Freezing is the unit operation in which the temperature of a food is reduced below its freezing point and a proportion of the water undergoes a change in state to form ice crystals. The immobilisation of water to ice and the resulting concentration of dissolved solutes in unfrozen water lower the water activity ($a_w$) of the food ($a_w$ is described in Chapter 1). Preservation is achieved by a combination of low temperatures, reduced water activity and, in some foods, pre-treatment by blanching. There are only small changes to nutritional or sensory qualities of foods when correct freezing and storage procedures are followed.

The major groups of commercially frozen foods are as follows:

- fruits (strawberries, oranges, raspberries, blackcurrants) either whole or pureéd, or as juice concentrates
- vegetables (peas, green beans, sweetcorn, spinach, sprouts and potatoes)
- fish fillets and seafoods (cod, plaice, shrimps and crab meat) including fish fingers, fish cakes or prepared dishes with an accompanying sauce
- meats (beef, lamb, poultry) as carcasses, boxed joints or cubes, and meat products (sausages, beefburgers, reformed steaks)
- baked goods (bread, cakes, fruit and meat pies)
- prepared foods (pizzas, desserts, ice cream, complete meals and cook–freeze dishes).

Rapid increases in sales of frozen foods in recent years are closely associated with increased ownership of domestic freezers and microwave ovens. Frozen foods and chilled foods (Chapter 19) have an image of high quality and ‘freshness’ and, particularly in meat, fruit and vegetable sectors, outsell canned or dried products.

Distribution of frozen foods has a relatively high cost, due to the need to maintain a constant low temperature. Distribution logistics are discussed further in Chapter 19 in relation to chilled foods and in Chapter 26. A recent advance in distribution of chilled and frozen foods is described by Jennings (1999), in which carbon dioxide ‘snow’ (Section 21.2.4) is added to sealed containers of food, which are then loaded into normal distribution vehicles. The time that a product can be held at the required chilled or frozen storage temperature can be varied from four to 24 hours by adjusting the
amount of added snow. Other advantages of the system include greater flexibility in being able to carry mixed loads at different temperatures in the same vehicle, greater control over storage temperature and greater flexibility in use, compared to standard refrigerated vehicles.

21.1 Theory

During freezing, sensible heat is first removed to lower the temperature of a food to the freezing point. In fresh foods, heat produced by respiration is also removed (Chapter 19). This is termed the heat load, and is important in determining the correct size of freezing equipment for a particular production rate. Most foods contain a large proportion of water (Table 21.1), which has a high specific heat (4200 J kg\(^{-1}\) K\(^{-1}\)) and a high latent heat of crystallisation (335 kJ kg\(^{-1}\)). A substantial amount of energy is therefore needed to remove latent heat, form ice crystals and hence to freeze foods. The latent heat of other components of the food (for example fats) must also be removed before they can solidify but in most foods these other components are present in smaller amounts and removal of a relatively small amount of heat is needed for crystallisation to take place. Energy for freezing is supplied as electrical energy, which is used to compress gases (refrigerants) in mechanical freezing equipment (Sections 21.2.1–3) or to compress and cool cryogens (Section 21.2.4).

If the temperature is monitored at the thermal centre of a food (the point that cools most slowly) as heat is removed, a characteristic curve is obtained (Fig. 21.1). The six components of the curve are as follows.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS</td>
<td>The food is cooled to below its freezing point (\theta_f) which, with the exception of pure water, is always below 0°C (Table 21.1). At point S the water remains liquid, although the temperature is below the freezing point. This phenomenon is known as supercooling and may be as much as 10°C below the freezing point.</td>
</tr>
<tr>
<td>SB</td>
<td>The temperature rises rapidly to the freezing point as ice crystals begin to form and latent heat of crystallisation is released.</td>
</tr>
<tr>
<td>BC</td>
<td>Heat is removed from the food at the same rate as before, but it is latent heat being removed as ice forms and the temperature therefore remains almost constant. The freezing point is gradually depressed by the increase in solute concentration in the unfrozen liquor, and the temperature therefore falls slightly. It is during this stage that the major part of the ice is formed (Fig. 21.2).</td>
</tr>
<tr>
<td>CD</td>
<td>One of the solutes becomes supersaturated and crystallises out. The latent heat of crystallisation is released and the temperature rises to the eutectic temperature for that solute (Section 21.1.2).</td>
</tr>
</tbody>
</table>

