 0.72 | 38.00 |
| 3.33 | 1.15 | 1.21 | 37.47 |
| 3.95 | 1.05 | 0.18 | 37.24 |
| 4.92 | 0.87 | 0.10 | 37.15 |
| 5.66 | 0.63 | 0.03 | 37.14 |

Source: Petrovic *et al.*, 1993.

Table 7.2 Relationship between freezing rate of beef M. longissimus dorsi and texture

| Freezing rate (cm h ⁻¹) | Texture | Tenderness | Juiciness |
|-------------------------------------|---------|------------|-----------|
| Control | 7.0 | 6.8 | 7.0 |
| 0.22 | 7.0 | 6.0 | 6.7 |
| 0.39 | 7.0 | 6.5 | 7.0 |
| 3.33 | 7.0 | 7.5 | 7.5 |
| 3.95 | 7.0 | 8.0 | 8.0 |
| 4.92 | 7.0 | 8.5 | 8.5 |
| 5.66 | 6.0 | 7.0 | 7.3 |

Source: Petrovic *et al.*, 1993.

Texture: 1 = extremely tough, 7 = extremely fine.

Tenderness: 1 = extremely hard, 9 = extremely tender.

Juiciness: 1 = extremely dry, 9 = extremely juicy.

small samples of mutton muscle (Sacks *et al.*, 1993). In all cases, drip loss after 2.5 months was at least double the percentage measured after 48 h (Table 7.3). After 2.5 months, drip loss from samples frozen using cryogenics was >2% less than in those using air freezing.

The most recent comparison (Sundsten *et al.*, 2001) revealed some commercial advantages of fast freezing, but no quality advantages. The studies compared three different freezing methods, spiral freezing (SF), cryogenic freezing (liquid nitrogen, LN) and impingement freezing (IF). The times required to freeze a 10 mm thick 80 g hamburger from +4 °C to -18 °C in the SF, LN and IF were 22 min, 5 min 30 s and 2 min 40 s, respectively. The authors state that dehydration was significantly higher for hamburgers frozen in SF (1.2%) compared to LN (0.4%) and IF (0.4%). No significant

Table 7.3 Drip loss (%) from 77.6 g samples of longissimus lumborum et thoracis frozen under different methods and thawed at 4 °C

| Freezing conditions | Freezing time to -2.2 °C | Freezing rate (cm h ⁻¹) | Storage time at -20 °C | |
|--------------------------|-----------------------------|--|---------------------------|--------------------|
| | | | 48 h | 2.5 months |
| Cryogenic, -90 °C | 15 min | 6.4 | 3.34 ^a | 9.49 ^a |
| Cryogenic, -65 °C | 22 min | 4.4 | 4.70 ^{ab} | 9.72 ^a |
| Blast freezer, -21 °C | 1.83 h | 0.55 | 5.53 ^b | 12.74 ^b |
| Walk-in-freezer, -21 °C | 1.88 h | 0.53 | 4.71 ^{ab} | 13.18 ^b |
| Domestic freezer, -25 °C | 1.96 h | 0.51 | 5.26 ^b | 11.72 ^b |

Means in the same column with different superscripts are different at $P > 0.05$ h

Source: Sacks *et al.*, 1993.

difference could be seen in cooking losses, even after storage for 2 months. Ice crystals were significantly larger in hamburgers frozen in SF compared to LN and IF. Sensory analysis revealed no difference in eating quality between the three freezing methods, even after storage for 2 months.

Slow freezing from a high initial temperature can provide conditions for microbial growth compared with a very rapid freezing process. Castell-Perez *et al.* (1989) predicted that slow freezing from an initial product temperature of 30 °C could result in an 83% increase in bacterial numbers compared with a 4% increase from 10 °C.

7.2 Freezing systems

7.2.1 Air

Air is by far the most widely used method of freezing food as it is economical, hygienic and relatively non-corrosive to equipment. Systems range from the most basic, in which a fan draws air through a refrigerated coil and blows the cooled air around an insulated room (Fig. 7.1), to purpose-built conveyerised blast freezing tunnels or spirals. Relatively low rates of heat transfer are attained from product surfaces in air systems. The big advantage of air systems is their versatility, especially when there is a requirement to freeze a variety of irregularly shaped products or individual products.

In practice, air distribution is a major problem, often overlooked by the system designer and the operator. The freezing time of the product is reduced as the air speed is increased. An optimum value exists between the decrease in freezing time and the increasing power required to drive the fans to produce higher air speeds. This optimum value can be as low as 1.0 ms⁻¹ air speed when freezing beef quarters rising to 15 ms⁻¹ or more for thin products.

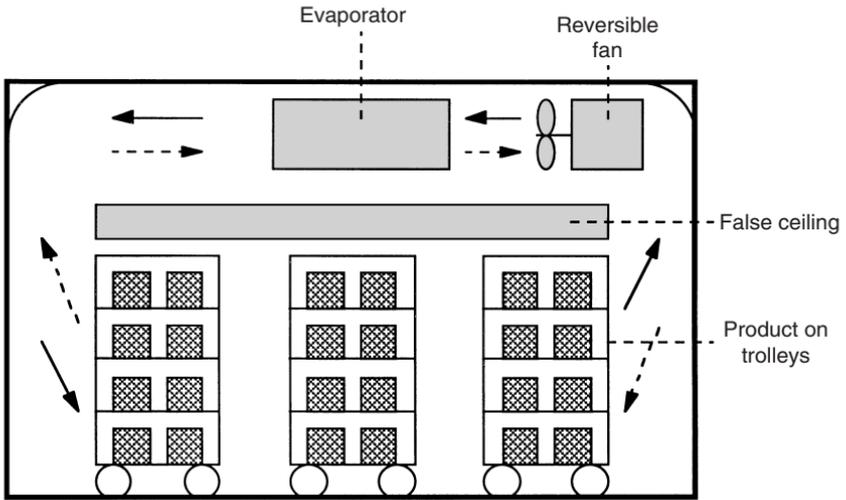


Fig. 7.1. Example of a freezing tunnel with longitudinal air circulation.

The use of impingement technology to increase the surface heat transfer in air and other freezing systems has received attention recently (Newman, 2001; Sundsten *et al.*, 2001; Everington, 2001). Impingement is the process of directing a jet or jets of fluid at a solid surface to effect a change. When the jets of fluid are very cold gas, the change is a dramatic increase in convective surface heat transfer coefficients. The very high velocity ($20\text{--}30\text{ms}^{-1}$) impingement gas jets, ‘breakup’ the static surface boundary layer of gas that surrounds a food product. The resulting medium around the product is more turbulent and the heat exchange through this zone becomes much more effective.

7.2.1.1 Batch systems

Placing food items in large refrigerated rooms is the most common method of freezing. Fans circulate air through refrigerated coils and around the products in an insulated room. Large individual items such as meat carcasses are hung from overhead rails, smaller products are placed either unwrapped or in cartons on racks, pallets, or large bins.

7.2.1.2 Continuous systems

In a continuous system, meat is conveyed through a freezing tunnel or refrigerated room usually by an overhead conveyor or on a belt. This overcomes the problem of uneven air distribution since each item is subjected to the same velocity/time profile. Some meat products are frozen on racks of trays (2m high), pulled or pushed through a freezing tunnel by mechanical means. For larger operations, it is more satisfactory to use feed meat on a continuous belt through linear tunnels or spiral freezers. Linear

tunnels are of simpler construction but are restricted by the length of belt necessary to achieve the cooling time required and on the space available in most factories. Spiral freezers are therefore a more viable alternative.

7.3 Contact freezers

Contact freezing 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 freezing offers several advantages over air cooling, i.e. there is much better heat transfer and significant energy savings. However, the need for regularly shaped products with large flat surfaces is a major hindrance.

Modern plate cooling systems differ little in principle from the first contact freezer patented in 1929 by Clarence Birdseye. Essentially the product is pressed between hollow metal plates containing a circulating refrigerant (Fig. 7.2). A hydraulic cylinder is used to bring the freezing plates into pressure contact with the product. These plates can be either horizontal or vertical.

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. 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%.

General advantages of plate freezers over air-blast carton freezers include:

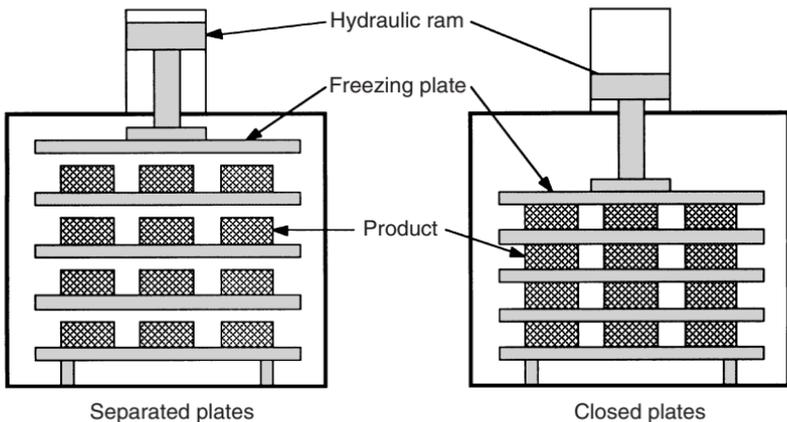


Fig. 7.2. Example of a horizontal plate freezer.

- Freezing is either faster for the same refrigerant evaporating temperature, or can take place at a higher evaporating temperature for a given freezing time.
- Product temperatures are easier to control, especially for smaller cuts.
- Power consumption is significantly reduced – savings of at least 30%, and possibly 50% or more, may be expected because air-circulating fans are not required and because higher evaporating temperatures can be used for the same effective cooling medium temperature.
- In many cases, less building space is required.
- The product remains uniform and flat after freezing, unlike air-blast frozen cartons which often bulge. The flat cartons result in stable loads, giving up to 30% higher space utilisation in cold stores. For transport, the stable pallets facilitate unitised loading, and some 8–10% more product can be loaded into a container.

Disadvantages of plate freezers relate mainly to cost aspects:

- Capital costs are significantly higher than for equivalent air-blast freezers. Manually loaded plate freezers are comparable in cost to automatic air-blast tunnel freezers. Fully automatic plate freezers are more expensive.
- High circulation rates of liquid refrigerant are required; this results in additional costs for larger accumulators and higher capacity pumps.
- For manual plate freezers, simultaneous loading and unloading may require higher labour input than for a batch air freezer.
- Each plate must be loaded with product of the same thickness.
- Damp cartons can stick to plates or cause jams when ice forms.
- Air infiltration must be minimised to prevent frost build up on plates.

Freezing unpacked meat has significant advantages because of the substantially shorter freezing times (Fleming *et al.*, 1996). Twice as many freezing cycles per day can be achieved with the bare product (Table 7.4).

Overall costs for plate freezing can be comparable to those for air-blast freezing. De Jong (1994) carried out a cost analysis (Table 7.5) for a beef plant using either plate or air blast freezers in New Zealand which assumed

Table 7.4 Predicted freezing time of meat blocks in a plate freezer operating at -30°C

| Thickness (mm) | Freezing time (h) | | Cycles per day | |
|----------------|-------------------|------|----------------|------|
| | Cartoned | Bare | Cartoned | Bare |
| 80 | 6.3 | 2.5 | 3 | 6 |
| 160 | 16.5 | 8.5 | 1 | 2 |

Source: Fleming *et al.*, 1996.

Table 7.5 Energy and cost requirements for beef plant freezing 3000 cartons per day

| | Four-batch air freezers | Automatic air blast | Manual plate freezers |
|------------------------------------|----------------------------|------------------------|--------------------------|
| <i>Energy analysis</i> | | | |
| Freezing time (h) | 38 | 38 | 17 |
| Freezer load (kW) | 573 | 477 | 400 |
| Power consumption (kW) | 689 | 570 | 462 |
| <i>Economic analysis (NZ\$000)</i> | | | |
| Capital cost | 1500 | 2200 | 2000 |
| Annual capital charges | 266 | 389 | 354 |
| Annual energy costs | 463 | 383 | 310 |
| Annual labour cost | 60 | 0 | 90 |
| Total annual cost | 789 | 772 | 754 |

Source: De Jong, 1994.

a net electricity cost of NZ\$0.10 per kilowatt hour, a capital recovery over 10 years and an interest rate of 12%.

7.4 Cryogenic freezing

Cryogenic freezing uses refrigerants, such as liquid nitrogen or solid carbon dioxide, directly. The method of cooling is essentially similar to water-based evaporative cooling, cooling being brought about by boiling off the refrigerant, the essential difference being the temperature required for boiling. As well as using the latent heat absorbed by the boiling liquid, sensible heat is absorbed by the resulting cold gas.

Owing to very low operating temperatures and high surface heat transfer coefficients between product and medium, cooling rates of cryogenic systems are often substantially higher than other refrigeration systems.

Most systems use total loss refrigerants, i.e. the refrigerant is released to the atmosphere and not recovered. Alternatively dichlorodifluoromethane (CCl_2F_2) (otherwise known as Freon 12, R.12 or F12) may be used in a recovery and recycle system, however, R.12 is not generally accepted in all countries. Because of environmental and economic factors total loss refrigerants must be both readily available and harmless, which limits the choice to atmospheric air and its components, liquid nitrogen (LN) and liquid or solid carbon dioxide (CO_2).

The particular characteristics of total loss refrigerants that may be regarded as advantages or disadvantages are listed in Table 7.6.

Cryogenic freezing is mainly used for small products such as burgers, ready meals, and so on. The most common method is by direct spraying of liquid nitrogen onto a food product while it is conveyed through an insulated tunnel.

Table 7.6 Advantages and disadvantages of total loss refrigerants in comparison with mechanical refrigeration

| Advantages | Disadvantages |
|---|----------------------------------|
| Low capital investment | High operating cost |
| High refrigerating capacity | High refrigerating capacity |
| Low weight when out of use | High weight at start of use |
| No residual weight (dry ice) | Limited duration without filling |
| No noise | Poor temperature control |
| Advantageous storage atmosphere (N ₂) | Reduced humidity |
| Bacteriostatic affect (CO ₂) | Suffocation hazard |
| Low maintenance requirements | Limited availability |
| Foolproof once installed (dry ice) | |

Impingement technologies are being used to increase heat transfer further (Newman, 2001). Newman states that when comparing the overall heat transfer coefficients of cryogenic freezing tunnels, impingement heat transfer is typically 3–5 times that of a conventional tunnel utilizing axial flow fans. With the increased overall heat transfer coefficient, one can either increase the freezing temperature to increase overall cryogen efficiency or continue to run at very cold temperatures and dramatically increase the overall production rate. Impingement freezing is best suited for products with high surface area to weight ratios, for example hamburger patties or products with one small dimension. Testing has shown that products with a thickness of less than 20 mm freeze most effectively in an impingement heat transfer environment. When freezing products thicker than 20 mm, the benefits of impingement freezing can still be achieved, however, the surface heat transfer coefficients later in the freezing process should be reduced to balance the overall process efficiency. The process is also very attractive for products that require very rapid surface freezing and chilling.

7.5 Freezing of specific products

7.5.1 Meat blocks

James *et al.* (1979) showed that air temperatures below -30°C and air velocities exceeding 5 m s^{-1} are required to freeze 15 cm thick meat blocks in corrugated cardboard cartons in less than 24 h (Fig. 7.3). Creed and James (1981) carried out a survey which indicated that only 58% of industrial throughput is frozen in times within $\pm 20\%$ of the actual freezing time required.

7.5.2 Beef quarters

James and Bailey (1987a) reported that brine spray and liquid nitrogen immersion systems had been used to freeze beef quarters. However, most

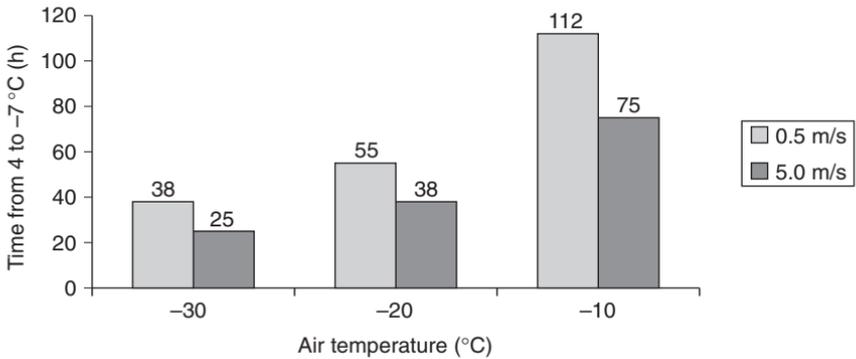


Fig. 7.3. Freezing time of 15 cm thick boxed blocks (source: James *et al.*, 1979).

Table 7.7 Average freezing time from 4 to -7°C at thermal centre of 50, 75 and 100 kg beef quarters

| Weight | 50 kg | 75 kg | 100 kg |
|-------------|-------|-------|--------|
| Hindquarter | 22 | 29 | 33 |
| Forequarter | 13 | 20 | 25 |

Source: James *et al.*, 1987.

investigations had used air. Temperature in air systems ranged from -11 to -40°C and weight loss from 0.3 to 1.19%. In their own investigations beef quarters ranging in weight from 40 to 140 kg were frozen in air at -32°C , 1.5 m s^{-1} .

On average, hindquarters below 50 kg and forequarters below 75 kg could be frozen in a 24 h operation (Table 7.7). There was no statistical difference in bacterial counts before and after freezing.

7.5.3 Mutton carcasses

Mutton production is seasonal and continuity of supply for processing can be achieved by frozen storage and subsequent thawing and boning (Creed and James, 1984).

Data from the investigations of Creed and James were used to verify a predictive program for freezing of mutton carcasses. The predictions indicated that any condition more severe than -20°C , 0.5 m s^{-1} , would achieve a 24 h freezing operation for unwrapped carcasses (Table 7.8). To guarantee an overnight (15–16 h) freezing cycle for wrapped carcasses, conditions more severe than -30°C , 4 m s^{-1} , would be required.

7.5.4 Offal

Although edible offal comprises 3–4% of the cold weight of a carcass there is little published data on its refrigeration (Creed and James, 1983). The

Table 7.8 Predicted freezing time from 4 to -7°C in thermal centre of unwrapped and stockinette wrapped carcasses

| | $-30^{\circ}\text{C}, 4 \text{ ms}^{-1}$ | $-30^{\circ}\text{C}, 0.5 \text{ ms}^{-1}$ | $-20^{\circ}\text{C}, 0.5 \text{ ms}^{-1}$ |
|-----------|--|--|--|
| Unwrapped | | | |
| 30 kg | 5.5 | 11.0 | 16.4 |
| 40 kg | 8.5 | 15.6 | 23.4 |
| Wrapped | | | |
| 30 kg | 8.0 | 12.5 | 19.0 |
| 40 kg | 12.0 | 17.8 | 26.5 |

Source: Creed & James, 1984.

Table 7.9 Freezing time equations for liver in plate freezer

| Block thickness (cm) | Equation |
|----------------------|---------------------------------------|
| 7.6 | $Y = -0.3547 + 54.4632 R + 0.02138 I$ |
| 10.2 | $Y = -0.1917 + 79.9314 R + 0.05203 I$ |
| 15.2 | $Y = -0.8020 + 212.119 R + 0.08880 I$ |

Source: Creed & James, 1983.

authors found that liver was amenable to plate freezing and the freezing time to -7°C (Y) was related to the initial temperature (I) and R the reciprocal of -1.5°C , the refrigerant temperature (Table 7.9).

The authors extended their studies to examine the effect of different packaging materials on freezing time (Creed and James, 1985).

7.5.5 Small products

The rate of freezing of unwrapped small meat products definitely affects the weight loss, with loss increasing as freezing rate decreases. There is also some evidence that it affects losses during cooking and sensory properties.

Freezing times of individual meat patties can range from tens of seconds to over an hour in different systems (Hanenian *et al.*, 1989). Everington (2001) has shown that when freezing thin (11 mm) burgers high air velocities will substantially reduce freezing times (Fig. 7.4). Freezing in nitrogen and CO_2 can substantially reduce the amount of weight loss from unwrapped patties when compared with air systems (Table 7.10). However, cooking losses were higher and overall patty quality lower in those frozen in nitrogen. This was mainly due to cracking in the immersion system.

When patties are stacked and placed in boxes before freezing, the freezing times increase by at least an order of magnitude. Studies carried out on packaged patties looked at freezing rates between 2 and -18°C ranging from 24 to 96 h (Berry and Leddy, 1989). Before freezing, tenderness scores

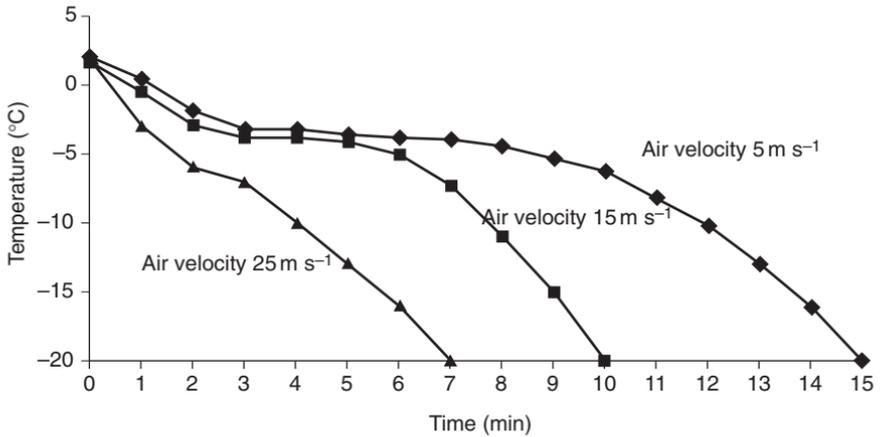


Fig. 7.4. Freezing 11 mm thick, 80 mm diameter beef burgers in air at -39°C (source: Everington, 2001).

Table 7.10 Freezing of beef patties from 2 to -10°C in different systems

| Method | Temperature ($^{\circ}\text{C}$) | Thickness (cm) | Freezing time (s) | Freezing rate (cm h^{-1}) | Weight loss (%) | Cooking loss (%) |
|---|------------------------------------|----------------|-------------------|--------------------------------------|-----------------|------------------|
| Air ($23 \text{ Wm}^{-2} \text{ K}^{-1}$) | -14 | 1.10 | 3939 | 0.5 | 2.0 | 34.4 |
| Air ($31 \text{ Wm}^{-2} \text{ K}^{-1}$) | -25 | 1.12 | 2047 | 1.0 | 1.7 | 34.6 |
| CO_2 snow | -78 | 1.13 | 129 | 16.5 | 0.1 | 35.9 |
| N_2 immersion | -196 | 1.13 | 22 | 97.3 | 0.1 | 37.7 |

Source: Hanenian *et al.* 1989.

measured using a taste panel (8-extremely tender to 1-extremely tough) ranged from 6.6 to 6.1. All the patties were rated as tougher immediately after freezing and after storage for 18 months (Fig. 7.5). Immediately after freezing, patties frozen in 96 h were significantly tougher than those frozen in 24 h, however, the difference was not significant after 18 months storage. Instrumental texture measurements were in general agreement with those from the taste panel (Fig. 7.5).

Commercial freezing rates can be very slow. Sausages at the centre of a pallet require 6–7 days to achieve -15°C from a starting temperature of 7°C (Wanous *et al.*, 1989). However, studies carried out on similar sausages frozen in 9 h, 2.4 and 6.8 days showed no effect of freezing rate on TBA values during frozen storage of 20 weeks.

Many small meat products such as cubes and strips of ham and poultry meat, poultry pieces, cooked meat balls, slices of salami and minced meat can be individually quick frozen (IQF) in a rotary cryogenic freezer

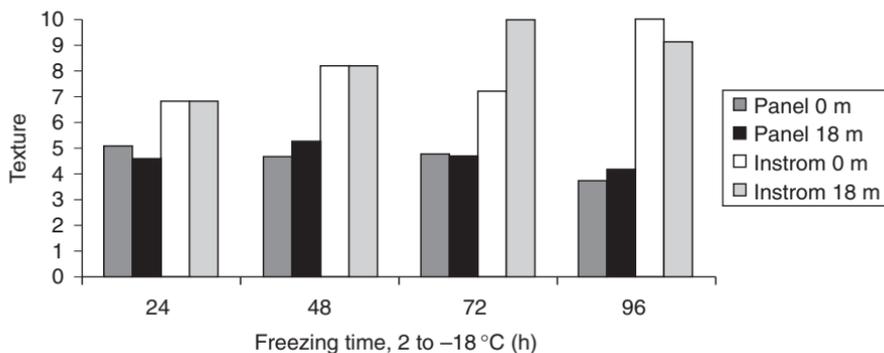


Fig. 7.5. Texture of patties measured by taste panel (8 = extremely tender, 1 = extremely tough) and Instrom (kg) after 0 and 18 months storage (source: Berry and Leddy, 1989).

(Thumel and Gamm, 1994). The product is sprayed with a fine mist of nitrogen to freeze the surface as it enters the drum. As the tilting drum rotates, it transports the food through a contracurrent flow of cold gas that completes the freezing process.

7.6 Tempering and crust freezing

There is no exact definition for the word ‘tempering’ in the meat industry. In practice ‘tempering’ can be a process in which the temperature of the product is either raised or lowered to a value that is optimal for the next processing stage. Tempering systems where the temperature of frozen product is raised in temperature are covered in the thawing and tempering chapter.

Tempering and crust freezing operations are used to produce the optimum texture in a chilled product so that it is suitable for mechanical processing. In this case, the product is semi-frozen so that it is stiff enough to be sliced, cubed and so on.

7.6.1 Pork loin chopping

Loins from lamb and pork are often processed by chopping with a high-speed chopper. Because of the deformation in this process the yield can be reduced. The yield can be increased by first tempering the meat, providing a stiff outer crust, by freezing with liquid nitrogen or a blast of very cold air. However, the process must be carefully controlled; if too much meat is frozen the subsequent chopped meat will have a large increase in the amount of drip formed, resulting in a loss in yield of some 4–5%. Hence, loin freezing processes must always be carefully controlled.

7.6.2 High speed ham slicing

Traditional production of ham slices consists in cooling formed ham logs in cold rooms to a core temperature of 2°C, a process that takes between 2 and 7 days (Lammertz and Brixy, 2001). The logs are cut in 1.5 mm thick slices using standard slicers at rates up to 500 slices per minute.

New high rate slicers operate at rates up to 1000 slices per minute. To produce high quality slices at this rate the ham logs have to be crust frozen to a temperature of -5°C at a depth of 7 mm. A number of different cryogenic freezers have been developed to perform the crust freezing process (Lammertz and Brixy, 2001).

7.6.3 High speed bacon slicing

An increasing proportion of bacon is being presliced and packed before it is delivered to wholesalers and retailers. To achieve the throughput required, slicers have to be operated at very high speeds. To maximise the yield of high quality slices from high-speed slicers the bacon has to be sliced in a semi-frozen tempered state. The optimum tempering temperature is a function of the bacon and the slicer. Most bacon tempering has been traditionally carried out in a long single stage process. However, more efficient two-stage processing systems are now common. The correct design and operation of such systems is critical to the cost effectiveness of the slicing process.

Bacon temperature is the critical parameter in a high-speed (typically 800–1400 slices per minute) slicing operation. This operation has more in common with the guillotining of metal than the slow speed slicing normally carried out in a butcher's shop. The bacon must be presented to the blade in a rigid semi-frozen state to minimise distortion and break-up on cutting. Obtaining the correct temperature throughout the bacon middle is crucial for a high yield of undamaged slices (James and Bailey, 1987b). High-speed photography has been used to demonstrate clearly the effect of incorrect slicing temperature. When the temperature was too low the hard bacon shattered and blade wear was excessive; when too high the soft bacon stuck to the blade and the fat was torn away from the lean. The optimum temperature for a particular operation depends on the salt content of the bacon, the maturation time, the type of slicer being used and the slicing speed.

Experiments carried out in the 1920s showed that there was a near linear relationship between the initial freezing point of lean pork and its salt content (expressed in grams of salt per 100 g of water in the meat). Consequently the initial freezing point, ice content at any temperature and the related slicing temperature depend upon both the salt and water content of the bacon. Work has shown that even using very carefully controlled curing methods there are still considerable variations in salt content within individual slices, between slices and between bacon sides in the same batch. This makes it difficult, and in a commercial situation impossible, to carry

Table 7.11 Salt and moisture contents in bacon middles from different suppliers

| Supplier no. | Salt (g/100g water) | | | Moisture (%) | | |
|-----------------|---------------------|---------|------|--------------|---------|------|
| | Maximum | Minimum | Mean | Maximum | Minimum | Mean |
| 1 | 7.1 | 2.9 | 5.1 | 73.5 | 65.3 | 69.6 |
| 2 | 6.5 | 2.7 | 4.1 | 74.0 | 68.0 | 71.1 |
| 3 | 4.7 | 2.9 | 4.0 | 72.5 | 68.6 | 71.0 |
| 4 | 5.9 | 2.1 | 4.1 | 74.6 | 65.0 | 71.8 |
| 5 | 6.3 | 2.2 | 4.2 | 74.2 | 63.9 | 70.9 |
| 6 | 5.9 | 2.5 | 5.0 | 72.6 | 64.3 | 70.3 |
| 7 | 6.5 | 3.1 | 4.9 | 74.4 | 67.5 | 71.1 |
| 8 | 4.6 | 2.2 | 3.2 | 74.2 | 70.0 | 72.2 |
| 9 | 6.3 | 2.6 | 4.7 | 74.7 | 66.3 | 69.7 |
| 10 | 5.2 | 2.7 | 4.1 | 74.8 | 65.3 | 70.3 |

Source: James and Bailey, 1987b.

out analytical tests that will define the optimum slicing temperature for a particular operation. This temperature must therefore be determined experimentally for each slicing operation, and tempering systems developed that will produce a uniform temperature throughout the product in the most efficient way.

7.6.3.1 Determination of slicing temperature

There is likely to be substantial variability in the bacon input to a slicing operation. A survey (James and Bailey, 1987b) found that mean percentage salt and water content of bacon supplied to a large slicing plant over a two-year period varied by 1.9 and 2.6%, respectively (Table 7.11). The effect on slicing of the variation in salt content, where the overall mean was 4.34%, was much greater than water, which had an overall mean of 70.8%. Maximum and minimum values from different suppliers were 7.1 and 2.1% for salt, and 74.8 and 63.9% for water. Initial freezing points, and consequently the optimum slicing temperatures could therefore vary by 5°C or more. Examination of freezing curves of bacon from three of the suppliers showed initial freezing points of -3, -3.5 and -6°C.

Currently the only method available for determining the optimum bacon temperature for a slicing operation is to carry out slicing trials at different bacon temperatures. Results from such a trial where the yield in each quality grade was determined are shown in Table 7.12. In the specific trial taking into account the relative quantities from each supplier, the best slicing temperature was found to be -9.5°C.

7.6.3.2 Tempering systems

A small number of operations use plate freezer, liquid immersion systems and cryogenic tunnels to temper bacon for high speed slicing. However, the majority of industrial systems employ air in a single or two-stage process.

Table 7.12 Yield (%) of slices in quality classes from bacon backs from different suppliers sliced at an equalised bacon temperature of -6.5 , -7.5 or -9.5°C

| Quality class | Prime/second | | | Thrifty/catering | | | Bits and pieces | | |
|--|--------------|--------|--------|------------------|--------|--------|-----------------|--------|--------|
| | -6.5 | -7.5 | -9.5 | -6.5 | -7.5 | -9.5 | -6.5 | -7.5 | -9.5 |
| Slicing temperature ($^{\circ}\text{C}$) | | | | | | | | | |
| Supplier A | – | 93.6 | 94.7 | – | 3.7 | 3.0 | – | 2.7 | 3.3 |
| Supplier B | 79.1 | 82.0 | 81.7 | 12.5 | 8.3 | 8.8 | 8.11 | 9.7 | 9.5 |
| Supplier C | – | 79.9 | 75.7 | – | 10.2 | 9.7 | – | 9.9 | 14.6 |
| Supplier D | 84.1 | 90.8 | 93.8 | 10.8 | 6.0 | 2.8 | 5.1 | 3.2 | 3.4 |
| Supplier E | – | 81.5 | 78.8 | – | 11.8 | 9.6 | – | 6.7 | 11.6 |
| Supplier F | – | 76.4 | 78.5 | – | 10.4 | 10.3 | – | 13.2 | 11.2 |

Source: James and Bailey, 1987b.

7.6.3.2.1 Single-stage tempering

Single-stage tempering is a very simple process. The bacon middle, back and streaky joints are placed on the shelves of trolleys. The trolleys are then wheeled into a room operating at the desired slicing temperature. The bacon remains in the room until its temperature equalises to that of the room. It is then pressed and sliced.

For example, in a commercial single stage tempering system, backs were held for 18h in rooms operating at -9 to -14°C , 0.2 – 1.2 m s^{-1} with an average product weight loss of 1.18%. At weekends the backs remained in the rooms for a total of 64h and the average weight loss increased to 1.88%. After 18h the surface temperature had reached -10°C but the centre was still above -7°C .

A number of problems are inherent in a single-stage tempering operation. Equalisation times are long, after 18h there can still be a 3°C differential across the backs. Using a two-stage system for only half this time resulted in differentials of less than 1°C . The most obvious drawback of single-stage tempering is that to obtain the same throughput systems have to be far larger, probably by at least three-fold. It is also more difficult to obtain even air distribution and good temperature control in a large room. This problem is exacerbated in that the single-stage system has to fulfil conflicting roles. To remove heat from the bacon a reasonable air/product temperature difference and reasonable air movement are required. In contrast, towards the end of the process when all the required heat has been extracted, a very small temperature differential and minimum air movement are desirable to attain an even temperature and a reduced rate of weight loss.

7.6.3.2.2 Two-stage tempering

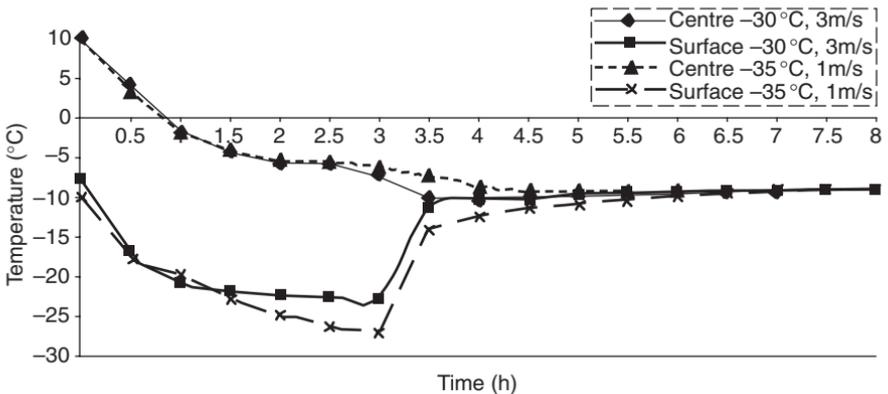
In a two-stage tempering process, an initial blast freezing operation is followed by a separate period of temperature equalisation. It is critical that

Table 7.13 Conditions in blast freezer, mean initial weights of bacon backs, % weight losses after 3 h and equilibrium temperatures

| Air conditions | | Weight | | Equilibrium temperature (°C) | No. samples |
|------------------|----------------------------|--------------|--------------|------------------------------|-------------|
| Temperature (°C) | Speed (m s ⁻¹) | Initial (kg) | 3 h loss (%) | | |
| -30 | 1.0 | 5.640 (0.51) | 0.71 (0.06) | -8.6 (0.3) | 6 |
| -30 | 3.0 | 5.150 (0.32) | 0.76 (0.08) | -11.6 (0.4) | 4 |
| -35 | 0.5 | 5.288 (0.13) | 0.66 (0.06) | -8.5 (0.4) | 6 |
| -35 | 1.0 | 5.375 (0.26) | 0.55 (0.07) | -9.9 (0.8) | 4 |

() = standard deviation.

Source: James and Bailey, 1987b.

**Fig. 7.6.** Surface and centre temperature in bacon backs during two-stage tempering operation (source: James and Bailey, 1987b).

the desired amount of heat is extracted in the initial blast freezing operation. Examples of conditions and final equalised temperatures are given in Table 7.13. Typical temperature histories at the surface and thermal centre of backs tempered at -30°C , 3.0 m s^{-1} and -35°C , 1.0 m s^{-1} are shown in Fig. 7.6. Surface temperatures tended to be a few degrees lower after 3 h at -35°C than at -30°C , whilst centre temperatures were very similar, *ca.*, -6°C . In each case the maximum temperature difference across the backs was less than 1°C after 3 h in the equalisation room and the temperature within any part of the back was within 1°C of the room temperature after 7 h.

It is critical that the refrigeration system is sized to extract the required amount of heat from the bacon. The energy released per kilogram of bacon in each half-hour period during one experiment varied by a factor of 2.7 from 0.0139 to $0.0051\text{ kWh kg}^{-1}$ (Fig. 7.7). The mean total energy extracted per kilogram of bacon in the 3 h operation was $0.0535\text{ kWh kg}^{-1}$.

In a two-stage system there are several practical considerations. In one study a 3 h blast freeze operation at -35°C , 1.0 m s^{-1} obtained the desired

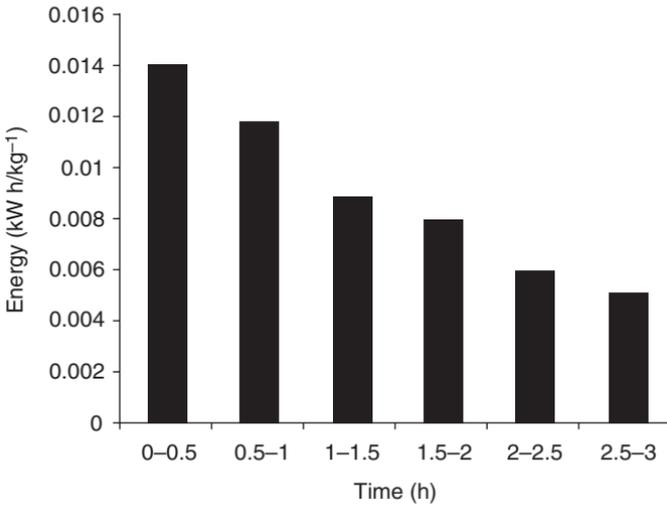


Fig. 7.7. Energy released (kWh kg^{-1}) by bacon backs over 0.5 h intervals during blast freezing at -30°C , 3.0 m s^{-1} (source: James and Bailey, 1987b).

equilibrium temperature of -9.5°C and achieved the lowest weight loss of 0.55%. However, these conditions were very critical and would not allow for a pull down period after loading, or the use of slightly thicker backs or bacon with a higher salt content. Adding heaters to the equalisation room to provide exact temperature control with slightly negative product load was considered more viable than trying to control the refrigeration against the positive load likely in practice. Air distribution and control would also be less exact at 3 m s^{-1} , and a variation of $\pm 0.5 \text{ m s}^{-1}$ in air velocity over the bacon backs would have far less effect on the final equalised temperature than a similar variation about a mean of 1.0 m s^{-1} . Operating conditions of -30°C , 3.0 m s^{-1} were therefore chosen for this particular industrial plant, because they were less critical and provided a degree of flexibility.

Investigations have shown clearly the need to size the refrigeration system to meet the initial rate of heat release from the warm bacon backs (James, 1997). In trials an experimental freezer was unable to maintain the desired set point of -30°C but rose to -27°C immediately after loading and took 1.5 h to recover fully. The average equalised temperature in this trial was 0.6°C higher than in two successive trials where less bacon was used and the freezer reached -30°C within minutes of loading. Although the average rate of heat release from the bacon backs during the freezing operation was $0.0175 \text{ kWh kg}^{-1}$ the refrigeration plant had to have twice this capacity to meet the rate of release during the first half hour. In the industrial situation heat ingress through the open door during loading and the considerable cooling requirement of the supporting racks also has to be taken into consideration. One practical solution is a central refrigeration

plant serving a number of separate freezing chambers. These can be loaded and unloaded in a sequence to provide the plant with a nearly constant refrigeration load enabling it to operate at optimum efficiency.

7.7 Conclusions

- 1 Under commercial conditions differences in freezing rates are unlikely to produce noticeable changes in the organoleptic quality of the meat produced. However, current legislation requires a minimum meat temperature of -12°C to be achieved before meat is moved from the freezing system. Freezing time is therefore of considerable economic importance.
- 2 Most unprocessed meat is either frozen in batch air systems as bone in carcasses, sides or quarters, or boned out in cartons. Freezing times in such systems are typically 25–72 h. Some offal is frozen in plate freezers.
- 3 Small processed items are typically frozen in continuous belt freezers or in cryogenic tunnels.
- 4 Crust freezing and tempering are increasingly being used to allow high speed mechanical portioning or slicing of meat and meat products. The final temperature distribution produced by the freezing system is critical in such operations.

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8

Thawing and tempering

Thawing has received much less attention in the literature than either chilling or freezing. In commercial practice there are relatively few controlled thawing systems.

Frozen meat, as supplied to the industry, ranges in size and shape from complete hindquarters of beef to small breasts of lamb, although the majority of the material is 'boned-out' and packed in boxes *ca.* 15 cm thick weighing between 20 and 40 kg. Thawing is usually regarded as complete when the centre of the block or joint has reached 0°C, the minimum temperature at which the meat can be boned or cut by hand. Lower temperatures (e.g. -5 to -2°C) are acceptable for meat that is destined for mechanical chopping, but such meat is 'tempered' rather than thawed. The two processes should not be confused because tempering only constitutes the initial phase of a complete thawing process.

Thawing is often considered as simply the reversal of the freezing process. However, inherent in thawing is a major problem that does not occur in the freezing operation. The majority of the bacteria that cause spoilage or food poisoning are found on the surfaces of meat. During the freezing operation, surface temperatures are reduced rapidly and bacterial multiplication is severely limited, with bacteria becoming completely dormant below -10°C. In the thawing operation these same surface areas are the first to rise in temperature and bacterial multiplication can recommence. On large objects subjected to long uncontrolled thawing cycles, surface spoilage can occur before the centre regions have fully thawed.

Most systems supply heat to the surface and then rely on conduction to transfer that heat into the centre of the meat. A few systems use electromagnetic radiation to generate heat within the meat. In selecting a thawing

system for industrial use a balance must be struck between thawing time, appearance and bacteriological condition of product, processing problems such as effluent disposal and the capital and operating costs of the respective systems. Of these factors, thawing time is the principal criterion that governs selection of the system. Appearance, bacteriological condition and weight loss are important if the material is to be sold in the thawed condition but are less so if the meat is for processing.

8.1 Considerations

The design of any thawing system requires knowledge of the particular environmental or process conditions necessary to achieve a given thawing time, and the effect of these conditions on factors such as drip, evaporative losses, appearance and bacteriological quality.

The process of freezing a high water content material such as meat takes place over a range of temperatures rather than at an exact point, because as freezing proceeds the concentration of solutes in the meat fluid steadily increases and progressively lowers the freezing temperature. Thawing simply reverses this process.

Thawing time depends on factors relating to the product and the environmental conditions, that include:

- dimensions and shape of the product, particularly the thickness
- change in enthalpy
- thermal conductivity of the product
- initial and final temperatures
- surface heat transfer coefficient
- temperature of the thawing medium.

The total amount of energy that must be introduced into the product is equal to the enthalpy change between the initial temperature and the average temperature required within the material after thawing. For the thawing process to be complete, no ice should remain and the minimum temperature has to be above -1°C . To thaw 1 kg of meat from a starting temperature of -40°C would require the addition of 300 kJ of energy if the meat was very lean, falling to about 180 kJ if very fat. Frozen meat that requires boning has to be completely thawed. However, an increasing proportion of meat is boned before freezing and if it is subsequently used in products such as pies, sausages, and so on, it can be cut by machine in a semi-frozen (tempered) state. To temper meat from -40°C to an average temperature of -4°C requires a heat input of approximately 100 kJ kg^{-1} , only one third of that required for complete thawing.

Thermal conductivity has an important effect on thawing. The conductivity of frozen lean meat is three times that of the thawed material. When thawing commences, the surface rises above the initial freezing point. Sub-

Table 8.1 Typical surface heat transfer coefficients (h) for different thawing systems

| System | Surface heat transfer coefficients ($\text{W m}^{-2} \text{K}^{-1}$) |
|-----------------------|--|
| Air-free convection | 5–15 |
| Air-forced convection | 10–70 |
| Water | 100–400 |
| Vacuum steam heat | 150–1000 |
| Plate | 100–300 |

sequently, an increasing thickness of poorly conducting material extends from the surface into the foodstuff, reducing the rate of heat flow into the centre of the material. This substantially increases the time required for thawing.

The main environmental factors are the temperature of the thawing medium and the surface heat transfer coefficient (h) which is a function of the shape and surface condition of the product, the thawing medium used and its velocity. Except for very simple configurations, h cannot be derived theoretically and must be measured experimentally. Few such measurements have been made for the thawing of foodstuffs (Arce and Sweat, 1980; Vanichseni, 1971), but typical ranges of h for the main thawing systems are given in Table 8.1.

In air thawing, h is not constant and is a function of relative humidity (James and Bailey, 1982). In the initial stages, water vapour condenses onto the frozen surface, immediately changing to ice. This is followed by a stage where vapour condenses in the form of water until the surface temperature is above the dew point of the air and all condensation ceases. The varying rate of condensation produces substantial changes in the value of h during the thawing process.

8.2 Quality and microbiological considerations

There are few published data relating thawing processes to the palatability of meat and eating quality is generally independent of the thawing method. However, two reports indicated that cooking directly from the frozen state produced less juicy lamb rib loins (Woodhams and Smith, 1965) and less tender beef rolled rib joints (James and Rhodes, 1978) when compared with meat that had been thawed before cooking.

The main detrimental effects of freezing and thawing meat is the large increase in the amount of proteinaceous fluid (drip) released on final cutting, yet the influence of thawing rate on drip production is not clear. There was no significant effect of thawing rate on the volume of drip in beef (Empey, 1933; Ciobanu, 1972) or pork (Ciobanu, 1972). Several authors

(Cutting, 1974; Love, 1966) concluded that fast thawing rates would produce increased drip, while others showed (Finn, 1932; Singh and Essary, 1971) the opposite. Thawing times from -7 to 0°C of less than 1 min or greater than 2000 min led to increased drip loss (James *et al.*, 1983). The results are therefore conflicting and provide no useful design data for optimising a thawing system.

The principle criteria governing quality of thawed meat are the appearance and bacteriological condition. These are major factors if the product is to be sold thawed but are less important if the food is destined for processing and heat treatment.

Microbiological problems can arise during thawing of food in bulk. While centre temperatures may not exceed 0°C , the exterior surface may be held at 10 – 15°C for many hours, or even days. During this time extensive growth of spoilage organisms can occur on the surface. The time required for microbiological numbers to reach 'spoilage' levels will largely be dependent upon the number of microbes initially present and the temperature. Since freezing and frozen storage have little effect on the number of viable microbes present, material of poor microbiological quality before freezing is likely to spoil more quickly during thawing (Roberts, 1974). The use of high thawing ($>10^{\circ}\text{C}$) temperatures for carcass meats tends to lead to large increases in microbial numbers (James and Creed, 1980; Bailey *et al.*, 1974).

Little published data exist on microbiological effects of thawing meat. Buttiaux (1972) reported that water thawing was more successful for beef than for pork if the meat was to be stored. Consequently, care must be exercised in extrapolating from one meat species to another. Results with pork suggested that air thawing gives final counts about ten times higher than thawing in 3% brine, whereas with beef Heinz (1970) reported counts lower by a factor of about 10 for air (4 – 5 m s^{-1} ; 10°C) as opposed to flowing water (10°C). Kassai (1969) also found no significant increase in bacteriological numbers when thawing beef carcasses in air (0.2 – 0.3 m s^{-1} , 15 – 20°C , 96% relative humidity, (RH)). Shoulders of lamb (Vanichseni *et al.*, 1972) thawed in air (0.2 m s^{-1} ; 18°C) or water (45°C) had bacterial counts that increased respectively by factors of 1.74 and 1.12; humidity and air velocity also influenced the results of air thawing.

It is often asserted that thawed food is more perishable than fresh or chilled produce, but experiments (Kitchell and Ingram, 1956; Kitchell and Ingram, 1959) have failed to demonstrate any difference of practical significance between the growth of meat spoilage organisms on fresh or thawed slices of meat. Greer and Murray (1991) found that the lag phase of bacterial growth was shorter in frozen/thawed pork than in fresh pork, while the generation time was unaffected.

Under commercial conditions, microbiological sampling of frozen meat may be of limited relevance. Small frozen samples will be thawed in a laboratory, probably under conditions unlike those used later to thaw whole blocks. On the laboratory samples, extensive microbial growth during

thawing is unlikely, while on commercial blocks it is probable. Hence, the laboratory count reflects the number of microbes on the frozen meat but not necessarily on meat after commercial thawing.

Microbial counts incubated at 1 °C and 20–25 °C assess the storage life of meat at chill and intermediate temperatures. Counts at 37 °C give an indication of contamination from human and animal sources. Thawing under conditions that permit growth of bacteria counted at 1 °C and 25 °C will result in meat of poorer quality in terms of storage life. Thawing conditions allowing heavy growth of bacteria counted at 37 °C are undesirable since food-poisoning bacteria (such as *Salmonella* spp.) may be capable of growth.

The appearance of the surface of thawed meat is similarly related to the time spent in a given environment. Since this time will be a function of the material thickness, it is not possible to define one overall set of conditions for optimal appearance. For example, the air temperature, velocity and relative humidity required to thaw small joints satisfactorily in a reasonably short time would almost certainly cause problems if used to thaw whole quarters of beef. In general both the appearance and final bacterial condition in air thawing systems improve as the temperature of the thawing medium falls, but the extended thawing times involved may be unacceptable for other reasons related to operating requirements. A compromise must therefore be reached which for a given material could well differ from one factory to the next.

8.3 Thawing systems

There is no simple guide to the choice of an optimum thawing system (Table 8.2). A thawing system should be considered as one operation in the production chain. It receives frozen material which should be within a known temperature range and of specified microbiological condition. It is expected to deliver that same material in a given time in a totally thawed state. The weight loss and increase in bacterial numbers during thawing should be within acceptable limits, which will vary from process to process. In some circumstances, for example a direct sale to the consumer, the appearance of the thawed product is crucial, in others it may be irrelevant. Apart from these factors the economics and overall practicality of the thawing operation, including the capital and running costs of the plant, the labour requirements, ease of cleaning and the flexibility of the plant to handle different products, must be considered.

8.3.1 Conduction

The main conduction-based thawing methods rely on air, water or steam condensation under vacuum.

Table 8.2 Advantages and disadvantages of different thawing systems

| | | Advantages | Disadvantages |
|--------------------|-------------------------|--|---|
| Conduction systems | Air | Easy to install: can be adapted from chill rooms. Low velocity systems retain good appearance | Very slow, unless high velocities and high temperatures are used, when there can be weight loss, spoilage and appearance problems |
| | Water | Faster than air systems | Effluent disposal. Deterioration in appearance and microbiological condition. Unsuitable for composite blocks |
| | Vacuum-heat (VHT) | Fast. Low surface temperatures. Very controllable. Easily cleaned | Deterioration in appearance. High cost. Batch size limited |
| Electrical systems | Microwave/ Infra red | Very fast | Problems of limited penetration and uneven energy absorption. Can cause localised 'cooking'. High cost |
| | Resistive | Fast | Problems of contact on irregular surfaces |

8.3.1.1 Air thawing

Air thawing systems transfer heat to the frozen material by conduction through the static air boundary layer at the product surface and the rate of heat transfer is a function of the difference in temperature between the product and the air and the air velocity. Air systems are very flexible and may be used to thaw any size of meat cut from whole carcasses to individual steaks.

8.3.1.1.1 Still air

Thin blocks (<10cm) of meat can be thawed overnight at room temperature and, provided the surface of the product does not become too dry, the thawed product can be perfectly acceptable. Air temperatures should not be greater than 15°C.

For thicker materials still air thawing is not recommended, since thawing times extend to days, rather than hours, and the surface layers may become

warm and spoil long before the centre is thawed. Still air thawing is practicable only on a small scale, because considerable space is required, the process is uncontrolled and the time taken is often too long to fit in with processing cycles. The sole advantage is that little or no equipment is required.

8.3.1.1.2 Moving air

The majority of commercial thawing systems use moving air as the thawing medium. Not only does the increased h value produced by moving air result in faster thawing but it also produces much better control than using still air. Control of relative humidity is important with unwrapped products to reduce surface desiccation and increase the rate of heat transfer to the foodstuff, 85–95% RH being recommended for meat (Bailey *et al.*, 1974).

With 250 g slabs of meat (Zagradzki *et al.*, 1977) weight loss was a function of temperature, velocity and relative humidity. In all cases, increasing the air temperature, or decreasing the air velocity produced a decrease in percentage weight loss at 85–88% RH or an increase in weight gain at 95–98% RH. Changes ranged from a 2.5% weight gain at 5°C, 5 ms⁻¹, 85–88% RH, to a 0.51 weight gain at 25°C, 1 ms⁻¹, 95–98% RH.

8.3.1.1.3 Two-stage air

Two-stage air thawing has often been proposed as a means of shortening the thawing process. In the first stage, a high air temperature is maintained until the surface reaches a predetermined set temperature, thus ensuring a rapid initial input of energy. The air temperature is then reduced rapidly and maintained below 10°C until the end of the thawing process. Heat flows from the hotter surface regions to the centre of the frozen foodstuff, lowering the surface temperature to that of the ambient air. Since this temperature is below 10°C, and the overall thawing time is short, total bacteria growth is small. A patent (1974) has been taken out on a two-stage thawing system using almost saturated air between 35 and 60°C, followed by air between 5 and 10°C after the surface temperature of the product has reached 30–35°C. The first stage normally takes 1–1.5 h, the second 15–20 h and it is claimed that weight loss is low and drip loss minimal.

8.3.1.2 Water thawing

The mechanism of heat transfer in water is similar to that in air, but because the heat transfer coefficients obtained are considerably larger, the thawing times of thinner cuts are effectively reduced. However, there are practical problems that limit the use of water thawing systems: boxed or packaged goods (unless shrink-wrapped or vacuum-packed) must be removed from their containers before they can be water thawed, composite blocks of boned-out pieces break up and disperse in the thawing tank, and handling difficulties arise which preclude the use of large cuts such as carcasses.

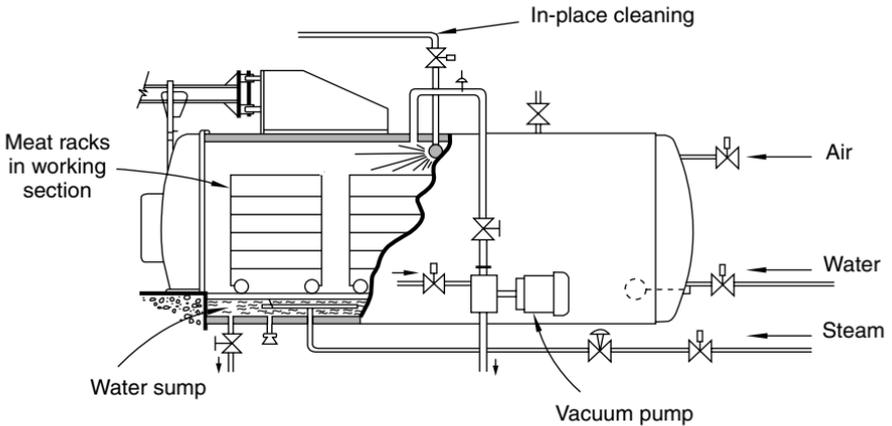


Fig. 8.1 APV-Torry vacuum thawing plant (source: Bailey and James, 1974b).

8.3.1.3 Vacuum-heat thawing

A vacuum-heat thawing (VHT) system (Fig. 8.1) operates by transferring the heat of condensing steam under vacuum to the frozen product. Theoretically, a condensing vapour in the presence of a minimum amount of a non-condensable gas can achieve a surface film heat transfer coefficient far higher than that achieved in water thawing. The principle of operation is that when steam is generated under vacuum, the vapour temperature will correspond to its equivalent vapour pressure. For example, if the vapour pressure is maintained at 1106 N m^{-2} , steam will be generated at 15°C . The steam will condense onto any cooler surface such as a frozen product. The benefits of latent heat transfer can be obtained without the problems of cooking which would occur at atmospheric pressure.

With thin materials, thawing cycles are very rapid, enabling high daily throughputs to be achieved. The advantage of a high h value becomes less marked as material thickness increases and beef quarters or 25 kg meat blocks require thawing times permitting no more than one cycle per day. Under these conditions, the economics of the system and the largest capacity unit available (10–12 tonnes) severely restrict its application.

8.3.2 Electrical methods

In all of the methods described above, the rate of thawing is a function of the transfer of heat from the thawing medium to the surface of the meat and the conduction of this heat into the centre of the carcass or cut. In theory, electrical systems should overcome these problems because heat is generated within the material and the limitations of thermal conductivity are circumvented. In such systems the kinetic energy imparted to molecules by the action of an oscillating electromagnetic field is dissipated by inelas-

tic collisions with surrounding molecules and this energy appears as heat. Thus electromagnetic radiation may be used to heat foodstuffs.

Three regions of the electromagnetic spectrum have been used for such heating: resistive 50 Hz; radio frequency 3–300 GHz and microwave 900–3000 GHz.

8.3.2.1 *Resistive thawing*

A frozen foodstuff can be heated by placing it between two electrodes and applying a low voltage at normal mains frequency. As the electric current flows through the material, it becomes warm (ohmic heating). Electrical contacts are required and product structure must be uniform and homogeneous, otherwise the path of least resistance will be taken by the current, resulting in uneven temperatures and runaway heating. Frozen meat at a low temperature does not readily conduct electricity, but as it becomes warmer, its electrical resistance falls, a larger current can flow and more heat is generated within the product. In practice, the system is only suitable for thin (5 cm) homogeneous blocks such as catering blocks of liver since current flow is very small through thick blocks and inhomogeneities lead to runaway heating problems.

8.3.2.2 *Radio frequency*

During radio frequency thawing, heat is produced in the frozen foodstuff because of dielectric losses when a product is subjected to an alternating electric field. In an idealised case of radio frequency heating the foodstuff, a regular slab of homogeneous material at a uniform temperature is placed between parallel electrodes and no heat is exchanged with its surroundings. When an alternating electro magnetic force is applied through the electrodes the resulting field in the slab is uniform, so the energy and the resultant temperature rise is identical in all parts of the food (Sanders, 1966).

In practice this situation rarely applies. Foodstuffs are not generally in the shape of perfect parallelepipeds, frozen meat consists of at least two components, fat and lean. During loading frozen meats pick up heat from the surroundings, the surface temperature rises and the dielectric system is not presented with the uniform temperature distribution required for even heating.

By using a conveyerised system to keep the product moving past the electrodes and/or surrounding the material by water, commercial systems have been produced for blocks of oily fish and white fish (Jason and Sanders, 1962). Successful thawing of 13 cm thick meat blocks and 14 cm thick offal blocks have also been reported (Sanders, 1961) but the temperature range at the end of thawing (44 min) was stated to be -2 – 19°C and -2 – 4°C , respectively, and the product may not have been fully thawed.

To overcome runaway heating with slabs of frozen pork bellies, workers (Satchell and Doty, 1951) have tried coating the electrodes with lard,

placing the bellies in oil, water and saline baths and wrapping the meat in cheesecloth soaked in saline solution. Only the last treatment was successful but even that was not deemed practical.

8.3.2.3 Microwave thawing

Microwave thawing utilises electromagnetic waves directed at the product through waveguides without the use of conductors or electrodes. Whilst the heating of frozen meat by microwave energy is potentially a very fast method of thawing, its application is constrained by thermal instability. At its worst, parts of the food may be cooked whilst the rest is substantially frozen. This arises because the absorption by frozen food of electromagnetic radiation in this frequency range increases as the temperature rises, this dependence being especially large at about -5°C , increasing as the initial freezing point is approached. If for any reason during irradiation a region of the material is slightly hotter than its surroundings, proportionately more energy will be absorbed within that region and the original difference in enthalpy will be increased. As the enthalpy increases so the absorption increases and the unevenness of heating worsens at an ever-increasing rate. Below the initial freezing point the temperature increase is held in check by thermal inertia since for a given energy input the temperature rise is inversely proportional to the thermal capacity. If irradiation is continued after the hot spot has reached its initial freezing point, the temperature rises at a catastrophic rate.

A hybrid microwave/vacuum system, in which boiling surface water at a low temperature was used to cool the surface, thawed 15 cm thick cartoned meat in 1–2 h without runaway heating, but problems of control and cost would appear to limit the commercial use (James, 1984). Despite a widespread belief to the contrary, microwave thawing systems have not been commercially successful. However, microwave tempering systems (see later) have found successful niche applications in the meat industry.

8.3.3 Published thawing data for different meat cuts

Process design data is available on thawing of frozen pork legs, lamb shoulders and carcasses, beef quarters and boned-out meat blocks.

8.3.3.1 Thawing of pork legs/hams

Bailey *et al.* (1974) made a comparative experimental study of thawing of frozen pork legs of different weights in air, water and vacuum heat thawing (VHT) systems with respect to thawing time, weight loss and appearance. A comprehensive chart (Fig. 8.2) was produced for the determination of thawing times over a range of process operating conditions (Bailey and James, 1974a).

Thawing time increased almost linearly with leg weight for all systems. Thawing in water was faster than in air at any given temperature, but

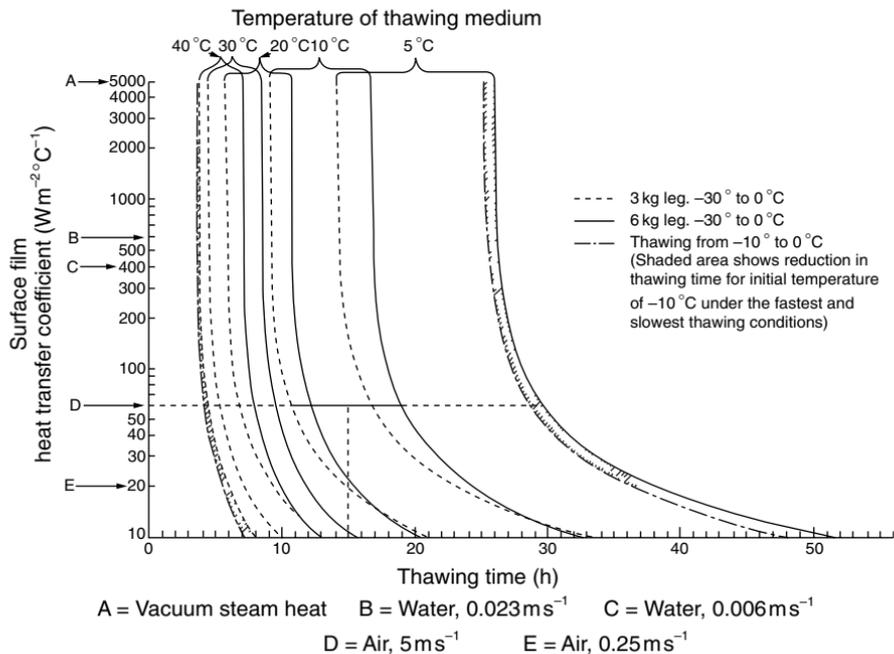


Fig. 8.2 Prediction of thawing times of frozen pork legs from -30 – 0°C (source: Bailey and James, 1974a).

Table 8.3 Mean percentage weight losses (fresh to thawed states) for pork legs thawed in air, water or vacuum

| Thawing medium | Velocity of medium (m s^{-1}) | Thawing temperature ($^\circ\text{C}$) | | |
|----------------|--|--|-----------|-----------|
| | | 10 | 20 | 30 |
| Air | 0.25 | +0.9 (18) | +1.0 (27) | +1.1 (20) |
| | 5.5 | +0.9 (18) | -1.0 (14) | -1.0 (15) |
| Water | 0.006 | +1.0 (8) | +1.1 (10) | +1.2 (8) |
| | 0.023 | +1.2 (8) | +1.1 (13) | +0.7 (6) |
| VHT | | +1.3 (14) | -0.2 (14) | -0.6 (13) |

() Number of samples.

Source: Bailey and James, 1974a.

increasing the water velocity had very little additional effect. VHT was not appreciably faster than water thawing at any temperature, demonstrating that for materials of this thickness conductivity is the rate controlling factor.

The pork legs increased in weight by $1 \pm 0.3\%$ under any of the conditions of thawing in air or water, with the exception of high velocity air where losses of 1% were recorded (Table 8.3). A similar increase was recorded in VHT at 10°C but there were small losses of weight at 20 and 30°C .

Table 8.4 Bacterial changes in pork legs thawed in air, water or VHT

| Thawing medium | Temp. of medium (°C) | Velocity of medium (ms ⁻¹) | Number of samples | Mean bacterial count (log ₁₀ cm ⁻²) at incubation temperature | | | | | |
|----------------|----------------------|--|-------------------|--|------|-------|-----------------------|-------|-----|
| | | | | Initial (before freezing) | | | Final (after thawing) | | |
| | | | | 37°C | 25°C | 1°C | 37°C | 25°C | 1°C |
| Air | 10 | 0.25 | 6 | 4.4 | 5.0 | 4.7 | 4.3 | 4.6 | 5.2 |
| | | 5.5 | 6 | 4.1 | 4.9 | 5.0 | 4.6 | 5.5 | 5.6 |
| | 20 | 0.25 | 6 | 4.2 | 4.9 | 4.9 | 5.1 | 5.4 | 5.1 |
| | | 5.5 | 6 | 2.7 | 3.3 | 1.6 | 5.2 | 6.3 | 6.1 |
| | 30 | 0.25 | 6 | 3.4 | 4.2 | 1.1 | 4.6 | 5.0 | 3.9 |
| | | 5.5 | 6 | 3.5 | 4.1 | 2.5 | 4.2 | 4.4 | 4.6 |
| Water | 10 | 0.006 | 10 | 4.8 | 7.0 | – | 5.1 | 7.5 | – |
| | | | | | | | (4.5) | (5.6) | |
| | | 0.023 | 10 | 5.7 | 7.7 | – | 5.0 | 7.0 | – |
| | | | | | | | (4.4) | (5.6) | |
| | 20 | 0.006 | 10 | 4.8 | 7.4 | – | 6.0 | 6.9 | – |
| | | | | | | | (6.3) | (7.1) | |
| | 0.023 | 10 | 5.1 | 6.6 | – | 6.1 | 6.7 | – | |
| | | | | | | (6.0) | (6.2) | | |
| 30 | 0.006 | 10 | 5.2 | 6.9 | – | 6.6 | 7.2 | – | |
| | | | | | | | (6.6) | (7.7) | |
| | 0.023 | 10 | 4.8 | 6.9 | – | 7.0 | 7.4 | – | |
| | | | | | | (6.1) | (6.6) | | |
| VHT | 10 | – | 6 | 3.7 | 4.8 | 4.8 | 3.3 | 4.1 | 5.0 |
| | 20 | – | 6 | 4.3 | 5.1 | 3.6 | 5.8 | 6.2 | 6.0 |
| | 30 | – | 6 | 3.5 | 4.8 | 3.1 | 4.8 | 5.2 | 3.4 |

Source: Bailey *et al.*, 1974.

The surface of legs thawed in air at 10°C, 85% RH at low velocity was moist but not wet and the colour of both skin and cut surface was good. At higher temperatures, the appearance was less attractive. The skin of legs thawed at high air velocity was light brown in colour and rather dry and parchment like. This condition did not improve with storage. Legs from the water and VHT systems were very wet and the colour of the cut surface was extremely pale. However, considerable improvements in the condition of the surface and in the colour of legs thawed at 10°C were noted after holding for some time in a chill room.

Changes in bacterial numbers during thawing in air or water could not be related solely to the temperature of the thawing medium or its velocity; in both cases, the interactions of thawing medium and its velocity were significant (Table 8.4). Air at 10°C/0.25 ms⁻¹ gave the best result and both 10°C/5.5 ms⁻¹ and 20°C/0.25 ms⁻¹ were satisfactory. In water, decreases in bacterial counts were obtained at 10°C/0.023 ms⁻¹ and small increases at 10°C/0.006 ms⁻¹. In VHT, the difference between initial and final bacterial numbers increased with increased thawing temperature.

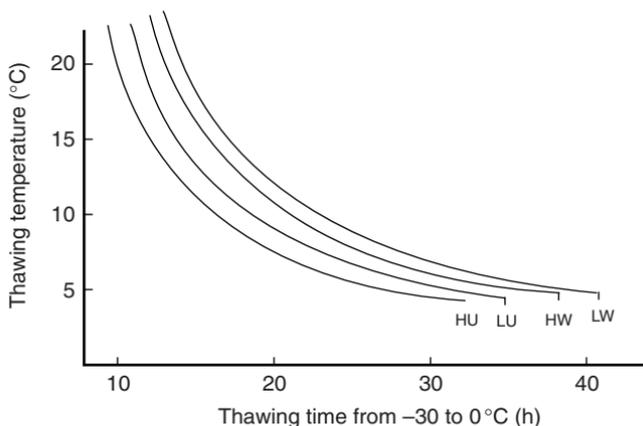


Fig. 8.3 Relationship between thawing time and thawing temperature for lambs of 20kg average weight, thawed unwrapped (U), wrapped (W) at 0.75 m s^{-1} (L) or 2.25 m s^{-1} (H) (source: Creed *et al.*, 1979).

Two-stage air thawing of hams was the subject of a patent issued to the Danish Meat Research Institute. It was claimed that thawing times could be reduced by thawing in near saturated air at 45°C until the surface approaches 30°C followed by subsequent thawing in air at 12°C and 90% RH. Little information was given on appearance and bacteriological condition.

8.3.3.2 Thawing of lamb shoulders and carcasses

Vanichseni *et al.* (1972) found that the thawing times of lamb shoulders (3.9–4.6kg) ranged from 60h in air at 2°C , 70% RH and 0.1 m s^{-1} to 2h in water at 50°C and 0.05 m s^{-1} . The appearance of water-thawed shoulders was judged to be quite attractive after drying and equilibration for 30 min in air at 10°C , whilst that of air-thawed shoulders deteriorated with increasing air velocity and decreasing relative humidity. A high relative humidity was maintained to minimise weight loss and no significant changes in bacterial numbers were recorded on the small number of samples tested.

From their data, Creed *et al.* (1979) produced a time–temperature relationship plot for determining thawing times of wrapped and unwrapped lamb carcasses at air velocities of 0.75 and 2.25 m s^{-1} over the temperature range from 5 to 20°C (Fig. 8.3). Applying this relationship to commercial requirements they concluded that the optimal condition for thawing wrapped lambs in 24h was to use air at 10°C and 0.75 m s^{-1} and for unwrapped lambs 7.5°C and 0.75 m s^{-1} . For overnight schedules (*ca.* 15h) wrapped lambs would require air at 20°C and 0.75 m s^{-1} and unwrapped lambs 15°C and 0.75 m s^{-1} . Changes in bacterial numbers for these conditions would be insignificant and produce meat of sufficiently good appearance to be sold in the thawed state.

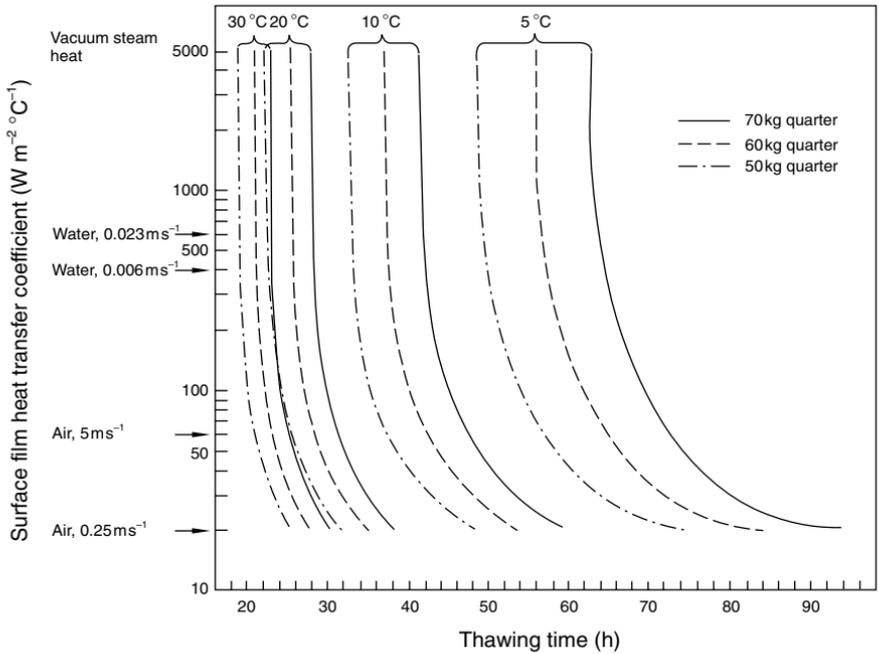


Fig. 8.4 Predicted relationship between thawing time from -30 – 0 °C and surface film heat transfer coefficient for frozen beef forequarters (source: James and Creed, 1980).

8.3.3.3 Thawing of beef quarters

Heinz (1970) investigated the thawing of beef hindquarters in water at 10 °C and concluded that water thawing had no advantage over air thawing in terms of thawing time. Subsequent drying in air was thought to be a necessary process, after which the quarters showed weight gains of 0.5–1.7% over the weight in the frozen state. Surface bacterial counts were a factor of 10 greater than those thawed in air.

The EEC policy of intervention purchase, freezing and storage of beef quarters created a demand for data on thawing such cuts, and consequently an experimental investigation was carried out by James *et al.* in 1977. This work was consequently extended to provide comprehensive charts for the determination of thawing times of frozen beef forequarters (Fig. 8.4) and beef hindquarters (Fig. 8.5) over a range of air, water and VHT thawing conditions (James and Creed, 1980).

Thawing quarters at 5 and 10 °C had little effect on appearance. The use of higher temperatures led to a darkening of the lean, most marked on the cut surfaces, and the drying out of thin sections, especially on the forequarters, giving a parchment like appearance. Owing to this deterioration all quarters that were thawed at 30 °C, and those without very good fat covering that were thawed at 20 °C, were only suitable for further processing.

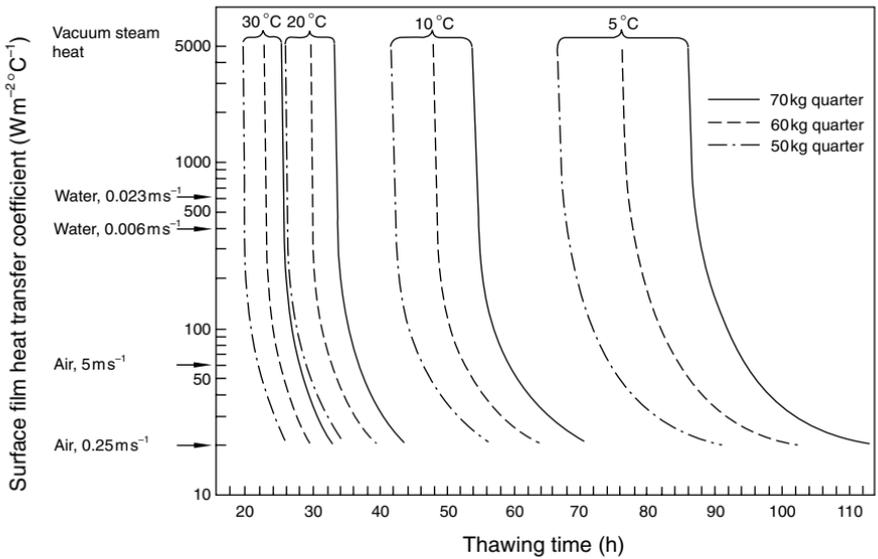


Fig. 8.5 Predicted relationship between thawing time from -30 – 0°C and surface film heat transfer coefficient for frozen beef hindquarters (source: James and Creed, 1980).

Quarters with a good fat covering thawed at 20°C were of retail quality after some trimming. A small number of quarters were thawed using a high humidity (95% RH) at 30°C . This procedure stopped drying but produced a pale damp slimy surface that was deemed to be commercially unacceptable.

Changes in bacterial numbers showed there to be a trend for the final count to increase with increased thawing temperature. This was most clearly seen with hindquarters thawed at 30°C , in which counts incubated at 35, 25 or 1°C were significantly higher than those from any other thawing temperature (Table 8.5). Temperature curves showed that during such thawing the surface spent times in excess of 40h at temperatures above 5°C . The equivalent figure for forequarters was only 20h, but in a commercial situation both hindquarters and forequarters would be left to thaw for the same time resulting in similarly large increases in the bacterial counts on the forequarters.

8.3.3.4 Thawing of boned-out meat blocks

The majority of frozen boned-out meat, ranging in size from large primal joints to small pieces and trimmings, is packaged in 25kg lots within solid or corrugated fibreboard cartons, usually containing a polyethylene sheet inner liner. An average carton size is $61 \times 40 \times 15\text{ cm}$ (Creed and James, 1981). Minimum thawing times are attained by defrosting the blocks in the unwrapped state, but it is not always possible to remove the polyethylene liner prior to thawing.

Table 8.5 Bacterial changes on beef quarters thawed in air at 5, 10, 20 and 30 °C

| | Temp. of medium (°C) | Number of samples | Mean bacterial count ($\log_{10} \text{cm}^{-2}$) at incubation temperature | | | | | | | | | | | |
|-------|-------------------------------|-------------------------|---|------|-------|------|------|------|-----------------------|------|-------|------|------|------|
| | | | Initial (before freezing) | | | | | | Final (after thawing) | | | | | |
| | | | 37 °C | | 25 °C | | 1 °C | | 37 °C | | 25 °C | | 1 °C | |
| | | | Fat | Lean | Fat | Lean | Fat | Lean | Fat | Lean | Fat | Lean | Fat | Lean |
| Fores | 5 | 13 | 3.47 | 2.89 | 4.30 | 3.49 | 3.84 | 3.12 | 3.64 | 3.04 | 4.43 | 4.20 | 4.69 | 4.27 |
| | 10 | 13 | 3.58 | 2.77 | 4.13 | 3.37 | 3.53 | 2.89 | 3.71 | 4.07 | 4.55 | 6.11 | 4.31 | 5.92 |
| | 20 | 18 | 3.40 | 3.02 | 3.91 | 3.63 | 3.52 | 3.10 | 4.74 | 4.43 | 4.91 | 5.32 | 4.54 | 5.09 |
| | 30 | 12 | 4.16 | 3.55 | 4.73 | 4.05 | 4.13 | 3.46 | 6.09 | 5.12 | 5.92 | 5.70 | 5.63 | 5.02 |
| Hinds | 5 | 10 | 3.44 | 3.58 | 3.82 | 4.03 | 2.89 | 3.00 | 3.82 | 3.78 | 4.75 | 4.64 | 4.30 | 4.24 |
| | 10 | 13 | 3.28 | 3.68 | 4.31 | 4.30 | 3.72 | 3.59 | 4.55 | 4.48 | 5.39 | 5.49 | 5.04 | 5.23 |
| | 20 | 14 | 3.64 | 3.86 | 3.86 | 4.37 | 3.41 | 3.46 | 5.45 | 5.26 | 5.93 | 5.81 | 5.20 | 5.52 |
| | 30 | 12 | 3.88 | 3.54 | 4.73 | 4.52 | 4.24 | 3.83 | 6.45 | 6.70 | 7.39 | 7.37 | 6.98 | 6.96 |

Source: James *et al.*, 1977.

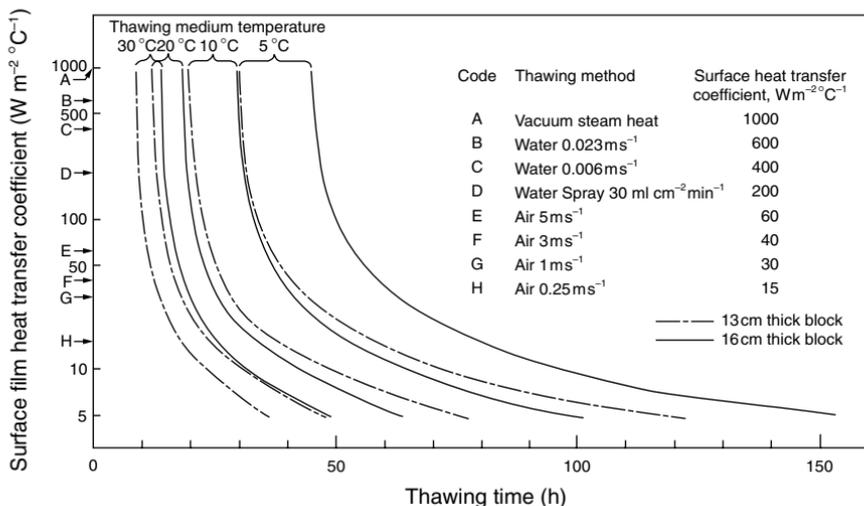


Fig. 8.6 Predicted relationship between thawing time from -30 – 0 °C and surface film heat transfer coefficient for unwrapped boneless meat block (source: Creed and James, 1981).

James and Bailey (1980) studied the thawing of such blocks in air and by VHT. This work was extended by Creed and James (1981) to provide a comprehensive chart (Fig. 8.6) relating the thawing of unwrapped boneless beef blocks to various environmental conditions from a combination of predicted and experimental data. The commercial advantage of VHT in terms of reduced thawing time is small because conductivity is the rate controlling factor for such thick materials. The real advantage of VHT is attained with thin (2.5 cm) blocks where thawing times of less than 1 h are possible, but such blocks do not normally exist in commercial operations.

Bailey and James (1974b) also examined two-stage air thawing of commercial meat blocks. For commercial convenience it is desirable that two-stage thawing operates with 7 day's supply in the first (conditioning) phase and 1 day's supply in the second (thawing) phase. The thawing phase environmental conditions in this experiment were defined by an industrial user as 10 °C and $1 ms^{-1}$. The investigation was therefore concerned with establishing the temperature and air velocity in the conditioning phase necessary to satisfy the requirements that:

- the final thawing period be as short as possible and no greater than 24h,
- the block remains in good physical condition at the end of the conditioning phase to allow movement to the second phase, i.e. no break-up or excessive drip,
- acceptable bacteriological levels are achieved at the end of both conditioning and thawing phases.

It was shown that these requirements could be met if the polyethylene wrapped blocks were conditioned in air at $+0.5^{\circ}\text{C}$ and 0.25 ms^{-1} . However, the method was only successful if the mean air temperature was exactly 0.5°C . Increasing this temperature by 0.5°C caused 'overconditioning' and consequent handling problems; decreasing the temperature by 0.5°C caused 'underconditioning' and final thawing times in excess of 24h. The process was therefore considered impracticable for commercial operations.

James (1984) demonstrated that thawing times of wrapped meat blocks could be significantly reduced using a hybrid microwave/vacuum system. Using a prototype microwave/vacuum system (2.5kW, 915Mhz), single 15cm thick meat blocks inside solid fibreboard cartons were thawed in 1 or 2h cycles. Weight losses averaged 7.6%. Unpublished values from industrial thawing systems that handle similar types of blocks range from 3–10%.

8.3.4 Commercial practice

The previous sections have described experimental data on meat thawing systems. The following few examples illustrate the wide range of thawing systems used by industry (James and Crow, 1986). Despite considerable interest in the use of different thawing systems, for example vacuum/steam, plate and microwave, all the commercial processes investigated used either air or water.

8.3.4.1 Air systems

- 1 30 tonnes per day of intervention beef quarters were thawed for boning in a modified chill room from -18°C to a minimum deep temperature above 0°C . The process was carried out in two stages. In a first stage, lasting 38h, live steam was injected into the room to maintain it at $10\text{--}12^{\circ}\text{C}$ and 95% RH. The air temperature was then reduced and maintained at $0\text{--}1^{\circ}\text{C}$ for a further 6h. This system was very effective, achieving a maximum surface temperature of 10°C and a small temperature difference, $0\text{--}2^{\circ}\text{C}$, throughout most of the quarters at the end of thawing. Average weight loss was 0.2%. The only real problem was caused by the wide weight range, 60–110kg, of quarters being thawed. To avoid the overthawing of light and underthawing of heavy quarters the meat was sorted into weight groups and the heavy quarters placed in the area with the highest air velocity.
- 2 100 tonnes per week of manufacturing beef in 15cm thick cartons were thawed by a canned meat company in a large ($46 \times 15\text{ cm}$) uninsulated shed with heater units. Pallets of cartoned meat were placed in an adjacent cold store at 0°C for 16h before the packaging was removed and the blocks restacked in a single layer on racks. The racks were then placed in front of the heater units for 24–48h. During this time some were moved away from the heaters to a cooler part of the room and any fully thawed material not immediately required was moved back into

the cold store. Meat entering the process varied in temperature from -15 to -3°C and the aim was to have the meat fully thawed but below 7°C on exit. In general this aim was achieved, however, some surfaces rose to ambient temperature while ice crystals were found in deep tissues. The method was very weather dependent and required double handling, almost constant supervision, and its operation relied heavily on the subjective skills of the operator. Drip was a problem.

- 3 A large company that deboned beef quarters and lamb legs and prepared them for cooking or refreezing, and cut, diced or minced beef primals, used three slightly different thawing methods. All the frozen meat entered the thawing systems at -20°C . Cartons of beef primal and lamb legs, and wrapped quarters were placed in factory air heated to 16°C by propane heaters. Lamb legs were thawed for 16–18h and beef quarters and primals for 60h. Other quarters were thawed for 7 days in a chill room at $4-5^{\circ}\text{C}$. Cartons of beef primals and lamb legs on pallets were also thawed in a combined system for 3–4 days at $4-5^{\circ}\text{C}$ then 12–16h at 16°C . The first method tended to produce very variable thawing, with ice still present in the centre, discolouration at the surface and high drip losses. The others produced good results but were very slow.

8.3.4.2 Water systems

- 1 One hundred 27kg cartons of pork legs, beef topsides or silversides were thawed per day by one company in tubs of mains water. The tubs $45 \times 75 \times 150\text{cm}$ were loaded with either 70 legs of pork or joints from 20 cartons of beef. Water was supplied to the tubs by hose and overflowed onto the floor, with effective circulation only occurring in the top 5 cm. Thawing times were typically 36–42h in winter when the water temperature was 4°C reducing to 16–24h in summer. The system was considered to be satisfactory but trimming and deboning of pork was difficult if thawing was not complete. Up to 3% in weight was lost from the silversides.
- 2 A large canning company thawed 10 tonnes a day of 10cm thick frozen blocks of kidney in tanks of water. The blocks on pallets were removed from a -18°C cold store and left for a few hours in the ambient air before the carton and wrappings were removed. The blocks then thawed for 12 hours in static water before the taps were turned on and thawing continued for 5–12h. At the end of the cycle the kidneys at the top of the tank were at the water temperature while some at the bottom would still be frozen. Complete removal of the polyethylene film was also a real problem. Introducing compressed air into the bottom of the tank reduced temperature stratification but caused frothing.
- 3 One company thawing 1–1.5 tonnes of beef topsides per day found that final temperature affected weight gain. At $-1-0^{\circ}\text{C}$ the gain was 2.1%, $0-4^{\circ}\text{C}$, 1.3% and at $4-6^{\circ}\text{C}$, 0.2%. The joints were placed in warm water

at 35°C and within an hour the water cooled to 10°C. Ten hours later the temperature was 6°C at the top and 2°C in the middle of the tank. Warm water was added again after 18h. The addition of some form of water circulation and temperature control would have produced a more consistent final product.

- 4 In another application a purpose-built thawing system steam heated water in a reservoir and then passed it through 90 × 120 × 90cm tanks at a constant temperature of 10°C. Blocks of tongue thawed from -20°C to between 0 and 2°C in an overnight 14–18h cycle. This system showed the advantage of designing a system to meet the requirements of the product.

8.4 Tempering

Hamburgers, sausages, canned meats, pet foods, frozen prepared foods, portion controlled steaks and specialities rely heavily on frozen ingredients. Much of this frozen meat is tempered rather than thawed before processing. Tempering as an alternative to thawing eliminates the accompanying problems of drip loss, bacterial growth and other adverse changes.

8.4.1 Requirements for cutting and processing equipment

Tempering of frozen block meat allows much better control over product quality and texture and enables the use of a greater percentage of frozen ingredients. Frozen meat blocks are processed from both a frozen and a tempered condition in the manufacture of sausages, canned meats and hamburger patties. The processing of frozen (untempered) blocks that are prebroken is somewhat limited. Grinding employs torque, a force that produces a twisting effect. When grinding through a perforated plate with small openings, 3mm, this force on frozen meat lowers the freezing point allowing it to pass through the plate and the meat refreezes as it exits. This phenomenon is called regelation and most processing equipment downstream is unable to accommodate this frozen putty type material (Koberna, 1986).

Chopping in a rotating bowl will shatter frozen meat with little control over particle size. However, if warm water and additives are introduced some products can be produced, particularly pet food.

There are many examples of mechanical requirements for uniform product temperature (Koberna, 1986). If we again consider slicing and then dicing, the consequences of processing below the zone of optimum temper (undertempering) may be blade breakage and yield loss from shattered meat, excessive fines and slices of non-uniform thickness. The consequences of overtempering may also be in the form of yield loss from ragged edges and incomplete shearing of connective tissue resulting in pearling. Temper

Table 8.6 Effects of undertempering and overtempering on some meat processing applications

| Process | Effects of undertemper | Effects of overtemper |
|--|---|--|
| Grinding | Equipment failure, shattered or regelated meat, excessive fines | Crushes meat tissue, blood loss |
| Bowl chopping | Shattering, blade damage, excessive fines | Connective tissue or gristle oversized, soft meat overchopped |
| Slicing | Equipment failure, curled and shattered slices | Incomplete or ragged slices |
| Dicing | Equipment failure, excessive fines, broken dices | Incomplete dices, pearling |
| Log pressing | Equipment failure, plain slippage, shattering ragged surface | Squeeze out (blood loss), ragged surface |
| Individual portion pressing | Fracturing, incomplete die filling | Squeeze out, forming not possible |
| Temperature control for patty forming | Equipment failure, lack of weight control, incomplete forming, lack of patty bind | Lack of weight control, ragged edges, sticky patties, wasted refrigeration |
| Temperature control for sausage blending | Unsatisfactory protein extraction and stuffing, smeared appearance | Protein loss, increased yield loss in cooking, wasted refrigeration |

for particle size and definition in comminuting is very important to the appearance and texture of coarse-ground sausages, meat sauces and yield in protein extraction. Tempering is important for heat balance considerations, such as controlling the temperature of ground meat in the patty forming machine or controlling the temperature of a sausage blend. Table 8.6 summarises some of the results associated with undertempering and overtempering for some meat processing applications.

8.4.2 Requirements for prebreaking

The first unit operation in many meat product lines is termed prebreaking, and is the process of taking large meat pieces (especially in the form of frozen blocks, of up to 30kg each) and producing smaller pieces which can be handled by the primary comminution procedure. A variety of pre-breakers are available commercially, including chippers, guillotines, flakers and grinders, some of which can handle a 30kg block in its entirety, whilst others require the block to be divided initially, usually by band sawing.

Before the meat enters the process, it is usually tempered, although some prebreakers are able to operate on hard frozen meat.

Equipment failure through the use of meat that is too cold is a very clear effect of using undertempered meat, but, if we assume the meat is within the range the prebreaker can handle, the effects of different temperatures at prebreaking may be more subtle. Similarly, although it seems to be well known that prebreaking hard frozen meat is detrimental to product cohesion or 'bind', information on other quality aspects is hard to come by. The influence of prebreaking on product quality has received less attention than the effects of later stages of manufacture, and what literature there is has usually been restricted to the use of meat grinders for prebreaking beef.

Some characteristics of frozen meat are worth mentioning before product quality is considered. Information on the tensile properties of frozen and thawed lean beef has shown that anisotropy of tensile strength according to fibre orientation is far less marked in frozen beef than in thawed beef (Munro, 1983). From changes in the ultimate tensile strength as a function of strain rate, the shape of stress/strain curves, and the observed mode of fracture and appearance of fracture surfaces, it has been suggested that frozen beef exhibits viscoelastic fracture at high temperatures and low strain rates, and brittle fracture at low temperatures and high strain rates (Munro, 1983).

This tendency towards brittle fracture with lower temperature is the reason frozen meat shatters under various practical conditions, such as bowl chopping. Tensile strength and sample modulus (the maximum slope of the stress/strain curve prior to fracture) increased with decreasing temperature, the most marked increase occurring between 0°C and -10°C. Dramatic changes in the physical properties of meat also occur over this range (Miles, 1974).

8.4.2.1 Effect on cooking loss and 'bind'

Gumpen (1978) showed that prebreaking at low temperatures produces poor quality emulsion type sausages. Meat which had been prebroken at -20 to -30°C, then thawed, gave products with reduced fat binding, showed considerable oiliness, and had a loose and unsatisfactory texture. In a second study (Harbitz and Egelandsdal, 1983) similar sausages from meat ground at -20 or -7°C were judged less hard, more coarse, more adhesive, more oily, more juicy, and lost more fat on microwave reheating than those from meat ground at -2, -0.5 (at which temperature the meat was presumably thawed) or +4°C. Cooking losses from beefburgers made from the meat prebroken at either -20 or -7°C were greater than the other treatments.

At Langford, flaked and formed patties were made from beef tempered to either -8°C or -3°C then prebroken by grinding. Prebroken meat from each temperature was then 'retempered' before flaking in order to check for any interactive effect between the two operations. Patties prebroken

Table 8.7 Effect of prebreaking by grinding at either -3 or -8°C on cooking loss and 'texture' of flaked and formed beef patties

| Temperature at prebreaking ($^{\circ}\text{C}$) | -3 | | -8 | | Significant difference |
|---|--------------------|----------------------|--------------------|--------------------|------------------------|
| Temperature at flaking ($^{\circ}\text{C}$)* | -3 | -8 | -3 | -8 | |
| Cooking loss (% uncooked weight) | 25.6 ^b | 27.3 ^b | 25.6 ^b | 32.1 ^a | <0.05 |
| Resistance to deformation (N cm^{-1}) | 5.3 ^a | 4.6 ^b | 4.4 ^b | 4.7 ^{a,b} | <0.001 |
| Compressive strength (N cm^{-1}) | 352.5 ^a | 299.7 ^{a,b} | 274.8 ^b | 287.8 ^b | <0.001 |
| Residual strength (N cm^{-1}) | 826.3 ^a | 511.0 ^d | 683.0 ^b | 575.2 ^c | <0.001 |

Means in the same row with the same superscript are not significantly different ($P > 0.5$).

* Prebroken meat was retempered by holding at indicated temperature for at least 72 h before flaking.

Source: Ellery, 1985.

and flaked at -8°C had significantly greater cooking loss than the other treatments (Table 8.7). Instrumentally assessed 'texture' (Jones *et al.*, 1985) was also influenced by prebreak temperature; with meat flaked at -3°C , resistance to deformation, compressive strength and residual strength were all significantly reduced in products from meat prebroken at -8°C than that from meat prebroken at -3°C .

The fact that grinding causes more shattering (i.e. brittle fracture) at -8°C than at -3°C can be simply but dramatically demonstrated by comparing the number of particles present in a constant mass sample. Using video image analysis, differences in particle size distribution have been observed between meat prebroken at -5°C and at -3.5°C .

The effect on particle size is potentially of direct relevance because the perception of particle size is a key aspect of quality in this type of product (Jones *et al.*, 1985), but its effect on bind is puzzling. In the presence of salt, myofibrillar proteins should be easier to extract from smaller pieces, and the accepted wisdom is that this will lead to better bind (although an increased proportion of smaller particles produced at lower temperatures can be expected to produce a 'mushy' texture (Dransfield *et al.*, 1984) in the absence of salt). However, there seems to be good agreement that lower temperature at prebreak leads to poorer bind. Particles of the same size but produced at different temperatures could conceivably have different structures that might influence bind; an earlier suggestion that the high pressures and shear forces occurring during grinding colder meats leads to denaturation of proteins (Gumpen, 1978) is probably not correct (Jolley *et al.*, 1986). Evans and Ranken (1975) established that increased cooking losses from meat ground whilst frozen are attributable to the release of free lipid from broken fat cells.

Table 8.8 Effect of prebreaking by grinding at either -3 or -6°C on cooked yield and 'welling' of flaked and formed beef patties

| Temperature at prebreaking ($^{\circ}\text{C}$) | -3 | | -6 | | Significant difference |
|---|-------------------|------------------|--------------------|--------------------|------------------------|
| | Coarse | Fine | Coarse | Fine | |
| Degree of comminution | | | | | |
| Weight of fluid released on puncturing (g) (1) | 5.6 ^a | 3.5 ^c | 4.0 ^{b,c} | 5.4 ^{a,b} | $P < 0.001$ |
| Weight of fat expressed as weight of fluid released (%) (2) | 44 ^{a,b} | 54 ^a | 47 ^{a,b} | 37 ^b | $P < 0.05$ |
| Cooking loss before puncturing (%) (1) | 24 ^b | 30 ^a | 26 ^b | 26 ^b | $P < 0.01$ |
| Cooking loss after puncturing (%) (2) | 28 ^b | 33 ^a | 29 ^b | 30 ^b | $P < 0.05$ |

Means in the same row with the same superscript are not significantly different ($P > .05$). Sources: (1) Jolley and Rangeley, 1986; (2) unpublished data from the same study.

8.4.2.2 Influence on other aspects of quality

Poor control over temperature at prebreaking has been blamed for variability in the amount of fluid released when a cooked, flaked and formed patty is cut (Jolley and Rangeley, 1986); the phenomenon is known by names such as 'welling' or 'bursting'. The effect seemed to depend on the degree of comminution (Table 8.8). With comparatively coarse comminution (240 flake head) more fluid was released from patties made from meat prebroken at -3°C than those from meat prebroken at -6°C . The reverse was true for comparatively fine comminution (further grind through 10mm plate, then flaked through 120 head). The juice expelled from finely comminuted products made from meat prebroken at -3°C had proportionally more fat than that from meat prebroken at -6°C .

These results on 'welling' come from a factory-based experiment aimed at assessing the importance of interactions between three processing factors (temperature at prebreaking, degree of comminution and blend time) and two raw material factors (level of added fat and level of added salt). Products (excluding those finely comminuted) from the same study were assessed for eating quality by consumer panels at two locations.

Results obtained using simple analysis of variance are shown in Table 8.9 which shows that the effect of temperature at prebreaking again depended on another factor, this time the level of salt in the final product. With 1% salt, patties produced from meat prebroken at -6°C tended to be favoured; with 0.5% salt the effect of prebreak temperature was clearer, with products from meat at -3°C being favoured, and considered more meaty.

8.4.3 Microwave tempering

Despite the widespread industrial use of tempered meat there is little published process design data for meat tempering operations, with the exception of commercial claims for microwave processing units.

Table 8.9 Effect of prebreaking by grinding at either -3 or -6°C on eating quality of flaked and formed beef patties as assessed by consumer panel

| Temperature at prebreaking ($^{\circ}\text{C}$) | -3 | | -6 | | Significant difference |
|---|-----------------|-----------------|-----------------|-------------------|------------------------|
| | 0.5 | 1.0 | 0.5 | 1.0 | |
| Salt in product (%) | | | | | |
| Texture | 53 | 46 | 48 | 52 | <0.05 |
| Taste | 54 ^b | 46 ^a | 45 ^a | 50 ^{a,b} | <0.05 |
| Meatiness | 64 ^b | 53 ^a | 52 ^a | 55 ^a | <0.05 |
| Overall | 50 | 44 | 45 | 48 | 0.053 |

Meatiness: not very meaty (0), very meaty (100) (no mid-point).

Means in the same row with the same superscript are not significantly different ($P > 0.05$).

Source: Jolley *et al.*, 1986.

James and Crow (1986) provide some data on the use of microwaves for tempering meat blocks. The batch unit investigated would accept 5 meat cartons in a single layer on a pallet that was pushed over rollers manually into the microwave chamber. Microwave power was provided by a 30kW magnetron (variable down to 20kW) operating at 896MHz, from which the microwaves entered the chamber via waveguides situated at the top and bottom. Rotating metal discs were positioned above and below the product to provide a more uniform microwave field and the loaded pallet was subjected to cyclic lateral movements of 90mm during irradiation.

It is clear from Table 8.10 that blocks processed directly from frozen storage can be acceptably tempered in a batch microwave unit to a mean temperature of *ca.* -3°C (range -5 – 0°C) with no hot spots. Tempering times varied from 3.5 to 5.0 min with block types (1) and (2) (Table 8.10) and at least two combinations of microwave power and processing time produced acceptable results. The frozen cartons of flank that contained a higher percentage of fat caused more runaway heating problems, and low microwave power (20kW) applied for 6.5 min was required to achieve the desired results.

In general, microwave tempering of blocks which had been allowed to warm up in factory ambient temperatures for 8h was unsatisfactory. Surface temperatures, especially at the corners of the meat blocks, rose to unacceptable levels and there was substantial drip loss from thawed surfaces.

These results indicate that it would be difficult if not impossible to produce a uniform power/time combination for all types of 'standard 27 kg blocks'. For optimal tempering, trials have to be carried out to determine the correct power and time setting for each type of block. Blocks sorted into batches of similar type should be processed directly from frozen storage under the predetermined conditions.

Table 8.10 Effects of block types, weights of frozen meat and initial meat temperature on final meat temperature and condition of meat blocks tempered in a batch microwave unit

| Block type (weight) | Initial temperature (°C) | Microwave power (kW) | Process time (min) | Final temperature (°C) (meat condition) | |
|---------------------|--------------------------|----------------------|--------------------|---|-------------------------|
| 1 25–30 kg | -15 | 28 | 3.5 | -7 to -2 | |
| | | | 4.0 | -4 to -2 (soft corners) | |
| | | | 4.5 | -4 to -1 (soft surfaces) | |
| | | | 4.5 | -3 to -2 (locally +2) | |
| | | | 4.75 | -4 to -2 (surfaces +2) | |
| | | 25 | 5.0 | -3 to -2 (surfaces 0) | |
| | | | 5.0 | -4 to 0 | |
| | | | 30 | 3.0 | -5 to -2 |
| | | | | 5.5 | -3 to -2 (corners +3) |
| | | | 30 | 5.0 | -5 to +2 |
| 2 27–37 kg | -15 | 28 | 4.0 | -5 to -4 (soft spots) | |
| | | | 4.5 | -4 to -3 (soft spots) | |
| | | | 5.0 | -4 to -2 (surface <2) | |
| | | | 30 | 6.0 | -4 to +27 (v. variable) |
| | | | | 6.0 | -6 to +25 (v. variable) |
| | | 30 | 5.0 | -5 to +6 (spot at +54) | |
| | | | 30 | 4.0 | -6 deep, -1 surface |
| | | | | 5.0 | -5 deep, 0 surface |
| | | | 6.0 | -5 deep, some cooking | |
| | | | 6.0 | -5 deep, some cooking | |
| 3 25–27 kg | -15 | 20 | 6.5 | -4 to -2, uniform | |
| | | | 7.0 | -5 deep, hot spots | |
| | | | 5.0 | -5 uniform | |
| | | 30 | 5.0 | -5 deep, hot spots | |

Source: James and Crow, 1986.

Successful tempering can be achieved in minutes using a microwave system, compared with 1–14 days that is required in industrial air tempering systems. Continuous conveyerised microwave tempering systems using either a single 60 kW magnetron or two 40 kW magnetrons can temper 2–2.5 tonnes per hour depending upon fat content.

In large throughput operations the continuous microwave tempering plant provides considerable flexibility, in that changes in raw material requirements, for the post-tempering processes, can be accommodated in minutes. Using air tempering systems, at least 1 day and up to 8 days are required to accommodate equivalent changes.

Many advertisements for microwave systems claim higher product yield because of reduction in evaporative and drip loss during tempering. Since the majority, if not all, of conventional plants temper material in a wrapped form, evaporative losses are insignificant, whilst substantial periods at air temperatures above 0°C would be required before thawing of surface tissues occurred and drip became apparent.

8.4.4 Commercial practice

The following data from a limited survey of tempering systems (James and Crow, 1986) indicate that most meat tempering was carried out in air-based conduction systems. At the time there were *ca.* 17 fully operational microwave tempering systems for meat in the UK, 12 of which were small batch units and the remainder continuous tempering tunnels. A number of the batch systems were used as either one stage of a hybrid microwave/conduction system or to augment large conduction systems by fast tempering of small batches of urgently required material.

The survey revealed substantial variations in all aspects of conduction-based tempering systems, with the exception of the raw material which was consistently 27 kg frozen blocks of meat in 15 cm thick cartons. Throughputs of frozen material ranged from less than a 1 tonne pallet of *ca.* 40 cartons to over 20 tonnes per day, and the tempered material was used in a variety of products, including beefburgers, re-formed meat, minced products, pies and canned goods. Typical data from a selection of tempering operations (Table 8.11) show initial temperatures ranging from -10 to -27°C , final temperatures from -2.5 to -15°C , and tempering times from less than 1 day to 12 days. In one operation, times of up to 14 days were commonly used.

Tempering operations within individual companies were very uncontrolled and variable, as demonstrated by factory A where initial meat temperatures ranged from -10 to -18°C and tempering times from 7–12 days.

In the majority of operations, the blocks, on the pallets used during frozen storage, were transferred by fork lift or stacker trucks directly into the tempering rooms. In a few cases attempts were made to improve the

Table 8.11 Tempering configurations, initial and final product and environment temperatures, and tempering times for cartons of frozen meat (*ca.* 27 kg in weight, 15 cm thick) in industrial systems

| Factory | Tempering configuration | Temperatures ($^{\circ}\text{C}$) | | | Tempering time (days) |
|---------|-------------------------|-------------------------------------|---------|---------------|-----------------------|
| | | Initial | Final | Ambient | |
| A | Palletised | -14/-12 | -3 | -8 then -3/-1 | 5 then 7 |
| | Palletised | -10 | -3 | -8 then -3/-1 | 1 then 6 |
| | Palletised | -15 | -2.5 | -8 then -3/-1 | 3.5 then 6 |
| | Palletised | -18 | -3 | -8 then -3/-1 | 6 then 5 |
| B | Palletised | -18 | -15/-6 | 0 | 0.9 |
| | Racked | -18 | -4.5 | 14 then 0 | 0.2 then 0.7 |
| C | Palletised | -20/-18 | -10/-5 | 0 | 1.0 |
| D | Palletised | -20 | -6 | -5/-3 | 6 to 7 |
| E | Palletised | -27/-23 | -8/-5.5 | -3/-1 | 0.9 |
| | Racked | -27/-23 | -5/-4 | -3/-1 | 0.9 |
| F | Palletised | -18 | -8/-3.5 | -4/-3 | 1.0 |
| | On trolleys | -18 | -5/-3.5 | -4/-3 | 0.8 |

rate of heat transfer into the cartons and reduce the effective unit thickness by placing the cartons in single layers on racks or trolleys. This produced a more even temperature distribution in the tempered blocks of meat. In most cases, however, the gap between blocks was too small and/or the air velocity in the tempering room too low to optimise tempering times.

8.5 Conclusions

- 1 Available thawing systems are based either on heat conduction into the product from the surface or on internal generation of heat using electromagnetic radiation. The latter systems appear to be unsuitable if complete thawing is required because of problems of thermal instability and runaway heating.
- 2 There is no evidence to suggest that the method of thawing significantly affects the palatability of the meat when subsequently cooked. Quality is therefore assessed by appearance and bacteriological condition.
- 3 The efficiency of a given thawing process is a function of the thickness of the material to be thawed. The advantage of systems utilising high surface film heat transfer coefficients lessens markedly as material thickness increases; consequently VHT and water thawing systems offer little advantage over air thawing systems in terms of reduced thawing time for most commercial operations.
- 4 Appearance and bacteriological condition of the thawed meat are generally better in air thawing than in either water thawing or VHT. The optimal temperature for most operations appears to be 10°C, 0.25 ms⁻¹ and 85% RH. However, thawing times are long, e.g. 2–3 days for beef quarters.
- 5 The choice of a practical thawing system for meat is limited. Standard 25kg, 15cm thick cartoned blocks can only be thawed in air blast systems. Large quantities of beef quarters or lamb or pig carcasses are again restricted to air thawing systems. Water thawing is possible for vacuum packaged primal meat cuts and pork joints that are to be subsequently cured.
- 6 Industrial thawing systems use either air or water as the thawing medium. Few of these systems are well designed and consequently thawing tends to be very variable with, in some cases, high surface temperatures combined with ice in deep tissues of the same material. Thawing times in air are long, 2–3 days being typical for quarters or meat blocks, and drip losses are high. Water thawing can be very effective if circulation is maintained and temperatures are controlled but effluent disposal can cause problems.
- 7 Quite small differences in temperature during processing operations such as prebreaking or cutting can have quite large effects on product quality.

- 8 The amount of ice to a certain extent determines the physical properties of meat; this changes rapidly within the range -2 to -1 °C. It is very difficult to measure temperature accurately under commercial conditions, and an error of 0.5 °C within the range represents 25% ice.
- 9 Unless tempering is well controlled, product variability is liable to be high.
- 10 Prebreaking at lower temperatures produces smaller particles which do not bind together well; this is not necessarily a bad thing, as a soft texture may be desirable in some products.
- 11 Industrial microwave tempering systems can provide a practical alternative to conventional air-based systems in many situations especially if flexibility and/or large throughputs are important. However, capital costs are high and running costs substantial.
- 12 The majority of commercial tempering is carried out using air conduction systems in which tempering times can vary from 0.8–14 days. Many of these systems have not been particularly well designed and are often operated in a haphazard manner, consequently there is considerable variation in temperatures, -10 to -2.5 °C, in the tempered product.

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9

Transportation

Developments in frozen transport in the 19th century established the international food market. In 1877, a cargo of frozen meat was sent from Buenos Aires to France. The following year 5000 frozen mutton carcasses were transported from Paraguay to France. In 1880, the S. S. Strathleven arrived in London with a cargo of 40 tons of frozen Australian beef, and by 1910 Great Britain was importing 600 000 tons of frozen meat. Further developments in temperature controlled transportation systems for chilled products have led to the rapid expansion of the 'fresh' food market. The sea transportation of chilled meat from Australia to European and other distant markets, and road transportation of chilled products throughout Europe and the Middle East is now common practice. Air freighting is increasingly being used for high value perishable products such as strawberries, asparagus and live lobsters (Sharp, 1988). 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'.

9.1 Sea transport

Historically it was the need to preserve meat during sea transport that led to the development of mechanical refrigeration and the modern international trade in foodstuffs. 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. With

Table 9.1 Guidelines for meat shipment

| | Vacuum pack, 0°C | Vacuum pack, -1.5°C | CO ₂ , -1.5°C |
|------|------------------|---------------------|--------------------------|
| Pork | 6 weeks | 8 weeks | – |
| Lamb | 7 weeks | 10 weeks | >12 weeks |
| Beef | 10 weeks | 14 weeks | – |

Source: Heap, 1997.

conventional vacuum packing it is difficult to achieve a shelf-life in excess of 12 weeks with beef and 8 weeks for lamb (Gill, 1984). Controlled/modified atmospheric packaging can extend this by many weeks. Work in New Zealand has shown that a shelf-life of up to 23 weeks at -2°C can be achieved in cuts of lamb (Gill and Penney, 1986). The cuts were individually packed in evacuated bags of linear polyethylene, and then placed in a foil laminate bag that was gas flushed and filled with a volume of carbon dioxide (CO₂) approximately equal to that of the meat. Similar storage lives are currently being achieved with beef primals transported from Australia and South Africa to the EU. Heap (1997) stated that assuming good standards of preparation and prompt cooling, the times given in Table 9.1 could be used as approximate guidelines for long distance meat shipment.

These times rely on the meat being at or below the storage temperature before loading. The two to four week advantage of transporting meat at -1.5°C rather than 0°C is lost if the meat is loaded at a temperature above 0°C. Cooling in the centre of a load of meat is very slow and the meat will be well into its journey before the desired temperature is achieved.

Most International Standard Organisation (ISO) containers for food transport are either 6 or 12 m long, hold up to 26 tonnes of product and can be 'insulated' or 'refrigerated' (Heap, 1986). The refrigerated containers incorporate insulation and have refrigeration units built into their structure. The units operate electrically, either from an external power supply on board the ship, or in dock, or from a generator on a road vehicle. Insulated containers utilise either plug-type refrigeration units or may be connected directly to an air-handling system in a ship's hold or at the docks. Close temperature control is most easily achieved in containers that are placed in insulated holds and connected to the ship's refrigeration system. However, suitable refrigeration facilities must be available for any overland sections of the journey. When the containers are fully loaded and the cooled air is forced uniformly through the spaces between cartons, the maximum difference between delivery and return air can be less than 0.8°C. The entire product in a container can be maintained to within ±1.0°C of the set point.

Refrigerated containers are easier to transport overland than the insulated types, but often have to be carried on deck when shipped because of

problems in operating the refrigeration units within closed holds. On board ship, they are therefore subject to much higher ambient temperatures and consequently larger heat gains which make it far more difficult to control product temperatures.

For bulk transportation of frozen meat, refrigerated cargo ships are commonly used (Heap, 1997). Frozen meat is generally stored and transported at -18°C or below. Unlike chilled meat, small temperature changes during loading and unloading can be tolerated with frozen meat.

9.2 Air transport

In the 1990s, the volume of perishables transported by air increased by 10–12% per year (Stera, 1999). 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 and 20°C . Perishable cargo is usually carried in standard containers, sometimes with an insulating lining and/or dry ice but is often unprotected on aircraft pallets (Sharp, 1988).

Sharp's studies in Australia have led to the following recommendations for air transport of chilled foods:

- Insulated containers should always be used to reduce heat gain.
- Product should always be precooled and held at the required temperature until loading.
- With products that deteriorate after any surface freezing, dry ice should not be used.
- Containers should be filled to capacity.
- A thermograph should accompany each consignment.

9.3 Overland transport

Overland transportation systems range from 12m refrigerated containers for long distance road or rail movement of bulk chilled or frozen products to small uninsulated vans supplying food to local retail outlets or even directly to the consumer. Some of the first refrigerated road and rail vehicles for chilled product were cooled by air that was circulated by free or forced systems, over large containers of ice (Ciobanu, 1976). Similar systems using solid carbon dioxide as the refrigerant have also been used for cooling of transport vehicles. However, most overland vehicles for long distance transport are now mechanically refrigerated.

9.3.1 Types of refrigeration system

The majority of current road transport vehicles for chilled foods are refrigerated using either mechanical, eutectic plates or liquid nitrogen cooling systems.

9.3.1.1 Mechanical units

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

Irrespective of the type of refrigeration equipment used, the product will not be maintained at its desired temperature during transportation unless it is surrounded by air or surfaces at or below that temperature. This is usually achieved by a system that circulates moving air, either forced or by gravity, around the load. Inadequate air distribution is probably the principle cause of product deterioration and loss of shelf-life during transport. Conventional forced air units usually discharge air over the stacked or suspended products either directly from the evaporator or through ducts towards the rear cargo doors. Because air takes the path of least resistance it circulates through the channels which have the largest cross-sectional area. These tend to be around rather than through the product. 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 avoid any product contact with the inner surfaces of the vehicle because this would allow heat ingress during transport. Many trucks are now being constructed with an inner skin that forms a return air duct along the side walls and floor, with the refrigerated air being supplied via a ceiling duct.

9.3.1.2 Eutectic plates

Eutectic plate cooling systems are used in refrigerated vehicles serving local distribution chains. The eutectic plate consists of a coil, through which a primary refrigerant can be passed, mounted inside a thin tank filled with a eutectic solution. Standard eutectic solutions freeze at temperatures between -3 and -50°C and Table 9.2 lists some that have been applied in food chilling systems. A number of these plates are mounted on the walls and ceilings or used as shelves or compartment dividers in the vehicles. Two

Table 9.2 Freezing point and latent heat of fusion of some eutectic solutions

| Eutectic solution | Freezing point (°C) | Latent heat of fusion (kWh m ⁻³) |
|-----------------------|---------------------|--|
| Carbonate of soda | -3 | 92 |
| Potassium bicarbonate | -6 | 85 |
| Potassium chloride | -10 | 94 |
| Ammonium chloride | -15 | 89 |
| Sodium chloride | -21 | 74 |

Source: Lenotre, 1988.

methods are commonly used for charging up the plates: (1) when the vehicle is in the depot the solutions are frozen by coupling the plates to stationary refrigeration plants via flexible pipes and (2) a condensing unit on the vehicle is driven by an auxiliary drive when the vehicle is in use and an electric motor when stationary.

To provide the required cooling capacity, the plates should be mounted so that air can circulate freely over both sides and over the product. Most systems rely on gravity circulation but some are equipped with fans, ducts and dampers for temperature control.

Eutectic systems are chosen for the simplicity, low maintenance and quietness of their operation but can suffer from poor temperature control.

9.3.1.3 Liquid nitrogen

A typical liquid nitrogen system consists of an insulated liquid nitrogen storage tank connected to a spray bar that runs along the ceiling of the transport vehicle. Liquid nitrogen is released into the spray bar via a thermostatically controlled valve and vaporises instantly as it enters the body of the vehicle. The air is then cooled directly utilising the change in the latent and sensible heat of the liquid nitrogen. Once the required air temperature has been reached the valve shuts off the flow of liquid nitrogen and the temperature is subsequently controlled by intermittent injections of liquid nitrogen.

Many advantages are claimed for liquid nitrogen transport systems (Table 9.3). It is also claimed that that long hauls can be carried out since vehicles are available that will maintain a chilled cargo at 3°C for 50h after a single charge of liquid nitrogen and that overall costs are comparable with mechanical systems.

9.3.2 Observations of transport

Gill and Phillips (1993) found that the deep temperature in beef sides and quarters at the time of their loading into transport vehicles in three USA plants ranged from 6 to 18°C (Fig. 9.1). Maximum surface temperatures

Table 9.3 Claimed advantages of liquid nitrogen refrigerated vehicles

Advantages of nitrogen refrigerated vehicles

| | |
|------------------------------|---|
| Simple, dependable operation | Improved pay loads |
| Minimum maintenance | Improved vehicle utilization |
| Accurate temperature control | Rapid initial temperature reduction |
| Uniform cargo temperature | Modified atmosphere transportation |
| Silent operation | Environmentally acceptable |
| Low capital costs | Multicompartment triple-temperature operation |
| Low operating costs | Flexible refrigeration |

Source: Smith, 1986.

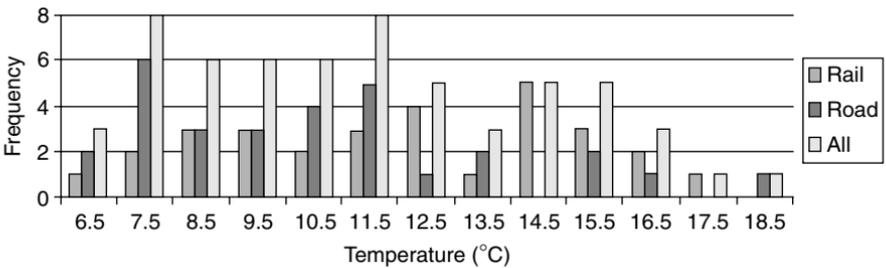


Fig. 9.1 Deep leg temperatures when loaded into railway wagons or road trailers (source: Gill and Phillips, 1993).

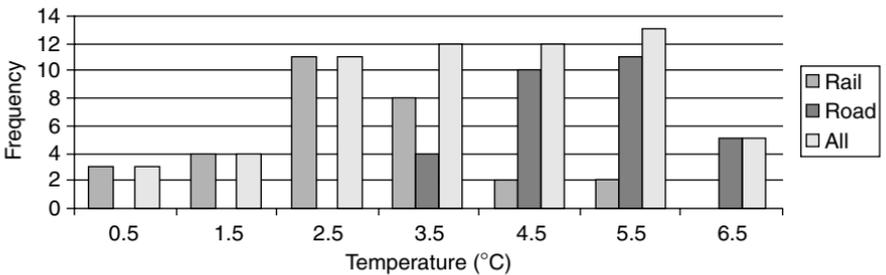


Fig. 9.2 Maximum surface on beef sides and quarters when loaded (source: Gill and Phillips, 1993).

were also high and ranged from 0.5 to 6.5°C (Fig 9.2). In rail wagons the surface temperature decreased during the first 24h and was subsequently maintained at a temperature of $0 \pm 1^\circ\text{C}$. In the road vehicles the surface temperature fell slowly during the whole journey and had not attained a steady minimum value when unloaded. On average the deep temperature of sides in rail wagons reached 1°C after 72h. Temperatures in quarters in road vehicles were still above 2°C after 120h.

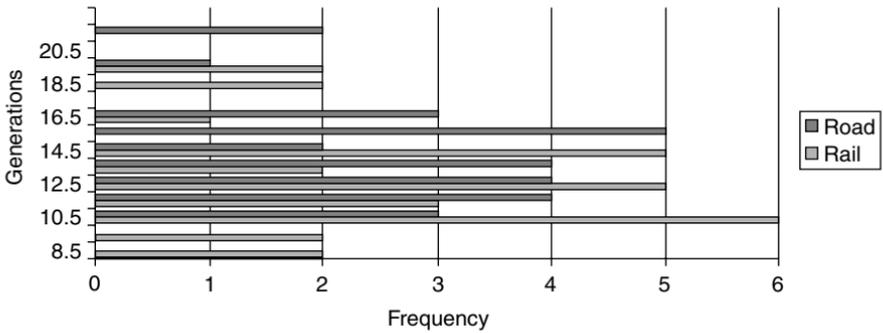


Fig. 9.3 Predicted proliferation of pseudomonads during rail and road transportation of beef (source: Gill and Phillips, 1993).

Journey times varied from 3.8 to 6.7 days and it was calculated that during that time pseudomonads could proliferate by between 8 and 22 generations (Fig. 9.3). Adequate air movement through the load in the rail vehicles produced even temperature distributions. The authors thought that by better policing of the temperature set point, rail transportation could be substantially improved. However, road vehicles could not cool the meat during transport and had to be loaded with cold meat.

In general it is not advisable to rely on product cooling during transportation, however, in the Netherlands ‘in transport cooling’ is an integral part of a processing system for pork carcasses that allows pigs to be dispatched on the same day they are killed.

Studies have been made on the long distance chilled transportation of ‘retailer-ready’ portions of beef and their subsequent retail display life (Bell *et al.*, 1996). Cuts 10cm thick weighing between 750 and 1000 g were packed in clear plastic high oxygen barrier film, metallised film or conventional vacuum bags. Cuts in clear plastic or metallised film were further packed in oxygen-free saturated carbon dioxide atmosphere. Cuts were then stored and transported for between 39 and 89 days at between 0 and -1°C . However, colour stability of the fats limited the retail display life to *ca.* 48h. The lean meat colour and sensory attributes remained acceptable for 48h after the cuts were rejected because of grey-green fat discolouration.

9.3.3 Problems particular to local delivery vehicles

In a 1970–71 survey of vehicles used to transfer chilled meat from small abattoirs to shops (Table 9.4), almost 70% were unrefrigerated and 20% had no insulation (Cutting & Malton, 1972).

Eight of the mechanically refrigerated vehicles had propane-driven R 12 compressors, and one diesel, and they could be mains-operated when static.

Table 9.4 Types of road vehicle investigated in Meat Research Institute (MRI) Survey (1970–71)

| System | No. of cases |
|-----------------------------|--------------|
| Mechanical | 9 |
| Liquid nitrogen | 2 |
| Insulated, non refrigerated | 18 |
| Uninsulated | 7 |

Source: Cutting and Malton, 1972.

The uninsulated vehicles were mostly 10cwt (0.5 ton) delivery vans, with no partition between driver and load.

Since that time the intensifying demand from legislation and retailers for lower delivery temperatures, has put increasing pressure on fleet operators to improve temperature control. However, there are substantial difficulties in maintaining the temperature of chilled foods transported in small refrigerated vehicles that conduct multi-drop deliveries to retail stores and caterers. The vehicles have to carry a wide range of products and operate under diverse ambient conditions. During any one delivery run, the chilled product can be subjected to as many as fifty door openings, where there is heat ingress directly from outside and from personnel entering to select and remove product. The design of the refrigeration system has to allow for extensive differences in load distribution, dependent on different delivery rounds, days of the week and the removal of product during a delivery run. The ability of a refrigeration system to respond to sudden demands for increased refrigeration is often restricted by the power available from the vehicle. All these problems combine to produce a complex interactive system.

In the UK, current sales of chilled foods are expanding. The overall market worth for chilled foods increased from £5.8 billion in 1992 to £6.2 billion in 1993. In the meat industry the traditional range of pies, pasties, sausages and cooked meats has been rapidly developed with the addition of fermented meats, restructured products, Kievs, salads, stir fry products, and vegetarian burgers and rissoles. Traditional meat product manufacturers are now aiming to extend their range of products to include items such as gourmet-style meals without artificial colours, flavours or preservatives.

Retailers are discovering that considerable quality and economic advantages can be derived from maintaining chilled products at temperatures far closer to their initial freezing point. Increasingly, fleet operators will be forced to deliver chilled foods at temperatures between 0 and 2°C.

9.3.4 Design and operation of local distribution vehicles

There will be few real advances in the design of chilled distribution vehicles until there is a firm understanding of the interaction between the

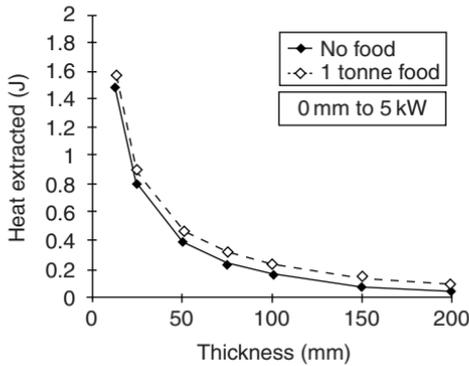


Fig. 9.4 Heat extracted by the refrigeration plant during the standard journey for vans with different thickness of insulation, with and without food (source: Gigiel, 1998).

refrigeration system, the vehicle's construction, the air movement within the vehicle, the external environment, the operation of the vehicle and the temperature of the foodstuff. A project recently completed by the Food Refrigeration and Process Engineering Research Centre (FRPERC) as part of a MAFF LINK scheme has produced a predictive model that will assist fleet operators in specifying the design of and the equipment for small delivery vehicles (Gigiel, 1998).

Refrigerated vehicles are developed and tested in carefully controlled conditions. Owing to the large number of interacting variables, as many as possible are held constant during the tests. The prediction programme allows for systematic alteration of one or more variables whilst simulating the operation of a vehicle in a complex, realistic way.

The verified model has provided valuable data on the factors influencing food temperature and van performance.

9.3.4.1 Van insulation

The heat extracted by the refrigeration system during the journey is shown plotted against the thickness of insulation in Fig. 9.4. Only a small thickness of insulation greatly reduces the amount of heat that has to be extracted, the amount decreasing with the reciprocal of the thickness of insulation. In all cases, van and food temperatures were maintained at less than 5°C. This was only achieved in the case with no insulation by fitting the vehicle with a refrigeration system with a nominal capacity of 10kW. The food in the van modified the action of the thermostat and reduced the running time of the refrigeration system and the heat extracted by it. The reduction was 43% when the insulation was 75 mm thick.

9.3.4.2 Infiltration

The heat extracted from a poorly sealed van was 86% more than from a well-sealed van (Fig. 9.5). However, infiltration during the time that the



Fig. 9.5 Heat extracted by the refrigeration plant during the standard journey for a well, and a poorly sealed van (source: Gigiel, 1998).

door is closed is a relatively small proportion of the total refrigeration load. In this vehicle, fitted with a nominal 2 kW cooling system, the state of the seals did not cause the temperature of the food to increase to more than 5°C during the journey.

9.3.4.3 *Weight of fittings and thermal mass of lining*

The weight of the fittings and the thermal mass of the lining form a sizeable refrigeration load and take a finite amount of time to cool. However, in a sales van this normally takes place late in the evening or in the early hours of the morning when ambient temperatures are low and no other loads are imposed on the van. The load is therefore smaller than the size of the refrigeration plant fitted and the short pull down time from 28 to 5°C would not warrant keeping the refrigeration system running all night. However, if the vehicle was in continuous use for the transport of foods at different temperatures (chilled and frozen) then pull-down times between changing loads could be a serious disadvantage.

9.3.4.4 *Door openings*

The heat extracted from a closed van is very small (Fig. 9.6). Door openings greatly increase the heat load and, when the van engine drives the refrigeration system, this extra heat must all be removed during the period when the van is moving. Several factors interact when the number of door openings increases. The complete journey takes longer and during the extended journey the ambient temperature and the solar radiation on the van is different from the early part of the journey. If the length of time that the door is left open at each stop is also increased from 5 to 10 min then the temperature of the air around the food in the van increases more during each stop. The refrigeration plant therefore operates at a higher evaporat-

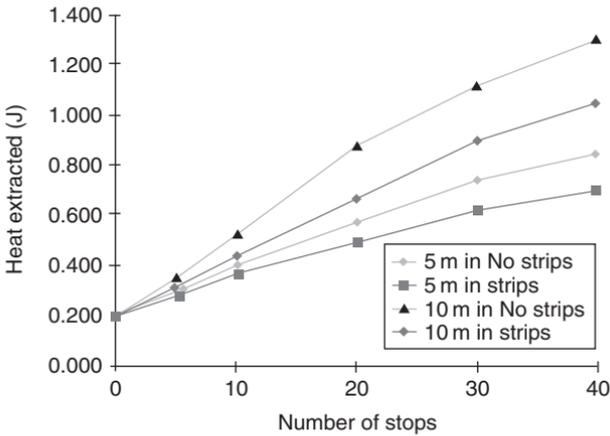


Fig. 9.6 Rate of heat extract from the van, averaged over the periods when the vehicle is moving, as a function of the number of stops the van makes (source: Gigel, 1998).

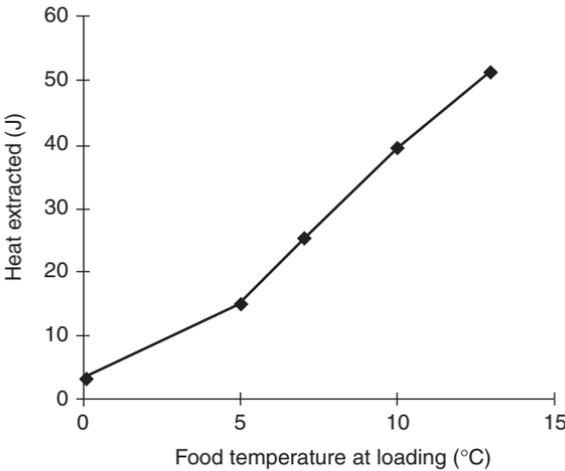


Fig. 9.7 Heat extracted by the refrigeration plant during the standard journey when the food is loaded at different initial temperatures (source: Gigel, 1998).

ing temperature (and hence it has greater capacity) when reducing the temperature once the doors are closed and the vehicle starts moving again. The time during which the refrigeration plant can run remains the same as the number of drops increases and therefore the rate of heat extraction increases approximately linearly with the number of stops.

9.3.4.5 Initial food temperature

The heat extracted by the refrigeration system is 4 times greater if the food is loaded at 7°C than if it is loaded at 0°C (Fig. 9.7). In the case predicted,

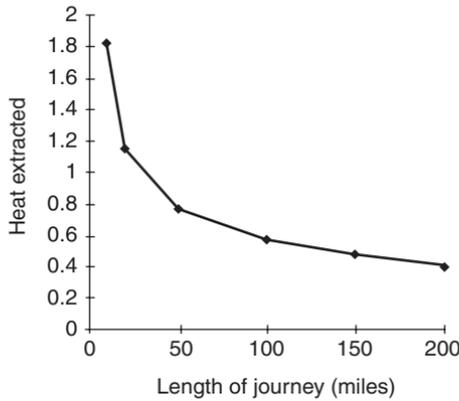


Fig. 9.8 Rate of heat extracted from the van averaged over the periods when the vehicle is moving as the length of the journey decreases (source: Gigiel, 1998).

the food was spread out over the shelves of the van and so cooled down quickly. If the food had been stacked on the floor with little or no air circulation through the food then the heat extracted would have been less, but the food would have remained warm.

9.3.4.6 Length of journey

As the length of the journey gets shorter while the number of drops remains the same the heat entering the van during the stops must be extracted in shorter time intervals between each stop. The rate of heat extraction therefore varies inversely with the length of the journey (Fig. 9.8). It is easier to maintain food temperatures on long journeys than when there are a large number of stops with little time spent travelling between each stop.

9.3.4.7 Solar radiation

A journey was simulated for a large refrigerated vehicle, designed for carrying frozen food on a long journey. The reflectance of the outer surfaces of the trunker had little effect on the heat extracted by the refrigeration system and none on the temperature of the food (Fig. 9.9). However, when the vehicle was moving the solar radiation absorbed at the surface was convected away into the ambient air much quicker and significantly reduced the heat load on the refrigeration system compared to that of a stationary vehicle.

9.4 Changes during transportation

The effect of different chilling treatments and vacuum or polyethylene packaging of offal on changes during a 13–15 day distribution change

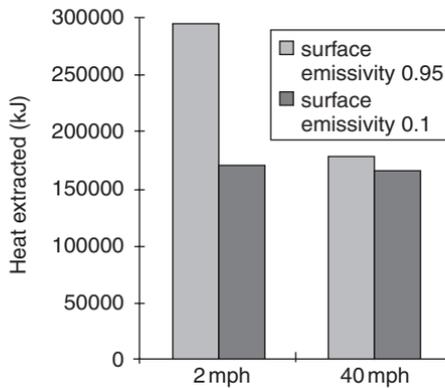


Fig. 9.9 Heat extracted from a trucker with 2 different surface reflectances and when moving and stationary for the same period (source: Gigiel, 1998).

Table 9.5 Weight losses during storage and transportation of vacuum-packed offal

| | % Weight loss during storage and transportation | | | | | |
|---------|---|------------|-------------|------------|-------------|------------|
| | Beef | | Pork | | Lamb | |
| | Not chilled | Prechilled | Not chilled | Prechilled | Not chilled | Prechilled |
| Liver | 3.97 | 2.97–5.52 | 2.45 | 1.61–3.82 | 3.53 | 3.49–6.91 |
| Hearts | 5.07 | 1.08–2.31 | 6.11 | 3.79–5.63 | 3.10 | 1.53–3.64 |
| Tongues | 0.23 | –0.07–0.50 | 2.13 | 2.89–3.38 | 1.03 | 0.93–1.91 |
| Kidneys | 0.11 | 0.06–0.83 | 1.03 | 1.15–1.18 | – | – |

Source: Stiffler *et al.*, 1985.

Involving overland and sea transportation has been investigated by Stiffler *et al.* (1985) and Vanderzant *et al.* (1985). One overall conclusion of the authors was that polyethylene was not a suitable packaging method because of quality deterioration in the products. The chilling treatments had little appreciable effect on the organoleptic quality characteristics, with the exception of liver which benefited from prechilling. Increases in aerobic plate counts of vacuum-packed offals were usually less for samples that had been prechilled.

Weight losses during storage and 11 days of transportation varied from approximately zero to 7% (Table 9.5). After transportation microbial levels ranged from 5.2 to 7.57 log₁₀ cfu cm⁻² with the samples from offal that had been prechilled tending to have slightly lower bacteria levels (Table 9.6).

Table 9.6 Bacterial levels on liver and tongues after storage and transportation

| | Aerobic plate counts (log cfu cm ⁻²) after storage and transportation | | | | | |
|---------|---|------------|-------------|------------|-------------|------------|
| | Beef | | Pork | | Lamb | |
| | Not chilled | Prechilled | Not chilled | Prechilled | Not chilled | Prechilled |
| Liver | 6.26 | 5.88–6.67 | 7.08 | 5.43–6.38 | 6.69 | 5.20–6.00 |
| Tongues | 6.66 | 5.46–6.54 | 7.43 | 6.43–7.53 | 7.57 | 6.68–6.85 |

Source: Vanderzant *et al.*, 1985.

9.5 Conclusions

- 1 Food must be at correct temperature before loading. Precooling of meat is essential before long distance transportation to distant markets.
- 2 Food temperature can be kept within $\pm 0.5^{\circ}\text{C}$ of set point in large containers.
- 3 With good temperature control, transportation times of 8–14 weeks can be achieved and still allow for a time on retail display.
- 4 There are substantial difficulties in maintaining the temperature of chilled meats transported in small refrigerated vehicles that conduct multi-drop deliveries to retail stores and caterers. During any one delivery run, the chilled product can be subjected to as many as 50 door openings, where there is heat ingress directly from outside and from personnel entering to select and remove product.
- 5 The design of the refrigeration system has to allow for extensive differences in load distribution, dependent on different delivery rounds, days of the week and the removal of product during a delivery run.

9.6 References

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10

Chilled and frozen storage

Theoretically, there are clear differences between the environmental conditions required for cooling, which is a heat removal/temperature reduction process, and those required for storage where the aim is to maintain a set product temperature. However, in many air-based systems, cooling and storage take place in the same chamber and even where two separate facilities are used, in many cases not all the required heat is removed in the cooling phase. This failure to remove the required heat can be due to a number of causes:

- insufficient time allowed
- insufficient refrigeration capacity to cater for high initial product load
- overloading
- variability in size of products
- incorrect environmental conditions.

Extensive data are available on the optimum storage conditions and attainable chilled and frozen storage lives for many products (IIR, 2000; IIR, 1986; ASHRAE, 1998).

10.1 Storage life terms

There are a wide range of rather confusing definitions used to define storage life. The EC directive (Commission of the European Community, 1989) states simply that frozen storage must 'preserve the intrinsic characteristics' of the food. Although this is probably every food technologist's aim, many different criteria can be used to measure these characteristics. The IIR

recommendations (1986) define frozen storage life as being 'the physical and biochemical reactions which take place in frozen food products leading to a gradual, cumulative and irreversible reduction in product quality leading such that after a period of time the product is no longer suitable for consumption or the intended process'. This definition tends to indicate that a frozen product may deteriorate until it is in a very poor condition before storage life ends, and so rather contradicts the EC definition.

IIR (1986) recommendations also include the term of practical storage life (PSL). PSL is defined as 'the period of frozen storage after freezing during which the product retains its characteristic properties and remains suitable for consumption or the intended process'. Bøgh-Sørensen (1984) describes PSL as 'the time the product can be stored and still be acceptable to the consumer'. Both of these definitions of PSL depend on the use of sensory panels, leading to the difficulty of defining acceptability and selecting a panel that represents consumers.

Another term referred to is high quality life (HQL). This concept was developed in the 'Albany' experiments started in 1948. HQL is 'the time elapsed between freezing of an initially high quality product and the moment when, by sensory assessment, a statistically significant difference ($P < 0.01$) from the initial high quality (immediately after freezing) can be established' (IIR, 1986). The control is stored at -40°C or colder to minimise quality changes. Although well suited to research work, some drawbacks have been noted.

The actual definition of storage life and the way it is measured has therefore been widely left to the assessment of individual authors. In some cases sensory assessment has been coupled with chemical or instrumental tests, which although probably more repeatable than human judgements, are again used at the author's discretion. Food technologists have no standard way of estimating shelf-life. Researchers have used many different methods of assessing samples, often with little thought of the initial quality, pre-freezing treatment or size of their samples. This deficiency has led to poor conclusions and recommendations that can be misleading to users of the data.

The IIR (2000) definition of chilled storage is very similar to that of frozen storage life. Expected or practical storage life is 'the greatest length of time for which the bulk of the produce may be stored either with maximum commercially acceptable loss of quality and nutritive value or with maximum acceptable wastage by spoilage'.

10.2 Chilled storage

Extensive data are available on the attainable chilled storage lives for many products (Table 10.1). In most cases the limiting factors that control the chilled storage life of meat are based on bacterial growth. 'Off' odours and slime caused by microorganisms are detected when populations reach *ca.*

Table 10.1 Chilled storage times

| | Storage time (days (sd)) in temperature range (°C) | | | |
|-----------|--|---------|---------|---------|
| | -4.1 to -1.1 | -1-2 | 2.1-5.1 | 5.2-8.2 |
| Bacon | | 45 (6) | 15 (3) | 42 (20) |
| Beef | 40 (26) | 34 (32) | 10 (8) | 9 (9) |
| Cold meat | | 14 (9) | 20 (17) | 8 (0) |
| Lamb | 55 (20) | 41 (46) | 28 (34) | |
| Meals | 34 (18) | 15 (7) | 21 (38) | 18 (4) |
| Offal | 7 | 7 (6) | 14 (7) | |
| Pork | 50 (58) | 22 (30) | 16 (16) | 15 (18) |
| Poultry | 32 (18) | 17 (10) | 12 (11) | 7 (3) |
| Rabbit | | 9 (7) | 13 (6) | |
| Sausage | 80 (43) | 21 (16) | 36 (28) | 24 (10) |
| Veal | 21 | 10 (6) | 49 | 49 |

Source: IIR, 2000.

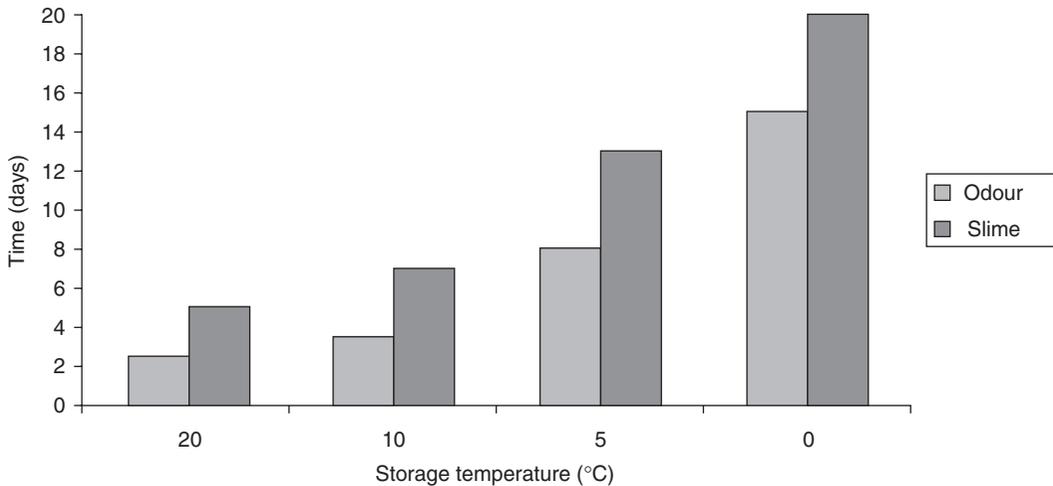


Fig. 10.1 Time (days) for odour or slime to be detected on beef sides with average initial contamination stored at different temperatures (source: Ingram and Roberts, 1976).

10^7 – 10^8 organisms cm^{-2} . Temperature is the principal factor affecting the rate of microbial growth and hence the shelf-life of chilled meat.

10.2.1 Unwrapped meat

Temperature is the prime factor controlling storage life of wrapped meat. Odour and slime will be apparent after *ca.* 14.5 and 20 days, respectively, with beef sides stored at 0°C (Fig. 10.1). At 5°C , the respective times are significantly reduced to 8 and 13 days.

Table 10.2 General levels of microbiological contamination reported on meat carcasses throughout the world

| Type of meat | Country | APC* (log ₁₀ organism) | Reference |
|----------------|-------------|--------------------------------------|---------------------------------|
| Beef | UK | 1.9–3.7 | Ingram and Roberts (1976) |
| | Sweden | 2.2–3.4 | Ingram and Roberts (1976) |
| | New Zealand | 1.3–4.3 | Ingram and Roberts (1976) |
| | New Zealand | 1.4–2.2 | Newton <i>et al.</i> (1978) |
| | Norway | 1.3–3.9 | Johanson <i>et al.</i> (1983) |
| | EU | 2.3–3.9 | Roberts <i>et al.</i> (1984) |
| | UK | 3.4–3.8 | Hudson <i>et al.</i> (1987) |
| | New Zealand | 0.4–3.3 | Bell <i>et al.</i> (1993) |
| | Australia | 3.2 | Anon (1997) |
| | Canada | 1.5–3.2 | Gill <i>et al.</i> (1998b) |
| | UK | 2.45–4.29 | Hinton <i>et al.</i> (1998) |
| Lamb/ sheep | New Zealand | 2.5–2.9 | Newton <i>et al.</i> (1978) |
| | Spain | 4.96 | Prieto <i>et al.</i> (1991) |
| | New Zealand | 2.3–4.1 | Bell <i>et al.</i> (1993) |
| | New Zealand | 3.9–4.6 | Biss and Hathaway (1995) |
| | Australia | 3.9 | Anon (1997) |
| Pig | UK | 2.5–3.3 | Ingram and Roberts (1976) |
| | Norway | 2.6–3.9 | Johanson <i>et al.</i> (1983) |
| | Denmark | 1.6–3.8 | Christensen and Sørensen (1991) |
| | Italy | 4.3–5.0 | Barbuti <i>et al.</i> (1992) |

* Values are not directly comparable since different sampling techniques and incubation temperatures have been used.

The initial level of bacterial contamination will of course affect the storage life. Over 40 years ago Ayres (1955), in his comprehensive review of microbiological contamination in slaughtering, concluded that an aerobic population of 4.0–5.0 log₁₀ cfu cm⁻² and an anaerobic population of between 3.7 and 4.7 log₁₀ cfu g⁻¹ would be reasonable for wholesale cuts of meat. Surveys from the mid-1970s have shown that in general levels of between 1 and 4 log₁₀ cfu g⁻¹ can be expected on red meat carcasses (Table 10.2).

Specific surfaces of the carcass can have very high levels of initial contamination. Beef subcutaneous fat has been shown to have a high initial microbial load and a capacity to support extensive bacterial growth (Lasta *et al.*, 1995). Initial values of total viable counts increase from an initial value of 5.4 to 10.0 log₁₀ cfu cm⁻² after 11 days in a moist environment at 5 °C (Fig. 10.2). No noticeable deterioration in appearance of the sample was found after 14 days which was worrying. This type of material is often incorporated in manufactured products or could provide a cross contamination source.

The above results were obtained on the surface of samples stored in air nearly saturated with water vapour. There is much industrial belief that the surface of meat carcasses must be allowed to dry or storage life will be com-

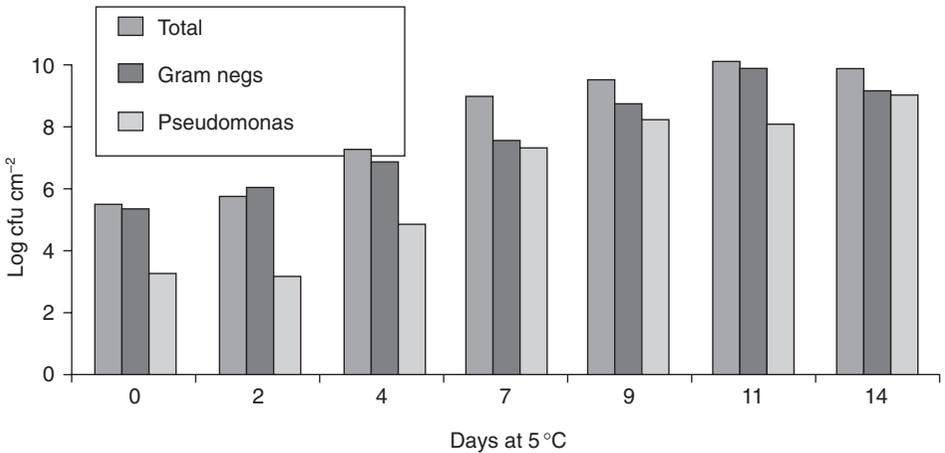


Fig. 10.2 Growth of bacteria on naturally contaminated beef-brisket fat stored at 5°C (source: Lasta *et al.*, 1995).

promised. There appear to be no clear scientific studies that store carcasses under a range of industrial conditions to prove or disprove this belief. Investigations on pork chilling (Greer and Dilts, 1988) have shown that while conventional chilling significantly reduces the level of mesophilic bacteria, this does not occur when spray chilling. However, this work found that after boning there was no significant difference in bacterial counts on loins produced by either treatment. Other studies found no difference in off-odours during storage and retail display of pork chops from pork cooled under either of the two methods, though the appearance of the spray chilled samples deteriorated slightly faster than those treated conventionally (Jeremiah and Jones, 1989).

10.2.2 Wrapped meat

TTT (time–temperature–tolerance) and PPP (product–process–packaging) factors significantly influence the storage life of chilled meat (Bøgh-Sørensen *et al.*, 1986). In some cases the initial processing stage can have more effect than the subsequent storage conditions. After manufacture, sausages made from hot-boned pork had higher total bacterial counts ($4.1 \log_{10} \text{cfu g}^{-1}$) than those from cold-boned meat ($2.7 \log_{10} \text{cfu g}^{-1}$) (Bentley *et al.*, 1987). When they were stored at 4 or -1°C for 28 days there were no differences between counts at the two temperatures. However, the counts were very high, 8.7 and $8.9 \log_{10} \text{cfu g}^{-1}$, in both cases.

In vacuum-packaged primals, Egan *et al.* (1986) have shown that the temperature of storage and pH determines both the storage life and the nature of the changes during storage (Table 10.3).

Flora on high pH (>6.0) beef cuts, vacuum packaged in polyvinylidene chloride (PVDC) reached maximum levels in 6 weeks at 1°C compared

Table 10.3 Storage life and nature of spoilage of vacuum-packaged pork

| Meat pH | 0 °C | | 5 °C | |
|---------|----------------------|--------------------------|----------------------|---|
| | Storage life (weeks) | Spoilage characteristics | Storage life (weeks) | Spoilage characteristics |
| 5.4–5.8 | 6 | Flavour changes, souring | 3–4 | Flavour changes, souring |
| 6.2–6.5 | 4–5 | Variable | 2–3 | Greening, odour of H ₂ S, putrefaction |

Source: Egan *et al.*, 1986.

with 12 weeks for normal pH beef (Gill and Penney, 1986). In metalized polyester or aluminium foil laminate vacuum packs, times were 9 and 15 weeks respectively.

At a lower temperature Jeremiah *et al.* (1995a, b) have shown that off-flavour development, coinciding with lactic acid bacteria reaching maximum numbers, currently restricts the storage life of carbon dioxide (CO₂) or vacuum-packaged pork at –1.5 °C to 9 weeks. Based on appearance, CO₂-packaged and vacuum-packed pork loin had storage lives of over 15 weeks and slightly over 12 weeks, respectively. Only small differences were found between pork loins from dark, firm, dry (DFD); pale, soft, exuding (PSE) and normal quality groups. They believed that reducing the current levels of microbial contamination would allow storage life to be extended to meet all domestic and export requirements. Bell *et al.* (1996) detected no major off odours after 98 days at –0.1 °C from hot-boned bull beef that had been cooled and stored in vacuum or CO₂ packs. On opening, the appearance of the strip loins was also acceptable. However, overageing was believed to have reduced the retail display life of the meat. The authors thought that the process could produce high quality beef for catering use with a storage life of 70 days.

The effect of temperature and packaging was clearly demonstrated by Lee *et al.* (1985) and Gill and Harrison (1989). Only small changes in microbial numbers (Fig. 10.3), pH, drip and off-odour were found in vacuum or vacuum plus gas flushed packs of pork after 49 days storage at –4 °C (Lee *et al.*, 1985), whilst green discolouration was significant after 14 days at 3 and 7 °C and 28 days at 0 °C. The amount of drip loss increased substantially with both length and temperature of storage (Fig. 10.4). Drip loss from pork liver tends to be higher than that from muscle and increases more rapidly during storage. At a storage temperature of 5 °C losses increased from 1.9% after 1 day to *ca.* 6% after 6 days (Strange *et al.*, 1985).

Gill and Harrison (1989) found that vacuum-packed cuts of pork longissimus dorsi muscle (skin on) were grossly spoiled by *Brochothrix thermosphacta* after 2 weeks storage at 3 °C compared with 5 weeks at –1.5 °C. Cuts

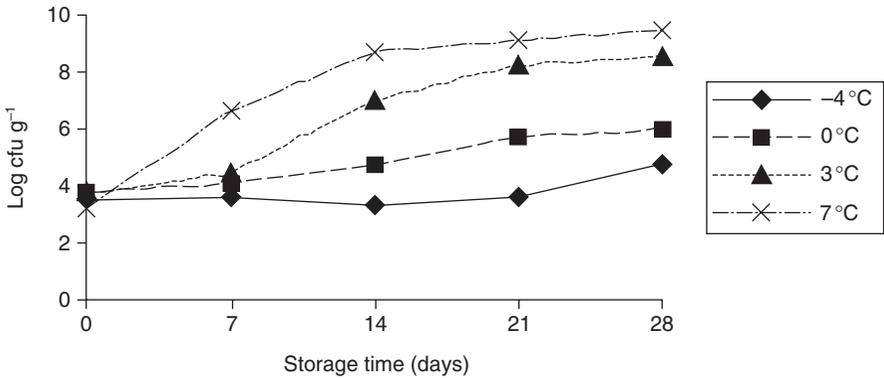


Fig. 10.3 Growth of psychrotroph counts (\log_{10} cfu g^{-1}) on vacuum-packed cubed pork at -4 , 0 , 3 and 7°C (source: Lee *et al.*, 1985).

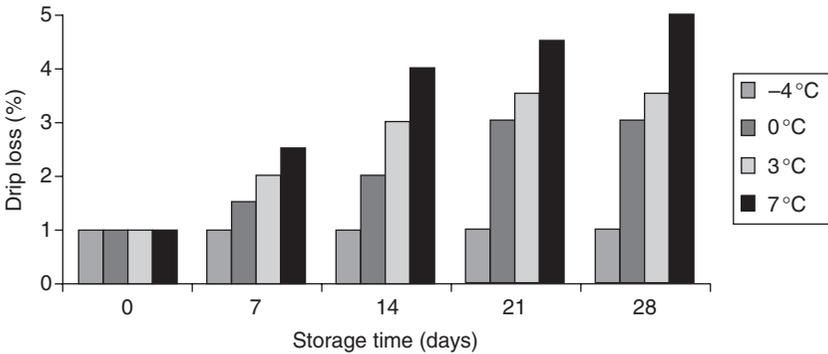


Fig. 10.4 Drip loss from vacuum-packed cubes of pork stored at -4 , 0 , 3 and 7°C (source: Lee *et al.*, 1985).

packed under CO_2 spoiled after 5.5 weeks storage at 3°C . Growth of *Brochothrix thermosphacta* was suppressed when the pork was stored under CO_2 at -1.5°C . Growth of Enterobacteriaceae caused gross spoilage of an increasing proportion of cuts between 18 and 26 weeks. Until spoilage occurred, the eating quality of the pork was little affected by the length of storage.

In audits carried out in New Zealand to improve the shelf-life of vacuum-packed chilled lamb, changing the chilling practice was found to have the largest effect (Gill, 1987). It was found that the significance of the relatively small numbers of organisms added to carcasses during dressing was greatly magnified by their growth during carcass cooling. Small changes to the chilling practices alone extended the storage life by up to 50%. The length and conditions used during ageing can also affect the storage life of meat (Nortjé and Shaw, 1989). Beef loin steaks from primals that had been aged

for 3 weeks in vacuum packs discoloured more rapidly and off-odours developed sooner than those from meat that had been hung in air for one week or vacuum packed for one week. The poorer storage stability was explained by higher initial levels of bacteria because of growth during ageing. Rancidity development was only detected in the 3-week-aged steaks that were stored at 6°C.

Studies have also shown that there is an interaction between storage and retail display. The retail display life of pork from CO₂ packaged primals depends on the length of time the primals have been stored (Greer *et al.*, 1993). On appearance criteria, the display life in days is 4.60–0.15 (weeks in storage), whilst on odour criteria the display life in days is 5.03–0.17 (weeks in storage).

The tenderness, juiciness and flavour of beef patties has been found to deteriorate during chilled storage with the flavour deteriorating less at 0°C than at 4 or 8°C (Bentley *et al.*, 1989). Drip loss increased with storage temperature from 3.2% at 0°C to 3.3% at 4°C and 4.6% at 8°C. Drip loss was also affected by the type of packaging with greater drip in vacuum packs than in 100% nitrogen or CO₂ back-flushed packs. Total plate counts increased from 2.7 to 7.2 log₁₀ cfu cm⁻² after 7 days and to 8.6 log₁₀ cfu after 21 days of storage but no effect of storage temperature or packaging type was detected.

10.2.3 Cooked products

The influence of temperature on the storage life of vacuum packed sliced cured meat products is shown clearly in Table 10.4.

Precooked beef roasts can be stored for 28 days at 4°C (Stites *et al.*, 1989). The roasts of beef chuck were prepared in vacuum cooking bags with phosphate salt and cooked to a centre temperature of 70°C. They were then

Table 10.4 Storage life for vacuum-packed sliced cured meat products

| Temperature (°C) | Storage life (days) | | | |
|---------------------|---------------------|------------------|---------------------|---------------------|
| | Bologna sausage | Smoked fillet | Cooked pork loin | Cooked pork loin |
| 12 | 7 | – | 21 | – |
| 8 | 11.5 | 9 | 33 | 16.5 |
| 5 | 21.5 | 10 | 66 | 31.5 |
| 2 | 33 | 11.5 | 78 | 52.5 |
| 0 | 42 | 22.5 | 141 | 64 |
| –3 | 11 | 33 | 165 | >64 |

Source: Bøgh-Sørensen *et al.*, 1986.

chilled and stored at 4°C. Sensory attributes were acceptable after 28 days and total plate counts less than 100 per gram. Studies by Tanchotikul *et al.* (1989) have shown that the susceptibility to oxidation in precooked roasts during chilled storage increased as the end-point cooking temperature increased.

Addition of 0.25 or 0.5% polyphosphate to restructured, battered and breaded, cooked beef and pork nugget products protected them from off-flavours and lipid oxidation during chilled storage (Huffman *et al.*, 1987). Similar effects have been shown for garlic and onion juices (Jurdi-Haldeman *et al.*, 1987). Garlic and onion juices were added to minced lamb which was then made into patties and cooked. After 0, 3 and 7 days of storage at 5°C, TBA values were lower in patties from the two treatments than the control.

Although the market for preprepared sandwiches is expanding rapidly there are little published data on their chilled storage life. One study in the USA has looked at the storage life of commercially processed sandwiches including processed meats, roast beef and hamburgers packed in 50% CO₂:50% air mixture and stored at 4°C (McMullen and Stiles, 1989). Storage life ranges from 35 days for processed meat sandwiches, 28 to 35 days for roast beef and only 14 days for hamburgers. Both microbiological and taste panel tests were used to determine shelf-life. The sandwiches were heated to 50–55°C in a microwave oven before tasting. In general the untrained taste panel found sandwiches acceptable after maximum microbial levels were achieved.

Substantial differences in counts were found between replicates and between samples from the same replicates (Table 10.5). Coliform counts never exceeded 2 cfu g⁻¹. Further studies investigated laboratory packing in 30, 50 and 70% CO₂ with either air or nitrogen. Excluding oxygen from the beefburger packs extended the shelf-life from 14 to 35 days.

Table 10.5 Growth of lactic acid bacteria in beefburgers stored in a modified gas atmosphere at 4°C

| Week | Lactic acid bacteria (cfu g ⁻¹) | | | |
|------|---|-------------------------|-------------------------|-------------------------|
| | Replicate 1 sample 1 | Replicate 1 sample 2 | Replicate 2 sample 1 | Replicate 2 sample 2 |
| 1 | <1 × 10 ² | <1 × 10 ² | <1 × 10 ² | <1 × 10 ² |
| 2 | <1 × 10 ² | <1 × 10 ² | 6.0 × 10 ² | 5.4 × 10 ³ |
| 3 | 1.4 × 10 ² | 2.7 × 10 ³ | 1.0 × 10 ² | 9.2 × 10 ³ |
| 4 | 4.5 × 10 ⁷ | 1.0 × 10 ² | 2.8 × 10 ⁴ | 4.1 × 10 ⁶ |
| 5 | 4.7 × 10 ⁶ | 1.4 × 10 ⁴ | 1.2 × 10 ⁷ | 1.4 × 10 ⁵ |
| 6 | 2.0 × 10 ⁶ | 3.0 × 10 ³ | <1 × 10 ² | 1.4 × 10 ⁶ |

Source: McMullen & Stiles, 1989.

10.3 Frozen storage

This chapter is a brief summary of a full review by James and Evans (1997). The factors that influence the storage life of frozen meat may act in any one of three stages: prior to freezing, during the actual freezing process and postfreezing in the storage period itself.

10.3.1 Oxidative rancidity

The importance of fat oxidation in frozen meat is illustrated by a short quotation from a paper published by Lea (1931); 'it is often the deterioration of the fat which limits the storage life – from the point of view at least of palatability – of the meat'. This view has been reiterated many times, and as freezing technology has improved it is true to say that fat oxidation remains the obstacle to very long-term storage of frozen meat. Early studies on fat oxidation and freezing were reviewed by Lea (1938) and Watts (1954).

10.3.1.1 Mechanism of oxidation

The reaction of oxygen with fatty acids produces peroxides. It is the breakdown products of the peroxides that produce the characteristic objectionable odour and flavour of rancid meat. The development of oxidative rancidity in meat is affected by two groups of factors, one group consisting of the built-in characteristics of the meat and the other group consisting of those factors involved in the treatment of the meat. The former are mainly under the control of the farmer or are innate characteristics of the living animal, whereas the latter can be controlled by the abattoir, the meat packer or the cold store operator. Although the first group cannot be changed by the meat processor it is necessary to consider their effect so that procedures may be modified to limit them. Before discussing either group it is necessary to look at the process of fat oxidation in the hope that knowledge of the process will indicate the ways in which it may be controlled.

The reaction of oxygen with fat is an autocatalytic process. Once the reaction starts, the products of the reaction stimulate it to go faster. The initial reaction is between a molecule of oxygen and a fatty acid to form a peroxide. This is a slow reaction but like any other chemical reaction its rate is increased by raising the temperature. The rate is also influenced by the type of fatty acid. Saturated fatty acids react slowly, but unsaturated fatty acids react more rapidly, and the more double bonds that a fatty acid contains, the more reactive it is. The presence of peroxides in fat does not change the flavour, it is the breakdown products of the peroxides which produce the rancid odour and flavour. The breakdown of peroxide is accelerated by heat, light, organic iron catalysts and traces of metal ions, especially copper and iron. The breakdown products of the peroxides cause the oxygen to react more rapidly with the fatty acids, thus producing the autocatalytic effect.

The type of fatty acid present in the meat is therefore of major importance in determining its oxidative stability. Beef and mutton tallow, both very hard fats, which contain few unsaturated fatty acids are much more stable than lard, a softer fat, which contains a large quantity of unsaturated fatty acids. The effect of fatty acid composition can, however, be much more subtle. Lea (1936) observed that feeding an ounce of cod liver oil per day to pigs increased the susceptibility of the fat to oxidation by a factor of 5, although the change in the iodine value of the fat was negligible. This result may be compared with the studies of Dahl (1957) where an increase in the linoleic acid content of pig fat from 7% to 15.6%, which increased the iodine number by 10 units, only reduced the oxidative stability by one quarter. The reason for the difference is that the quantity of polyunsaturated fatty acids from the cod liver oil that was stored in the pig fat was small. However, since these fatty acids contained 4, 5 and 6 double bonds, the initiation of oxidation was much easier than in the fat where the high iodine number was produced by an increase in a fatty acid with only 2 double bonds. The relative susceptibility of oleic, linoleic and linolenic acids, with 1, 2 and 3 double bonds respectively, to oxidation is 1:12:100 (Kuhn and Meyer, 1929).

10.3.1.2 *Natural antioxidants*

In view of the ease with which fat oxidation takes place one might enquire whether it occurs in the living animal, and if not, why not? The answer is that it does but only to a small extent. Nor does it occur in meat immediately after slaughter. The reason is the presence in the animal tissues of antioxidants which prevent the peroxide breakdown products from catalysing the oxidation. The major antioxidant in meat is alpha-tocopherol or vitamin E. Deficiency of vitamin E in many animals leads to the oxidation of the adipose tissue, which turns yellow (Dam, 1957). Such material from pigs would of course not pass inspection, but even meat having a lowered alpha-tocopherol content would be less stable in frozen storage. The situation is well documented in the case of the turkey, which has low levels of alpha-tocopherol. The injection of alpha-tocopherol into turkeys decreased the thiobarbituric acid value, a measure of oxidation of the frozen carcass, and improved the flavour (Webb *et al.*, 1972).

Fatty acid composition and the antioxidant status of the tissue are the main factors affecting oxidation, which are fixed in the animal before slaughter. The fatty acid composition of the diet readily changes the fatty acid composition of pig fat, but has little effect in ruminants. The antioxidant levels of the tissues are not greatly affected by changes in the quantity in the diet, since little of the added alpha-tocopherol finds its way to the fat. However, prolonged low levels of alpha-tocopherol in the diet can reduce the quantity in the animal. Feeding high levels of polyunsaturated fatty acids can also reduce the body's stores of alpha-tocopherol because of the extra quantity needed to prevent oxidation. The alpha-tocopherol

content of cereals may be reduced if the grain is stale and the lipids have started to oxidise and destroy it. Not all the fat depots on the carcass are equally susceptible to oxidation. Subcutaneous fat in most species is much softer (more unsaturated) than the internal fat.

10.3.1.3 Phospholipids

Although the bulk of the fat in a carcass is in the visible fat depots, all cells in the animal's body contain phospholipids as part of their structure. Furthermore, the phospholipids contain large quantities of polyunsaturated fatty acids that are not readily influenced by the nature of the dietary fatty acids. The greater susceptibility of phospholipids to oxidation compared with the neutral lipids of ground pork was observed by Younathan and Watts (1960). Phospholipids have been used as antioxidants under certain conditions, but the mechanism by which they function is not understood and it is not known if they exhibit any antioxidant activity in fresh meat.

10.3.2 Prefreezing treatment

Some prefreezing factors, that is, species differences, animal to animal variation or differences between cuts of meat, are inherent in the animal. There are also other factors including feeding and transport that may have an effect on frozen storage.

Species is the main prefreezing factor that is commonly believed to influence the frozen storage life. Table 10.6 provides data from three sources on the storage life of meat from different species and the average and range from all the publications located.

There is up to a two-fold difference between species in recommended storage times, but more important is the relative ranking, in terms of which can be stored for the longest time, which varies between the sources. When all the available data found in the literature are considered the picture becomes even more confusing. Average values for the storage lives of the different species at -18°C (Table 10.6) have a different ranking to that generally accepted and the range of storage lives is very large.

Table 10.6 Frozen storage life (months) for different species

| Source temperature ($^{\circ}\text{C}$) | 1 -20 | 2 -18 | 3 -18 | Average at -18 | Range at -18 |
|---|----------|----------|----------|-------------------|-----------------|
| Species | | | | | |
| Beef | 12 | 12 | 18 | 10.2 | 2.8-19.4 |
| Pork | 6 | 8 | 12 | 17.4 | 2.8-23.3 |
| Lamb | 10 | 12 | 24 | 7.8 | 2.8-24.3 |
| Chicken | 12 | 10 | 18 | 13.6 | 6.0-23.3 |

Source: James and Evans, 1997.

Few publications compare the meat of more than two species under directly comparable conditions. Under similar ageing and packaging regimes beef was found to store for 69 weeks, pork for 53 weeks and lamb for 44 weeks at -18°C . At -18°C pork remained palatable for longer than lamb but at higher temperatures the lamb was more stable. It seems fair to conclude that most work points towards a difference, but not necessarily a consistent difference, in frozen storage life between species.

To look at animal to animal variation, two trials were carried out in New Zealand where lamb was stored at -5°C . In the first trial the lamb was judged rancid after 20 weeks and in a duplicate trial the lamb was found to store for 40 weeks. The only variation that could be determined was that different animals were used in the two trials. There appear to be large variations between animals which cause changes in the storage life of meat, but why these differences exist is not completely understood.

Feeding influences frozen storage life. Pork from pigs that had been fed materials containing offal or household refuse had half the practical storage life than that from pigs which had been fed conventional diets (Bailey *et al.*, 1973). Rations with large amounts of highly unsaturated fatty acids tend to produce more unstable meat and fat. The feeding of fish oils or highly unsaturated vegetable oils to poultry is known to produce fishy flavours in the meat but there is some debate as to whether this diet directly affects frozen storage times. The linoleic acid content of meat probably plays a major role in storage. There has been a general trend in the UK for pigs to be leaner and therefore to have greater proportions of linoleic acid in their tissues. There is a possibility that pork may store less well than might be expected from results dating from 10 or 20 years ago.

Reports of variations in the storage life of different cuts of meat are scarce and primarily show that light meat stores for a longer time than dark meat. This is thought to be due to either higher quantities of haem pigments in the dark muscle, or to higher quantities of phospholipids which are major contributors to oxidised flavour in cooked meat.

Increased stress or exhaustion can produce PSE or DFD meat, which is not recommended for storage mainly due to its unattractive nature and appearance.

Meat is generally not frozen until rigor is complete and a degree of conditioning has taken place, otherwise toughening and increased drip can occur. In red meat, there is little evidence of any relationship between chilling rates and frozen storage life. However, there is evidence that increasing the time in chilled storage before freezing reduces frozen storage life. Carcasses which have been electrically stimulated have prolonged storage lives and this could be attributed to the shorter interval between slaughter and freezing. In poultry, the chilling method does have an effect on storage life. Air chilled broilers had significant flavour changes after 3 months at -12°C and -20°C , whereas immersion chilled birds only exhibited changes at -12°C after 6 months and were stable at -20°C . Water chilling of

broilers produced a more favourable taste in the leg and breast meat than air chilling.

Processing of meat prior to freezing generally results in a lengthened storage time. Heating prior to freezing can result in a 50% longer PSL for sausages. However, the heating process could be critical since muscles cooked to higher temperatures are most susceptible to oxidative changes during storage. Heat treatments such as frying tend to produce short storage lives, probably because of the high fat content of the product. Breaded products are often fried and although breading alone may have a protective effect on a product, the addition of oil may have a counteractive effect.

A process such as mincing has been found to affect storage of comminuted products and this is probably due to the induced heating and the increased surface area that results. Addition of fat to mince can lower storage life unless a high grade wrapping material, which has the ability to exclude air, is used to wrap the product. Smoking is generally advantageous owing to the antioxidant properties of the smoke. Smoked broilers and ham store well for over a year without serious quality change.

Additives, such as spices, seasoning, antioxidants and protein concentrates can influence storage life. The use of vegetable extracts such as onion juice, yellow onion peel, hot water extracts of aubergine (egg plant), potatoes and sweet potatoes have been shown to help control rancidity in beef and turkey meat. However, an addition of salt may also reduce the storage life because of increased rancidity. Mechanically recovered meat is used in a range of meat products, but can cause storage problems owing to its high fat content and increased rancidity.

10.3.3 Freezing process

There are few data to suggest that in general the method of freezing or the rate of freezing has any substantial influence on the subsequent storage life of a food. There is some disagreement in the literature about whether fast (cryogenic) or slow (blast) freezing is advantageous. Slightly superior chemical and sensory attributes have been found in food cryogenically frozen in a few trials, but other trials did not show any appreciable advantage, especially during short-term storage.

The method of freezing clearly affects the ultrastructure of the meat. Slow freezing ($1\text{--}2\text{ mm h}^{-1}$ for example) tends to produce large ice crystals extracellularly, whilst quick freezing (e.g. 50 mm h^{-1}) gives smaller crystals in and outside cells. Obviously, a temperature gradient will occur in large pieces of meat and result in a non-uniform ice morphology. Fast freezing tends to produce a lighter coloured product as the small ice crystals scatter the light more than larger crystals and this enhances the surface appearance of poultry skin. However, there are no data to suggest that the ultrastructure influences storage life.

10.3.4 During frozen storage

Three factors concerning storage; the storage temperature, the degree of fluctuation in the storage temperature and the type of wrapping/packaging in which the meat is stored, are commonly believed to have the main influence on frozen storage life.

10.3.4.1 Storage temperature

To quote from the IIR Red book 'storage life of nearly all frozen foods is dependent on the temperature of storage...' and in the book a table is provided of practical storage lives of different foods at three storage temperatures. An extract is given in Table 10.7. However, few papers have been located where data are presented from experiments on the PSL of meat at different storage temperatures. Many of those that have been located are on products that do not meet the lower temperature longer storage rule (normal stability).

Experimental data from many different publications have been plotted against the temperature of storage for beef (Fig. 10.5), pork (Fig. 10.6) and lamb (Fig. 10.7). There is a clear effect of temperature on storage life, with lower temperatures resulting in extended storage, but considerable scatter between results at any one temperature.

It has been shown that rancidity in bacon is increased by higher salt content and that the rates of chemical reactions are accelerated as the temperature is lowered when packed in permeable wrap. Cured pork products are known to have an abnormal temperature profile between -5°C and -60°C and store less well between -30°C and -40°C .

Table 10.7 Practical storage life (months) at different storage temperatures

| Product | -12°C | -18°C | -24°C |
|---------------------|-----------------------|-----------------------|-----------------------|
| Beef carcasses | 8 | 15 | 24 |
| Beef steaks/cuts | 8 | 18 | 24 |
| Ground beef | 6 | 10 | 15 |
| Veal carcass | 6 | 12 | 15 |
| Veal steaks/cuts | 6 | 12 | 15 |
| Lamb carcasses | 18 | 24 | >24 |
| Lamb steaks | 12 | 18 | 24 |
| Pork carcasses | 6 | 10 | 15 |
| Pork steaks/cuts | 6 | 10 | 15 |
| Sliced bacon (vac.) | 12 | 12 | 12 |
| Chicken, whole | 9 | 18 | >24 |
| Chicken parts/cuts | 9 | 18 | >24 |
| Turkey, whole | 8 | 15 | >24 |
| Ducks, Geese, whole | 6 | 12 | 18 |
| Liver | 4 | 12 | 18 |

Source: IIR, 1986.

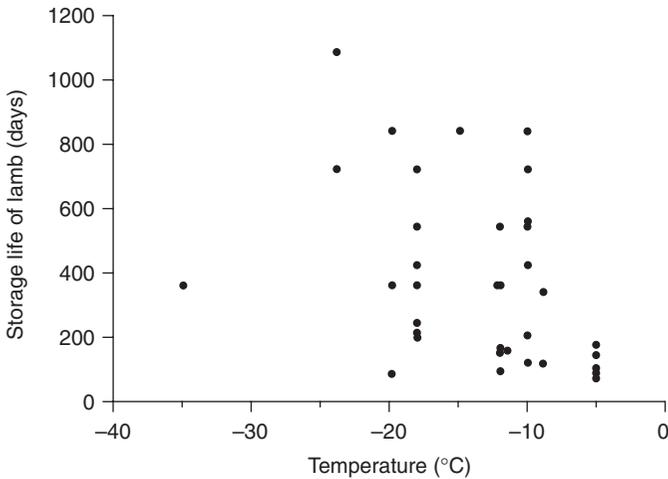


Fig. 10.7 Experimental data on storage life of lamb at different temperatures (source: James and Evans, 1997).

ference between samples of lamb stored at -5 and 35°C . A trained taste panel could differentiate between the two temperatures and scored the samples stored at -5°C as rancid.

10.3.4.2 Temperature fluctuation

Fluctuating temperatures in storage are considered to be detrimental to the product. However, it has been reported that repeated freeze–thaw cycles do not cause any essential change in the muscle ultrastructure (Carroll *et al.*, 1981) and that several freeze–thaw cycles during the life of a product cause only small quality damage (Wirth, 1979) or possibly no damage at all. In fact, a slight but significant improvement in samples that had been frozen and unfrozen several times was found by one taste panel (Jul, 1982).

Minor temperature fluctuations in a stored product are generally considered unimportant, especially if they are below -18°C and are only of the magnitude of $1\text{--}2^{\circ}\text{C}$. Well-packed products and those that are tightly packed in palletised cartons are also less likely to show quality loss. However, poorly packed samples are severely affected by the temperature swings. There is disagreement about how much effect larger temperature fluctuations have on a product. Some authors consider that temperature fluctuations have the same effect on quality of the product as storage at an average constant temperature (Dawson, 1969); others consider fluctuations may have an additive effect (Van Arsdell, 1969; Bech-Jacobsen and Bøgh-Sørensen, 1984). There is evidence that exposure to temperatures above -18°C rather than temperature fluctuations may be the major factor influencing quality deterioration (Gortner *et al.*, 1948).

10.3.4.3 Packaging

Packaging has a large direct effect on storage life, especially in fatty foods and in extreme cases it has an indirect effect owing to substantial increases in the freezing time. A number of examples have occurred where large pallet loads of warm boxed meat have been frozen in storage rooms. In these cases, freezing times can be so great that bacterial and enzymic activity results in a reduction of storage life. In most cases, it is the material and type of packaging that influences frozen storage life. Wrapping in a tightly fitting pack having a low water and oxygen permeability (such as a vacuum pack) can more than double the storage life of a product. Waterproof packing also helps to prevent freezer burn and tight packing helps to prevent an ice build up in the pack. When a product is breaded, packaging appears to have little effect and in a trial where breaded pork chops and breaded ground pork were packed in poor and very good packs an effect of packing could not be found.

Rancidity occurs in unwrapped meat because its surface dries, allowing oxygen to reach subcutaneous fat. Without wrapping, freezer burn may occur causing extreme toughening and the development of rancidity in the affected area. Packaging can be effective in some cases in reducing discolouration by lessening oxygen penetration into the meat. Lighting, especially ultraviolet, can also increase fat oxidation (Volz *et al.*, 1949; Lentz, 1971). Exposure to the levels of light found in many retail frozen food display areas can cause appreciable colour change within 1–3 days. Development of off-flavour can be accelerated and may be noticeable within 1–2 months on display. Products kept in dark or opaque packages may therefore be expected to retain colour longer than those exposed to the light.

10.4 Types of storage room

10.4.1 Bulk storage rooms

Most unwrapped meat and poultry and all types of wrapped foods are stored in large rooms where air is circulated. To minimise weight loss and appearance changes associated with desiccation, air movement around the unwrapped product should be the minimum required to maintain a constant temperature. With wrapped products low air velocities are also desirable to minimise energy consumption. However, many storage rooms are designed and constructed with little regard to air distribution and localised air velocities over products. Horizontal throw refrigeration coils are often mounted in the free space above the racks or rails of product and no attempt is made to distribute the air around the products.

Using a false ceiling or other form of ducting to distribute the air throughout the storage room can substantially reduce variations in velocity and temperature. It is claimed that an even air distribution can be maintained using air socks, with localised velocities not exceeding 0.2 m s^{-1} .

10.4.2 Controlled atmosphere storage rooms

Controlled atmosphere storage rooms were developed for specialised fruit stores, especially those for apples. Interest is growing in the application of this technique to other commodities including meat. In addition to the normal temperature control plant these stores also include special gas-tight seals to maintain an atmosphere which is normally lower in oxygen and higher in nitrogen and carbon dioxide than air. An additional plant is required to control the CO₂ concentration, generate nitrogen and consume oxygen.

There is growing interest in the use of controlled atmosphere retail packs to extend the chilled storage and display life of red meats, poultry and meat products. Since the packs tend to be large and insulate the products, efficient precooling before packaging is especially important if product quality is to be maintained.

10.4.3 Jacketed cold stores

Cooling the walls, floor and ceiling of a store produces very good temperature control in the enclosed space with the minimum of air movement. It is especially suitable for controlled atmosphere (CA) storage and for unwrapped produce that is very sensitive to air movement or temperature fluctuations. The refrigerated jacket can be provided by embedding pipe coils in the structure or utilising a double skin construction through which refrigerated air is circulated.

Although the refrigerated jacket is efficient in absorbing any heat input from the surroundings, the lack of air circulation within the enclosed space means that heat removal from the product is very limited. Care must therefore be taken to (1) attain the desired storage temperature throughout the product before storing, (2) minimise any heat loads produced during loading and unloading, and (3) provide the supplementary refrigeration required for any products which respire.

10.5 Conclusions

The rate of spoilage of meat depends upon the numbers and types of organisms initially present, the conditions of storage (temperature and gaseous atmosphere), and characteristics (pH, water activity a_w) of the meat. Temperature is by far the most important factor.

Spoilage is characterised by off-odours, slime formation and discolouration. The type of micro-organisms present defines the pattern of spoilage. The dominance, and thus type of spoilage, is dependent on the storage conditions (temperature and gaseous atmosphere).

In general spoilage occurs when the microbial population reaches *ca.* 7–8 log cfu cm⁻².

Those bacteria responsible for the spoilage of carcass meat grow most rapidly above 20°C. Any reduction below this temperature will extend the storage life. Broadly speaking bacterial growth will be half as fast at 5°C as at 10°C and half as fast again at 0°C, i.e. meat should keep roughly four times longer at 0°C than at 10°C.

Although a great deal has been written on the frozen storage life of different meats, the underlying data are backed up by a relatively small number of controlled scientific experiments. Most of the scientific data date back to the time when meat was either stored unwrapped or in wrapping materials that are no longer used. It is not surprising when we consider the changes in packaging and handling methods over the last century that there is a considerable scatter in data on storage lives for similar products.

In recent years energy conservation requirements have caused an increased interest in the possibility of using more efficient storage temperatures than have been used to date. Researchers such as Jul have questioned the wisdom of storage below -20°C and have asked whether there is any real economic advantage in very low temperature preservation. There is a growing realisation that storage lives of several foods can be less dependent on temperature than previously thought. Since research has shown that meat and poultry often produce non-linear time-temperature curves there is probably an optimum storage temperature for a particular product. Improved packing and preservation of products can also increase storage life and may allow higher storage temperatures to be used. One suggestion is that with storage at -18°C, low stability meats such as mechanically recovered meat should be stored for 8 months or less, medium stability meats such as pork and processed meats should be stored for between 8 and 15 months, and high stability meats, which include all meat and poultry except pork, could be stored for more than 15 months.

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11

Chilled and frozen retail display

In general, display cabinets have to accommodate three types of meat and meat products: (1) chilled wrapped, (2) chilled unwrapped and (3) frozen wrapped products. The required display life and consequent environmental conditions for wrapped chilled products differ from those for unwrapped products. The desired chilled display life for wrapped meat and meat products ranges from a few days to many weeks and is primarily limited by microbiological considerations. Retailers of unwrapped meat and delicatessen products, for example sliced meats and paté, normally require a display life of one working day. Frozen products can remain on display for many weeks.

11.1 Chilled display of wrapped meat and meat products

To achieve the display life of days to weeks required for wrapped chilled meat, the product should be maintained at a temperature as close to its initial freezing point, -1.5°C , as possible. To maintain product temperature in the range -1 – 0°C is the stated aim of at least one manufacturer of multi-deck display cases for wrapped meat (Brolls, 1986). Growth of *Salmonella* is prevented by temperatures below 7°C . Whilst growth of *Listeria monocytogenes* is slowed by refrigeration, it still multiplies very slowly even at 1°C unless the pH is below *ca.* 5.0. Consequently displaying meat at temperatures consistently in the -1 – 3°C range would substantially improve product safety.

Air movement and relative humidity (RH) have little effect on the display life of a wrapped product, but the degree of temperature control

can be important especially with transparent, controlled atmosphere packs. During any control cycle, the cabinet temperature rises, heat enters the pack, the atmosphere inside the pack warms with consequent reduction in relative humidity and increase in the surface temperature of the product. As the surface temperature rises so does its saturation vapour pressure (a factor controlling evaporation) and more water evaporates into the sealed atmosphere of the pack. If the cabinet temperature was stabilised then evaporation would continue until the atmosphere became saturated. However, in practice the cabinet air temperature cycles and as it is reduced the wrapping film is cooled. If it reaches a temperature below the dew point of the atmosphere inside the pack, then water vapour will condense on the inner surface of the pack. This film of water can obscure the product and consequently reduce consumer appeal. As the cycling process continues the appearance of the product deteriorates.

To maintain product temperatures close to 0°C, the air off the 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 will then rise to 10–12°C and the temperature of the product will rise by at least 3°C (Brolls, 1986). External factors such as the store ambient temperature, the siting 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 air flow 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 -8.0–14.0°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 owing to radiant heat pick up from store and cabinet lighting. It has also been stated that products in transparent film over-wrapped packs can achieve temperatures above that of the surrounding refrigerated air owing to radiant heat trapped in the package by the 'greenhouse' effect. However, specific investigations failed to demonstrate this effect (Gill, 1988).

11.1.1 Factors affecting display life

The display life of wrapped meat can be affected by the diet of the animal and the treatment of the meat before display. During display for 8 days at 4°C TBARS values were lower and Hunter 'a' values higher in pork chops from pigs fed with a high 100–200 mg α -tocopherol acetate per kilogram diet than those fed with 10 mg kg⁻¹ (Monahan *et al.*, 1994). Lipid oxidation and colour deterioration were also faster during display of chops that had

been previously frozen and thawed before display. Overageing of meat can limit its display life. Bell *et al.* (1996) found that hot-boned bull beef aged at 5°C for 6 days could only be displayed for 24 h at 5°C before it was unacceptable because of its dull dark lean tissue and grey to green discoloration of the fat. Similar meat that was unaged but also stored for 70 days at $-1.0 \pm 0.5^\circ\text{C}$ could be displayed for 48 h.

Retail display characteristics of steaks from hot-boned *logissimus dorsi* (LD) and *M. semimembranosus* (SM) muscles from electrically stimulated sides were found to be similar to those from cold-boned unstimulated sides (Griffin *et al.*, 1992). Whole muscles from both treatments were stored for up to 21 days before cutting into steaks. The colour of the lean from meat stored for 21 days was brighter than that stored for 7 or 14 days. Lean colour, fat colour and overall appearance scores all decreased with time over the 5 day display period.

Previous storage will reduce the display life of meat and it is better to store meat in large pieces. Meat that had been minced before storage lost its red colour more rapidly during display than that minced immediately before display (Madden and Moss, 1987). The addition of carbon dioxide (CO₂) prior to storage has a beneficial effect on colour and bacterial growth during display. Additions of 2–4 g of solid CO₂ per kilogram of meat resulted in growth of total viable bacterial counts similar to that of unstored controls. However, total anaerobic levels were much higher than controls.

Storing prepacked meat in a gas flushed 'mother' bag has been advocated as a method of extending the chilled storage life without reducing the retail display life of the packs. Scholtz *et al.* (1992) packed pork loin chops in individually overwrapped Styrofoam trays which were then bulk packed in vacuum bags which were subsequently inflated with 100% CO₂. After up to 21 days storage in the mother bags at 0°C the packs had a subsequent retail display life of 4 days. A retail display life of 4 days could only be attained after storage for 14 days in modified atmosphere packs or for 7 days in vacuum skin packs.

A display life of 6 days can be achieved in pork loin chops obtained from fresh pork loins and vacuum packed in high oxygen-barrier films (Vrana *et al.*, 1985). The chops were displayed at $2 \pm 2^\circ\text{C}$ for cycles of 14 h under an illumination of 1614 lux, followed by 10 h in the dark. Under similar conditions chops packed in high oxygen-permeable film had a display life of 4 days.

11.1.2 Layout of chilled cabinet

A typical cabinet has a refrigeration unit behind the display area. The chilled air from the refrigeration unit is blown by a fan and delivered to the relevant area by duct work behind the display area (Fig. 11.1). After the air has been delivered to the display area it is then drawn back into the duct through a grille and is refrigerated again to continue the cycle.

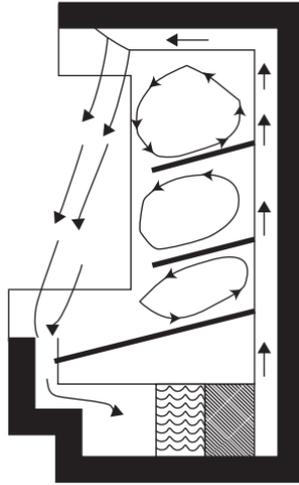


Fig. 11.1 Multi-deck display cabinet for wrapped products.

The duct provides two functions: (1) to provide cold air through the holes in the rear panel and (2) to provide an air curtain at the front of the cabinet. The holes in the rear panel direct chilled air over the food and the air curtain provides a thermal barrier between the chilled display area and the store.

A 'perfect' cabinet would have its chilled air form a closed cycle, much like a domestic refrigerator when the door is closed. In reality warm moist air from the surrounding store entrains with chilled air from the air curtain causing a loss of chilled air from the cabinet and a gain of warm air and moisture.

11.1.3 Air curtain

The air curtain differs from a solid door as it provides no physical barrier between customer and product, but is similar to a door in that it does provide a thermal barrier. The air curtain is a jet of chilled air of about 1 ms^{-1} that exits the duct at the top of the cabinet and falls down the face of the cabinet to the return grille. Owing to the fact that the temperature of the air from the air curtain is lower than the surrounding air, it is denser and therefore is aided by natural convection in its downward motion.

The air curtain is very sensitive and its effectiveness has other implications. An ineffective air curtain is likely to have the following effects:

- Increased temperature of product,
- Increased icing up and therefore more defrosts of the refrigeration coil,

- Increased energy consumption of the refrigeration compressor. About 60% of electricity consumed in modern supermarkets is used by display cabinets for frozen and chilled foodstuffs,
- Decreased temperature in the store next to the cabinet. This is described as the 'cold feet effect' and can lead to temperatures as low as 10°C in the centre of refrigerated aisles.

There are many variables affecting the efficiency of the air curtain, for example:

- The temperature difference between the chilled air and the store air,
- The velocity of the air curtain,
- The thickness of the air curtain,
- The pressures either side of the curtain,
- Obstructions in the path of the air curtain.

Some cabinets use a dual air curtain which has an extra jet of air parallel to the first jet but on the store side. This jet has the same velocity as the first jet but the air is not refrigerated as it is taken from the store and is therefore at store temperature.

The idea behind the dual air curtain is that there will be little entrainment between the two air jets as they are travelling at the same speed. Therefore there will be little heat gain through the barrier between the two air curtains. The entrainment will take place at the interface between the second curtain and the store, and because there is no temperature difference between this jet and the store there will be no heat infiltration.

One of the difficulties of dual air curtains is getting them to stay together all the way down the front of the cabinet. As the first curtain is chilled it will be forced downwards due to natural convection but this will not happen to the second curtain because it is not colder than the surroundings.

11.1.4 Cabinet development

Getting the air curtain to work properly is critical to the correct operation of the cabinet. Temperatures of the food simulants inside the cabinet can be monitored within specified store conditions to see if the cabinets meet the required specifications. British Standard methods of test for commercial refrigerated cabinets are contained in parts 1–8 of BS 6148 with part 3 covering the determination of temperature. The determinations are carried out in a controlled environment corresponding to the climatic class of interest. Temperatures are measured in M-packages, 50 × 100 × 100 mm packages of a meat simulant, positioned at defined positions in the cabinet. Set positions are 150 mm from the centre line and within 150 mm of one end with additional positions for large cabinets. The standard also states 'In addition to these M-packages, two extra M-packages shall be located within the useful net volume so that the maximum and minimum test package

temperatures will be recorded.' The difficulty of achieving this requirement has already been described in papers by Marriott (1992) and Gigiél and James (1992). These two papers also clearly reveal the need for test procedures that will relate to the likely performance of the cabinets within the retail environment.

When the products do not meet the required temperatures it is often the air curtain that is to blame. The air curtain is invisible and so it needs to be made visible to check that it is doing what is required.

Smoke is probably the most used method to view the air curtain. When smoke is blown into the air curtain it can be clearly seen. The cabinet can now be modified and its effect viewed using smoke.

11.1.5 Computer modelling

Developing a cabinet can be a very lengthy process. The cabinet temperatures are not steady with time, as the cabinet's coil ices up and then defrosts. Any movement in front of the cabinet will have an effect on the air curtain and product temperatures. Any changes made to the cabinet may not have an immediate effect on product temperatures, therefore a number of small changes to a display cabinet can be a time-consuming and costly process.

Computational fluid dynamics (CFD) is becoming widely accepted as a tool that can be used to aid development of display cabinets. CFD allows the user to make changes to a computer model of the cabinet and see its effect before changing the real thing. If computing resources allow it, a number of changes can be made to a computer model relatively quickly and the best case tried on a real cabinet.

CFD has been used to show the effect of removing shelves from a retail display cabinet (Foster, 1995). A two-dimensional model of a chilled cabinet was used to predict the effect of removing shelves from the cabinet (Fig. 11.2). The predictions showed that the refrigeration consumption was least (570 W per metre length of cabinet) when the case was fully loaded. As shelves were removed from either the top downwards or bottom upwards, the energy consumption increased to a maximum of 653 W m⁻¹ when all of the shelves were removed. CFD predictions of the cabinet with different configurations of shelving demonstrate that when shelves are removed, pressure differences between the cold cabinet and the store cause the air curtain to bend inwards. This causes more mixing between the cold and warm air, increasing product temperature, reducing store temperatures and increasing energy consumption.

11.1.6 Store conditions

One factor that can greatly effect the operation of a retail display cabinet is its positioning relative to the store's heating and ventilation system (Foster, 1997). Because of the cold feet effect, supermarket stores are keen

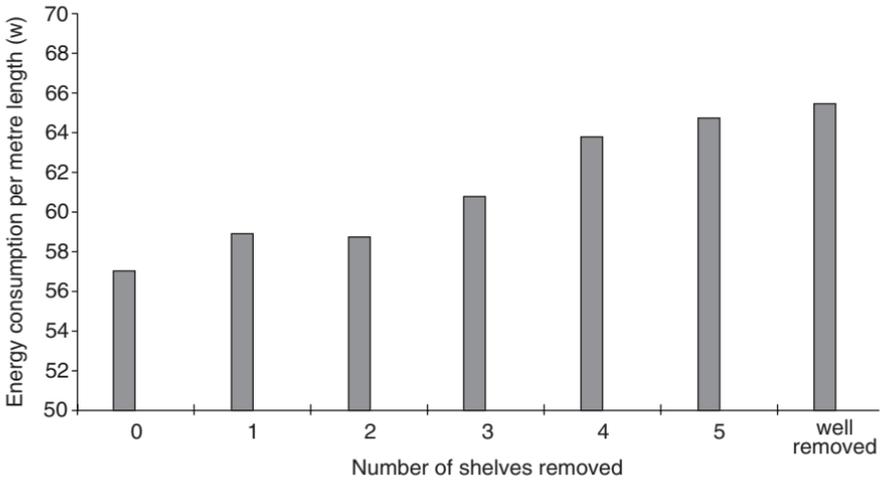


Fig. 11.2 Refrigeration load per metre length of cabinet as shelves are removed from the top downwards (source: Foster, 1997).

to put heat into the store near the cabinets. This has to be carefully controlled, as fast moving air near an air curtain will disrupt it. If the air is also warm it can greatly affect the temperature of the product inside.

11.2 Retail display of unwrapped meat and delicatessen products

The market for delicatessen meat products in the UK was estimated to be worth *ca.* £3 billion in 1992. The demand for delicatessen products has been influenced by a number of factors over the last few decades, ranging from demographic changes to membership of the European Union (MLC, 1992). The delicatessen market as a whole has benefited from the belief that delicatessen products are fresh and natural, and for their convenience, all of which make them attractive to the consumer.

It has been recognised for many years that temperatures close to the initial freezing point ($0 \pm 1.0^\circ\text{C}$) are required to provide a long display life for unwrapped meat. Studies have shown that control of relative humidity over the surface of sliced meats and other delicatessen products is critical if a high quality display life is to be achieved.

Surveys carried out in a number of EU countries revealed retail display cabinets to be the weakest link in the chill chain (Malton, 1972; Moerman, 1972; Bøgh-Sørensen, 1980; Lyons and Drew, 1985). Product temperatures in Denmark (Fig. 11.3) were very similar to those measured in Sweden and the UK. Poor temperature control, either in terms of a temperature

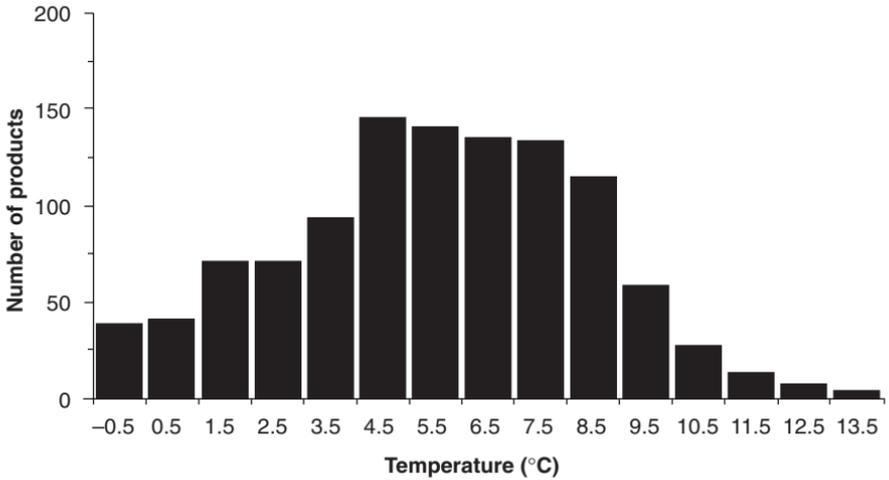


Fig. 11.3 Product temperatures in chilled display cabinets in Denmark (source: Bøgh-Sørensen, 1980).

gradient within a cabinet or due to fluctuations in temperature, is one of the problems when using retail display cabinets (James and Swain, 1986). Many practical problems associated with retail display of meat and meat products arise from failure to ensure that display cabinets are suitable for the product.

11.2.1 Types of cabinet

Considerable quantities of chilled unwrapped meat and sliced delicatessen products are now sold from refrigerated display cabinets of one type or another. Display cabinets for delicatessen products are available with gravity or forced convection coils and the glass fronts may be nearly vertical or angled up to 20 degrees. Sections through three of the commonest types of delicatessen cabinet are shown in Fig. 11.4. In the gravity cabinet (Fig. 11.4a), 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 the forced circulation cabinets (Fig. 11.4b and c), air is drawn through an evaporator coil by a fan. It is then ducted into the rear of the display, returning to the coil after passing directly over the products (Fig. 11.4b), or forming an air curtain (Fig. 11.4c), via a slot in the front of the cabinet and a duct under the display shelf (James, 1996).

11.2.2 Appearance changes

Changes in appearance are normally the criteria that limit display of unwrapped products rather than microbiological considerations. Deterio-

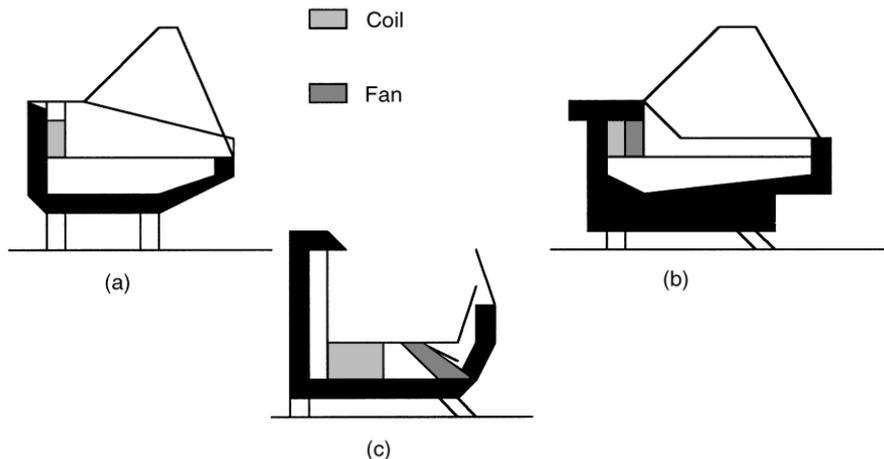


Fig. 11.4 Three types of retail display cabinet for unwrapped products.

Table 11.1 Relationship between evaporative weight loss and appearance of sliced beef topside after display for 6 h

| Evaporative loss (g cm^{-2}) | Change in appearance |
|---|---|
| up to 0.01 | Red, attractive and still wet; may lose some brightness |
| 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 |

Source: James and Swain, 1986.

ration in the appearance of unwrapped meats has been related to the degree of dehydration (Table 11.1), which makes the product unattractive to consumers (James and Swain, 1986). Weight loss on its own cannot only be a measure of performance but also has important economic considerations to the retailers. In the UK, the direct cost of evaporative weight loss from unwrapped products in chilled display cabinets was estimated to be in excess of 6.25 m euros per annum (James and Swain, 1986).

11.2.3 Effects of environmental conditions

The rate of dehydration is a function of the temperature, velocity and relative humidity of the air passing over the surface of the food. James and Swain (1986) found that changes in relative humidity had a substantial effect with a reduction from 95 to 40% causing increasing weight loss over a 6 h display period by a factor of between 14 and 18 (Fig. 11.5). The effect of air velocity on weight loss was compounded by that of relative

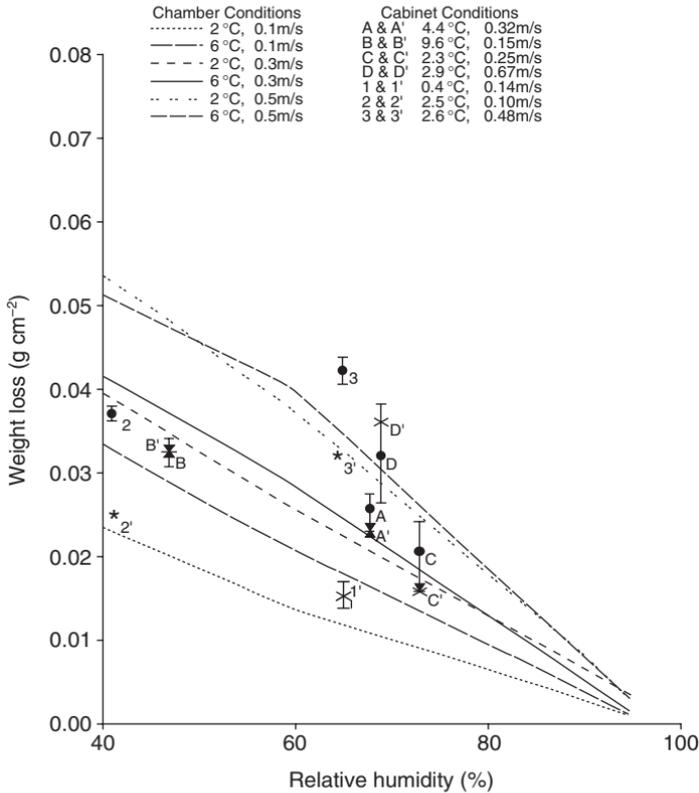


Fig. 11.5 Mean weight loss of samples of corned beef after display for 6 h at different relative humidities, air velocities and temperatures (source: James and Swain, 1986).

humidity. Raising the air velocity from 0.1 m s^{-1} to 0.5 m s^{-1} had little effect on the weight loss at 95% RH, however, the magnitude of the effect increased as relative humidity decreased producing maximum changes at 40% RH. When changing the temperature from 2 to 6 °C the effect on the weight loss was far smaller than the changes in relative humidity or air velocity.

In their mathematical prediction of weight loss, Fulton *et al.* (1987) and James *et al.* (1988a and b) showed that fluctuations in temperature or relative humidity had little effect on weight loss. The weight loss under fluctuating conditions was identical to that experienced under the mean of the fluctuations.

Evans and Russell (1994a, b) also showed that relative humidity was the main factor controlling weight loss in the display life of delicatessen products. At a relative humidity of 40% the effect of surface drying became apparent after *ca.* 100 min. At 85% RH the products could be displayed for

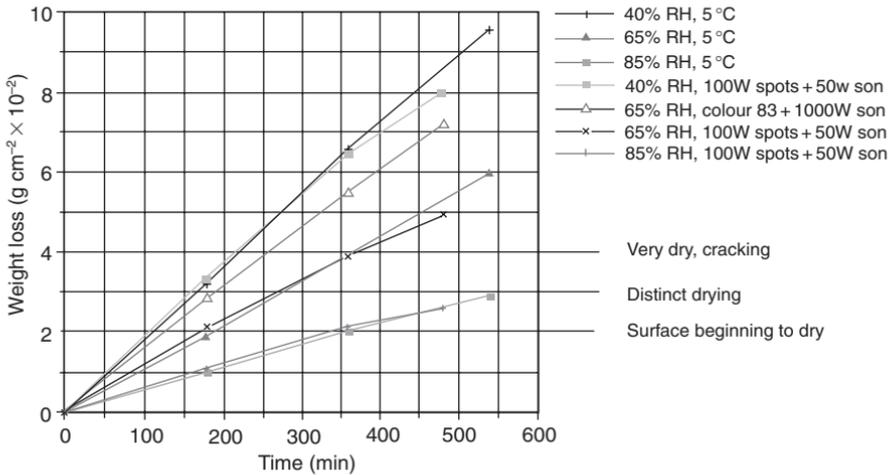


Fig. 11.6 Comparison of mean weight loss at different relative humidities and lighting regimes for delicatessen products (source: Evans and Russell, 1994).

between 4 to 6 h before surface drying could be noted. The overall weight loss at 40% RH was approximately 3 times that at a relative humidity of 85%.

In the same work Evans and Russell also found that changing the lighting combination of 50 W sons and 100 W halogen lights to 100 W sons and a colour 83 fluorescent significantly increased the weight loss. The increase was similar in magnitude to that produced by a 20% reduction in relative humidity. On average the rate of weight loss under the combination of 50 W sons and 100 W halogen (spot) lights was approximately 1.4 times less than the 100 W sons and colour 83 fluorescent lighting (Fig. 11.6).

11.3 Retail display of frozen wrapped meat

Frozen display of meat is part of the frozen chain that includes freezing, storage and transportation, retail display and finally domestic storage.

The purpose of retail display is to present the meat to the consumer in the most attractive way, whilst maintaining the quality of the frozen product. As long as the meat or meat product is maintained below -12°C its bacterial state will not deteriorate. Its taste, texture and appearance are the main quality factors that can deteriorate during frozen display.

11.3.1 Factors controlling display life

The many factors that control the display life of frozen meat start with the live animal and the treatment of the meat prior to freezing. During display,

temperature, temperature fluctuations and packaging are the main display parameters that control the quality factors.

11.3.1.1 Prefreezing treatments

Lanari *et al.* (1994) have shown that dietary vitamin E supplement fed to the live animal improved pigment and lipid stability of frozen beef stored under illumination and in the dark at -20°C . These results complemented their earlier publication (Lanari *et al.*, 1993) which showed that the colour of control samples of longissimus lumborum deteriorated in 1 day compared with 11 days for treated samples stored in the dark. Under an illumination of 1614 lux the treated samples deteriorated after 38 days. The advantages of using vitamin E supplementation in the extension of chilled and frozen storage life was reviewed by Liu *et al.* (1995).

Further studies (Lanari *et al.*, 1995) have shown that blooming time, the atmosphere used for blooming, vitamin E supplementation and illumination (1614 lux) all affect the colour display life of beef (Table 11.2).

11.3.1.2 Display temperature

The operating temperature of a retail display cabinet is a compromise between the operating economics, quality factors and legislation.

The Quick Frozen Foodstuff Regulations (1990) are fundamentally quality based and among the main provisions is temperature control of the product. Essentially a quick frozen product must be maintained at or colder than -18°C throughout the cold chain. The only exception is in retail cabi-

Table 11.2 Mean and 95% confidence interval (CI) of display life based on colour changes during frozen display

| | Gas | Bloom | Display life (days) | | | |
|--------------|----------------|-------|---------------------|---------|-------------|-------|
| | | | In Dark | | Illuminated | |
| | | | Mean | CI | Mean | CI |
| Control | Air | 1 | 62 | 56–68 | 0 | – |
| | | 6 | 79 | 73–85 | 0 | – |
| | | 48 | 0 | – | 1 | 0–2 |
| Control | O ₂ | 1 | 65 | 61–69 | 0 | – |
| | | 6 | 85 | 79–90 | 10 | 9–12 |
| | | 48 | 45 | 38–51 | 25 | 22–29 |
| E supplement | Air | 1 | 96 | 72–119 | 7 | 2–12 |
| | | 6 | 125 | 108–141 | 9 | 8–10 |
| | | 48 | 118 | 88–148 | 32 | 27–38 |
| E supplement | O ₂ | 1 | 83 | 75–91 | 15 | 12–17 |
| | | 6 | 182 | 157–206 | 21 | 18–23 |
| | | 48 | 212 | 181–243 | 73 | 68–78 |

Source: Lanari *et al.*, 1995.

nets where temperatures warmer than -18°C are tolerated, consistent with good storage practice but not warmer than -12°C . During testing, cabinets have to achieve slightly more stringent criteria. European retail cabinet standards (EN441-6:1994, in the above), state that using food simulant 'M' Packs, the highest temperature of the warmest M-package should be equal to or lower than -15°C . They also state that the lowest temperature of the warmest M-package should be equal to or lower than -18°C . No lowest temperature is quoted for the coldest package.

11.3.1.3 Temperature fluctuations

Temperature fluctuations can increase the rate of weight loss from meat. Cutting & Malton (1974) reported that a retail cabinet operating at -15°C produced greater product dehydration than another cabinet operating at -8°C . This was shown to be due to the much wider air temperature fluctuation in the -15°C cabinet, ranging from -5 to -21°C compared with $\pm 1.5^{\circ}\text{C}$ in the -8°C cabinet. Successive evaporation and condensation (as frost) caused by such a wide temperature differential resulted in exaggerated in-package dehydration.

However, it is not clear if temperature fluctuations actually reduce storage life. Gortner *et al.* (1948) found that fluctuations in temperature of pork between -17.8 and -6.7°C produced the effect of an average temperature of -12.2°C . They also suggested that exposure to temperatures warmer than -18°C rather than temperature fluctuations may be the major factor influencing quality deterioration.

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' heat sources change. 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 meat, allowing the ingress of any packaging gases into the meat. 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 .

11.3.1.4 Packaging material

All frozen meat and meat products are wrapped before they are placed in retail display. The principal reason for packaging meat during frozen storage is to minimise moisture loss. Moisture loss causes deleterious effects on the texture, flavour and colour of the meat. Molecular oxygen in contact with the meat surface produces metmyoglobin, an undesirable dark discolouration of the meat. This can be reduced by shrink-wrapping of packaging onto the surface.

In moisture-permeable packs, condensation onto the refrigeration coil in the cabinet reduces its effectiveness, by reducing the heat transfer rate and restricting the mass flow of air through the heat exchanger. In moisture-impermeable packs the overall weight of each pack remains the same, but they will suffer from frosting, reducing the visual appeal and possibly inducing a dry texture. The high reflectance of small ice crystals on the surface of frozen meats and on the packaging can make the meat appear unacceptably light in colour. The requirements for protection are to provide low permeability to oxygen and water, and a high resistance to tearing under impact and shear, to reduce the incidence of dehydration from the meat surface, which can lead to undesirable effects, such as freezer burn. Packaging can act to dampen the effects of external temperature fluctuations.

Lighting, especially ultraviolet, can also increase fat oxidation. The inclusion of an ultraviolet-light barrier in the packaging material significantly improved the colour stability of minced beef during frozen display at -18°C (Anderson *et al.*, 1989). The use of a barrier that excluded light below 350 nm would improve display at temperatures up to 5°C . Trials were conducted at FRPERC (Food Refrigeration and Process Engineering Research Centre, University of Bristol) to determine packaging characteristics to minimise the transmission of radiant energy. The results indicated that lighter colours, for example, yellow and white, absorbed less radiant heat (absorption values ranging from 0.12 to 0.21) and darker colours absorbed more radiant heat (values from 0.4 to 0.82). Shiny gloss surface finishes exhibited lower absorption values (0.15) in contrast to matt finishes (0.34). Under similar conditions the absorption coefficient of a dark matt material was 500% greater than a light coloured shiny material (615 compared with 105 W m^{-2}).

11.4 Overall cabinet design

There are a number of different types of display cabinet. Under the EU save programme 'Energy labeling of supermarket refrigerated cabinets', cabinets are categorised according to the service rendered to the user. Examples are shown in Fig. 11.7. The categories are:

- Open top/glass top well type – refrigerated display cabinet, open top, with products stored generally on one horizontal shelf. Chest type, no access to products all round the cabinet,
- Island site – refrigerated open top display cabinet with access to products all round,
- Multi-deck open fronted – refrigerated display cabinet incorporating a number of tiered shelves (graduated or horizontal) for the storage of food products, with open front access,

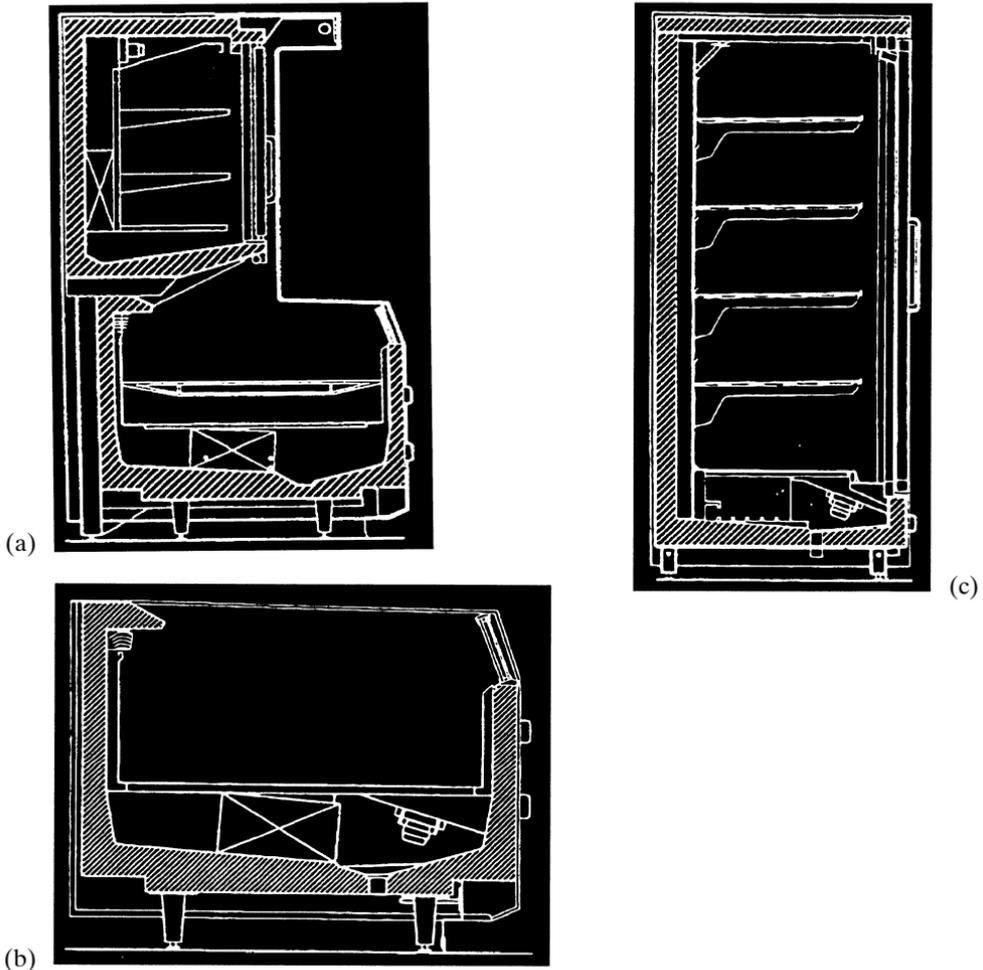


Fig. 11.7 Types of display cabinet. (a) Combined multi-deck glass fronted upper section connected to open top well-type. (b) Open top well-type and island site. (c) Multi-deck glass or open fronted.

- Multi-deck glass fronted – upright refrigerated display cabinet with a minimum of one glass wall (glass door cabinet).

11.4.1 Air circulation and temperatures

The air in a display cabinet gains heat from interaction with the warm ambient air and the product, which itself warms owing to radiant heat gain. Cabinets using natural convection to maintain product temperatures have

exposed coils at the front and the rear situated above the product loading level. This design produces recirculation from the sides to the centre of the cabinet, with the cooler air falling onto the product and rising as it absorbs energy, then being drawn back toward the heat exchanger. The air velocity is low ($<0.2 \text{ m s}^{-1}$) which is desirable to reduce interaction with the store ambient air, but is susceptible to external influence such as drafts and customer interaction. Supermarkets do not use cabinets that are cooled by convection solely, but make use of this by forcing recirculation of the chilled cabinet air behind metallic panels underneath the product which assist in maintaining product temperatures at the base and sides of the load.

The purpose of air flow over the products is to provide an effective barrier to warm ambient air and to provide limited heat extraction from the product surface. The major thrust in cabinet design has been to reduce the warming of the refrigerated air as it flows over the product. This has resulted in the development of devices for air movement to ensure a uniform distribution of air across the cabinet length. The most popular methods use axial or propeller fans. Variations in the velocity of the air 'curtain' will increase shear with ambient air and induce localised mixing. This is exaggerated by differences in product loading height, merchandising labels, restriction in air flow by icing and frosting of heat exchanger coils. Cabinets should be designed to use air flows as low as possible to maintain cabinet air temperatures at the desired levels. This will minimise ambient air mixing, ideally the air should 'roll' over the product, typically at velocities of 0.5 m s^{-1} .

The development of low radiant energy transmission glass and high insulation techniques has encouraged the adoption of more glass to increase product visibility. This has necessitated the use of antimist heating to keep the glass clear, which increases energy use, unless heat can be recovered from another part of system.

11.4.2 Effect of doors and lids

Cabinets are evaluated under ISO climate class conditions determined by the type of climate in which they are to be used. For example, for temperate climates the external conditions are 25°C and 60% RH, for tropical climates, 40°C and 40% RH. Blinds and lids have been shown to provide the greatest benefit to cabinets using natural convection. These are mostly applied out of retail hours, such as overnight. Results of trials comparing the refrigeration effect using different types of blinds indicated that the major difference was caused by the infiltration load, which is a function of the area of the front opening (caused by gaps at the side of blinds). Typically the blinds reduced the heat removed by the evaporator from 8.8 to 3.6 kWh.

The application of permanent doors or sliding lids provides significant benefits over open fronted or top cabinets, by maintaining the temperature

of the exposed product for longer periods, although in poorly performing cabinets, these will only extend the storage period and not maintain the desired temperature. Generally, over an 8 h test period with 12 s door openings every 10 min to simulate customer usage, only the exposed products experienced an increase in temperature, this being a function of the air velocity, temperature and distribution. Permanent or sliding doors also offer energy benefits, imposing a reduced load on the refrigeration system together with reduced infiltration of moist air which results in less frosting and icing on the coil, therefore maintaining the air distribution and imposing a lower defrost energy requirement.

11.4.3 Effect of radiant heat

The absorption of heat at the product surface of exposed packs results in localised warming of the product surface caused by the 'greenhouse effect'. A joint ECE/Codex Alimentarius group of experts agreed to accept a margin of 10 °C between the top layer of product and the air temperature in the cabinet to take into account exterior influences such as radiant heat. Therefore it is important not only to select packaging to minimise the transmission and absorption of radiant heat but to reduce its incidence on the product surface, from both cabinet and store lighting, as well as from solar radiation.

Temperatures within meat simulant packs should be measured both at the centre position and the surface. The surface location will provide an indication of the direct effect of external influences, such as defrosts and radiant heat during simulated retail conditions. The centre location is a measure of the average product temperature as the effect of external influences are modified by the thermal properties of the meat.

Cabinet air temperatures cannot therefore be used as an accurate representation of product temperature, as product surface temperatures can be warmer than the return air temperature.

11.4.4 Measurement methods

Continuous control and measurement of cabinet performance is related either to the temperature of the evaporative heat exchanger and/or the temperature of the air returning to the heat exchanger. A more sophisticated method is to produce a weighted average of the air off and air return temperatures, to simulate an average product temperature. A few systems also use a food simulant pack to monitor the centre product temperature. Owing to the reasons discussed earlier, none of these methods will quantify localised product warming. These current methods assume that the cabinet is operating effectively and research has shown that this is not necessarily the case.

Inexpensive methods of quantifying cabinet performance were

evaluated by FRPERC. The results indicated that thermochromic liquid display indicators (LCDs) could be used to indicate cabinet operational status, such as breakdowns in fan operation, defrosts and the subsequent recovery period (up to 22 min) and icing of the evaporator. Product overloading was detected by LCDs positioned on the merchandising strip on the front of the shelf or on the front Perspex riser of a well-type cabinet. However, LCDs could not be used as accurate indicators of product temperatures. Radiant heat levels measured at the exposed surface of the frozen meat were 22.6 W m^{-2} , provided by four fluorescent tubes (116 W). This level did not affect the temperature at which the colour transition occurred. The most rapid method of providing an indication of cabinet performance is to use infrared spectroscopy to scan product surfaces for localised hot spots. These measurements should be confirmed with single point thermocouples connected to hand-held digital thermometers.

11.5 Conclusions

The performance requirements and specifications of a cabinet need to be defined in advance, to determine the cabinet's fitness for purpose. These include the maximum quantity of meat to be displayed, meat packaging, loading pattern and temperature on loading. Environmental conditions such as climate class, radiant heat and proximity to draughts also need to be taken into account. This information allows manufacturers and retailers to evaluate the performance of the cabinets under representative conditions.

In general:

- 1 It is essential to maintain relative humidity in display cabinets of at least 85% or above to achieve display periods for unwrapped meat and meat products of 6–9 h.
- 2 Types of lighting are also an important point to be considered with lower heat output lighting producing lower weight losses. Certain delicatessen products are particularly sensitive to radiant heat gains from illumination and therefore it is essential to evaluate each product individually in order to determine the ideal display conditions.

Recent developments in commercial retail cabinets have been concentrated in two main areas:

- 1 The application of new refrigeration techniques to produce more energy efficient, environmentally friendly and reliable systems: this has been investigated using secondary refrigerants, eutectic plates and air cycle refrigeration using direct injection of refrigerated air, obviating the need for fans.
- 2 Improving the operational effectiveness by reducing the refrigeration

load: this can be achieved by improving the air distribution and minimising the interaction and infiltration of the ambient air. Reducing radiant heat gain using optical fibres, low energy bulbs and modified packaging, and the application of physical barriers including doors and lids will also reduce heat gains.

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Consumer handling

Since the mid-1980s there has been a considerable increase in legislation defining maximum temperatures during the production, distribution and retailing of chilled food. However, as soon as the food is purchased by the consumer, it is outside of any of these legislative requirements. Increasingly food poisoning incidents have been found to be due to mishandling of food in the home with insufficient refrigeration or cooling being the most frequent factor causing disease (WHO, 1992). Of the 1562 cases of food poisoning reported during 1986–1988, 970 (62%) were caused in the home. Consumer handling of products may not be as intended or envisaged by the manufacturer. Many chilled products are purchased on the basis of the ‘fresh image’, but then frozen at home (Brown, 1992).

After a chilled or frozen product is removed from a retail display cabinet it is outside a refrigerated environment whilst it is carried around the store and then transported home for further storage. In the home it may be left in ambient conditions or stored in the refrigerator/freezer until required. There are few published data on consumers’ attitudes to chilled food and their handling procedures in the home. The majority of the data quoted here have been obtained from a survey of 252 households which was funded by the Ministry of Agriculture Fisheries and Food (MAFF) in the UK (Evans *et al.*, 1991). As part of the survey, participants were asked questions to assess their attitude to food poisoning, shopping habits and the length of time they stored chilled foods in the home. Monitoring was then carried out to determine the length of time and temperature foods were stored at in the home. These data were augmented with experimental data from laboratory studies on the performance of refrigerators and temperature changes during transportation to the home.

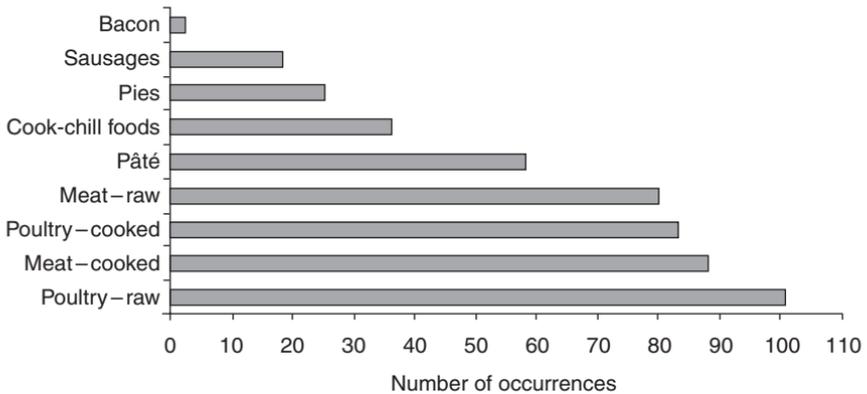


Fig. 12.1 Meat products considered a food poisoning risk (source: Evans *et al.*, 1991).

12.1 Consumer attitudes to food poisoning

In the survey consumers were initially asked about their concern about food poisoning. The greatest number of participants (56.7%) were either only slightly concerned or not at all concerned about food poisoning. However, 31.7% of participants were concerned or very concerned about food poisoning (answers were restricted to concern about food from shops and did not include concern about food poisoning due to restaurant or fast food-type meals or food).

When asked to name foods that they considered might constitute a food poisoning risk most of the respondents (73%) considered poultry to be a problem. Raw poultry was considered to be a greater risk than cooked poultry. Meat was also considered likely to cause food poisoning with 66.7% of participants mentioning either raw or cooked meat as a potential problem (Fig. 12.1).

12.2 Shopping habits and transport from retail store to the home

The frequency of shopping governs the length of time chilled food is stored in the home. Most consumers, 99.2% of the survey population, shopped on at least one day a week and few (16.3%) less than twice a week for chilled food. The greatest number (33.7%) shopped for food 3–4 days per week, closely followed by 26.2% who shopped 5–7 days per week and 23.8% who shopped on two days. Generally shopping was divided into trips for large quantities (defined as greater than one bag) and small amounts of food (less than one bag). The majority of households (84.5%) shopped for small quantities of chilled food on a variable basis, as required.

Most participants in the survey carried out their main shopping between 1 and 5 miles from their homes and few householders travelled more than 5 miles to shop. Most people (85.3%) used a car to transport their main shopping home. Small quantities of food were generally bought close to the home, reflecting the availability of shops in the towns surveyed. Most householders (87.6%) who bought small quantities of food transported it home either on foot or by car.

Unprotected chilled food will warm up during transportation. Survey results showed that consumers took on average 43 min to bring meat, fish or dairy items home from the shops and place them in a refrigerator. The greatest number of items were transported home and placed in a refrigerator within 13 min. Although most people bought food home well within 60 min there were a number of items which took far longer to be bought home (up to 2 days) and placed in a refrigerator.

Although insulated bags and boxes are widely sold, only a small percentage of consumers (12.7%) used them to transport some of their food home. The vast majority (87.3%) of people did not use any means of protecting food from temperature gain during transportation.

Increases in product temperatures during transportation can be considerable. In investigations, the temperatures of 19 different types of chilled product (including a variety of meat products) were monitored during a simulated journey from the supermarket to home (James and Evans, 1992a). One sample of each product was placed in a precooled insulated box containing eutectic ice packs and the second left loose in the boot of the car. The car was then driven home and the product removed and placed in a domestic refrigerator after a total journey time of 1 h.

Additional investigations looked at 9 types of frozen product, including frozen chicken, meat pie, lasagne and pizza (Evans, 1994). Products were purchased and transported to the Research Centre where the products were tempered and temperature sensors inserted into the geometric centre of each food and where possible a second sensor inserted just below the surface of the sample. The products were then refrozen to a temperature of *ca.* -25°C and then transferred to a car where the above procedure was repeated. After a journey time of 1 h the products were placed in the freezer section of a domestic refrigerator. The ambient temperature during both journeys ranged from 23 to 27°C .

Initial product temperatures of the chilled meats measured when the food reached the car ranged from 4°C to over 20°C (Table 12.1). Some of the meat product temperatures in samples placed in the boot rose to around 30°C during the 1 h car journey whilst most of the samples placed in the insulated box cooled during the car journey except for a few at the top of the box which remained at their initial temperature.

Product temperatures in the frozen foods were close to -25°C when placed in the car. Temperatures of products placed in both the cold box and at ambient temperature rose during the 1 h journey. Temperatures of

Table 12.1 Maximum temperatures ($^{\circ}\text{C}$) measured in meat products after being transported for 1 h in the boot of a car without protection or within a cooled insulated container

| Product | Unprotected | Cool box |
|---------------|-------------|----------|
| Minced beef | 18 | 9 |
| Sausage (raw) | 28 | 15 |
| Smoked ham | 30 | 14 |
| Beef pie | 24 | 7 |
| Sausage roll | 28 | 12 |
| Lasagne | 21 | 6 |

Source: Evans *et al.*, 1991.

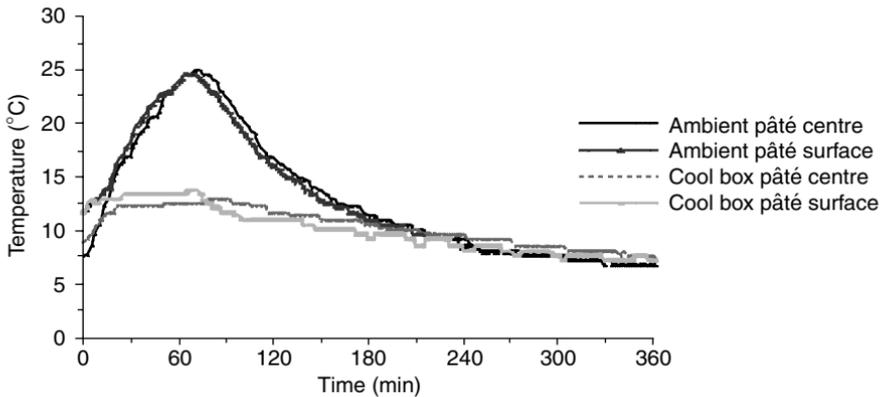


Fig. 12.2 Temperature changes in pâté during domestic transportation (source: Evans *et al.*, 1991).

chickens and meat pies placed at ambient temperature reached temperatures approaching 10°C . Frozen meat products in the cold box kept below -10°C for the period of the journey.

Thin sliced chilled products showed the highest temperature changes during transport, whereas temperature gains in thicker products such as chicken and pâté (Fig. 12.2) were smaller. A similar trend was seen with the frozen products. After being placed in the domestic refrigerator, 'warm' chilled products required *ca.* 5 h before the temperature at the surface was reduced below 7°C . 'Warm' frozen products placed in a domestic freezer required at least 5 h to reduce centre product temperatures to below -15°C .

Predictions made using a mathematical model that calculated bacterial growth from temperature/time relationships indicated that increases of up to 1.8 generations in bacterial numbers (Table 12.2) could occur in the chilled foods during this transport and domestic cooling phase. The model assumed that bacteria required a time to acclimatise to the change in temperature (the lag phase) and that no acclimatisation had occurred during

Table 12.2 Maximum temperature measured and increase in bacterial numbers in chilled foods during 1 h in car followed by 5 h in a domestic refrigerator

| Product | Conditions | Maximum temperature (°C) | <i>Pseudomonas</i> (generations) | <i>Clostridium</i> (generations) |
|------------------|---------------|--------------------------|----------------------------------|----------------------------------|
| Pâté | Ambient, car | 25 | 1.5 | 0.4 |
| | Cool box, car | 13 | <0.4 | 0.0 |
| Chicken – raw | Ambient, car | 24 | 1.6 | 0.2 |
| | Cool box, car | 4 | 0.0 | 0.0 |
| Chicken – cooked | Ambient, car | 28 | 1.8 | 0.7 |
| | Cool box, car | 12 | 0.0 | 0.0 |
| Prawns | Ambient, car | 37 | 1.3 | 1.6 |
| | Cool box, car | 14 | 0.0 | 0.0 |

Source: Evans *et al.*, 1991.

display. If this rather optimistic assumption was not made then up to 4.2 doublings of *pseudomonas* and growth of both *salmonella* and *listeria* were predicted. Only very small increases in bacterial numbers (<0.4 generations) were predicted in products transported in the insulated box, owing to the maintenance of lower product temperatures. Although it was unable to prevent bacterial growth, the cold box did ensure that bacterial growth was minimal and was substantially less than if transported in ambient conditions.

12.3 Refrigerated storage in the home

The length of time consumers store chilled foods after purchase will affect their safety. In the survey consumers thought that the majority of meat and meat products (raw meat, cooked meat, raw poultry, cooked poultry, prepared meals, pizza/quiche, cold pies and sausages) would store well for 2 days. However, a number of people considered that these foods could be stored for more than 7 days and sometimes as long as 30 days. Most participants thought that products such as bacon and pâté could be stored for up to a week, although a few people considered that storage of up to 30 days was acceptable. Fresh fish was generally considered to store less well, with most participants stating that they would only store fish for 1 day or less.

The range in anticipated storage life for different food types varied considerably. Opinions on the storage lives of individual foods ranged from 0.5 to 7 days (range 6.5 days) for cold pies and sausages to between 0.5 to 30 days (range 29.5 days) for pâté and bacon. The minimum storage life for all meats and meat products was either a quarter or half a day. A small number of householders thought that they could store chilled foods for periods of up to 30 days. Bacon and pâté were both thought to be acceptable after this

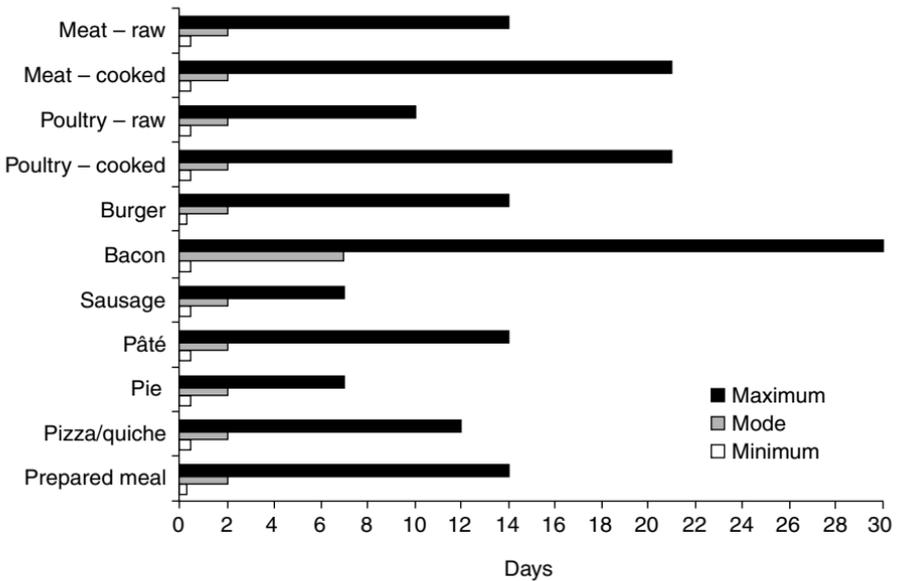


Fig. 12.3 Minimum, modal and maximum storage lives of chilled meat and meat products stated by householders (source: Evans *et al.*, 1991).

period by a small proportion of participants. Cooked meat and poultry were also thought to store for up to 21 days by a few householders (Fig. 12.3).

It was interesting to note that although poultry and meat were considered a likely cause of food poisoning, participants did not necessarily consider that these foods had short storage lives. It is therefore possible that people do not associate storage time as being related to any food poisoning problem.

Consumers do not always 'practice what they preach'. When the food stored in consumers' refrigerators was examined, actual storage times were generally greater than storage times stated in the questionnaire. Almost 67% of the food was kept for longer periods. Actual storage times were greater than the stated storage time for all meat, fish and dairy items except pies which were thought to have an acceptable storage life of 3.3 days and were stored for 3.2 days (Table 12.3).

12.4 Temperatures in domestic food storage

The refrigerator is a common household device and very few households in the UK do not own a refrigerator or fridge-freezer for storage of chilled foods. Fridge-freezers have become increasingly popular in the last 20 years in the UK and now provide almost 50% of the market (Anon, 1990). These

Table 12.3 Mean actual and perceived storage life

| Food | Actual mean storage life (days) | Perceived mean storage life (days) |
|------------------|---------------------------------|------------------------------------|
| Meat – raw | 3.9 | 2.4 |
| Meat – cooked | 5.4 | 4.5 |
| Poultry – raw | 3.3 | 2.5 |
| Poultry – cooked | 3.9 | 2.4 |
| Bacon | 8.2 | 6.6 |
| Sausages | 5.6 | 4.1 |
| Paté | 10.3 | 4.1 |
| Pies | 3.2 | 3.3 |

Source: Evans *et al.*, 1991.

figures were almost replicated in the survey where only 3 of the households did not own a working refrigerator and 49.4% owned a fridge-freezer. Almost 32% owned an ice box type refrigerator and the rest larger refrigerators.

The temperature at which a refrigerator operates is critical for the safe storage of chilled food. Recommendations concerning the microbiological safety of foods advise that maximum temperatures in domestic refrigerators should not exceed 5°C (Richmond, 1991).

Consumers in the survey were therefore asked what temperature they tried to operate their refrigerator. Nearly all participants were unable to name actual temperatures and gave answers based on the method they used to set the temperature dial (Fig. 12.4). A large number of people (32.8%) set their refrigerators according to the weather, setting the refrigerator to a lower temperature (higher setting) in the summer. It was interesting to note that although 38 participants had a thermometer in their refrigerator only 30 actually used the information to set their refrigerator temperature.

To evaluate temperatures within each refrigerator, a miniature data logger with 3 air and 2 product sensors was placed into the refrigerator to monitor temperatures every 8s and to record mean temperatures every 5min for a period in excess of 7 days. Air temperature sensors were positioned in the top, middle and bottom sections of the refrigerator and a simulated food product (87mm diameter by 28mm high disc of 'Tylose', a food substitute, in a petri dish) placed on the middle shelf. Sensors were placed in the geometric centre and centrally on the surface of the Tylose disc (Fig. 12.5).

Results showed that the mean temperature over 7 days (evaluated from top, middle and bottom sensors) ranged from -1 to 11°C. The overall mean air temperature for all the refrigerators in the survey was 6°C, with 70% of refrigerators operating at average temperatures above 5°C (Fig. 12.6). An investigation carried out in Northern Ireland found similar results with 71% of refrigerators having a mean internal temperature above 5°C (Flynn

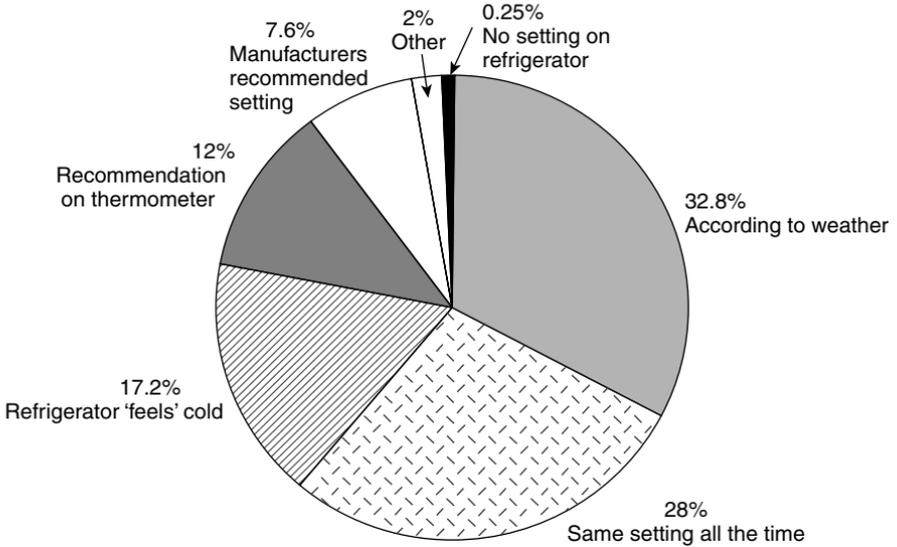


Fig. 12.4 Methods used to set refrigerator temperature (source: Evans *et al.*, 1991).

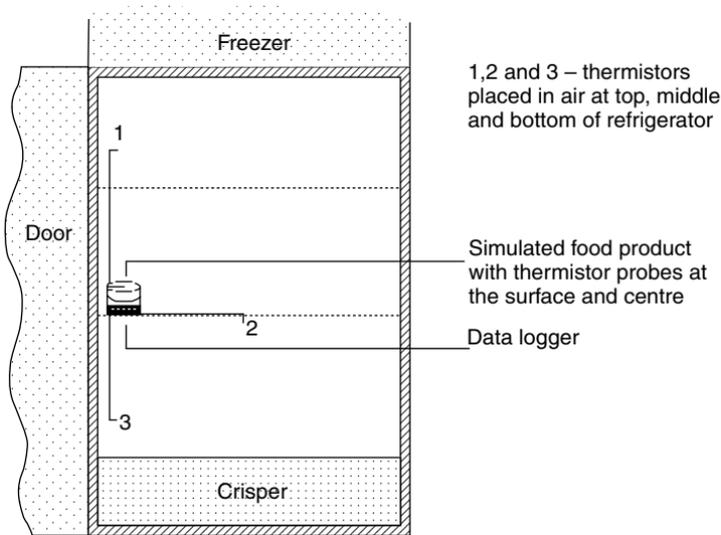


Fig. 12.5 Position of miniature data logger and sensors within refrigerator (source: Evans *et al.*, 1991).

et al., 1992). A US study of food discard patterns and reasons found 21% of refrigerators were at or above 10°C (Van Garde and Woodburne, 1987).

An analysis of percentage time spent between certain temperatures, calculated for all refrigerators, showed that the greatest proportion of time

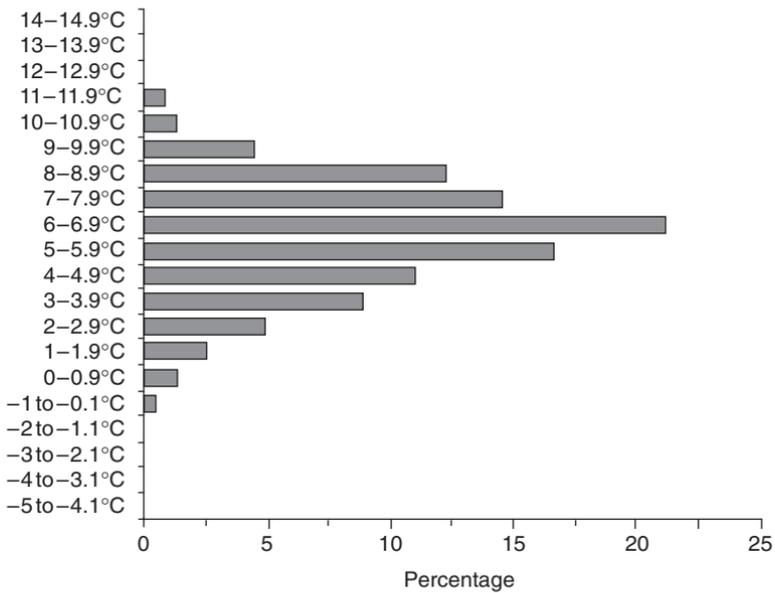


Fig. 12.6 Overall mean temperatures for all refrigerators in survey (source: Evans *et al.*, 1991).

Table 12.4 Position of highest temperature within refrigerators investigated

| Position | % of refrigerators | |
|----------|-------------------------------|------------------------------|
| | Highest mean temperature (°C) | Lowest mean temperature (°C) |
| Top | 69.9 | 20.3 |
| Middle | 8.1 | 45.1 |
| Bottom | 22.0 | 34.6 |

Source: Evans *et al.*, 1991.

(80.3%) was spent between 3 and 8.9°C. Only small amounts of time were spent above 9°C (Fig. 12.7). However, only 4 refrigerators (1.6%) in the whole survey operated below 5°C during all the monitoring period and 33.3% of refrigerators spent all their time above 5°C.

A further analysis showed that in 69.9% of refrigerators the warmest place was in the top and in 45.1% the coolest place was in the middle (Table 12.4). However, the top of the refrigerator was not always the warmest and the bottom was not always the coldest place (Table 12.5, Fig. 12.8).

The mean temperature range within a refrigerator was found to vary between refrigerator types. Ice box refrigerators had the smallest range

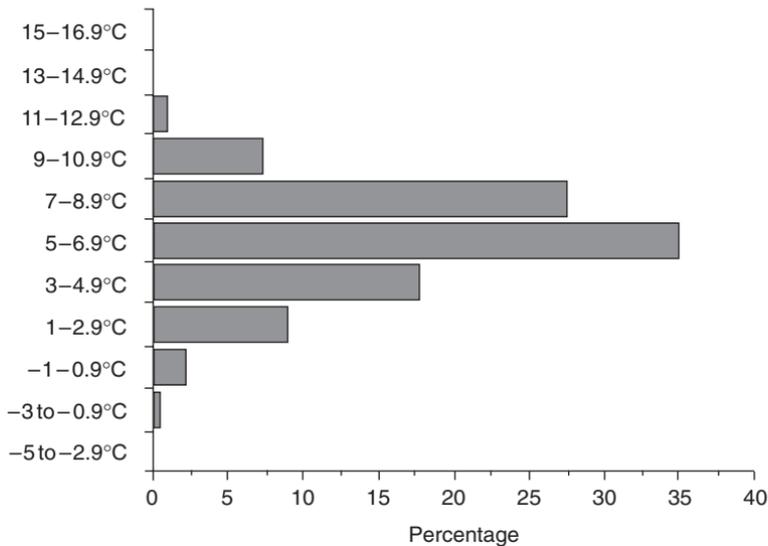


Fig. 12.7 Frequency distribution of temperatures in all refrigerators (source: Evans *et al.*, 1991).

Table 12.5 Positions of lowest and highest mean temperatures in refrigerators investigated

| Refrigerator type | % of lowest mean temperatures in: | | | % of highest mean temperatures in: | | |
|-------------------|-----------------------------------|--------|--------|------------------------------------|--------|--------|
| | Top | Middle | Bottom | Top | Middle | Bottom |
| Ice box | 48.1 | 41.6 | 10.4 | 28.6 | 11.7 | 59.7 |
| Fridge-freezer | 10.6 | 45.5 | 43.9 | 84.6 | 8.9 | 6.5 |
| Larder | 0.0 | 50.0 | 50.0 | 100.0 | 0.0 | 0.0 |

Source: Evans *et al.*, 1991.

(average 1.8°C), whereas the range in temperature in fridge-freezers and larder refrigerators was nearly twice as great (average of 3.4°C in fridge-freezers and 3.7°C in larder refrigerators) (Table 12.6, Fig. 12.9). A survey carried out in China found higher ranges in temperature within domestic refrigerators with only 2.3% of the refrigerators surveyed operating with a temperature range of less than 6°C: 34.1% had differences of 8–12°C, 34.1% in the range of 12–14°C and 29.5% differences greater than 14°C (Shixiong and Jing, 1990).

The time for storage of frozen foods in the UK is based on the star-rating system (Table 12.7). This was introduced in the early 1960s relating equipment capability with frozen food keeping quality (Ware, 1974; Sanderson-Walker, 1979).

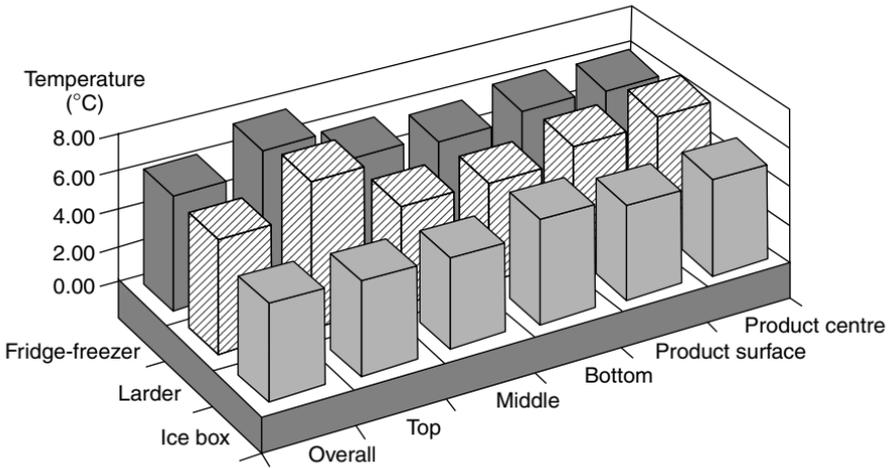


Fig. 12.8 Mean temperatures within refrigerator types investigated (source: Evans *et al.*, 1991).

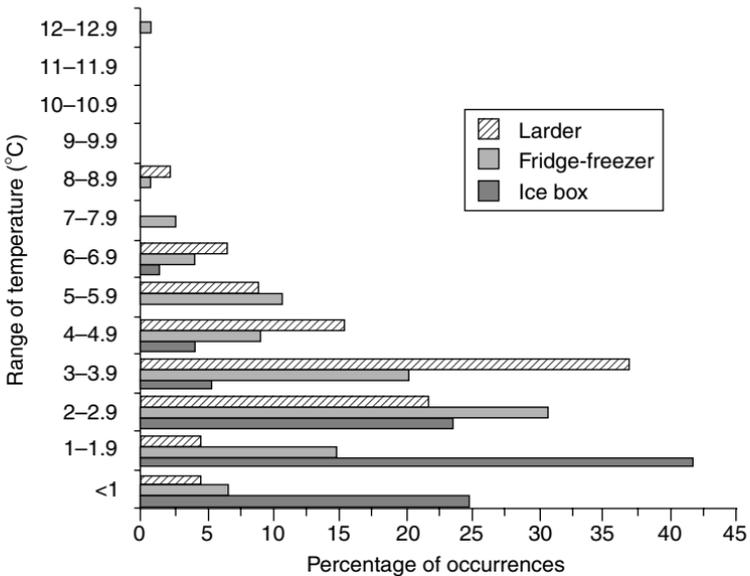


Fig. 12.9 Range of mean temperature distribution within refrigerator types investigated (source: Evans *et al.*, 1991).

The advantages of the star-rating system (Sanderson-Walker, 1979) are that (1) it is a simple and easily understood method of giving consumers some indication of recommended storage time at home; (2) it is supported by the equipment manufacturers (who indicate the performance of their

Table 12.6 Temperature range in refrigerator types investigated

| Range in temperature (°C) | Ice box | Fridge-freezer | Larder |
|---------------------------|---------|----------------|--------|
| Minimum temp range | 0.2 | 0.1 | 0.5 |
| Maximum temp range | 7.0 | 12.04 | 9.0 |
| Mean temp range | 1.8 | 3.4 | 3.7 |

Source: Evans *et al.*, 1991.

Table 12.7 Star-rating system

| | Storage temperature | Storage time | Capability of equipment |
|------|------------------------|----------------|---|
| ★ | Not warmer than -6 °C | Up to 1 week | Storage only |
| ★★ | Not warmer than -12 °C | Up to 1 month | Storage only |
| ★★★ | Not warmer than -18 °C | Up to 3 months | Storage only |
| ★★★★ | Not warmer than -18 °C | Up to 3 months | Can freeze down fresh food from room temperature to -18 °C as well as store |

Source: Evans *et al.*, 1991.

appliances using the star-rating) and frozen food manufacturers (who indicate storage times using the star-rating on their packets).

However, few data have been published on temperatures and actual consumer use of domestic freezers.

12.5 Performance testing of domestic refrigerators

After purchase, chilled food can spend a period of between a few hours and many weeks in a domestic refrigerator. However, few data have been published on the temperature performance of domestic refrigerators either under controlled conditions or in use. Data can be found on energy consumption (Dlugoszewski and Minczewski, 1984), evaporator coil design (Karpinski, 1984), and the shelf-life advantages to be gained with product stored in a special refrigerator containing a 0 °C chamber with fan air circulation (Olsson, 1988). Current standards for domestic refrigerators contain some temperature tests that are carried out under controlled conditions on empty, closed refrigerators. In domestic use, refrigerator doors are opened regularly, are not usually empty but range from near empty to crammed full, and often food at ambient temperature, or above, is placed in them.

Some data have been published from experiments carried out on examples of 3 types of refrigerator (James *et al.*, 1989; James and Evans, 1992b). These were a 6 cubic foot dual compressor fridge-freezer (no.1), a 6 cubic foot single compressor fridge-freezer (no.2) and a 4 cubic foot free standing domestic refrigerator with an ice box compartment (no.3).

12.5.1 Performance of empty appliances

When set to the manufacturers recommended setting, temperatures in the ice box refrigerator (no.3) were uniform and low with a minimum of -1.4°C on the bottom shelf and a maximum of 5.9°C in the door. Average temperatures were between *ca.* 0.5 and 1.5°C on the shelves and just above 3°C in the door with a cycle of less than 0.5°C . There was a much larger temperature range in the two fridge-freezers, 1.7 – 14.3°C in no.1 and -6.7 to 10.7°C in no.2. Average temperatures were far less uniform in the chilled food compartment of the fridge-freezers. In fridge-freezer no.1 the average temperature of the top shelf was up to 5°C higher than that measured on the middle shelf which was the coolest area in the appliance. Highest average temperatures of *ca.* 7.5 and 10°C were measured on the top shelves of the fridge-freezers. In fridge-freezer no.2 the average temperature on the bottom shelf reached -2°C at the minimum point in the temperature cycle.

12.5.2 Performance of loaded appliances

Loading 12 packs (dimensions $100 \times 150 \times 25$ mm) of Tylose (a simulated food) that had been precooled to 5°C into the ice box refrigerator reduced the mean temperatures by between 1.2 and 2.0°C (Table 12.8). The temperature change caused by loading was similar in magnitude in fridge-freezer no.2 where the mean temperature of the top shelf rose by 0.7°C and the mean at other positions dropped by between 0.5 and 1.1°C . It was also noted that the length of the refrigeration cycle increased from *ca.* 0.75 to 1 h. In fridge-freezer no.1 the magnitude of the temperature cycle was substantially reduced. The magnitude and position of the maximum

Table 12.8 Maximum, minimum and mean temperatures on shelves and in door of refrigerators

| Position | | Ice box | | Fridge-freezer no. 1 | | Fridge-freezer no. 2 | |
|--------------|---------|---------|--------|----------------------|--------|----------------------|--------|
| | | Empty | Loaded | Empty | Loaded | Empty | Loaded |
| Top shelf | Maximum | 2.1 | 1.2 | 14.3 | 6.0 | 10.7 | 11.1 |
| | Minimum | 0.7 | -1.2 | 6.6 | 2.4 | 4.7 | 5.2 |
| | Mean | 1.5 | 0.3 | 10.2 | 3.8 | 7.3 | 8.0 |
| Middle shelf | Maximum | 2.2 | 0.4 | 8.0 | 6.9 | 5.4 | 4.9 |
| | Minimum | -1.0 | -2.6 | 1.7 | 4.3 | 0.9 | -0.1 |
| | Mean | 1.4 | -0.6 | 6.3 | 5.5 | 3.6 | 2.9 |
| Bottom shelf | Maximum | 1.6 | 4.0 | 8.0 | 9.8 | 5.0 | 3.7 |
| | Minimum | -1.4 | -3.0 | 2.4 | 5.7 | -6.7 | -5.8 |
| | Mean | 0.7 | -0.6 | 6.7 | 8.1 | 2.1 | 1.0 |
| Door | Maximum | 5.9 | 3.3 | 8.0 | 8.4 | 6.5 | 6.7 |
| | Minimum | 0.9 | -0.4 | 5.3 | 0.8 | 2.2 | 0.5 |
| | Mean | 3.2 | 2.0 | 6.9 | 3.8 | 4.2 | 3.7 |

Table 12.9 Time taken (h) to cool products from 20 to 7°C

| | Ice box | Fridge-freezer |
|-------------------|---------|----------------|
| Surface drumstick | 2.2 | 5.3–8.6 |
| Deep drumstick | 2.5 | 5.4–8.6 |
| Surface portion | 2.2 | 5.1–7.5 |
| Deep portion | 3.4 | 5.9–8.0 |

Source: Evans *et al.*, 1991.

temperature was also influenced by loading, from a value of 14.3°C and located on the top shelf, to a reduced value of 9.8°C and a location on the bottom shelf.

12.5.3 Effect of loading with warm (20°C) food products

Food is often loaded 'warm' into refrigerators after purchase from retail stores. Loading a small amount of warm (20°C) food, (2 joints (*ca.* 17.5 × 7.6 × 3.6 cm, 195 ± 10 g) and 2 drumsticks (*ca.* 12 × 6 × 3 cm, 120 ± 10 g)) of simulated chicken (Tylose) showed up the poor cooling performance of domestic refrigerators.

Over 2 h was required in the ice box refrigerator to reduce the surface temperature of the drumsticks and portions to 7°C compared with over 5 h in the fridge freezer (Table 12.9). Drumsticks in the domestic refrigerator always cooled faster than the larger portions. However, in the fridge-freezer, portions on the middle shelf cooled faster than drumsticks positioned on the top shelf.

12.5.4 Effect of door openings

In normal operation refrigerator doors are opened and left open for different periods while food is loaded and unloaded. In the ice-box refrigerator single door opening of either 3 or 6 min was compared with 3 or 6 1 min openings over a 1 h period.

Immediately after a 3 min door opening the average air temperatures ranged between 5.5 and 16°C compared with 0–2°C before the opening (Fig. 12.10). Within *ca.* 1 h of the door being closed the average temperatures had been reduced to within 1°C of their normal value.

With 3 1 min door openings the average temperatures tended to increase progressively with each subsequent opening and the degree of temperature recovery reduced (Fig. 12.11).

After a single 6 min door opening the average air temperature rose to between 7.5 and 16.5°C (Fig. 12.12). The air temperature slowly recovered over the next 2 h.

After each of 6 successive 1 min door openings the air temperature was warmer and the temperature after 9 min of recovery higher (Fig. 12.13).

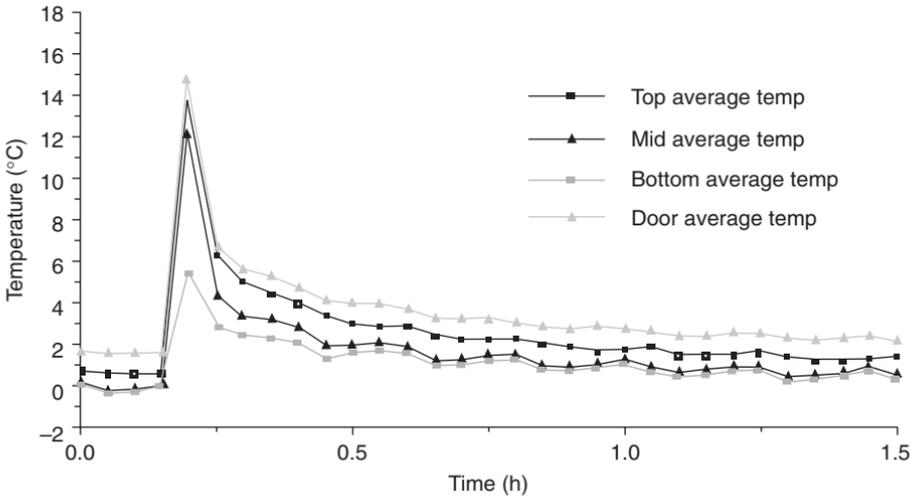


Fig. 12.10 Three min door opening (source: Evans *et al.*, 1991).

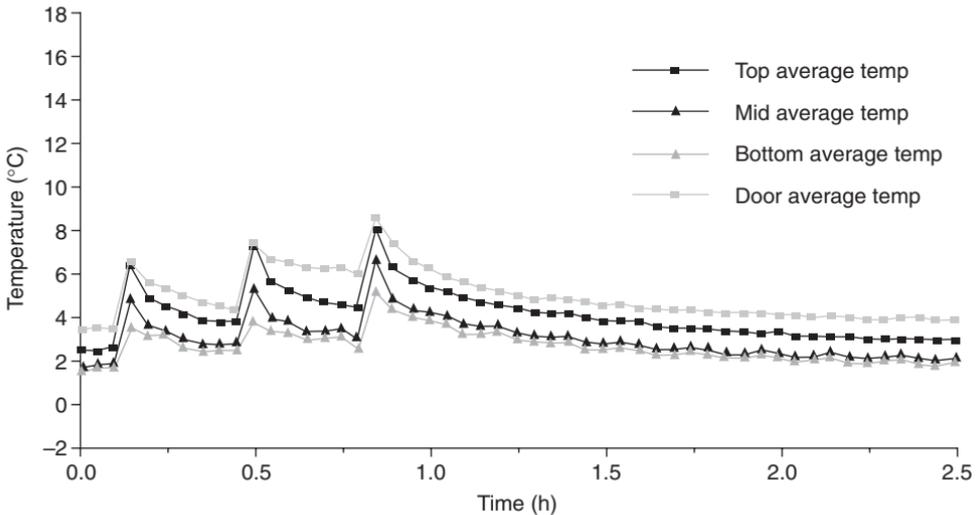


Fig. 12.11 Three 1 min openings at 20 min intervals (source: Evans *et al.*, 1991).

12.6 Performance testing of domestic freezers

Despite their widespread ownership and use, few data have been published on the temperature performance of domestic freezers. Much of what has been published has primarily been for the benefit of the consumer, giving practical instructions for 'home freezing', with little basis in scientific fact.

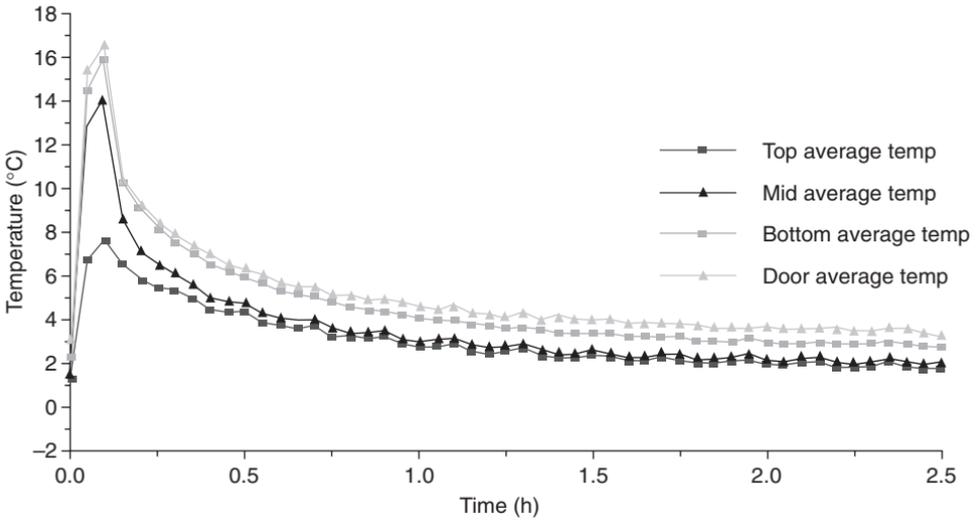


Fig. 12.12 Single 6 min door opening (source: Evans *et al.*, 1991).

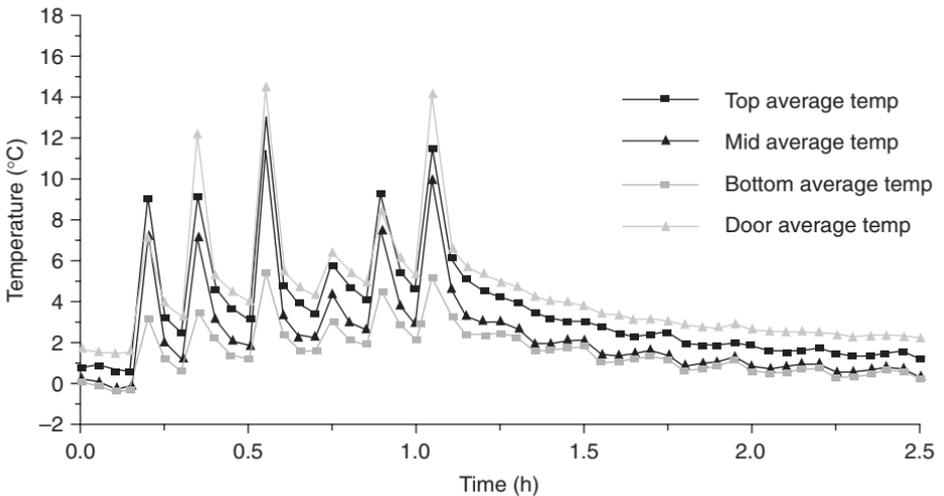


Fig. 12.13 Six 1 min openings at 10 min intervals (source: Evans *et al.*, 1991).

Bailey's work remains one of the few studies on the practical performance of domestic freezers (Bailey, 1974). Data can also be found on modelling the cooling curve of a food in a direct cooling-type domestic fridge-freezer (Murasaki *et al.*, 1981).

Freezer standards and manufacturers' claims place the emphasis on the ability to freeze fresh food within a 24 h period. The basis of this need to

'fast freeze' is that the organoleptic properties of foods are affected by freezing rate owing to their influence on ice crystal formation. It is true that freezing causes irreversible damage to the microstructure of meat, and it has long been shown by photomicrographs that the faster meat is frozen, the smaller the ice crystals produced. Above a certain rate these are predominantly intracellular, when by implication the damage to cell walls should be minimal. However, numerous other factors affect the ultimate size of ice crystals. They can grow in cold storage, at a rate that is faster the higher the temperature and the more it fluctuates. In meat they become progressively larger the longer the period between slaughter and freezing; in rapidly frozen, well-conditioned meat they are as large as in the case of very slowly frozen fresh meat. Furthermore, extracellular ice crystal formation is not necessarily disruptive because muscle cell wall membranes are elastic, unlike those of vegetable tissue.

Evidence in the literature indicates that organoleptically there would appear to be no differences between meat, after thawing and cooking, frozen in 24h, 48h or even longer, and there are no adverse reports on bacteriological deterioration of meat slowly frozen from the chilled state in this way (Bailey, 1974; 1976). In any case, even the best rates of freezing attainable in domestic food freezers are very slow in real terms. No experiments have established whether there is any merit in requiring the freezing of meat to be completed within 24h.

The recommendation is to set the freezer at its lowest temperature up to one day before adding a new batch of food for freezing. The setting should be returned to the norm (about -18°C) the next day and no more than one tenth of the total capacity of the freezer should be used for freezing fresh food in any 24h period.

12.7 Conclusions

It is clear from the data presented that the temperature of chilled and frozen meats can rise to unacceptably high values if transported without insulation in a car boot. These data were obtained in June 1989, a very sunny period, but higher ambient temperatures are not uncommon in mid-summer. The predictions carried out show that substantial increases in bacterial numbers can occur during transportation and subsequent re-cooling. It is not difficult to think of even worse situations where chilled products reside in the open backs of estate cars for many hours on hot summer days. However, a combination of increased consumer education and the use of insulated/precooled containers should solve this particular problem.

The basic design of domestic refrigerators has not changed in the last 50 years although their use and lately the type, complexity and microbiological sensitivity of the foods stored in them has markedly changed.

Designers have responded to market demands for more compact appliances and more features, for example chilled drink and ice dispensers, but temperature control is only advertised as a sales point on more expensive multicompartment refrigerators. Consumers now purchase and store a wide range of ready meals and other chilled products and they have demanded, and obtained, substantial reductions and in some cases the total elimination of preservatives and additives in these products. New chilled products are therefore inherently more bacterially sensitive and require closer temperature control than their predecessors. If current predictions that eating habits will change from the current pattern of set meals, to all day grazing, then the consequence is likely to be a demand for and purchase of more preprepared chilled foods and more visits to domestic refrigerators.

These results indicate that current refrigerators are unlikely to be able to maintain foods at the temperatures desirable for chilled products when subjected to more frequent door openings and the addition of 'warm' food. The appliances differ substantially in their ability to respond to door openings and loading with warm (20°C) food and both these operations are crucial to domestic operation. Since current and proposed standards only test empty closed appliances, these differences are not apparent to the consumer who only knows that they are tested to the relevant standard. These limited experiments indicate the problems in providing consumers with general recommendations and simple temperature test procedures. Recommendations such as 'by keeping the top of a fridge at 5°C, the bottom should be at 0°C' (Anon, 1990) may be applicable to the majority of appliances but not pertinent to specific appliances.

The consumer study of 252 households indicated that higher temperatures than desirable are to be found in current domestic refrigerators and that there is a need to educate consumers about the need for lower temperatures. This need should subsequently create a demand for domestic refrigerators that will maintain low temperatures under normal operating conditions. The data presented on the temperature performance of refrigerators in the laboratory indicates the need for different international standards that relate to food safety, quality and consumer usage of domestic refrigeration.

Experimental investigations into the performance of a typical household freezer have shown that only relatively small quantities of meat joints of weight 1.5 kg, packaged and loaded as in a domestic situation, can be frozen from +5 to -10°C in 24 h. However, evidence in the literature indicates that organoleptically there would appear to be no differences between meat frozen in 24 h, 48 h or even longer, and there are no adverse reports of bacteriological deterioration of meat slowly frozen from the chilled state in this way. No experiments have established whether there is any merit in requiring freezing to be completed within 24 h.

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Part 3

Process control

Thermophysical properties of meat

In chilling, freezing, thawing and tempering processes heat has either to be introduced or to be extracted from the meat to change its temperature. The rate at which heat can be removed or introduced into the surface of meat is essentially a function of the process being used, for example air blast, plate, immersion, and so on. However, the rate at which heat can flow from within the meat to its surface is a function of the thermophysical properties of the meat. If we continue to refrigerate meat in the form of carcasses, quarters or primals, heat flow within, rather than from, the meat will always limit our ability to achieve rapid uniform rates of temperature change.

We are interested in the thermal conductivity, which governs heat flow, and the specific heat, which is a measure of the amount of heat to be removed. Since the specific heat of meat is not constant with temperature it is often better to use the difference in enthalpy between the temperatures of interest to provide a value for the energy change required.

Meat is not a homogeneous product and in a carcass the three main components – fat, lean muscle and bone – have very different properties. In frozen meat the ice content dominates the thermal properties.

The basic structure of this chapter is based on the publications of Morley (1972a, 1974). Comprehensive reviews of the thermal properties of food can be found in Morley (1972b), Polley *et al.* (1980), Miles *et al.* (1983) and Rahman (1995). Few publications provide data on enthalpy, heat capacity and thermal conductivity of meat over the total temperature range -40 to $+30^{\circ}\text{C}$ that can be encountered in the refrigeration of meat. Two particular publications that do provide such data are, Tocci *et al.* (1997) on boneless mutton and Lind (1990) on minced lean meat.

Table 13.1 Mean thermal conductivities in chilling

| | Mean thermal conductivity ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$) | Variation with type |
|--------------------------------------|---|---------------------|
| Lean meat (also kidney and liver) | 0.49 | +0.05 |
| Fats | | +0.02 |
| Natural | 0.21 | |
| Rendered | 0.15 | |
| Bone | | +0.02 |
| compact bone | 0.56 | |
| spongy bone | 0.26 | |
| marrow | 0.22 | |

Source: Morley, 1972a.

13.1 Chilling

13.1.1 Thermal conductivity

Table 13.1 shows the mean thermal conductivities during chilling of lean meats, fats and bones, together with the total variation amongst the different samples considered. Thermal conductivity is given in watts per metre per $^\circ\text{C}$ ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$).

It can be seen that the thermal conductivity of lean meat is roughly two and a half times that of fat. Rendering fat reduces its thermal conductivity owing to the ensuing loss of water, which has a relatively high thermal conductivity of $0.60 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$. The thermal conductivity of bone varies throughout its structure. Hard, outer compact bone has a similar thermal conductivity to that of lean meat, whereas inner spongy bone and marrow, having high fat contents, are similar in thermal conductivity to fat. Beef liver has a similar thermal conductivity to lean meat, $0.49 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$, over the chilling temperature range from 30 to 0°C (Barrera and Zaritzky, 1983).

Little data are available on the thermal conductivity of meat in the cooking temperature range. For predictive purposes Baghe-Khandan *et al.* (1982) developed models based on the initial water (w_o) and fat (f_o) contents at 30°C to predict thermal conductivities at temperatures (T) up to 90°C and heating rates of $<0.5^\circ\text{C min}^{-1}$.

$$\text{For whole beef: } K = 10^{-3}(732 - 4.32f_o - 3.56w_o + 0.636T) \quad [13.1]$$

$$\text{For minced beef: } K = 10^{-3}(400 - 4.49f_o + 0.147w_o + 1.74T) \quad [13.2]$$

13.1.2 Specific heat

The specific heats of different types of meat are given in Table 13.2. The specific heats of fats are given in Table 13.3, and Table 13.4 shows the variability in specific heats between different bones.

Table 13.2 Specific heat of meat

| Type | Temperature range (°C) | Specific heat (kJ kg ⁻¹ °C ⁻¹) |
|--|------------------------|---|
| Beef, lean (74.5% water) | 0–10 | 3.6 |
| Beef, lean (0% water) | 0–10 | 1.3–1.4 |
| Beef (74.5–78.5% water) | 0–30 | 3.81 |
| Beef, lean (72% water) | 0–100 | 3.43 |
| Beef, fatty (51% water) | 0–100 | 2.89 |
| Beef, ground | 0–100 | 3.52 |
| Veal (77.5% water, 4.4% fat) | 0–32 | 3.68–3.60 |
| Veal (63% water) | 0–100 | 3.22 |
| Pork, lean (73.3% water) | 0–18 | 3.52 |
| Pork, lean (57% water) | 0–100 | 3.06 |
| Pork, fatty (39% water) | 0–100 | 2.60 |
| Pork (76.8% water) | 0–30 | 3.81 |
| Ham (52% water) | 4.5–24 | 3.8–3.5 |
| Bacon (50% water) | 0–100 | 2.01 |
| Bacon, back (69% water) | 0–18 | 3.39 |
| Lamb, loin (64.9% water, 11.7% fat) | 0–32 | 3.39 |
| Lamb, loin (52.5% water, 28.4% fat) | 0–32 | 2.93 |
| Lamb, loin (44.4% water, 39.4% fat) | 0–32 | 3.10–3.52 |
| Lamb, loin (52.3% water, 30.4% fat) | 0–32 | 3.14 |
| Lamb, forequarter (54.3% water, 25.1% fat) | 0–32 | 3.06 |
| Lamb, leg (57.8% water, 20.4% fat) | 0–32 | 3.18 |
| Lamb, rack (50.5% water, 29.2% fat) | 0–32 | 3.01 |
| Lamb, flap (49.9% water, 30.2% fat) | 0–32 | 2.89 |
| Mutton (70% water) | 0–100 | 3.39 |
| Chicken, lean (73% water) | 0–100 | 3.39 |

Source: Morley, 1972b.

Table 13.3 Specific heat of fats

| Type | Temperature range (°C) | Specific heat (kJ kg ⁻¹ °C ⁻¹) |
|---------------------------------------|------------------------|---|
| Beef (7.7% water) | 0–17 | 3.59 |
| Beef, kidney (rendered) | 5–25 | 4.06–3.89 |
| Beef, loin (rendered) | 5–25 | 7.49–3.60 |
| Beef, hind shin (rendered) | 4.5–25 | 5.53–3.35 |
| Pork (3.1% water) | 0–30 | 4.69–4.31 |
| Pork, hard fat (rendered, 0.2% water) | 5–25 | 5.78–3.73 |
| Pork, soft fat (rendered, 3.0% water) | 4–26 | 3.94–4.40 |
| Pork, American lard (0.1% water) | 0–21 | 4.80–3.34 |
| Pork, lard (water free) | 2–60 | 5.53–2.09 |
| Bacon, back (8.6% water) | 0–18.5 | 3.38 |
| Bacon, back (7.3% water) | 0–17 | 3.95 |
| Chicken (11.4% water) | 0–15 | 4.44 |

Source: Morley, 1972a.

Table 13.4 Specific heat of bones

| Type | Temperature range (°C) | Specific heat (kJ kg ⁻¹ °C ⁻¹) |
|------------------------|------------------------|---|
| Beef (32% water) | 0–18 | 2.46 |
| Pork (34% water) | 0–20 | 2.85 |
| Pork (35.4% water) | 0–19 | 2.39 |
| Pork (bone from chops) | 5–15 | 2.40 |
| Pork (bone from chops) | 5–38.5 | 2.75 |
| Pork (rib 31.5% water) | 5–15 | 2.21 |
| Pork (knuckle joint) | 5–15 | 2.23 |
| Chicken (35.6% water) | 0–21 | 2.92 |

Source: Morley, 1972b.

It can be seen that there is quite a small variation in the specific heat of different types of lean meat, whereas there is a relatively large variation in the specific heats of different fats. The specific heat of fat also varies greatly with temperature. This is due to latent heat associated with phase changes. The temperatures at which these occur depend on the type of fat. Studies by Morley and Fursey (1988) have shown that the values of specific heat and enthalpy change in fats measured during cooling differ from those measured during subsequent heating. This suggested that further fat solidification occurred during storage. Using thermal data obtained in inappropriate conditions could lead to errors in prediction of temperature changes.

The variability in the specific heat of fats with temperature should result in corresponding, though smaller, variations in the specific heats of cuts and carcasses, although no detailed investigations have been undertaken to show this. The effect of carcass composition variations on the mean specific heat in chilling can be estimated. The result is a total variation of about ± 0.05 from the specific heat of an average beef, pork or lamb carcass. There appears to be little difference between the specific heats of typical beef, pork and lamb carcasses.

Many specific heat tables for foods (e.g. ASHRAE Guide and Data Books) are based on Siebel's formula of 1892, i.e. calculated from the water content, assuming the solid content has a specific heat of 0.2 btu/lb °F. This can obviously result in considerable error, as for example in estimating the mean specific heat in chilling a typical beef, pork or lamb carcass. Siebel's formula gives a value that is about 35% too low.

13.1.3 Enthalpies

Published enthalpy values for meat are shown in Table 13.5. Further data for lean pork, pork sausage meat, beef sausage meat, beef mince, beef fat and pork kidney fat over the temperature range -40 to $+40$ °C can be found in Lindsay and Lovatt (1994).

Table 13.5 Published enthalpy values of meat

| Temperature (°C) | Enthalpy (kJ kg ⁻¹) | | | Temperature (°C) | Enthalpy (kJ kg ⁻¹) | | |
|---------------------|---------------------------------|-------|-------|---------------------|---------------------------------|--------|--------|
| | Pork | Beef | Lamb | | Pork | Beef | Lamb |
| 40 | 0 | 0 | 0 | 20 | -66.0 | -61.6 | -62.7 |
| 35 | -12.4 | -14.2 | -16.5 | 15 | -82.1 | -76.6 | -78.2 |
| 30 | -24.8 | -29.4 | -32.6 | 10 | -95.7 | -91.3 | -94.5 |
| 25 | -41.1 | -46.0 | -47.7 | 5 | -109.0 | -106.3 | -110.5 |
| | | | | 0 | -122.8 | -122.7 | -127.3 |

Source: Lindsay and Lovatt, 1994.

13.2 Freezing, thawing and tempering

13.2.1 Ice content

It is well known that, below its initial freezing point, meat becomes more frozen the lower the temperature. This is due mainly to the fact that freezing results in an increase in the concentration of the tissue fluids and consequently a lower temperature is required for further freezing to occur. About 10% of the water content does not appear to freeze even at absolute zero, and it is generally assumed to be too tightly bound to protein, while the remaining 90% of the water content is freezable. Although there is some disagreement between the various investigators about the amount of ice in lean meat at different temperatures, the work of Riedel (1957) is perhaps the most authentic. Figure 13.1 (after Riedel, 1957) shows the percentage of the freezable water that is frozen at different temperatures. Fikiin (1996) has reviewed Eastern European methods of predicting ice content.

It can be seen that freezing commences at *ca.* -1.5°C and although about half of the freezable water is frozen by -2°C , freezing is not entirely complete even at -30°C .

13.2.2 Heat extraction

Figure 13.2(a) (after Riedel, 1957) shows the heat extraction required in cooling lean meat from 0°C to temperatures down to -40°C .

On the commencement of freezing the heat extraction increases steeply owing to the high latent heat of freezing. Thereafter the heat extraction increases less and less steeply as the formation of ice diminishes, as in Fig. 13.1. For example, in cooling from -1 to -5°C the required heat extraction is $193 - 5 = 188\text{ kJ kg}^{-1}$, i.e. an average of $47\text{ kJ kg}^{-1}\text{ }^{\circ}\text{C}^{-1}$, whereas between -30 and -40°C , where freezing is virtually complete, only $1.9\text{ kJ kg}^{-1}\text{ }^{\circ}\text{C}^{-1}$ is required. If such calculations were made based on the water content, as is done in certain refrigeration books, erroneous results can arise, caused mainly by the fact that not all of the water content becomes frozen as is

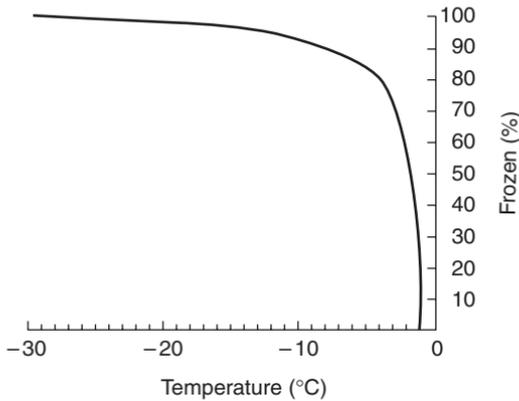


Fig. 13.1 Percentage of the freezable water that is frozen (source: Morley, 1974).

assumed. If, for example, the heat extraction required in cooling lean meat (74% water) between -1 and -5°C was calculated in such a manner, a value of 254kJkg^{-1} would be obtained, compared with 188kJkg^{-1} from Fig. 13.2(a).

Figure 13.2(b), (c), (d) and (e) shows the heat extraction required in freezing lamb loin cuts and carcasses (after Fleming, 1969).

The mean specific heat of fat in the main meat freezing region (-1 to -20°C , for instance), though very variable, is roughly $3\text{kJkg}^{-1}\text{ }^{\circ}\text{C}^{-1}$, compared with *ca.* $7\text{kJkg}^{-1}\text{ }^{\circ}\text{C}^{-1}$ for bone and $13\text{kJkg}^{-1}\text{ }^{\circ}\text{C}^{-1}$ for lean. Thus, the heat extraction required in freezing different meats depends mainly on the quantity of lean.

13.2.3 Thermal conductivity

The thermal conductivity of lean meat varies with temperature as shown in Fig. 13.3 (after Lentz, 1961). The thermal conductivity of ice is some four times that of water and thus the conductivity of lean meat increases with increasing ice content.

The thermal conductivity of lean meat also depends on the continuity of the ice to the flow of heat – the more continuous the ice structure, the greater the conductivity. Thermal conductivity in a direction parallel to the muscle fibres is some 8–30% greater than perpendicular to the muscle fibres (Hill *et al.*, 1967; Lentz, 1961). This is due to the fact that ice crystals are parallel to the muscle fibres and thus present a more continuous path for heat flow in this direction. Ice structure also varies with freezing conditions. Slow freezing produces large extracellular columns of ice of greater continuity than the small intracellular ice crystals produced by fast freezing. The mean thermal conductivity of fat is *ca.* $0.25\text{W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$, which is only about one sixth that of frozen lean. The thermal conductivity of bone varies

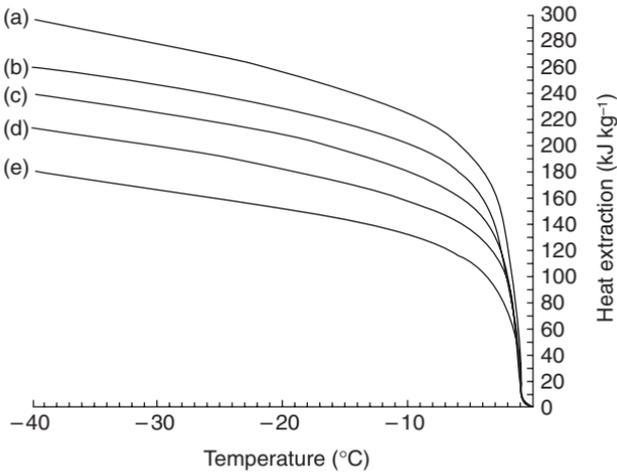


Fig. 13.2 Heat extraction required in cooling meat below 0°C (a) Lean meat (74% water, 4% fat), (b) lean loin cut (64.9% water, 11.7% fat, bone in), (c) moderately lean carcass (60% water, 22% fat), (d) moderately fat loin cut (52.5% water, 28.4% fat, bone in), (e) fat loin cut (44.4% water, 39.4% fat, bone in) (source: Morley, 1974).

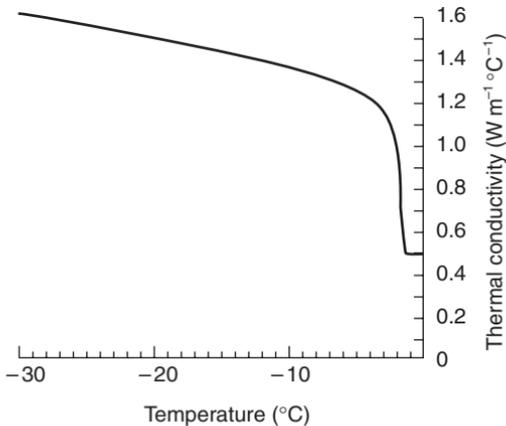


Fig. 13.3 Variation of the thermal conductivity of lean meat with temperature (source: Morley, 1974).

throughout its structure, being similar to that of fat in its inner region (spongy bone): $0.33 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ (Morley, 1966), whereas it is about double this in its outer region (compact bone): $0.64 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ at -30°C (Morley, 1974).

Beef liver has a similar thermal conductivity to lean meat $0.9 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$

Table 13.6 Specific gravity

| | Mean specific gravity |
|-------------------------|-----------------------|
| Lean meats (also liver) | 1.07 |
| Fats | 0.92 |
| Bones beef, fresh: | |
| humerus, femur | 1.33 |
| tibia | 1.41 |
| radius | 1.44 |
| cannon bones | 1.56 |

Source: Morley, 1972a.

at -2°C and rising to *ca.* $1.3\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$ at -30°C (Barrera and Zaritzky, 1983).

13.2.4 Density

A knowledge of the density of meat components is important in heat conduction analysis since density (ρ) appears in the general transient heat conduction equation. Table 13.6 shows the mean specific gravities during chilling of lean meats, fats and bones.

It can be seen that the density of bone is much greater than that of lean and fat and that there is a fairly large variation in density between different bones.

13.3 Mathematical models

Computer programs are now available such as COSTTHERM and FoodProp that will accurately predict the thermal properties of food from their compositional properties. In general a knowledge of the initial freezing point of the product is required to obtain accurate data in the freezing range. Programs are under development that will automatically predict the initial freezing point.

13.4 Conclusions

- 1 The thermal properties of meat are both a function of its composition and its temperature.
- 2 At temperatures above -1.5°C :
 - the thermal conductivity of lean meat is roughly two and a half times that of fat;
 - the specific heat of fat is also very variable with temperature.
- 3 At temperatures below -1.5°C :

- the thermal properties are a function of the ice content;
 - the thermal conductivity of lean meat is approximately three times that of the unfrozen material.
- 4 Because of the latent heat of freezing the enthalpy change between -1.5 and -5°C is very high for lean meat.

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Temperature measurement

It is often stated by those in the meat and refrigeration industries that ‘anyone can measure a temperature’. Many millions of measurements are made of both meat and environmental temperatures in the meat industry. However, in many cases the measurements made are an unreliable guide to the effectiveness of the refrigeration process. Even when the correct temperatures have been obtained the data are often poorly analysed and rarely acted upon.

If a group of people are asked to measure the temperature of a beef carcass, the number of values obtained is often the same as the number of people in the group. Few initially ask the obvious question, ‘what is meant by the temperature of the carcass?’ Is it the average temperature, the highest temperature, the lowest surface temperature, the average surface temperature . . . ?

The increase in temperature legislation and the desire of meat producers and retailers to maintain the organoleptic and microbiological quality of meat throughout the chilled and frozen distribution chain has created an increased demand for equipment and expertise on temperature measurement.

The industry needs to measure temperatures accurately, reliably, meaningfully, simply and cheaply. It needs to be able to analyse the data and respond when required. It needs the correct instrumentation and the expertise to collect and interpret the temperature data.

14.1 Instrumentation

The first consideration is the range of temperatures to be measured. For the meat industry, a range from -40 to $+150^{\circ}\text{C}$ would cope with the temperatures found in freezers, chillers, storage rooms, retail display cabinets and in water used for cleaning or scalding tanks in the abattoir. If they produce cooked meat products then the upper temperature may rise to 250 – 300°C .

As well as the measuring range, the range of ambient temperatures over which the instrument will work needs to be considered. The electronics of many temperature measurement instruments are designed to work to the specified accuracy only within certain ambient temperature ranges, usually 0 – 40°C . If temperatures in a cold store are to be measured the instrument itself may need to be kept warm until it is used.

14.1.1 Hand-held digital thermometers

Purely from a cost consideration many small producers and retailers rely on spot temperature checks obtained using hand-held thermometers to produce the temperature records they require. The main tasks they carry out with such equipment is the measurement of air temperature, between pack or product temperature, and the temperature of the meat itself. They require thermometers that are accurate, easy to use, react quickly and are robust. Ease of use is a personal judgement and best answered by trying out a range of instruments. Most modern electronic thermometers are reliable if handled with reasonable care. However, in general, the more robust the sensor the slower the response.

There are three types of digital thermometer generally available: thermocouple, platinum resistance or semi-conductor (thermistor). The name refers to the type of temperature sensor used. Type T (copper–constantan) thermocouple thermometers with a wide range of interchangeable sensors are the most widely used because of their wide temperature range and reasonable accuracy. The accuracy of the temperature measurement of a digital thermometer will depend on how accurate the instrument and the sensor are.

It can be seen from Table 14.1 that only thermometers based on thermistor or platinum resistance sensors can be guaranteed to provide better than $\pm 0.5^{\circ}\text{C}$ accuracy. However, it is possible to calibrate any thermometer at known temperatures and use the calibration curve obtained to correct errors in measured values. In many cases the supplier of the instrument can provide a calibration curve for a particular instrument/sensor combination.

Sensors do not immediately measure the temperature of the meat or air in which they are positioned. Their response rate depends on the sensor itself and the environment in which it is used. A thin sensor in a wet/solid food will respond rapidly, and a thick sensor in still air very slowly. When

Table 14.1 Accuracy of digital instrument, temperature sensor and overall temperature accuracy of combined thermometer

| | Instrument (°C) | Sensor (°C) | Both (°C) |
|---------------------|-----------------|-------------|-----------|
| Type K thermocouple | ±0.3 | ±1.5 | ±1.8 |
| Type T thermocouple | ±0.3 | ±0.5 | ±0.8 |
| Platinum | ±0.2 | ±0.2 | ±0.4 |
| Thermistor | ±0.2 | ±0.1 | ±0.3 |

Table 14.2 Response times (s) of sensors in air

| Sensor | Air condition | |
|-----------------------|---------------|--------|
| | Still | Moving |
| Bare thermocouple | 20 | 5 |
| Bare thermistor | 45 | 20 |
| Shrouded thermocouple | 150 | 40 |
| Shrouded thermistor | 260 | 50 |
| Shrouded platinum | 365 | 65 |

sensors are shrouded to improve their robustness their response times increase substantially (Table 14.2).

Most manufacturers supply a range of cased sensors (probes) normally made of stainless steel suitable for most applications. These include blunt-ended probes for general purpose use, needle-point or hypodermic probes for inserting into solid or semi-solid food, probes with spring-loaded ends for measuring surface temperatures or very robust probes that can be screwed or hammered into frozen meat.

Probe length is not important for measuring air and liquid temperatures. However, to check the deep leg temperature of a side of beef the probe needs to be at least 15cm long to measure the temperature at the deepest point.

14.1.2 Temperature recorders

There may often be a requirement to measure the values of temperatures at many different positions at the same time. The simplest solution to this problem is often to attach a multipole switch to a digital thermometer. A number of temperature sensors can then be connected to the switch and their temperatures monitored in succession. This procedure is commonly used in central plant rooms where an operator can routinely look at and record the temperatures at many different locations. A hand-held digital thermometer will provide information on one temperature at one

time. However, in many cases there is a need to measure temperatures over a long time period. In these situations a temperature recorder is required.

Historically, the temperature history of a point has been obtained using a temperature sensor connected to a moving chart. In its simplest form this is a stylus on the end of a bimetallic strip that bends in response to temperature changes and scratches a continuous trace on a carbon chart moved by a clockwork motor. More sophisticated devices use electrical temperature sensors attached to a small chart recorder. The recorders can be driven from batteries or direct from the mains and the chart can be circular or rectangular and mounted on a drum or on continuous rolls. Typically instruments will provide a continuous trace for up to a week, but some specially developed for long distance shipboard transportation of meat can operate for 6–8 weeks.

Increasingly, solid state electronic devices are being used to obtain the temperature history of a point. In most solid state devices the output from an integral electronic sensor is measured at set time intervals, converted to a temperature measurement and stored in a computer memory chip. In a small number of devices the interval between recordings can be adjusted and recordings started using buttons or switches on the instrument and the temperatures examined on an in-built display. A development is the use of small printers that can either be used to print out the temperatures as they are measured or attached after data collection is finished and the whole temperature history printed out. However, with the majority of instruments a small computer is required to set up start times, logging intervals and so on and recover the temperature recordings.

With many systems it is difficult to look at the temperature while it is being recorded or even check that the required information has been obtained before leaving the recording site. Some of the newest instruments are totally encapsulated in waterproof plastic and can be placed in direct contact with solid or even within liquid foods. Solid state devices can be very small, effectively tamper proof, and the value of the temperature at set times easily obtained, but the requirement for an associated processing facility substantially increases their cost. In many cases moving chart instruments may still provide the most economic and convenient solution to a monitoring problem. If precise temperature values at certain times are not required, then a quick examination of the chart may be sufficient to show that the temperature of the display cabinet, store room or transport vehicle has kept within the prescribed limits. However, obtaining temperature values from a small chart can be time consuming and inaccurate.

In some situations the actual or relative position of the sensing points is important, whilst in others the position of maximum or minimum temperature is required. There are few, if any, commercial sources of multi-point temperature probes and most have to be specially constructed. The sensors are attached to basic probes constructed from composite fibre or wood of

the smallest cross-sectional area that can be used, whilst maintaining the required robustness, to minimise heat conduction and achieve a rapid temperature response. For hygienic reasons, probes are thinly coated with inert epoxy resin.

Currently there is no real alternative to the use of an array of individual temperature sensors if data on temperature distribution are required. For over 50 years temperature sensors attached to multi-point chart recorders have been used to obtain the temperature history of up to 24 positions and these systems are still common in many processing plants. To differentiate between the sensors on the charts, a range of methods including different colours, line types or numbers have been used. As the number of sensors increases it becomes more and more difficult to identify individual sensors and/or temperature values. If the sole purpose of the recordings is to show that all the temperatures remain within upper and lower limits then chart recording systems are more than adequate. In situations where a more detailed analysis of the data is required then they are being increasingly replaced by microprocessor-controlled data logging systems.

Data loggers range from multisensor (typically 2–16 temperatures) versions of the solid state instruments already mentioned, to sophisticated processing systems with thousands of measurement points.

Two types of portable logging systems are available. The larger type (approximately the size of a large paperback novel) has built in displays and buttons or switches to set start times, time intervals between measurements and to scan through, using the display, the temperatures, that have been measured. Instruments can be purchased with between 2 and 16 plug-in temperature sensors, and some will display the maximum, minimum and mean temperature recorded by a particular sensor. For more detailed analysis of the temperatures, the recorded data are transferred to a personal computer. The PC is required to program the start time, recording interval and so on, and analyse the data with the smaller loggers. These instruments usually have a maximum capacity of 8 temperature sensors, 1 of which is often built into the instrument.

Developments in computer storage chips are continually extending the number of temperature values that can be held in both types of logger. Modern instruments would typically be able to take readings of 4 temperature sensors at 5 min intervals over a 2–3-week period. Further developments in electronics are extending the temperature range over which the instruments will operate. Some instruments will record accurately inside blast and spiral freezing systems whilst others can operate in ambient temperatures up to 70–80°C. For extended use at sub-zero temperatures special batteries are required. Logging systems have been developed which use insulated heat resistant cases to allow operation for several hours at temperatures up to 300°C. This allows measurement of product and processing temperatures in batch and continuous baking/cooking operations.

Most data logging systems that will measure over 20 temperatures are physically too big to be considered as truly portable even though some can be battery powered. Some have a built in display and keyboard but the majority are operated using a video display unit.

A basic system would consist of:

- a number of input cards to which the temperature sensors are connected,
- a card-based voltmeter to measure the output from sensors when instructed,
- a microcomputer to provide the instructions and convert voltages into temperature measurements,
- a storage system that could be floppy or hard disc, and a video display unit.

Many systems can be expanded to hundreds and in some cases thousands of temperature sensors by the addition of extra input cards, some of which can be up to a mile away from the central system.

The temperature measurement possibilities of large logging systems are only limited by the ingenuity of the programmer/operator. Different combinations of temperature sensors can be monitored at varying time intervals and the data displayed, analysed, used to control processes or set off alarms or be transmitted to central control rooms hundreds of miles away.

All three types of temperature sensor – thermocouple, thermistor and platinum resistance – are commonly used for multi-point temperature measurement. Thermocouples are cheap, especially if the wire is purchased in bulk, and very small sensors can be manufactured. Thermistors are more expensive, slightly larger but more accurate over limited temperature ranges. Platinum resistance sensors are typically 2–3 times the cost of thermistors, but are capable of better than 0.1 °C accuracy. Thin wire and thin film platinum resistance sensors can be very small. Commercial sensors are often enclosed in stainless steel sheaths, which makes them more robust, but increases their response time.

14.1.3 Time–temperature indicators

There are many different types of temperature or time–temperature indicators. Almost anything that undergoes a sensibly detectable change with temperature can be used. Liquid crystal devices change colour to indicate the temperature at the time they are observed and time–temperature indicators change irreversibly after a time dependent upon the temperature history or when a temperature threshold is exceeded.

Temperature indicators are already used as cheap, safe and hygienic thermometers in the food chain. Several types have been developed to the point where they have been introduced on some chilled and frozen foods in the USA and on chilled foods in France.

14.2 Calibration

Any temperature measuring system should be tested over the operating range at regular intervals to ensure accuracy and should also have a current calibration certificate from its manufacturer or official standards laboratory. The system can be checked by means of a calibration instrument, or against a reference thermometer that is known to be accurate. Melting ice (which if made from distilled water should read 0°C , or -0.06°C if made from tap water with 0.1% salt) may be used to check sensor accuracy. The ice should be broken up into small pieces and placed in a wide-necked vacuum flask with a depth of more than 50 mm. The system should be agitated frequently and the temperature read after a few minutes when stable. If differences of more than 0.5°C are found, the instrument should either be very carefully adjusted or sent for calibration.

Other simple calibration systems are available. These consist of a small stirred tank that can be filled with water or oil. The temperature of the stirred liquid is measured using a standard calibrated platinum resistance thermometer. The temperature sensors to be calibrated are placed in the liquid and compared with the standard measurement. The temperature of the liquid can be raised or lowered to different values by the addition of ice, cold liquid or hot liquid.

14.3 Measuring temperature data

Accurately determining the temperature of chilled meat throughout the cold chain is difficult. Training and experience are required to locate positions of maximum and minimum temperature in abattoirs, stores, vehicles and display cabinets. The problem is further exaggerated by changes in position with time caused by loading patterns and the cycling of the refrigeration plants. Obtaining a relationship between environmental temperatures (that can be measured relatively easily) and internal meat temperatures is not a simple process. Relating temperatures obtained in a non-destructive manner with internal meat temperatures again poses problems. Determining the temperature of cuts of meat with regular shapes is quite simple but doing so for irregular cuts of meat is more difficult.

All the temperature measurement problems associated with chill foods will equally apply to quick-frozen foods. In addition, there are a number of other problems. Many instruments have sensors that will accurately measure temperatures of -20°C and below, but the instruments themselves become inaccurate or fail to operate at low temperatures. If frozen foods are removed from their low temperature environment to one suitable for the instrument the surface temperature rises very rapidly. However, the main problem is that of actually inserting a temperature sensor into frozen meat.

14.3.1 Contact non-destructive methods

The surface temperature of a food or pack can be measured by placing a temperature sensor (such as those discussed above) in contact with the surface. In practice there are very large temperature gradients on both sides of the surface and the presence of the sensor can influence the temperature being measured. Extending the surface of the sensor to measure the average temperature over a larger surface area is one method used to minimise these problems. This method is recommended for such applications as between-pack measurement.

Since it is impossible to measure the temperature of an exposed surface accurately, the next best thing is to take a measurement of the temperature between two food items. As long as good thermal contact is achieved between the temperature sensor and the packs, a between-pack method should provide an accurate measurement of the pack temperature. If the thermal conductivity of the packaging material is high and the food makes a good thermal contact with the pack then the temperature measured will be close to that of the product.

With a product such as skin-wrapped chilled sausages the above requirements are satisfied. A temperature sensor, especially a flat-headed probe, can be sandwiched between two packs. An accurate measurement is obtained owing to the combination of a flexible food and a thin wrapping. With chilled food in cartons or bubble packs the accuracy is much lower.

The contact problems are much greater with a frozen product. Since the surface of a frozen product is not flexible, only point contact can be achieved between the surface of the product and that of the pack or probe. Using a flat probe with extended contact surfaces does not necessarily improve the accuracy of temperature measurement. In extreme cases, for example with frozen sausages, the contact surfaces may extend out into the air stream and measure air, not product temperature. With packs of small items such as diced meat the accuracy will be much better. Care must also be taken to precool the probe before temperatures are measured. This is especially important with low heat capacity packaging materials.

Alternatively 'temperature sensitive' paints can be painted directly onto the surface of interest and will accurately determine its temperature. However, painting foods is not a practical solution.

14.3.2 Non-contact non-destructive methods

Non-contact temperature measurement devices measure the amount of energy in an area of the infrared spectrum that is radiated from the surface being measured. Basic instruments measure the average temperature of the area in a small field of view. More complicated systems of thermal imaging provide a temperature picture of all the objects over a much wider area.

There are two types of detector currently used in low temperature infrared thermometers, thermopile detectors and pyroelectric detectors.

Thermopile detectors consist of a collection of rods that act as thermocouples to sense emitted thermal radiation. Pyroelectric detectors contain a crystal which exhibits temperature-dependent polarisation and requires the incident radiation to be 'cut' by a 'chopping device' to prevent currents building up within the crystal that nullify this charge.

A certain amount of knowledge is needed in order to interpret the values that such instruments give (Evans *et al.*, 1994; James and Evans, 1994). The first point to bear in mind when using infrared thermometry is that the temperature measured is the surface temperature. If the meat has been in surroundings that have not changed in temperature for a long period of time, then it is likely that the surface temperature will be very close to that of the meat beneath the surface. However, if the temperature of the surroundings is changing or has changed over the previous 24 h, then it is likely that the surface temperature will not be the same as the temperature deep within the meat.

For example, transfer a carton of frozen meat from a refrigerated lorry where the temperature has been maintained at -18°C to a refrigerated loading bay at 4°C , and the surface of the carton will warm very rapidly. Therefore, if an infrared thermometer is to be used to check the meat temperature the value must be taken before it is removed from the lorry if any degree of accuracy is to be obtained. Even temperature fluctuations of $\pm 2^{\circ}\text{C}$ caused by normal control fluctuations will mean that the surface temperature will differ significantly from the deep meat temperature. If the meat is still cooling down, its surface temperature will be warmer than the air temperature and, in turn, the interior of the meat will be warmer still.

These problems can be overcome if the operator is aware of them. For example, the temperature of the carton of frozen meat could be measured in the lorry, or if removed the carton could be opened and the temperature of an inner surface of one of the packs inside immediately read with the infrared thermometer. However, in doing this two of the principle advantages of using infrared have been removed: namely, being quick and totally non-destructive.

It is also necessary for the operator to know how much of the surface is 'seen' by the infrared instrument, as it will measure the 'average' temperature over the whole of this area. The target area can vary significantly from instrument to instrument and with the distance between the instrument and the surface.

A further complication in the use of infrared thermometers is reflected radiation. The instruments will 'see' the radiation emitted from a surface and also an amount of radiation from the surroundings that is reflected by that surface. The reflected radiation will therefore constitute an error. For warm objects at a temperature greater than their surroundings, the amount of reflected radiation will be small in relation to that from the surface and consequentially the error will be small. With frozen meat, the temperature of the meat is no warmer than, and often colder than, the temperature of

the surroundings. Therefore, the amount of reflected radiation coming from the surface constitutes a significant error.

However, the proportion of radiation emitted by a surface relative to that of a perfect black body is the same proportion of incident radiation that would be absorbed by the surface. If the absorptivity or emissivity of the surface is known and the surface is not transparent, which is true for all packaging materials except some plastics, the reflectance of the surface will also be known by subtracting the absorptivity from 1. Hence it is possible to calculate the extent of the error.

Unfortunately this requires a lot of information about the emissivity and reflectance of the various packaging materials and takes a long time. Therefore, the advantage of taking quick accurate readings will be lost.

The Meat Research Corporation in Australia (1995a) recommend that an infrared thermometer should be permanently located in beef chill rooms. It should be positioned to measure the surface temperature of one of the last sides to be loaded. It can then be used to provide a permanently logged output of surface temperature and control the refrigeration system. When the surface temperature has reached *ca.* 2°C the fan speed can be automatically reduced and the suction pressure raised. This will reduce both weight loss and operating costs.

Infrared systems have also been used to monitor the surface temperature of pig carcasses in chill rooms (Metternick-Jones and Skevington, 1992). The thermometer required a minimum stabilisation time of 120 min in the chill room. After this time the temperatures measured were within 1°C of other methods and were repeatable to the same accuracy.

14.3.3 Contact destructive methods

Determining the temperature of small cuts of meat with regular shapes is quite simple. Determining the temperature of irregular cuts of meat, particularly large pieces, is more difficult. Possibly the most difficult problem is ascertaining deep leg temperature in beef carcasses.

The Meat Research Corporation in Australia (1995b) recommend that the temperature sensor should touch the trochanter major (aitch bone), which is the 'knob' of bone on the opposite side of the femur to the hip joint. To locate the sensor in this position it should be inserted through the 'pope's eye' at an angle about 15–20° below the horizontal (Fig 14.1). It should be aimed at an imaginary vertical line approximately one-third of the distance from the Achilles tendon to the last tailbone.

Because conduction occurs along the steel shaft of a probe it is important that the probe is inserted as far as possible into the meat. For example, to take the temperature of a cut of meat it is better practice to insert the probe to its full depth along the long axis of the cut rather than to insert the probe to half its length through the short axis (CSIRO, 1991).

For manufacturers to produce accurate data on the freezing of their meat

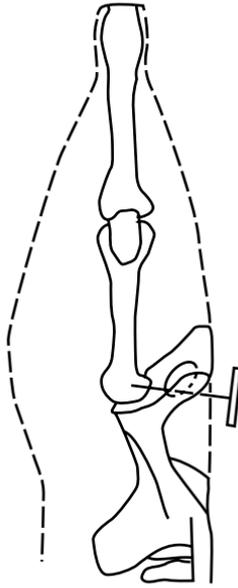


Fig. 14.1 Recommended position for taking deep leg temperatures in a chilled beef carcass (source: Meat Research Corporation, 1995b).

or meat products is a straightforward if time-consuming process. Temperature sensors have to be inserted and positioned close to the thermal centre prior to freezing. The samples are then packaged with the sensor leads sealed into the packs. If further information is required then additional sensors can be inserted close to the surface and at other positions of interest. With packs of small individual items care must be taken to maintain the position of the sensor within the pack when it is moved. Fixed or portable data loggers are then used to record temperatures during the freezing process, and throughout distribution if required, and the resulting data are analysed.

Routine determination of the temperature of frozen foods in the cold chain is a much more difficult process. Making a hole 2.5 cm or 3–4 times the probe diameter deep and then inserting a temperature probe sounds easy, but in practice is much more complicated.

There are three basic methods of making the hole: (1) forcing in a sharpened pointed instrument, (2) screwing in an auger-type bit or (3) drilling a hole. All cause problems with different types of frozen produce. Forcing a pointed instrument into frozen food at -18°C requires considerable force and the product has to be secured on a firm base to stop it slipping and to provide the resistance required. Fragile products such as beefburgers, pies, and so on will readily shatter when subjected to such treatment. An auger is better but the product still has to be restrained. Holding down a small

food pack by hand introduces a substantial amount of heat into the product. The choice of auger size is also a compromise. If the auger is too big it will shatter fragile products and produce a hole too big for the probe. If it is too small it can bend or even worse the end may break off in the frozen product. Using a portable electric drill is probably the best compromise. However, allowance must be made for the small temperature rise caused by the operation and in some products the food will clog the flutes of the bit and the tip may shear off in the product. The meat swarf produced by the drilling needs to be carefully collected to avoid it becoming a source of contamination.

14.3.4 Storage

14.3.4.1 Cold store

Research investigations have shown that it is very difficult to locate the warmest positions within a refrigerated space unless large arrays of temperature sensors are positioned within the space. This is not possible in a commercial operation. A UK code of practice (Department of Health, 1991) provides some guidance about the number and position of sensors in different situations. It recommends that the number of sensors should range from 2 for a 500–5000 m³ cold store to 6 for a cold store of over 8500 m³. The positions used in descending order of importance should be: at the maximum height of the food at the furthest position away from the cooler fans, or in the air return to the evaporator; along the walls at two thirds the height of the room away from the doors and not directly in the path of the air outlets from the evaporator; positioned 2 m above the floor level directly opposite the evaporator. The code also recommends monitoring the air from and returning to the evaporator coil.

The above are good general recommendations but they cannot be guaranteed to locate the warmest food positions. In poorly designed or badly loaded cold stores, air movement can be effectively non-existent around parts of the load. In a small number of situations heat infiltration through the fabric or doors can cause local warm areas.

Infrared radiation thermometers can have a useful role to play in locating areas of high temperature within cold stores. In cold stores the walls, ceilings, floors and the products are at similar temperatures. This minimises the problems of radiant energy from warmer surfaces being reflected by the surface of the body being measured and producing erroneous results. The only warm surface likely to produce problems is that of the person making the measurements. Errors caused by differences in emissivity between packaging materials are also reduced because most bulk packs tend to be wrapped in similar materials.

When checking the temperature data from air sensors, considering just the mean and the range of the temperatures is not sufficient. Air tempera-

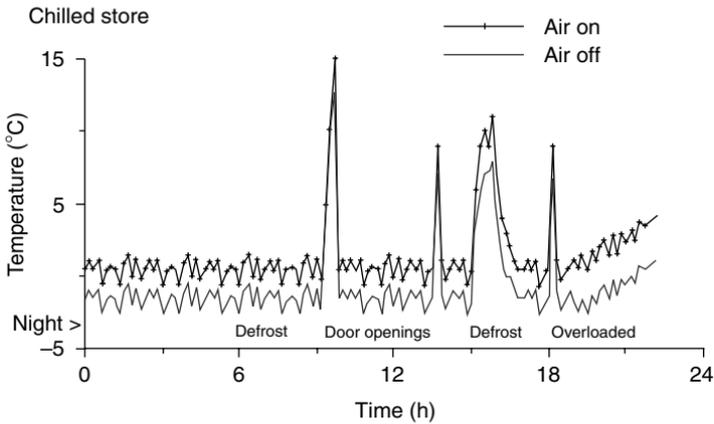


Fig. 14.2 Air temperatures in chill store.

tures cycling up and down over a few minutes will have little if any influence on the temperature of the food being stored. Long cycles of the same amplitude are much more likely to reduce product quality and result in temperatures above the legal minimum.

14.3.4.2 Chilled store

When monitoring air temperature in a chilled store, the best position is not by the door, (where the temperature will go up and down like a yo-yo as the door opens and closes), but in the air returning to the cooler. More information can be obtained on the functioning of the cold store if the air leaving the cooler is also measured (Fig. 14.2).

Apart from the normal control cycles, the air temperature rises dramatically as the door is opened and when the evaporator is defrosted. If the defrosts occur at reasonable intervals and the door discipline is good, the temperature will fall very quickly after each occasion back to its normal control temperature of 0°C. In most coolers there is also a difference between temperatures during the day, when the store is in use, and temperatures at night and at the weekend, when the store is not. If these are substantial it indicates that the meat being put into the chiller is too warm, the amount of time that the door is open is too long or the capacity of the cooler is not large enough.

14.3.5 Distribution

Monitoring representative temperatures within a distribution vehicle is a more difficult operation. The vehicles are designed to maintain the temperature of precooled loads and cater for a small amount of heat infiltration. In the code of practice it is suggested that the differential between the

air entering and leaving the evaporator is indicative of the performance of the refrigeration system. It recommends installing two sensors in the vehicle, one measuring the return air and the other on the ceiling at a position approximately three quarters of the length down the vehicle. In vehicles that are not fitted with forced air systems temperatures should be taken from above and below the load.

In practice, products near the rear door are often the warmest owing to heat pick up during loading and infiltration through doors and their seals. Temperature sensors positioned close to the doors will often provide a better indication of any temperature abuse. However, care must be taken when examining the temperature data to allow for rapid temperature rises during loading and unloading periods when the doors are open.

14.3.6 Retail

Most legislative requirements state that the temperature must be controlled in the centre of the meat to below a prescribed maximum. However, for quality control the temperature at the surface must also be controlled and this is often much more difficult. It is obviously impractical to measure the temperature of every piece of meat all the time. Therefore a system is needed to monitor how well things are doing from day to day without the need to take a large number of measurements. One way of doing this is to control the use of cabinets and chill rooms and to monitor the temperature of the air in them. If this is done then a large number of meat temperatures only need to be measured once. The temperature of the meat can then be related to the monitored air temperature, and thus monitored air temperatures in the future can be related to those of the meat. A thermometer is then only needed to check meat temperatures on delivery and if unusual circumstances occur, as they will do from time to time.

14.3.6.1 Cutting areas

In many countries there are no requirements for controlling temperatures in cutting areas in butchers' shops. However, it would be as well for these to be as low as possible and the area to be arranged so that meat can be quickly brought from the chiller, cut, and returned to either the chiller, or the display case, within the shortest possible time. When temperature monitoring is initially introduced it is a good idea to measure meat temperatures at the centre and at the surface before and after cutting to learn just how far temperatures rise during this process.

14.3.6.2 Retail display (chilled)

During retail display air temperatures should be measured entering and leaving the case. In the case of fan-assisted coolers this is where the air enters the display case at the top of the rear of the cabinet and returns back to the coolers through the return-air grill at the front of the cabinet. Air

temperature will fluctuate within wide limits during normal use of the display case and one-off measurements are of little use. Instead, the sensor of the thermometer should be inserted in the air stream and the temperature observed over a period of time when its rise and fall can both be observed. The maximum and minimum temperatures can then be recorded, or an average temperature if that facility is included in the thermometer.

An alternative way of obtaining an average temperature is to use a thermometer that is large and heavy and which consequently has a very slow thermal response. This can be inserted into the air stream and left to equalise over a long period of time, possibly over an hour. The temperature can then be recorded and will give a reasonable indication of the average air temperature at that point.

The monitored air temperatures would ideally be recorded at intervals automatically on a data logging system, but the cost of this can only be justified in larger shops. The alternative is to keep records measuring the temperature at the same time each day and preferably twice during the day and recording these on a data sheet. These data can be used to check whether the equipment is adequate for the uses to which it is put.

14.3.6.3 Retail display (frozen)

Display cases are much more difficult to maintain at frozen temperatures because of the much greater temperature difference between the display and store temperatures. The conditions that apply to chilled display cases remain applicable to frozen display cases but with greater effect.

Retail display cabinets for frozen food are likely to present the weakest link in the temperature chain. Individual retail packs of food will react more quickly to temperature changes than similar products in bulk packs. The packs are of necessity more exposed to outside ambient influences than in any other part of the cold chain. If they cannot be seen and easily handled by the consumer then they will not sell.

Retail display cabinets are designed to maintain the temperature of pre-cooled products and have a very limited capacity to extract heat from inadequately cooled food. Studies of chilled display cabinets have shown that it is very difficult to locate the position of the warmest areas in the cabinets. The same applies to display cabinets for frozen foods.

The Department of Health 1991 guideline suggests that monitoring air-on and air-off the evaporator coil will provide an indication of the performance of the cabinet. Monitoring temperatures at these positions will indicate if there are any changes in the performance of the cabinet. However, FRPERC confidential studies have shown that it is possible for all these temperatures to be below -12°C and still find warmer product in some areas of the cabinets.

Currently using large arrays of temperature sensors to obtain a relationship between the meat temperatures and those in the monitored positions is the only certain option available. Even then, monitoring the array

must be carried out over a complete operational cycle of the cabinet. Reflections and emissivity problems produce large errors in infrared temperature measurement in stores.

In general, in horizontal cabinets the warmest packs will be those at the surface in the centre of the display area. In forced air circulation cabinets the warmest packs will be in the top layer nearest to the air returning to the coil. However, the position of warm spots will vary with the performance of the individual cabinet and its position in the retail store.

One cost-effective method of locating the position of the warmest packs can be to use thermochromic temperature indicators. However, FRPERC investigations with chill cabinets have shown that obtaining a good thermal contact between the strip and the pack is critical if sensible results are to be obtained. It is too easy to measure the air, not the pack temperature, if a good contact is not obtained. With frozen product good contact is even more important and any ice formation on the pack will exaggerate the problem.

14.4 Interpreting temperature data

With modern equipment it is quite easy to gather data on the temperature history of many points both in and around a product. Producing firm conclusions from those data is not so easy and requires a clear understanding of the process being monitored and the reason for the monitoring. The certainty of the conclusions will depend upon the number of temperatures measured, their position and their accuracy.

Each monitoring task has its own particular problems and requirements, but the following examples illustrate a number of common problems and general methods of solution.

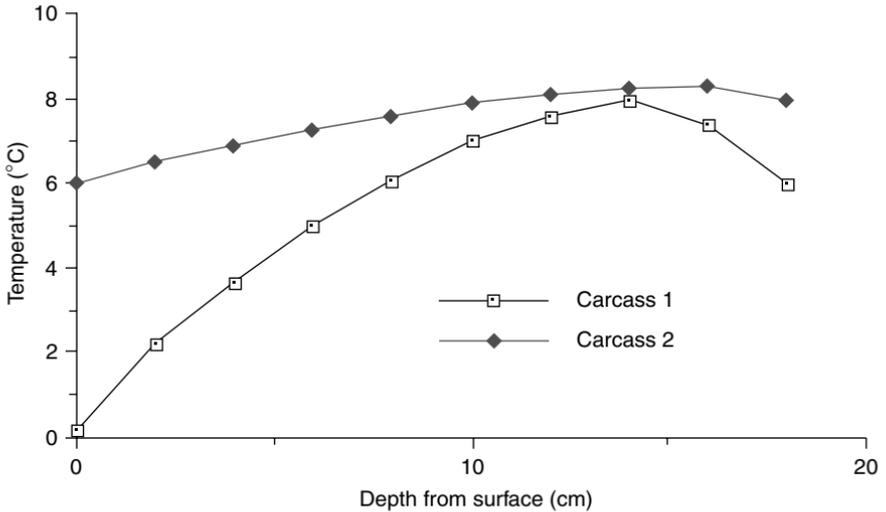
14.4.1 Example 1

EU export regulations for red meat require that the maximum temperature within a carcass side is reduced to 7°C before it is butchered or transported. Locating the maximum temperature in a side of beef is difficult, but as previously discussed it is normally found in the deep leg near the aitch bone (trochanter major). Taking measurements at different depths using a single or multi-point sensor is the best available method. Table 14.3 shows typical results from two different beef sides.

In both sides some of the temperatures are above 7°C, even allowing for an error of $\pm 0.5^\circ\text{C}$ in the values, so the meat is not chilled sufficiently to meet the regulations. However, far more useful information becomes apparent if the data are plotted (Fig. 14.3). In carcass 1 only a small volume of the meat, *ca.* 6 cm in diameter, is above 7°C and the surface is close to 0°C. If the beef side remained in the chiller for a short time longer, probably less

Table 14.3 Temperatures ($^{\circ}\text{C}$) measured after chilling at different depth in two beef sides

| Depth (cm) | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Carcass 1 | 0.2 | 2.2 | 3.7 | 5.0 | 6.1 | 7.0 | 7.6 | 8.0 | 7.4 | 6.0 |
| Carcass 2 | 6.0 | 6.5 | 6.9 | 7.3 | 7.6 | 7.9 | 8.1 | 8.2 | 8.3 | 8.0 |

**Fig. 14.3** Temperature at different depths from the surface of 2 beef carcasses.

than half an hour, it would achieve the legislative requirements. In the second side, approximately half the meat is above 7°C and the surface temperature has only been reduced to 6°C . Many hours of further cooling would be required to cool the meat fully.

Both sides had been in their respective chill rooms for over 30h when the measurements were taken. A surface temperature of 6°C in the second side points towards a high air temperature in the chill room as the most likely cause of the poor performance. In most cases a logical analysis of such data will provide the clues required to solve refrigeration problems.

14.4.2 Example 2

The importance of interpretation is demonstrated by analysing data obtained from the same relative position in two different chilled food display cabinets.

It is difficult to obtain any real impression of cabinet performance from the raw temperature data (Table 14.4). A basic analysis of the data in the

Table 14.4 Temperatures ($^{\circ}\text{C}$) measured in the same positions and at the same time intervals in 2 retail display cabinets

| Cabinet 1 | Cabinet 2 | Cabinet 1 | Cabinet 2 | Cabinet 1 | Cabinet 2 |
|-----------|-----------|-----------|-----------|-----------|-----------|
| 0.2 | 4.2 | 0.0 | 4.2 | 0.0 | 4.3 |
| 1.0 | 4.4 | 1.0 | 4.4 | 1.0 | 4.4 |
| 2.1 | 6.0 | 2.1 | 4.7 | 2.1 | 4.7 |
| 2.4 | 13.0 | 2.6 | 4.7 | 2.4 | 4.7 |
| 3.7 | 14.2 | 3.6 | 4.8 | 3.6 | 7.2 |
| 6.6 | 7.0 | 6.6 | 4.5 | 6.8 | 12.3 |
| 7.2 | 0.2 | 7.2 | 4.2 | 7.2 | 14.5 |
| 8.3 | 3.9 | 8.3 | 3.9 | 8.3 | 5.0 |
| 5.4 | 4.0 | 5.4 | 4.0 | 5.4 | -0.1 |
| 2.3 | 4.1 | 2.2 | 4.2 | 2.2 | 4.1 |
| -1.2 | 4.2 | -1.2 | 4.2 | -1.4 | 4.2 |
| 0.0 | 4.2 | 0.0 | 4.2 | 0.0 | 4.2 |
| 1.5 | 4.4 | 1.0 | 4.4 | 1.0 | 4.4 |
| 2.1 | 4.7 | 2.1 | 4.7 | 2.1 | 4.7 |
| 2.4 | 4.7 | 2.4 | 4.7 | 2.4 | 4.7 |
| 3.6 | 4.8 | 3.6 | 4.8 | 3.6 | 4.8 |
| 6.6 | 4.5 | 6.6 | 4.5 | 6.6 | 4.5 |
| 6.9 | 4.2 | 7.2 | 4.2 | 7.2 | 4.2 |
| 8.3 | 3.9 | 8.3 | 3.9 | 8.3 | 3.9 |
| 5.4 | 4.0 | 5.4 | 4.0 | 5.4 | 4.0 |
| 10.0 | 4.1 | 2.2 | 4.1 | 2.4 | 4.1 |
| 5.6 | 4.2 | -1.2 | 4.2 | -1.2 | 4.2 |

Table 14.5 Maximum, minimum, mean and standard deviation of temperatures ($^{\circ}\text{C}$) in two retail display cabinets

| | Maximum | Minimum | Mean | Standard deviation |
|-----------|---------|---------|------|--------------------|
| Cabinet 1 | 10.0 | -1.4 | 3.7 | 2.99 |
| Cabinet 2 | 14.5 | -0.1 | 4.9 | 2.40 |

table reduces each set of 66 measurements to the 4 shown in Table 14.5. Statistically there is no difference between temperatures measured in the 2 cabinets because the difference between the 2 means is far smaller than the standard deviation, which is a measure of the scatter within the measurements. However, intuitively most people would consider the first cabinet to be slightly better than the second because it has a lower mean and maximum temperature, and the minimum temperature would just avoid surface freezing of most foods.

Only when the data are plotted does the true significance of the data begin to appear (Fig. 14.4). The temperature in the first cabinet is regularly

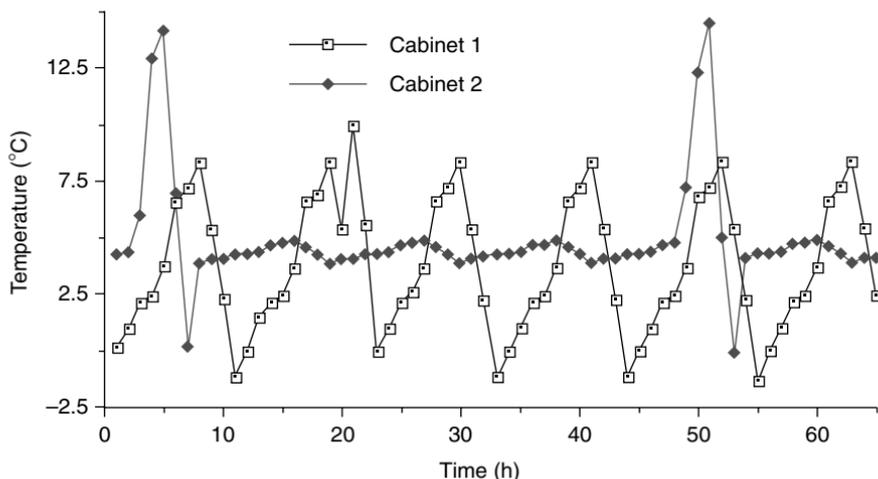


Fig. 14.4 Temperature history at points in same relative positions in 2 cabinets.

cycling by *ca.* 9°C from -1 to $+8$ °C, whilst the second cabinet spends the majority of its time at 4.4 ± 0.5 °C. The two temperature peaks probably indicate defrost periods that could be considerably reduced, if not eliminated, by correct adjustment. If further measurements revealed the same temperature pattern and degree of control throughout the cabinet, then the control setting could be adjusted to produce a maximum temperature that would substantially reduce the growth of pathogenic organisms.

14.5 Conclusions

- 1 While it may be literally true that ‘anyone can measure a temperature’ the meat industry needs to measure temperatures accurately, reliably, meaningfully, simply and cheaply.
- 2 It needs to be able to analyse the data and respond when required.
- 3 It needs the correct instrumentation and the expertise to collect and interpret the temperature data.
- 4 There is an increasing range of both simple and more sophisticated multi-point temperature measurement devices available. Monitoring the temperature of meat and meat products is therefore becoming less of a problem.
- 5 Deciding which temperatures are critical to the overall safety of the product and process, or will be needed to meet legislative requirements, is a more formidable process and requires training and expertise.
- 6 Producing firm conclusions from the data obtained is even more difficult and demands a clear understanding of the process and the reason for monitoring.

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15

Specifying, designing and optimising refrigeration systems

In specifying refrigeration equipment the function of the equipment must be absolutely clear. Refrigeration equipment is always used to control temperature. Either the meat passing through the process is to be maintained at its initial temperature, for example as in a refrigerated store or a packing operation, or the temperature of the meat is to be reduced, for example in a blast freezer. These two functions require very different equipment. If a room is to serve several functions then each function must be clearly identified. The optimum conditions needed for that function must be evaluated and a clear compromise between the conflicting uses made. The result will inevitably be a room that does not perform any function completely effectively.

There are three stages in obtaining a refrigeration plant. The first stage is determining the process specification, the second stage is drawing up the engineering specification, i.e. turning processing conditions into terms which a refrigeration engineer can understand, independent of the food process, and the third and final stage is the procurement of the plant.

15.1 Process specification

Poor design in existing chillers/freezers is due to a mismatch between what the room was originally designed to do and how it is actually used. The first task in designing such a plant is therefore the preparation of a clear specification by the user of how the room will be used. In preparing this specification the user should consult all parties concerned. These may be officials enforcing legislation, customers, other departments within the company and

engineering consultants or contractors, although the ultimate decisions taken in forming this specification are the user's alone.

15.1.1 Throughput

The throughput must be specified in terms of the species to be handled and whether they are split, whole, quartered, primal joints, and so on. If more than one species or type of cut is to be processed then separate specifications must be made for each product. The range and average weight and fatness of each product should also be specified. For example, large carcasses can take twice as long to chill as small carcasses under the same conditions, so it is important to be realistic in deciding on the weight range. To say that all types and weights of animals slaughtered are to go through one chiller or freezer will inevitably mean that compromises must be made in the design stages which will lead to an inadequate system.

A throughput profile is needed. Few meat plants slaughter the same number and weight of animals on each day of the week and therefore the average throughput is not adequate in the specification. The maximum capacity must be catered for and the chiller/freezer should also be designed to chill/freeze carcasses adequately and economically at all other throughputs.

15.1.2 Temperature requirements

The range of temperature requirements for each product must also be clearly stated. In deciding what this is or these are, several requirements, often conflicting, must be considered. First of all, what legislative requirements are there, for instance the EEC requirement at 7°C? What customer requirements are there? These may be your existing customers or they may be future customers who you are hoping to attract. What standard do you yourself have? Some companies sell a quality product under their own brand name, which should include a cooling specification. Finally it must be decided to what extent the above standards may be allowed to slip. The reason for this will become apparent later. Almost everyone in the meat industry allows their standards to slip to some extent; those that get caught and are called to task for this lose orders or have their production disrupted. These firms have turned their back on this problem and not dealt with it consciously and clearly. There are others who know well to what extent they can push the inspectors, or their customers and ensure that they stay within accepted limits.

15.1.3 Weight loss

If it is intended to save weight from the meat both during chilling/freezing and storage, it is useful to quantify at an early stage how much extra money can be spent to save a given amount of weight.

15.1.4 Future use

All the information collected so far, and the decisions taken, will be from existing production. Another question that needs to be asked is, will there be any changes in the use of the chiller/freezer in the future? In practice the answer to this question must always be 'yes'. Looking back into the past, no meat processor has remained static and within the foreseeable life of a chiller/freezer, anything between 10 and 50 years (judging by present chiller/freezer population), can any changes be envisaged and can these be quantified in as much detail as possible?

It is still not possible at this stage in the design to finalise the factory layout and operation. However, some estimate of how the factory will be operated, how it will be laid out, the size of chiller/freezer needed, and so on must be made at this point. This must be kept flexible until the engineering specification has been formulated (see later). It is common practice for the factory layout and operation to be decided in advance of writing the chilling/freezing specification. Lack of flexibility in changing these is often responsible for poor chiller performance once the factory is completed.

15.1.5 Plant layout

Chilling or freezing is one operation in a sequence of operations. It influences the whole system and interacts with it. An idea must be obtained of how the room is to be loaded, unloaded and cleaned, and these operations must always be intimately involved with those of the slaughter line, the sales team, the cutting and boning room, and the loading bay. Questions that need to be addressed include 'where will meat be sorted for orders?' and 'where will meat not sold be stored until a future date?' There is often a conflict of interests within a chiller/freezer. In practice the chiller/freezer is often used as a marshalling yard for sorting orders and as a place for storing carcasses that have not been sold. If it is intended that either of these operations are to take place in the chiller/freezer the design must be made much more flexible in order to cover the conditions needed in a marshalling area or a refrigerated store.

Meat must be loaded into and out of the freezer or chiller and the process may be continuous, batch or semicontinuous. In the case of batch and semicontinuous processes, holding areas will 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 available; a slow process will take more space than a fast process, for a given throughput. It may also be dictated by commercial constraints, such as the delivery of '1-day-old' meat to distribution outlets.

The above specifications will dictate the processing conditions. Most processes use air as a processing medium and its temperature, velocity and relative humidity are all usually critical to the process. The processes may

be in a single stage, in which case steady values will be specified, or they may be time dependent, as in a multi-stage process. In choosing the process conditions there will be an interaction with the earlier specified constraints. Some compromise may be needed, adjusting the time available for the process in order to obtain an optimal solution. Once the process conditions are fixed and the throughput and materials specified, the product load will also be fixed although this may not always be known. Where design data exist, they should be utilised to specify the product load.

Other refrigeration loads 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, the load profile is important.

The ambient design conditions must be specified. These refer to the temperatures adjacent to the refrigerated equipment and the temperatures of the ambient surroundings to which heat will ultimately be rejected. In stand-alone refrigerated processes this will often be the wet and dry bulb temperatures of the outside air. 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 a defrost does not take place and that the coil is cleared of frost before commencing this part of the process.

The above requirements should all be specified by the end-user. It is common practice throughout European industry to leave much of this specification to refrigeration contractors or engineering specialists. Often they are in a position to give good advice on this. However, since all the above are outside their control, the final decision should always be taken by the end-user, using their knowledge of how well they can control their overall process.

15.2 Engineering specification

The aim of drawing up an engineering specification is to turn the processing conditions into a specification that any refrigeration engineer can then construct and deliver without knowledge of the meat process involved. If the first part of the process specification has been completed, the engineering specification will be largely in place. It consists of 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 be drawing up a schedule for testing the engineering specification prior to handing over the equipment. This test will be in engineering and not product terms.

During this process the user must play an active part because a number of the decisions taken in this stage will affect other aspects of the operation. The specification produced should be the document that forms the basis for quotations, and finally the contract between the user and the contractor must be stated in terms that are objectively measurable once the chiller is completed. Arguments often ensue between contractors and their clients from an unclear, ambiguous or unenforceable specification. Such lack of clarity is often expensive to all parties and should be avoided.

15.2.1 Environmental conditions

The first step in this process is iterative and is shown symbolically in Fig. 15.1. First, a full range of time, temperature and air velocity options must be assembled for each cooling specification covering the complete range of each product. The list should also include future cooling specifications. Each must then be evaluated against the factory operation. For example, using a particular temperature and air speed around one product may give a chilling time to meet the temperature requirements already laid down of 18h. If the factory operation calls for maximum chilling time of only 12h then clearly the temperature/time combinations currently under review will not

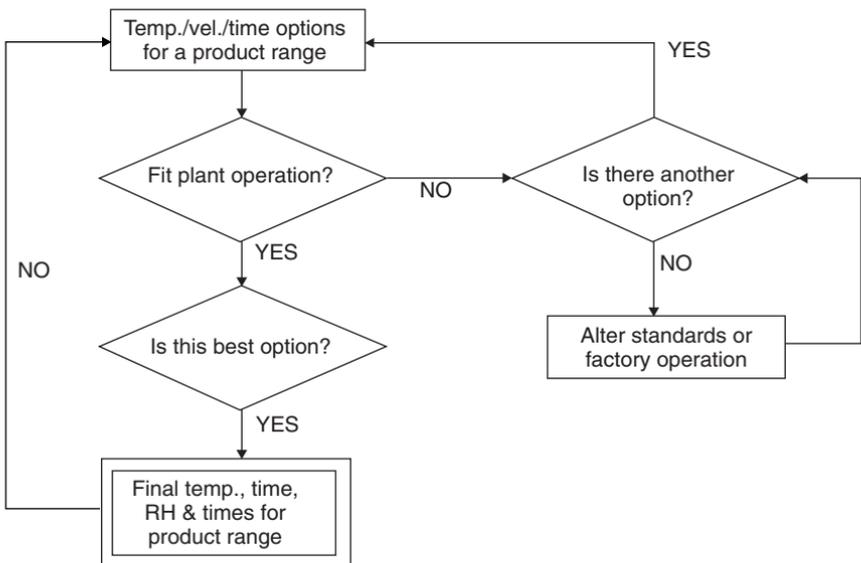


Fig. 15.1 Flow diagram for a selection of the environmental conditions.

fit. Therefore another option should be selected and the process repeated. If there are no more options available there are only two alternatives: either standards must be lowered, recognising in doing so that cooling specifications will not be met, or the factory operation must be altered.

Having found a temperature/velocity/time option that fits in with the plant operation the next question is, 'is this the best option?' All possible options must be evaluated in order to ensure that the optimum is obtained. From this a final set of times, temperatures, air speeds and relative humidities will be obtained. In a chiller/freezer intended for several uses with product going to different customers this list can be quite long and if future uses are also included it can be longer still.

15.2.2 Room size

Using throughput information from the user specification and the chilling/freezing times now worked out, the size of the room can be determined. To achieve this, the operation of the whole abattoir may have to be changed and also the flow of carcasses to and from the chiller/freezer, the position of doors, and so on.

If the size and position of the room has been rigidly fixed before this stage, the cooling times determined above will not be met.

15.2.3 Refrigeration loads

Refrigeration load calculations can now be performed, leading to a load profile for the room.

Table 15.1 shows a typical load profile for an 'imaginary' beef chiller. This chiller is to have two uses: first, to chill beef in a single stage process, and second, to store previously chilled beef sides. The product loads have been worked out for three separate conditions (in practice more may well be needed), the peak load, which will occur at the end of the loading period, the average load during chilling and the load on the room when it is used for storing previously cooled sides of beef.

The peak product load can be obtained from data provided in other chapters of this book. This load is very high and occurs for only a short period of time. The average product load is then calculated, based on the amount of heat to be extracted over the entire chilling period divided by the time available for chilling. Finally, when the room is used as a chill store there will be no product load in the room.

The infiltration load is the next most important feature yet there is little published information. The best is possibly in the ASHRAE guide. When loading a beef chiller the doors are invariably left open for long periods allowing a fully established air flow to take place to and from the room either from gravity through a single door or by a through flow of air if more than one door is open. Designers often decide that the door will only be

Table 15.1 Refrigeration loads for a beef chiller

| | Refrigeration load (kW) | | |
|-----------------|-------------------------|-----------|-----------|
| | Peak | Average | Store |
| Product load | 40 | 16.8 | nil |
| Infiltration | 17 | 0.5 | 0.5 (<17) |
| Fabric | 2 | 2 | 2 |
| People | 0.25 | nil | nil |
| Lighting | 1.5 | nil | nil |
| Evaporator fans | 6 | 6 | 6 |
| Contingency | – | 2.5 (10%) | – |
| Defrost | – | (<12) | (<12) |
| 18 h running | – | – | – |
| Totals | 66.8 | 27.8 | 8.5 (<25) |

'Peak' refers to the maximum load at the end of loading, 'average' to the load during chilling when the product is at its average value, and 'store' to the loads present when the chiller is used to store previously cooled sides.

open for short periods and that fully established airflow will never occur. However, most chiller doors stand open for *ca.* 8 h in every 24 h and they are certainly open while the chiller is being loaded. This infiltration load occurs at the same time as the peak product load, i.e. immediately at the end of the loading period, and it is therefore important that the infiltration load is added to the product load to find the maximum loading on the chiller. Experimental data obtained by FRPERC have shown that the ASHRAE calculations are approximately correct and are therefore recommended. They are often of an order of magnitude higher than figures used by designers of chill rooms. The infiltration load during chilling, when the average product load occurs, is much smaller because the door is normally closed or only opened for short intervals. It is therefore more acceptable to use quite small infiltration loads during this time to allow for air exchange through faulty door seals or for short door openings only. When the room is being used as a store, particularly if it has been unloaded, there may be periods when the infiltration load rises to maximum levels again and this has been shown in Table 15.1.

The fabric load is shown next in Table 15.1 and is insignificant compared to the previous two loadings. The same applies to the heat load imposed by people in the chiller and by lighting. Unfortunately both these loads are normally concurrent with the peak product and infiltration loads and must therefore be added to these to calculate the total peak load.

The evaporator fans also produce quite high loads. At this point in the design an approximate figure for evaporator fan power must be used but when the final design is completed and more accurate data are available, this must be substituted and the calculations reworked. In the current

example the evaporator fans are left running continuously and therefore the load is the same under peak cooling conditions as when the room is used as a store.

A contingency or safety factor is often added to the above calculations, to allow for errors. In the table of loads this has been added to the average figures, but left out when calculating the peak load. This is because the peak load occurs for only short times and errors in it have less effect than at other times.

Some designers add on an 'allowance for 18h running'. This needs some explanation. In many cooling applications the loads on the refrigeration plant are fairly constant over a day. If the refrigeration plant were installed to meet these loads then it would be running for almost 24h a day in order to meet them. This is felt to be 'bad' for the refrigeration plant and it is considered desirable that the plant should have rest periods in between run times and therefore an allowance is added to ensure this. Such an allowance is irrelevant in a batch chilling process where a peak load rapidly declines. It is also often only used as a euphemism for a (quite large) contingency.

When a room is defrosted, cooling stops and some heat is added. When the refrigeration plant reverts to cooling there is an additional heat load on the room. It is a wise precaution to ensure that defrosts do not occur at the same time that peak cooling is required and therefore no further allowance needs to be added to the peak heat loads. However, defrosts may be needed during cooling and when the room is used as a store and therefore the extra cooling has been shown in Table 15.1, but not added into the totals.

In this example of an 'imaginary' chiller the total heat load is over twice the calculated average heat load. Thus if the refrigeration plant was sized to meet only the average load it would only have half the required capacity. Another point to notice is that the load on the room, when used as a store, even when the outside temperatures are very high, is very small compared to both the peak and average loads and is for the most part due to the evaporator fans running continuously. These points will be considered in more detail below.

The load profile can now be plotted and, for the hypothetical example already discussed, is shown in Fig. 15.2. At the start of the plot the room is running with no product load and with the doors closed. The load then increases when the doors are opened and the room is washed out or possibly unloaded. Warm carcasses are then loaded into the room and the load rapidly reaches the peak product load that occurs at the end of the loading period. Thereafter, the doors are closed and the load rapidly declines. At the end of the chilling cycle, the doors are again opened to remove the carcasses and the infiltration load so caused increases. During the chilling period additional peaks occur after defrosts. Note that the plant only runs at its full or peak load for less than 4% of the time. It runs at or above half load for 25% of the time and for over 70% of the time runs at less than a quarter of its design load.

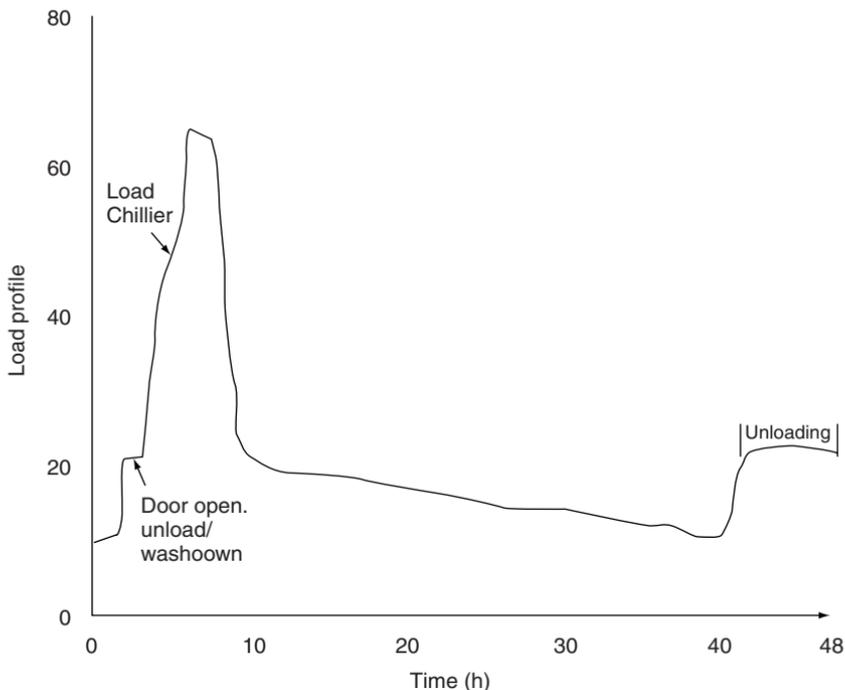


Fig. 15.2 An example of a refrigeration load profile for a beef chiller.

15.2.4 Refrigeration plant capacity

The capacity of the refrigeration plant must now be decided. Will the peak heat load be met? If so the planned chilling times and the specification agreed will be achieved. If not, the desired schedule will not be attained, but there will be a saving in the capital costs of the refrigeration plant and more economical running will be achieved since the plant will be running at less than quarter capacity for over 71% of the time. Large refrigeration plants working at low loads are very inefficient and therefore very costly to run. If a smaller plant is used, it will have a smaller turn-down ratio and its efficiency at part load, the majority of time that it will run, will be higher, therefore saving operating costs.

There are some possible solutions to the designer's dilemma. If refrigeration capacity is demanded elsewhere in the plant, but at different times, the provision of a central plant serving both facilities can make use of this diversity. It is therefore important at this stage to look at the refrigeration load profile for the entire plant – there may be blast freezers which are only operated well after the time that the peak chilling load has passed and by careful design a refrigeration plant may be installed and shared between both facilities. However, this only applies to a part of the refrigeration plant, the compressors and condensers, and not the evaporators. Another solution

is to install a plant that is smaller than needed and recalculate the extended cooling times that will occur, still meeting the chilling/freezing specification. When the refrigeration load increases above that at which the refrigeration plant can extract air, temperature in the chiller/freezer will rise. As the air temperature rises two things happen: the product load is reduced and the capacity of the refrigeration plant will increase. The effect of these two changes is that after a time a balance is achieved when the load arising from the carcasses is extracted by the plant and cooling can then continue in the normal way until the temperature is reduced back down to its original level. If data were available on cooling during pull-down it would be possible to recalculate the extended cooling periods, check whether these fitted with the other user requirements and still install a refrigeration plant which would meet an agreed specification.

Another option is to spread the loading time of the chiller/freezer over a longer period, and so reduce the peak product loads. However, this normally causes disruption in the planned operation of the abattoir, with decreasing productivity, and is therefore rarely used.

Whatever decision is taken, the peak product load that the refrigeration plant is expected to accommodate should be clearly stated in the agreed engineering specification and a load profile should also be given to ensure that the refrigeration designer provides a plant that will run efficiently over the entire product load range.

15.2.5 Relative humidity

The relative humidity in the chill room must also be defined in the engineering specification. When the chiller is empty and the latent heat load negligible, relative humidity depends upon the evaporation temperature. The wet bulb temperature will slowly be reduced until it approaches evaporation temperature, at which point no more water will be extracted from the room and the humidity will remain stable. As the latent heat load in the room increases from the loading of warm wet carcasses, the amount of water vapour evaporated increases the relative humidity in the room. The relationship between latent heat load and relative humidity depends upon two factors: the design of the evaporator coil and plant cycling. Only an infinitely deep coil will produce discharged air with a wet bulb temperature equal to the evaporator temperature. During refrigeration plant off-cycles, no water is extracted from the air and the relative humidity will rise, only to be pulled down again when the refrigeration plant is switched back on. Therefore, to obtain a high relative humidity in the room to reduce weight loss during the latter parts of chilling and storage, a high evaporation temperature and a large coil area are needed. This ensures that the refrigeration plant runs for only very short periods of time and when it is running it only extracts the minimum amount of water from the air.

Since humidity is normally only important in the latter stages of chilling,

when the load on the refrigeration plant is small, relative humidities greater than 90% can be specified. The engineering specification should specify the relative humidity under full sensible heat load, i.e. the lowest hypothetical relative humidity that can be obtained, and also under part load conditions, when advantage can be taken of the reduction in load to raise evaporation temperatures in the space.

15.2.6 Ambient design conditions

The conditions in the air outside the chiller/freezer must also be defined in the engineering specification. Both the infiltration and fabric loads are dependent on the outside temperature which therefore has an important effect on the capacity of the refrigeration plant. Ambient temperature also affects the capacity of the refrigeration plant because heat must be rejected above this temperature via a cooling tower or condenser. If it is intended that the room should function under all possible ambient conditions, very high ambient wet and dry bulb temperatures must be specified. However, these normally occur only during exceptional circumstances and, only briefly at or soon after midday. For design purposes, temperatures that are not exceeded for more than 2.5% of the total time in the year are normally acceptable and often a figure of 5% is used. Both wet and dry bulb temperatures should be specified, giving the option of using an evaporative-type of condenser or cooling tower for heat rejection to the atmosphere, which leads to a more efficient and smaller cooling plant.

15.2.7 Defrosts

The occurrence of defrosts should also be specified to avoid peak periods while still ensuring that during these peak periods the evaporator is clear of ice. It is normal in abattoirs to defrost the evaporators and the chillers at 6 hourly intervals. Although this is often desirable immediately after the peak latent heat load has been removed from the room, it is unnecessary during the later stages of cooling and when the room is used as a store. Limiting defrosts can reduce both energy consumption and weight loss during subsequent use and therefore should be included in the engineering specification.

15.2.8 Engineering design summary

The engineering specification should therefore include each of the items shown below:

- chiller, freezer air temperature, air speed and relative humidity for each product specification (covering complete range) and the time that each of these periods will be operating,

- the ambient air temperature, both wet and dry bulb,
- the load – peak, average and store,
- infiltration load, i.e. the number of doors and the time they will remain open, under what circumstances and conditions,
- evaporator and condenser temperatures.

All the conditions laid down in the engineering specification can be measured and therefore do not depend upon variation in usage or even abuse of the chiller and should therefore form the basis of a contract.

15.3 Procurement

The engineering specification should be sent out to tender. If tenders have been selected for the quality of their equipment and all accept the tender conditions and say they can meet the design and test conditions specified, the lowest tender would normally be chosen. The contractor is normally responsible for the detailed engineering design, construction and commissioning and the only need is to check that this work is carried out in a professional way. The first responsibility of the contractor is to carry out the acceptance tests. These test the performance of the refrigeration equipment in terms of the engineering specification, and the plant should not be accepted until satisfactory tests have been carried out. The plant can then be handed over and training given to the plant operators in the correct use of the refrigeration equipment. The plant then needs to be commissioned by the factory personnel, systematically increasing throughput until process tests can be carried out. These ensure that the original process specification actually achieves the intended results in terms of temperatures, throughputs and yield.

15.3.1 Plant design

Once the engineering specification has been written and agreed, the plant design is relatively straightforward. The difficult decisions have already been taken. The details of refrigeration plant design have been laid out in many other textbooks and will not be repeated here. However, one problem area is specific to carcass chillers and this is the selection of evaporators.

15.3.1.1 Evaporators

An evaporator has two functions. The first function is to remove heat and moisture from the air in order to maintain the correct design conditions. The second function is to move air around the room. Standard evaporators are designed for the first function, but the second is largely ignored and some evaporator manufacturers do not even publish information on how

their evaporators may be used for this purpose. This is partly because air movement in the room not only depends on the evaporator design but also depends on the shape of the room, position of the beams, and so on. Some general points follow.

Air movement is controlled by blowing air and not sucking; this means that it will move under the effects of dynamic or static pressure. A moving jet of air will not go on moving forward indefinitely but will be slowed down by friction against solid surfaces and by friction and entrainment of static air adjacent to it. The throw of the jet is the maximum distance that the air will move until it slows down to a specific velocity. If the air is thrown under a ceiling or along another solid surface, the coriander effect will increase the length of the flow, whereas if the air is thrown out into a void with friction on all sides, mixing and entrainment will slow the jet in a shortened distance. Any beams, light fittings or solid objects in the path of the jet will serve to deflect it and turn it in another direction and therefore have a pronounced effect upon the air movement within the space.

Air can be distributed in a space above the rails, possibly with a false ceiling or via plenums or ducts. Estimates of air movement in a chiller are sometimes based on the cross-sectional area and the volume of air passing through it. Although this gives an average velocity over that cross-sectional area it is often very deceptive since this velocity rarely occurs around the carcasses. Such calculations are more useful in designing blast freezers when a horizontal flow of air moves through a tunnel. They may sometimes be used in prechillers which function as blast chillers, similar to blast freezers with high air velocity and a large refrigeration load and consequently a large column of air movement.

In Fig. 15.3 several ways of distributing air from the evaporators around a chiller are shown. Each uses the void above the rail for primary distribution. As air is blown under the ceiling it is drawn across by the coriander effect towards the far wall. On the way air is entrained from around the carcasses and drawn into the jet until the jet expands and starts hitting the rails. This deflects a proportion of air down, around and through the carcasses. If the velocity of the jet is more than the maximum velocity required around the carcasses, by the time it reaches the far wall (throw), or another jet, a down draught will occur at that point, moving to the floor and then in turn be deflected back across the floor.

Some problems that occur arise from a conflict between the two functions of the evaporator. If it is selected to meet the peak product load, the air velocities created can be excessive, i.e. the throw will be greater than the distance from the evaporator face to a wall or jet facing it. Sometimes the situation is reversed, i.e. the throw is too small. There are several possible solutions:

- the evaporator selection can be changed to alter the discharge velocity,
- the fans can be altered from draw through to blow through or vice versa,

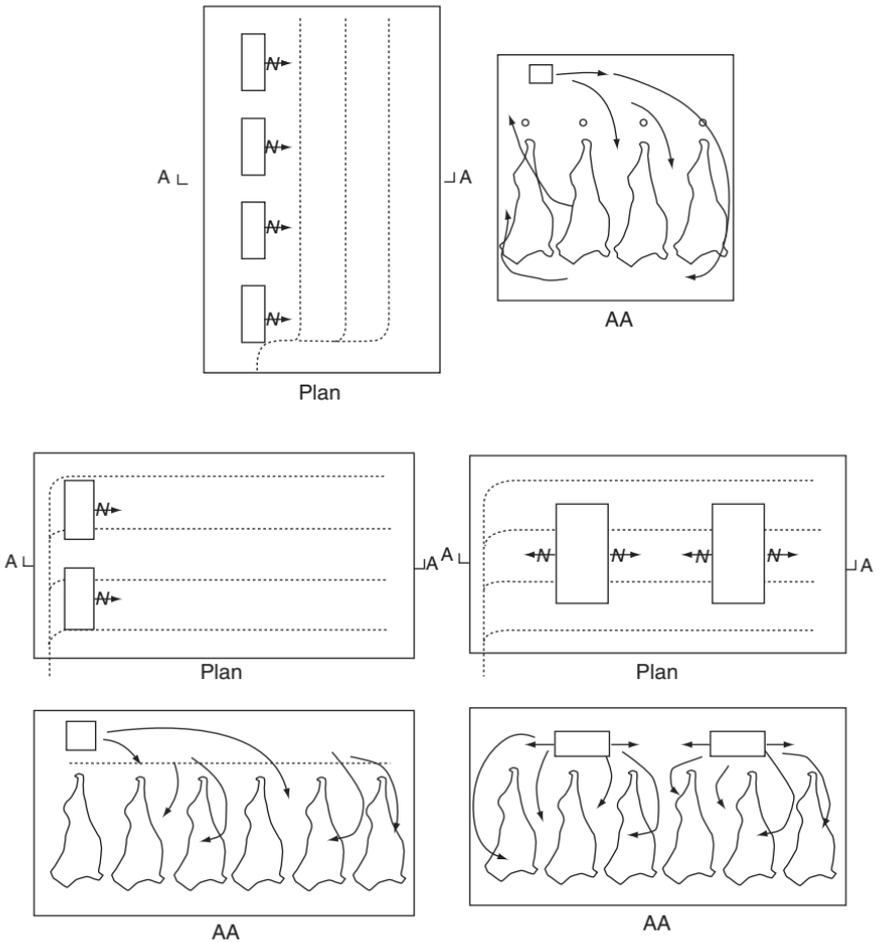


Fig. 15.3 Examples of air movement produced by different evaporator positions.

- the discharge angle of the jet can be altered,
- the position of the evaporator can be altered.

In the final design a combination of the above can be used.

However, in the authors' opinion, although there is considerable information relating to air movement there is still insufficient information available to design a uniform air velocity around *all* carcasses and it must be recognised there will be a range of air velocities in the room and hence a range of cooling conditions.

The largest refrigeration load during carcass storage and in the latter stages of cooling is that of the evaporator fans. These are selected to extract the peak-cooling load where high velocities are needed. There are several

options available to the designer to reduce excessively high air velocities during the second stage of chilling and during storage. The first is to use two-speed motors; another is to switch off a number of fans on each evaporator unit or even a number of the units. Although this will cause an uneven air distribution within the store, it has often proved adequate to maintain temperatures throughout the room during storage. Often the conflict is so great that such solutions are not possible. In these circumstances it would probably be better to design a separate refrigeration system for use when the chiller is used as a store. For instance, one refrigeration plant is designed for chilling a separate plant with a sock diffuser system used for storage, giving ideal velocities during both functions. The smaller refrigeration plant installed for storage will operate much nearer its maximum load for long periods and hence be far more efficient than the much larger chilling plant operated under the same circumstances.

15.4 Optimisation

This covers both existing and new processes. The procedure is similar in both cases with the difference that there are few constraints on new processes but there are less design data available. The first step will be definition, the next will be looking at improvements and this will be subdivided into improving process conditions and equipment and improving existing equipment and its use.

15.4.1 Process definition

The first step in the process definition is to define, in objective terms, what the process consists of. As in specifying equipment, the user must quantify the throughput, the initial and final temperatures, and any change in yield and/or temperature that is desired in the process. The next step is to measure what has actually been achieved and what process flows are needed to achieve it. The latter will consist, for example, of the amounts of water, energy, labour and so on that are required by the process.

The next step is to identify what limitations or constraints there are on the process. In existing processes this will often be the time available for the process, the space available, possibly limitations on the amount of power available and financial constraints. The final step is to compare the existing process with an ideal process as a measure of the efficiency improvement. If process design data are available they can be used to optimise the process within the constraints already listed to see how far it can be moved from its present performance towards the ideal. Often process design data are not available. For new processes these must be obtained through the use of mathematical models or pilot plant trials. In existing processes, the existing plant can be used to see the effect of changes of each variable.

Initially, only two values of each variable will be used. A theoretical analysis of the process will often indicate whether there will be an interaction between process variables. If there are, each level of a variable should be tested against each level of all other variables. Analysis of the results will indicate which variables are significant and in which direction they need to be moved. The significant variables can then be investigated more fully, often using a stepwise process, adjusting each variable slightly until the process no longer improves, then changing to the next variable and repeating the process. Final values should be evaluated in a separate trial in order to obtain a benchmark for future improvement. Often the optimum process conditions are already known but measurements in the existing process show that these are not being achieved.

A targeting and monitoring system of quality control is, therefore, required. The process variables should be monitored, the results over a significant period analysed and targets set. The results of the monitoring and the targets should be clearly indicated to the operators and maintenance staff. Subsequent monitoring usually shows a marked improvement in performance. If problems still persist then it may be that additional training of staff is required in order to improve their performance.

15.4.1.1 An example of the system in use

Customer complaints were being received by a meat processing factory that the temperature of meat being delivered was warmer than required. This prompted the factory to investigate the performance of their blast freezing operation. Initially, only the air temperatures in the blast freezer were monitored. This indicated that during the night shift staff were leaving the doors open for long periods, causing large increases in temperature. It was further realised that the temperature increased progressively during defrosts. The maintenance staff became aware that there was a serious problem with the defrosting, which was slowly building up to a crisis point. This prompted them, on their own initiative, to clear the coils completely of ice and to instigate more frequent defrosts. However, temperatures in the frozen store did not improve and it was realised that more frost was forming on the coils than had been allowed for in the initial design.

The monitoring was increased to measure the defrost water collected from the coils. The main source of frost on the coils was from infiltration through the doors to the frozen chamber. This indicated that the doors were used far more frequently than allowed for in the original design. In order to optimise the performance of the system within the constraints of the factory, a monitoring system was placed on the doors. In addition a new loading and unloading system was introduced to limit the number of door openings and the staff instructed in its use. As a result, the plant was able to deliver meat to its customers at the correct temperature. After a while, the monitoring system was allowed to lapse and with the absence of feed-

back the problem returned and customer complaints were again received. The solution was to reinstate the monitoring of the cold room doors, of the cold store air temperature and the amount of defrost water collected and to feed the results back on a regular basis to the operating staff. Because they had already been trained in the correct use of the store this was sufficient to correct the problem.

The point of this example is that defrosts are often ineffective. If the defrosts do not occur frequently enough, then the evaporator can become sufficiently blocked to impair performance. This can cause a build up of ice which it is not possible to remove within the normal defrost period. If the defrost period does not last long enough in order to remove the ice completely from the evaporator, then the same problem will occur again. Normal settings for defrost in such a room would be half an hour every 6 or 12h. It is possible that in the past the number and extent of defrosts had been insufficient in order to remove ice from the coils.

15.4.1.2 Action needed to maintain the performance of the room in the future

The user of the cold room is instructed by the contractor on how to inspect the evaporator for build up of ice. When this is first observed the user is instructed on how to force extra defrosts in order to remove the ice before it becomes a problem and impairs the performance of the temperature control of the room.

The contractor and user should agree on the maximum number and duration of door openings and the user should ensure that these opening times are not exceeded. The user of the cold store should plan the movements of frozen material in and out of the room in order to minimise the time that the cold store remains open. The roller shutter door at the front of the unit does not need to extend to the full height of the door opening. It could be stopped short at the top and louvers fitted in the remaining space above the door. The discharge condensing unit can then be ducted to discharge air directly outside, drawing fresh air back in over the unit. Thus, the air temperatures around the condensing unit can be considerably reduced.

Should the amount of time which it is considered necessary to have the cold store open for the movement of frozen goods prove to be considerably greater than that allowed for in the design, then the entrance to the cold store should be modified in order to reduce the amount of warm, moist air entering the room while the door is open. This could be effected by constructing a lobby or vestibule around the cold store, which is refrigerated to chill room conditions. Frozen material should be brought through into this chilled area first, then the door between the chilled area and the shop closed. The door between the cold store can then be opened and the material loaded from chill room into the cold store. This will reduce the amount of water vapour entering the cold store by a factor of *ca.* 70%.

15.5 Conclusions

The performance of refrigeration systems is a major source of conflict between users and refrigeration contractors. The adoption of the approach outlined in this chapter should avoid these conflicts. If performance problems occur then the approach will clearly identify which partner is responsible for sorting out the problem.

Users must accept responsibility for the process specification. They must clearly identify what they wish to achieve and take into account their expansion plans. Outside input may help them clarify their requirements and options but the final decision is theirs.

From a clearly defined process specification, an engineering specification can be written that defines the requirements in terms of the conditions that have to be produced within the refrigerated enclosure. This will define space limitations, for example, the tests to be carried out before acceptance and any monitoring/control instrumentation.

The process specification and its development into an engineering specification are the critical steps in obtaining a system that works. The rest of the procedure should follow automatically. However, the cost factor should not be forgotten. Often the initial quotations are outside the user's budget and during discussions cost savings are agreed. All too often, there is an implied change to the engineering specification and consequently to the process specification. Unless this is formally recognised and the specifications amended to take into account the change, a source of conflict in the future has been established.

Once the plant has been constructed and commissioned, routine monitoring and action when performance changes are the final key tasks in the maintenance of an optimum refrigeration system.

Secondary chilling of meat and meat products

Meat is chilled immediately after slaughter. Most of the subsequent operations in the cold chain are designed to maintain the temperature of the meat. Cooking is a very common operation in the production of many meat products and operators appreciate the importance of rapidly cooling the cooked product. However, any handling such as cutting, mixing or tumbling will add heat to the meat and increase its temperature. A secondary cooling operation is always required with chilled meat and meat products to reduce their temperature to approaching 0°C and maintain their storage life.

The aim of any cooking process for meat/meat produce is to ensure the destruction of vegetative stages of any pathogenic microorganisms. However, there is always the possibility that the cooking process will not kill some microorganisms that produce spores or that the food can become recontaminated. Therefore, microbiologists recommend that the temperature of the meat should be rapidly reduced, especially from approximately 60 and 5°C, to prevent multiplication of existing or contaminating bacteria. Rapid cooling is also desirable with cooked products to maintain quality by eliminating the overcooking that occurs during slow cooling.

There are specific cooling recommendations for cook–chill and cook–freeze catering systems. However, even with thin products these are difficult to achieve without surface freezing. Cooling large hams and other cooked meat joints is inherently a much slower process and studies have shown that companies often have very poor cooling systems.

The methods available to cool meat joints, pies and other cooked products have been described in detail by James (1990a). A review of the use of vacuum cooling in the food industry has been published by McDonald and Sun (2000).

The majority of plants rely on air blast cooling systems for the chilling of pre-cooked meat products. In batch systems the products, packs or trays of cooked material are placed directly on racks in the chiller or on trolleys that can be wheeled into the chiller when fully loaded. Continuous systems range from trolleys pulled through tunnels to conveyorised spiral or tunnel air blast chillers.

Some meals and products are chilled using cryogenic tunnels, however, care must be taken to avoid surface freezing. Imperviously packed products can be chilled by immersion in cooled water or other suitable liquid. With some cooked products such as large hams in moulds and sausages, chlorinated water sprays can be used in the initial stages of cooling. Increasingly, pie fillings are pressure-cooked and vacuum cooled. With many products an initial cooling stage using ambient air can often substantially reduce the cooling load in the cooling system.

16.1 Cooked meat

16.1.1 Legislation

In the UK the Food Safety (Temperature Control) Regulations (1995) apply to any food that 'is likely to support pathogenic micro-organisms or the formation of toxins' and that must be kept at or below 8°C. Regulation 11 does not define a cooling time or rate, only that the food should be cooled *as quickly as possible* following the final heating stage.

The guidance document to the above regulations produced by the Department of Health is even less specific. Under heading VIII, cooling of food, paragraph 47 it states: 'The cooling period for any food would not be regarded as unacceptable merely because other equipment, not present at the business, could have cooled the food more quickly. The time taken to achieve cooling must be consistent with food safety. Cooling will often be a step which is critical to food safety'.

The Meat Products (Hygiene) Regulations (1994) contain special conditions for meat-based prepared meals. They require that the meat product and the prepared meal shall be refrigerated to an internal temperature of +10°C or less within a period of not more than 2h after the end of cooking. However, they then go on to state that produce may be exempt from the 2h period where a longer period is justified for reasons connected with the production technology employed. The wording is similar in the EC Meat Products Directive.

In the USA the essential rules of the US Regulations (318.17 9 CFR CH III, 1.1.96 edition) on safe cooling of cooked meats are:

- Chilling shall begin within 90 min after the cooking cycle is completed.
- All products should be chilled from 48.8°C to 12.7°C in no more than 6h.

Table 16.1 Recommended good practice and maximum cooling times for uncured meat

| Cooling time (h) | Good practice | Maximum |
|-------------------|---------------|---------|
| To 50°C | 1 | 2.5 |
| From 50°C to 12°C | 6 | 6 |
| From 12°C to 5°C | 1 | 1.5 |
| Total time to 5°C | 8 | 10 |

Source: Gaze *et al.*, 1998.

Table 16.2 Recommended good practice and maximum cooling times for cured meat

| Cooling time (h) | Good practice | Maximum |
|-------------------|---------------|---------|
| To 50°C | 1.25 | 3.25 |
| From 50°C to 12°C | 7.5 | 7.5 |
| From 12°C to 5°C | 1.25 | 1.75 |
| Total time to 5°C | 10.00 | 12.50 |

Source: Gaze *et al.*, 1998.

- Chilling shall continue and the product should not be packed for shipment until it has reached 4.4°C.

These US Federal Regulations have been widely adopted outside areas under the control of the USDA, including by European retailers. Further recommendations have been made by Gaze *et al.*, 1998. Their main recommendations are that:

- ‘For a typical uncured cooked meat product, made from good quality raw material under hygienic conditions and with sound process controls, it is suggested that the following limitations (Table 16.1) for cooling time from completion of the cooking process should apply.’
- ‘For products which are cured (defined as minimum 2.5% salt on water phase and 100 ppm nitrite in-going), these times may be extended (Table 16.2). As an approximation it is suggested this be by 25%.’

16.1.2 Practical

In many industrial cooking operations whole hams and large meat joints are often cooked and cooled in an intact form and then supplied to restaurants or retail shops where they are sliced before sale. Surveys (Cook, 1985; James, 1990b and c; Gaze *et al.*, 1998) have shown that industry uses a variety of methods for cooling whole hams (Table 16.3, Table 16.4 and Table 16.5). In these processes the earlier data showed that cooling times were as long

Table 16.3 Examples of commercial ham cooling in the UK

| Cooling method | Weight (kg) | Height of joint (cm) | Cooling time to 20°C (h) | Total (h) | Final temperature (°C) |
|--|-------------|----------------------|--------------------------|-----------|------------------------|
| In metal mould in chill room 17°C to 6°C, 0.2 ms ⁻¹ | 6.4 | 19 | 12 | 1.4 | 15 |
| In bag in chill room -3°C to -10°C, 0.3 ms ⁻¹ | 7.3 | 18 | 9.3 | 21 | 2 |
| In bag water shower then chill room at -1°C then 3°C to 5°C | 6.8 | 18 | 6.6 | 14 | 5 |
| In bag in ambient 15°C to 7°C | 6.8 | 20 | - | 13.5 | 24 |

Source: James, 1990c.

as 21 h, and final temperatures high: 15–20°C (Table 16.3, Table 16.4). In the later study cooling times were still as long as 16 h but final temperatures were no higher than 8°C (Table 16.6).

A similar picture is seen in data on the cooling of cooked pork with final temperatures as high as 12°C and cooling times of up to 20 h (Table 16.4). Corresponding figures for the cooling of cooked beef were 15°C and 22 h (Table 16.4). Data obtained from numerous sources within the UK catering industry by Mottishaw (1986) indicate that the cooling procedures for bulk-cooked meats could also vary considerably (Table 16.6). For example, some meat products are said to be cooled to 1°C in 2 h, whereas at the other extreme, products may take 72 h to cool to 4°C. Commonly, a 4.5 kg product will take 12 h to cool below 5°C and larger products could take longer. In addition, there is often a delay before chilling begins, this may vary from 10 min up to 6 h.

16.1.3 Experimental studies

The most relevant cooling data for cooling of cooked meat from laboratory investigations are shown in Table 16.7. A simple process for estimating the immersion cooling time of beef roasts has been produced by Nolan (1986). Generally, the results show that immersion cooling is almost twice as fast as air cooling at the same temperature. Vacuum cooling was an order of magnitude faster than immersion cooling but the weight loss was substantially (over twice) higher. Using a less severe vacuum treatment or a combination of the different methods is likely to provide an optimum solution.

The James and Bailey (1982) study showed that in ham cooling, a 0.75 h initial cooling period in ambient air reduced the initial load on the refrigeration by a factor of almost 2. If the ham was placed straight into air at

Table 16.4 Previously unpublished survey data on cooling of cooked meat in industry and shops

| Meat | Wt kg | Diam mm | Method | Wrap | Initial temp °C | Time (h) to 50°C | 10°C | Final temp/time | | | | | | | | |
|-------|-------|---------|--|-------------|-----------------|------------------|-------------------------------|-----------------|------|-----|--------------------------------------|--------|----|-----|-----|-----|
| Ham | 6.35 | 191 | Chill room 17–6°C 0.2 ms ⁻¹ | Metal mould | 71 | 3.6 | – | 15/14 | | | | | | | | |
| | | | | | 70 | 3.8 | – | 15/14 | | | | | | | | |
| | 7.26 | 178 | Chill room –3/–1°C 0.3 ms ⁻¹ | Sealed bag | 69 | 3.8 | 12.7 | 2/21 | | | | | | | | |
| | | | | | 68 | 3.4 | 12.5 | 2/21 | | | | | | | | |
| | 6.80 | 203 | Shop air 15–7°C <0.2 ms ⁻¹ | Sealed bag | – | 4.8 | 20.0 | 9/21 | | | | | | | | |
| | | | | | – | 4.7 | 20.0 | 9/21 | | | | | | | | |
| | | | | | 69 | 3.7 | – | 24/13.5 | | | | | | | | |
| | | | | | 75 | 4.2 | – | 21/13.5 | | | | | | | | |
| | | | | | 75 | 4.7 | – | 23/13.5 | | | | | | | | |
| | | | | | 75 | 4.3 | – | 22/13.5 | | | | | | | | |
| Bacon | 6.80 | 178 | Shower 20 min, chill 3/5°C 4 h | Sealed bag | 72 | 2.6 | 9.3 | 5/14 | | | | | | | | |
| | | | | | 76 | 1.9 | – | 14/12.5 | | | | | | | | |
| | 4.54 | 114 | Factory air, 20–12°C | Bag | 71 | 2.6 | – | 15/13.5 | | | | | | | | |
| | | | | | 76 | 2.7 | – | 16/13.5 | | | | | | | | |
| Pork | 6.80 | 203 | Shower 20 min, chill –1°C 4 h, chill 3/5°C | Bag | 77 | 2.2 | 6.8 | 5/12 | | | | | | | | |
| | | | | | 79 | 2.2 | 7.2 | 5/12 | | | | | | | | |
| | 5.44 | 165 | Shop 30–20°C 7 h, chill 18–6°C | Bag | 82 | 4.5 | 19.5 | 12/20 | | | | | | | | |
| | | | | | 2.04 | 76–101 | Kitchen 22°C 2 h, chill 2/5°C | Uncovered | 100 | 2.0 | 5.9 | 4/7.5 | | | | |
| | | | | | | | | | 100 | 1.9 | 5.5 | 4/9.0 | | | | |
| Beef | 5.90 | 165 | Kitchen 23°C 1.5 h, chill 13–5°C | Netted | 93 | 2.4 | 13.0 | 9/15 | | | | | | | | |
| | | | | | 70 | 2.6 | 11.0 | 0/16 | | | | | | | | |
| | 6.80 | 152 | Chill 20–0°C | Netted | 75 | 4.4 | 22.0 | 15/22 | | | | | | | | |
| | | | | | | | | | 75 | 4.4 | 22.0 | 15/22 | | | | |
| | – | 101 | Blast chill –5/–3°C 1.2 ms ⁻¹ | Uncovered | 90 | – | 3.4 | 7/3.9 | | | | | | | | |
| | | | | | | | | | 3.86 | 127 | Blast chill 4/5°C 2 ms ⁻¹ | Netted | 73 | 1.7 | 5.3 | 5/7 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | 3.40 | 127 | Chill 1/2°C 0.3 ms ⁻¹ | Netted | 71 | 1.9 | 6.8 | 9/7 |
| 3.63 | | | | | | | | | | | | | | | | |

Table 16.5 Examples of commercial ham cooling in the UK

| Cooling method | Cooling time (h) | | Temperature (°C) | |
|--|------------------|---------|------------------|-------|
| | Total | To 10°C | Initial | Final |
| In casings and moulds in batch air chillers at -1°C, 0.93 ms ⁻¹ | 16 | 7 | 65 | 4 |
| In casings and moulds in forced air at 0°C | 8 | | 70 | 3 |
| Dry cured hams in conveyorised system using refrigerated brine | 10 | 6 | 75 | 3 |
| Premium hams in conveyorised system using refrigerated brine | 14 | 6 | 75 | 3 |
| Rind-on hams in conveyorised system using refrigerated brine | 8 | 5.5 | 75 | 5 |
| Chill room with moderate air movement | 5 | 3.5 | 73 | 3 |
| In static air in a refrigerator | 15 | 10.5 | 80 | 8 |
| Revision of above. Immersion in ambient water followed by moving air | 8 | 5 | 78 | 0 |

Source: CCFRA survey, 1995.
Interpolated data from cooling plots.

Table 16.6 Summary of previously unpublished survey data on cooling of cooked meat in industry and shops

| Joint size | | Time (h) to 60°C | Time (h) to 50–10°C | Temp (°C) | Time (h) |
|-------------------------------|---------|------------------|---------------------|-----------|----------|
| 5.44–7.26 kg, 178 mm diameter | Average | 2.4 | 10.6 | 11.4 | 15.6 |
| | Range | 0.9/3.5 | 4.6/17.6 | 2/24 | 12/22 |
| 3.63–4.54 kg, 114 mm diameter | Average | 1.4 | 3.8 | 10.5 | 8.6 |
| | Range | 1/1.7 | 2.3/5.3 | 5/15 | 4/13.5 |
| 1.81–2.27 kg, 76 mm diameter | Average | 1.5 | 3.7 | 4 | 8.3 |

Microbiologically acceptable: 5 h 50–10°C, 12 h 10–1°C.

-2°C it released 220 Wh in the first hour compared with 118 Wh after 0.75 min in ambient air. In this case a period of ambient cooling would substantially reduce the peak heat load on the refrigeration system. Alternative methods of cooling are also available. A double cabinet cryogenic batch cooler has been used to cool cooked roast, smoked pork loin and smoked ham from 65°C to below 10°C with a weight loss of >0.5%.

Table 16.7 Cooling times (h) for meat joints from published sources

| Ref. | Cooling regime | 70–50 °C | 50–12 °C | 12–5 °C | 70–5 °C | 70–8 °C |
|------|--|----------|----------|---------|---------|----------|
| | Good practice | 1 | 6 | 1 | 8 | |
| | Maximum | 2.5 | 6 | 1.5 | 10 | |
| 1 | 3.75 kg vacuum packed beef roasts 330 × 160 × 130 mm | | | | | |
| | Vacuum | 0.1 | 1.4 | 0.9 | 2.4 | 2.1 |
| | Air 1 ± 1 °C | 1.5 | 4.2 | 2.8 | 8.5 | 6.9 |
| | Air 1 ± 1 °C, 2 ms^{-1} | 1.2 | 3.5 | 2.9 | 7.6 | 6.1 |
| | Air 1 ± 1 °C, 1 ms^{-1} | 1.5 | 4.2 | 4.6 | 10.3 | 8.1 |
| 2 | 7 kg hams in metal moulds | | | | | |
| | Air -2 °C, 5 ms^{-1} | 2.4 | 3.8 | 2.6 | 9.0 | 7.2 |
| | 0.75 h at 15 °C then -2 °C, 5 ms^{-1} | 3.0 | 4.0 | 2.9 | 9.9 | 7.9 |
| 3 | 5–5.5 kg (11–12 lb) ham logs 400 × 120 × 120 mm in metal moulds | | | | | |
| | 30 m water spray at 18 °C then air 0 °C, 3 ms^{-1} top rack | 0.6 | 4.0 | 2.1 | 6.7 | 6.0 |
| | 30 m water spray at 18 °C then air 0 °C, 3 ms^{-1} bottom rack | 0.4 | 3.9 | 2.2 | 6.5 | 5.5 |
| 4 | 0.94 kg beef slabs, 50 mm thick | | 50–10 °C | | | 70–10 °C |
| | Air 0 °C, 1.2 ms^{-1} | | 1.7 | | | 2.1 |
| | Water 0 °C | | 1.0 | | | 1.2 |
| | Vacuum | | 0.6 | | | 0.6 |
| | 2.7 kg rolled beef forequarter, 110 mm dia. | | | | | |
| | Air 0 °C, 1.2 ms^{-1} | | 4.4 | | | 5.1 |
| | Water 0 °C | | 3.1 | | | 3.6 |
| | Vacuum | | 0.3 | | | 0.4 |
| | 2.7 kg rolled beef silverside, 110 mm dia. | | | | | |
| | Air 0 °C, 1.2 ms^{-1} | | 4.0 | | | 4.9 |
| | Water 0 °C | | 2.6 | | | 3.1 |
| | Vacuum | | 0.6 | | | 0.7 |
| | 6.4 kg boned out turkey | | | | | |
| | Air 0 °C, 1.2 ms^{-1} | | 5.4 | | | 6.6 |
| | Water 0 °C | | 4.6 | | | 5.6 |
| | Vacuum | | 0.2 | | | 0.3 |
| | 7.1 kg boned out ham | | | | | |
| | Air 0 °C, 1.2 ms^{-1} | | 8.9 | | | 10.4 |
| | Water 0 °C | | 4.8 | | | 5.9 |
| | Vacuum | | 0.5 | | | 0.5 |

Sources: 1. McDonald *et al.* (2000); 2. James and Bailey (1982); 3. Anon (1987); 4. Burfoot *et al.* (1990).

16.2 Pastry products

16.2.1 Commercial operations

Although it should be a far simpler and quicker operation to reduce the temperature of small individual items, such as meat pies, many manufacturers allow an inadequate length of time for the cooling operation and the products are packaged at temperatures substantially above the storage value. After wrapping and boxing it is very difficult to remove the residual heat. Typically, pie manufacturers allow 1 h for their single-stage cooling operations and the core temperature of pies before packing can range from 17 to 37°C (Table 16.8).

The surface temperature of cooked products is very high when they leave baking ovens and consequently the difference between the surface and the ambient is very large at this time. To reduce energy usage and costs a number of manufacturers operate two-stage cooling operations utilising ambient air followed by sub zero air in the second stage (Table 16.10). Comparing the data from the first two examples in Table 16.9 and Table 16.10 it can be seen that similar final product temperatures are produced in the single- and two-stage cooling processes. The use of very low temperatures during single-stage cooling operations can produce quality problems due to freezing of the pastry at the surface of the products. In addition with some baked products manufacturers believe that the quality of the pastry suffers if taken below 10°C. One minced beef pie manufacturer used air at 12°C in the second stage of a two-stage cooling process to avoid this problem (Table 16.10). However, even when the cooling time was increased by 25%, the core temperature of the pie was 20°C at the packing stage. In two factories, large pies (4.5 kg) were also produced for catering use or to be sold after

Table 16.8 Examples of commercial single-stage cooling of pastry products in the UK

| Product | Type of chiller | Air | | Cooling time (h) | Temperature | |
|------------------------------|-----------------|------------|------------------------------|------------------|--------------|------------|
| | | Temp. (°C) | Velocity (ms ⁻¹) | | Initial (°C) | Final (°C) |
| Steak and kidney pie (185 g) | Spiral | -11/-17 | 0.5 | 1.0 | 90-95 | 17-20 |
| " | Spiral | -3 | 3-5 | 1.0 | 90-95 | 17-20 |
| " | Cold store | -30 | <0.2 | 1.0 | 90-95 | 30 |
| " | Ambient | 20 | 0.3 | 1.0 | 90-95 | 37 |
| " | Ambient | 20 | 3.5 | 1.0 | 90-95 | 32 |
| Sausage rolls | Spiral | -11/-17 | 0.5 | 0.8 | 93-96 | 10 |
| Pork pie (4.5 kg) | Ambient | 16-23 | <0.2 | 8.0 | 68 | 25 |

Source: James, 1990c.

Table 16.9 Examples of commercial two-stage cooling of pastry products in the UK

| Product | Type of chiller | Air | | Cooling time (h) | Temperature | |
|------------------------------|-----------------|------------|------------------------------|------------------|--------------|------------|
| | | Temp. (°C) | Velocity (ms ⁻¹) | | Initial (°C) | Final (°C) |
| Steak and kidney pie (185 g) | Ambient | 20 | 3–5 | 0.33 | 93 | – |
| | Spiral | –3 | 2 | 0.67 | – | 17–20 |
| " | Ambient | 20 | 3–5 | 0.33 | 93 | – |
| | Spiral | –3 | 0.3–1.4 | 0.67 | – | 22 |
| | Ambient | 20 | 0.3 | 0.33 | 93 | – |
| | Spiral | –3 | 2 | 0.67 | – | 24–27 |
| Minced beef pie (140 g) | Ambient | 20 | <0.2 | 0.16 | 96 | 80 |
| | Chill room | 12 | 1 | 1.08 | 80 | 20 |
| Gala pie (4.5 kg) | Ambient | 20 | <0.2 | 1.75 | 96 | 76 |
| | Chill room | 0 | <0.4 | 6.5 | 76 | 10 |

Source: James, 1990c.

slicing from delicatessen outlets. In a single-stage ambient cooling operation the centre temperature was still 25 °C (Table 16.8) after 8 h; however in the two-stage process the centre of the pie had been reduced to 10 °C after 6.5 h (Table 16.9).

16.2.2 Experimental studies

Data from the most relevant experimental studies on pie cooling are shown in Table 16.10. The importance of achieving a minimum required air velocity around small products was clearly demonstrated by data obtained from cooling pork pies (Fig. 16.1). To guarantee that all the crust remained above –2 °C on the unwrapped 400 g (70 mm high, 95 mm diameter) pies an air temperature of –1.5–±0.5 °C was used. At this temperature a small increase in air velocity from 0.5 to 1.0 ms⁻¹ reduced the cooling time by 85 min (almost 30%). Even at very high velocities (>6.0 ms⁻¹) appreciable reductions in cooling time were still being achieved. In a high throughput baking line (>1000 items per hour) the 7% increase in throughput, which would be achieved by raising the air velocity from 6 to 10 ms⁻¹ and consequently reducing the cooling time by 10 min, could justify the higher capital and running costs of larger fans. With larger pies cooling times of up to 6 h have been measured (Fig. 16.2). Only one reference (McDonald and Sun, 2000) to the vacuum cooling of pork pies has been located. This quotes a cooling time for 0.5 kg pies from 80 to 10 °C of over 8 h.

Table 16.10 Published data on the cooling of pork pies

| Reference | Pie weight (g) | Conditions | Time to 5°C (h) |
|-----------|----------------|--|-----------------|
| 1 & 2 | 75 | 20°C still air for 60 min jelly then 7°C until centre at 10°C then -20°C, 0.5 ms ⁻¹ | 3.0 |
| | | 20°C still air for 60 min jelly then -10°C, 5 ms ⁻¹ | 1.5 |
| | | 20°C still air for 60 min jelly then -20°C, 0.5 ms ⁻¹ | 1.6 |
| | | 20°C still air for 60 min jelly then 1°C, 0.5 ms ⁻¹ | 2.3 |
| | | 20°C still air for 70 min jelly then -30°C, 5 ms ⁻¹ | 2.9 |
| | | 0°C, 3 ms ⁻¹ for 63 min jelly then -30°C, 5 ms ⁻¹ | 2.6 |
| 3 | 235 | -1°C, 3 ms ⁻¹ | 1.5 |
| | 450 | -1°C, 3 ms ⁻¹ | >2.5 |
| | 900 | -1°C, 3 ms ⁻¹ | >6 |
| 4 | 450 | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 4 ms ⁻¹ | 3.2 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 10 ms ⁻¹ | 2.9 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -4°C, 4 ms ⁻¹ | 3.0 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 10 ms ⁻¹ | 2.6 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -10°C, 4 ms ⁻¹ | 2.5 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -10°C, 10 ms ⁻¹ | 2.2 |
| 5 | 450 | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 0.5 ms ⁻¹ | 4.6 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 1 ms ⁻¹ | 3.6 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 6 ms ⁻¹ | 2.9 |
| | | 17°C, 2 ms ⁻¹ for 38 min then -1.5°C, 10 ms ⁻¹ | 2.6 |

Sources: 1. Evans & Gigiel (1989a); 2. Evans & Gigiel (1989b); 3. James (1990b); 4. James *et al.* (1987); 5. James (1990c).

16.3 Solid/liquid mixtures

Meat slurries, mixtures of solid meat and a gravy/sauce are commonly used as pie/pasty fillings and a growing range of ready meals. Surveys have shown that many companies have problems in cooling meat slurries (Table 16.11) and in the centre of large vats of pie fillings, for example, cooling rates can be as slow as 2°C per hour. Subsequent laboratory studies showed that large

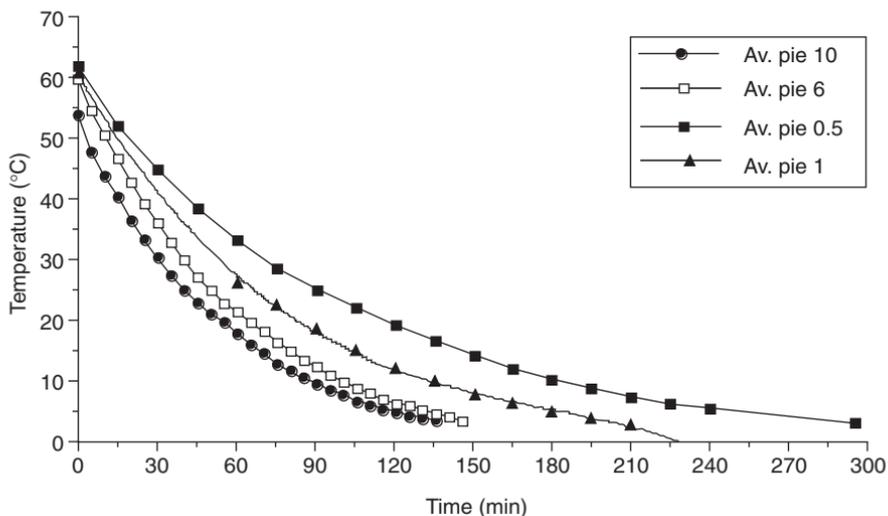


Fig. 16.1. Temperature at slowest cooling point in 400 g pork pies in air at -1.5°C and 10, 6, 1 and 0.5 ms^{-1} .

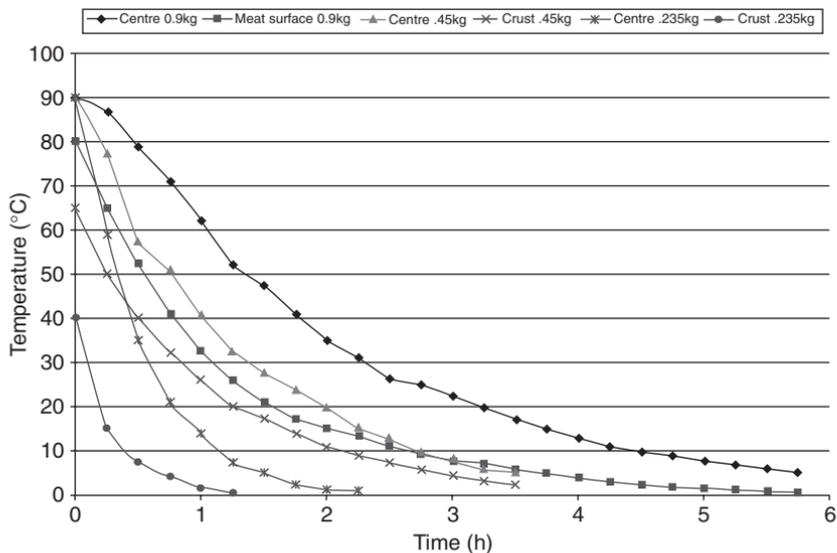


Fig. 16.2. Cooling of 0.235, 0.45 and 0.9 kg pork pies in air at -1°C , 3 ms^{-1} (source: James, 1990c).

Table 16.11 Examples of commercial cooling of meat slurries and soups in the UK

| Cooling method | Depth of slurry (cm) | Cooling time | | Temperature (°C) | |
|--|----------------------|--------------|-----------|------------------|-------|
| | | To 20°C (h) | Total (h) | Initial | Final |
| In ambient at 23°C in 0.6 m ³ vats | 50 | – | 16 | 99 | 64 |
| In 0.6 m ³ vats with cold water jacket then ambient at 21°C | 50 | – | 14 | 99 | 38 |
| In 38 cm diameter pans in chill room at 2 to 9°C | 17 | 9.8 | 16 | 93 | 12 |
| In 35 cm deep bucket at 20°C for 7 h then 7°C | 30 | 17.5 | 18 | 55 | 18 |

Source: James, 1990c.

1100 kg batches of meat sauce could be cooled from 85 to 10°C in less than 30 min using a vacuum cooling system. When a conventional blast air system was used the cooling time achieved was related to the product depth and even when the depth had been reduced to 70 mm the cooling time was in excess of 6.5 h.

16.4 Process cooling

Traditionally, ice has been added to meat mixtures during mixing and grinding to maintain their temperature. Liquid nitrogen (LN₂) can also be used to maintain the temperature of meat during mixing thus increasing the extraction of soluble muscle proteins. LN₂ or CO₂ can also be used to chill restructured meat during mixing and cutting to –3°C in approximately 10 to 15 min. Jowls and bacon fat in 1400 kg batches can be mixed and cooled from 7.3 to 0°C within 12 min. The system uses a cycle of 50 s LN₂ and mixing then 15 s mixing only to allow temperature equalisation. Cryogenic systems are also available to maintain temperatures during tumbling. In cooked ham manufacture the use of liquid nitrogen was claimed to reduce meat dust during tumbling, substantially shorten the process time and improve hygiene.

16.5 Cook–chill

The term ‘cook–chill’ usually refers to a catering system where food is prepared, cooked and cooled in a central facility before being distributed to

the place where it will be reheated and consumed. The term is equally applicable to the system of producing chilled ready meals for retail sale. Sales of chilled ready meals reached £973m in the UK in 2001 (www.chilledfood.org) and continue to rise. Within this market growth there is a strong move towards greater variety, with ethnic meals showing the fastest increase. This has meant that more meals than ever before are being produced by manufacturing facilities operating cook–chill systems, using a wide range of production methods and equipment.

16.5.1 Cook–chill guidelines

Cook–chill systems are normally used to supply food in institutional (hospitals, schools, canteens, etc.) catering operations. Normally the food is cooked and cooled under near industrial conditions. It is stored and transported to the institution under refrigeration and reheated (not cooked) before serving.

One of the key elements to a successful cook–chill operation is the strict monitoring and control of temperature throughout. Cooking rarely eliminates all food poisoning organisms and a number survive as spores that will germinate and grow if cooling rates are slow. In the UK the Department of Health Cook–chill Guidelines published in 1989 recommend maximum cooling regimes and the use of special equipment to rapidly reduce product temperatures after cooking. Many other countries in Europe have similar guidelines or recommendations for the cooling of cooked products (Table 16.12).

The UK Guidelines recommend that joints of meat or packs of food should not exceed 2.5 kg or 100 mm in thickness or height. It is also advised that containers have lids to help prevent contamination and to minimise dehydration during cooling. The Guidelines also state that the actual chilling process should commence as soon as possible after completion of cooking and certainly within 30 min of leaving the cooking process (this is to allow for portioning of meals). Smaller portions (less than 50 mm deep) should be chilled to between 0 and 3 °C within 90 min and larger portions

Table 16.12 Chilling time requirements for cooked foods in different countries

| Country | Chilling times | Chilling rate (°C/min) | Storage temperature (°C) |
|---------|--|------------------------|--------------------------|
| Denmark | from 65 °C to 10 °C in 3 hours | 0.31 | <5 °C |
| France | from 70 °C to 10 °C in 2 hours | 0.50 | 0–3 °C |
| Germany | from 80 °C to 15 °C in 2 hours (from 15 °C to 2 °C in 24 hours) | 0.54 | 2 °C |
| Sweden | from 80 °C to 8 °C in 4 hours | 0.30 | 3 °C |
| UK | from 70 °C to 3 °C in 1.5 hours | 0.74 | 3 °C |

to 10°C within 2.5 h after removal from the cooking process. Rapid cooling is also often desirable with cooked products to maintain quality by eliminating the overcooking that occurs during slow cooling.

The equipment used to chill products should have performance specifications such that it is capable of reducing the temperature of a 50 mm thick layer of food from 70 to 3°C (or less) in a period not exceeding 90 min when fully loaded. Air blast chillers are commonly used; to prevent freezing of the product, cooling air temperatures cannot be much below 0°C. Air temperatures from around -4°C to -2°C at speeds from 4 to 6.5 ms⁻¹ are commonly employed (Heap, 2000; Trott, 1989). However, there is little, if any, published data on the conditions required to achieve these times when cooling different cooked products.

16.5.2 Practical cooling time data

Investigations have been carried out into air blast cooling of bolognese meat sauce in metal trays of different depths but having the same lateral dimensions (Evans *et al.*, 1996). These trials showed that, assuming surface freezing was to be avoided and a simple single-stage operation used, only 10 mm depth of product could be chilled within these limits (Table 16.13).

A computer model was also developed which showed that other foods

Table 16.13 Cooling time to 10 and 3°C in trays with (without) lids under different cooling systems

| Tray depth (mm) | Flow regime | Initial temperature (°C) | Cooling times to 10°C (h) | | Cooling times to 3°C (h) | |
|-----------------|--------------------------|--------------------------|---------------------------|----------------|--------------------------|----------------|
| | | | Experimental | Vertical model | Experimental | Vertical model |
| 80 | Air 0.5 ms ⁻¹ | 70 | 11.9 (9.4) | | 19.3 (15.2) | |
| | Air 3.0 ms ⁻¹ | 70 | 6.4 (5.4) | | 10.5 (8.9) | |
| | Brine low | 65 | 4.60 | 3.24 | 7.31 | 5.07 |
| | | 80 | - | 3.53 | - | 5.37 |
| | Brine high | 65 | - | 3.21 | - | 5.02 |
| | | 80 | 4.93 | 3.51 | 7.83 | 5.32 |
| 40 | Air 0.5 ms ⁻¹ | 70 | 6.0 (4.3) | | 9.8 (6.9) | |
| | Air 3.0 ms ⁻¹ | 70 | 2.9 (2.9) | | 4.7 (3.3) | |
| | Brine low | 65 | 1.51 | 0.92 | 2.57 | 1.43 |
| | | 80 | - | 1.00 | - | 1.52 |
| | Brine high | 65 | - | 0.90 | - | 1.41 |
| | | 80 | 1.59 | 0.99 | 2.63 | 1.50 |
| 10 | Air 0.5 ms ⁻¹ | 70 | 1.5 (1.0) | | 2.2 (1.7) | |
| | Air 3.0 ms ⁻¹ | 70 | 0.8 (0.5) | | 1.2 (0.7) | |
| | Brine low | 65 | 0.22 | 0.10 | 0.35 | 0.16 |
| | | 80 | - | 0.11 | - | 0.17 |
| | Brine high | 65 | - | 0.09 | - | 0.15 |
| | | 80 | 0.21 | 0.10 | 0.34 | 0.16 |

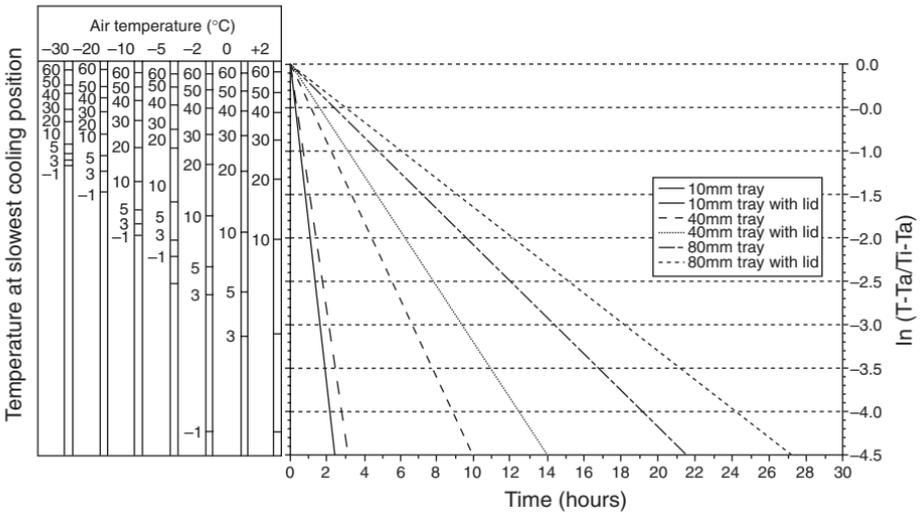


Fig. 16.3. Time required to cool centre of bolognese sauce in an air velocity of 0.5 ms^{-1} (source: Evans *et al.*, 1996).

such as beef curry and chicken Italian will have a similar cooling response to those produced for bolognese sauce. It can therefore be concluded that the cooling response of most meat-based convenience meal mixtures will be similar to that of bolognese sauce.

Although the Department of Health guidelines allow 30 min before chilling should commence, results showed that even allowing for this ambient cooling period it would still not be possible to cool a 40 mm thick product within the specified time (Fig. 16.3). Further reductions in cooling times could be achieved if air temperatures were reduced or air velocities increased (Fig. 16.4). However, as already stated, if air temperature were reduced product freezing would be likely to occur. Initial freezing points of the products examined were between -1.2 and -2.1 °C and therefore air temperatures of much below -2 °C could result in some degree of freezing. Alternatively, air velocities could be increased, a two-stage cooling system used, or an alternative cooling method with a higher rate of heat transfer could be considered, e.g. vacuum, cryogenic or immersion.

Further work has provided cooling times for cooked meat sauce using immersion cooling (Ketteringham and James, 1999). This cooling method has great potential for use in the food industry as it provides a more effective source of temperature reduction than air blast chilling which is in wide use at the moment. The rate of heat transfer is much greater when using a fluid to remove the thermal energy, than when using air. Typical values for surface heat transfer coefficients for air blast chilling of food products are less than $50 \text{ W/m}^2\text{°C}$ as compared to values greater than $500 \text{ W/m}^2\text{°C}$ for agitated water. Experimental data gathered from this work can be used to compare results to the previous work carried out using air blast chilling to

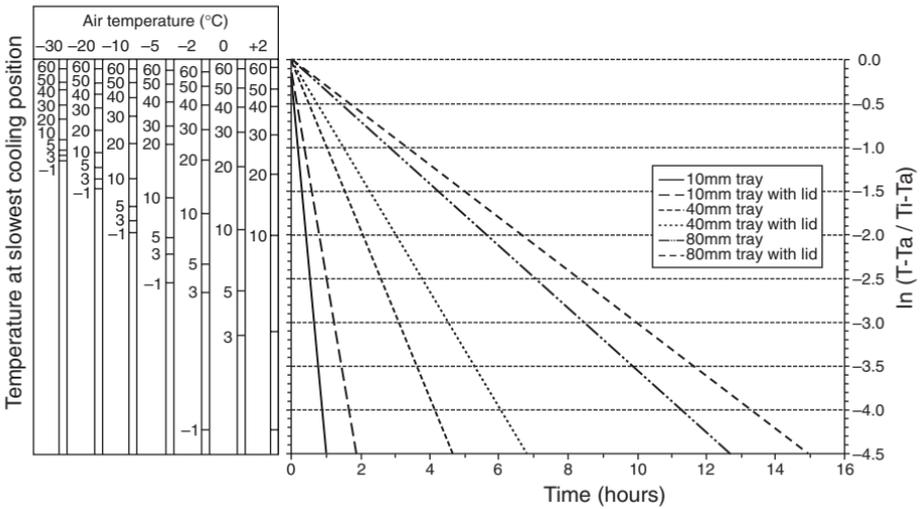


Fig. 16.4. Time required to cool centre of bolognese sauce in an air velocity of 3 ms^{-1} (source: Evans *et al.*, 1996).

determine if it is possible to meet the Department of Health cook–chill guidelines. Table 16.13 shows that there is a significant reduction in the cooling time of meat sauce from 70 to 3 °C using immersion compared to air blast chilling. However, these preliminary results indicate that even though there is an improvement, it is still not possible to cool 40mm thick meat sauce (in sealed lidded trays) from 70 to 3 °C in less than 2.25 h under these conditions. Therefore, to meet UK guidelines using immersion cooling using water at $-1 \text{ }^\circ\text{C}$ (to avoid surface freezing) product thickness still needs to be less than 40mm. It is estimated that a maximum product thickness of between 25 and 30mm could be cooled within the 1.5h UK guideline, but experimental trials have yet to verify this. Further reductions in cooling time with a single-stage immersion system could be achieved by using a packaging method that eliminates the insulating effect of the air trapped between the lid and the product. Vacuum packed product in hermetically sealed bags or pouches (as used in *Sous-vide*) could be used to ensure improved heat transfer and cooling rates, as long as product thickness is kept to a minimum.

16.5.3 Refrigeration problems in practice

Surveys of ready meal plants performing industrial scale cook–chill operations have highlighted a number of factors that impede the effective chilling of cooked products. Any delay and extension to the optimum cooling time, after cooking to the critical control temperature, will lead to shorter

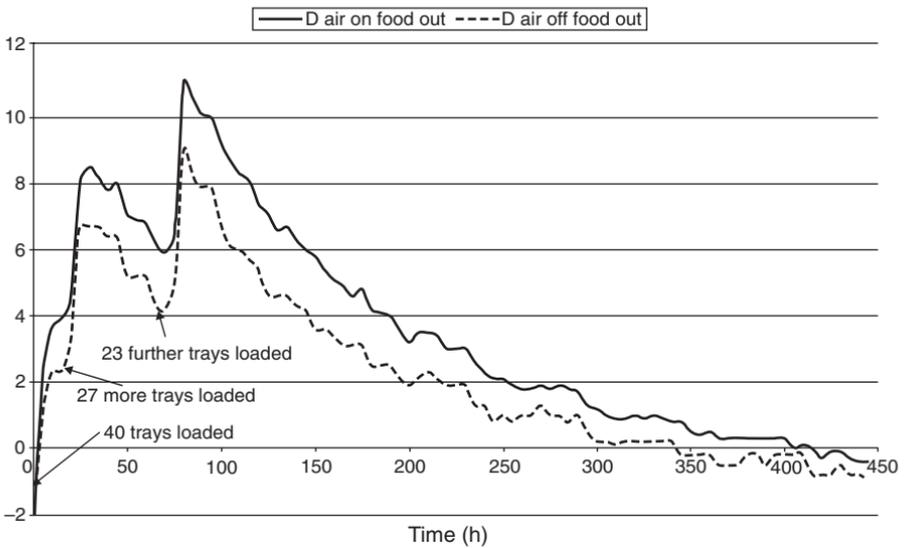


Fig. 16.5. Air on and air off coil temperatures during cooling in blast chiller.

shelf life of the product and greater risk of bacterial growth to unacceptable levels.

A key factor when considering the performance of a blast chiller is its ability to reduce the air temperature and maintain it at the control point. The longer the room takes to pull-down to the pre-set air temperature, the greater the delay to maximum cooling rate and hence the longer the product cooling time. Figure 16.5 shows clearly the effect of loading warm product into a blast chiller with insufficient refrigeration capacity. The temperature of the air returning to the cooling coil reached 8.5°C after the first batch of hot sauce was loaded and peaked at over 11°C after the final load. Seven and a half hours after loading the air temperature had still not recovered to its set point. During the survey of one facility, in approximately 40% of the chilling runs monitored, the blast chiller never managed to reduce the air temperature to its control point, indicating overloading/undersizing of refrigeration load capacity.

A practice that must be avoided is the removal of product from the blast chillers before the specified minimum temperatures have been reached. Loading of the blast chiller with hot product whilst partially chilled products are already being chilled has also been identified as causing problems. Monitored temperatures clearly show a rise in the air temperature as the hot product is introduced, which in turn causes a rise in product temperatures. Failure to ensure that evaporator coils are effectively defrosted and all fan units are operational before chilling can drastically reduce the effectiveness of blast chillers. These problems are associated with incorrect

operation of blast chillers and are not caused by incorrect design of the refrigeration system. These may all be obvious but have been observed on several occasions in more than one factory. Other problems include: incorrect thermostat settings resulting in too warm or even frozen product; insufficient airflow around all (or any) loaded products limiting effective heat transfer; deterioration in refrigeration performance due to lack of maintenance; leaving products too long in blast chillers designed to use sub-zero temperatures, resulting in partial product freezing.

16.6 Conclusions

- 1 There is a large and growing demand for data on methods and cooling times for a range of cooked products.
- 2 The majority of commercial systems use air as the cooling medium but vacuum and immersion offer viable alternatives.
- 3 With small products, increasing air velocities can substantially reduce the cooling time.
- 4 Results from practical trials using pilot scale facilities, indicate that achieving rapid cooling of cooked meat sauce type material in trays, to meet UK cook–chill guidelines, is only feasible with depths of less than 30 mm.
- 5 Experience from surveys of commercial chilled ready meal manufacturing facilities has highlighted that additional operational and design problems can add to the difficulty of meeting the rapid cooling requirements.
- 6 The importance is emphasised of putting in place strict scheduling of product and temperature monitoring and control throughout the production process, taking into account the additional complications of fluctuating demand and ‘just in time’ manufacturing.

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