Table 21.1 Water contents and freezing points of selected foods

<table>
<thead>
<tr>
<th>Food</th>
<th>Water content (%)</th>
<th>Freezing point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetables</td>
<td>78–92</td>
<td>−0.8 to −2.8</td>
</tr>
<tr>
<td>Fruits</td>
<td>87–95</td>
<td>−0.9 to −2.7</td>
</tr>
<tr>
<td>Meat</td>
<td>55–70</td>
<td>−1.7 to −2.2</td>
</tr>
<tr>
<td>Fish</td>
<td>65–81</td>
<td>−0.6 to −2.0</td>
</tr>
<tr>
<td>Milk</td>
<td>87</td>
<td>−0.5</td>
</tr>
<tr>
<td>Egg</td>
<td>74</td>
<td>−0.5</td>
</tr>
</tbody>
</table>
Crystallisation of water and solutes continues. The total time $t_f$ taken (the freezing plateau) is determined by the rate at which heat is removed.

The temperature of the ice–water mixture falls to the temperature of the freezer. A proportion of the water remains unfrozen at the temperatures used in commercial freezing; the amount depends on the type and composition of the food and the temperature of storage. For example at a storage temperature of $-20^\circ$C the percentage of water frozen is 88% in lamb, 91% in fish and 93% in egg albumin.

21.1.1 Ice crystal formation

The freezing point of a food may be described as ‘the temperature at which a minute crystal of ice exists in equilibrium with the surrounding water’. However, before an ice crystal can form, a nucleus of water molecules must be present. Nucleation therefore precedes ice crystal formation. There are two types of nucleation: homogeneous nucleation (the chance orientation and combination of water molecules), and heterogeneous nucleation (the formation of a nucleus around suspended particles or at a cell wall). Heterogeneous nucleation is more likely to occur in foods and takes place during supercooling (Fig. 21.1). The length of the supercooling period depends on the type of food and the rate at which heat is removed.

High rates of heat transfer produce large numbers of nuclei and, as water molecules migrate to existing nuclei in preference to forming new nuclei, fast freezing therefore produces a large number of small ice crystals. However, large differences in crystal size are found with similar freezing rates due to different types of food and even in similar foods which have received different pre-freezing treatments.

The rate of ice crystal growth is controlled by the rate of heat transfer for the majority of the freezing plateau. The time taken for the temperature of a food to pass through the critical zone (Fig. 21.2) therefore determines both the number and the size of ice crystals. The rate of mass transfer (of water molecules moving to the growing crystal and of solutes moving away from the crystal) does not control the rate of crystal growth except towards the end of the freezing period when solutes become more concentrated. Further details of the freezing process are given by Sahagian and Goff (1996).
21.1.2 Solute concentration

An increase in solute concentration during freezing causes changes in the pH, viscosity, surface tension and redox potential of the unfrozen liquor. As the temperature falls, individual solutes reach saturation point and crystallise out. The temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquor and ice is its eutectic temperature (for example for glucose this is $-5^\circ$C, for sucrose $-14^\circ$C, for sodium chloride $-21.13^\circ$C and for calcium chloride $-55^\circ$C). However, it is difficult to identify individual eutectic temperatures in the complex mixture of solutes in foods, and the term final eutectic temperature is therefore used. This is the lowest eutectic temperature at which a crystal of a mixture of solutes exists in equilibrium with the unfrozen liquor and ice.

Fig. 21.2  Freezing: (a) ice formation at different freezing temperatures; (b) temperature changes of food through the critical zone.

(After Leniger and Beverloo (1975).)
temperature of the solutes in a food (for example for ice-cream this is \(-55^\circ C\), for meat \(-50\) to \(-60^\circ C\) and for bread \(-70^\circ C\) (Fennema, 1975a). Maximum ice crystal formation is not possible until this temperature is reached. Commercial foods are not frozen to such low temperatures and unfrozen water is therefore always present.

As food is frozen below point E in Fig. 21.1, the unfrozen material becomes more concentrated and forms a ‘glass’ which encompasses the ice crystals. The temperature range at which this occurs depends on the solute composition and the initial water content of the food. Where the temperature of storage is below this temperature range, the formation of a glass protects the texture of the food and gives good storage stability (for example meats and vegetables in Table 21.2). Many fruits however, have very low glass transition temperatures and as a result suffer losses in texture during frozen storage, in addition to damage caused by ice crystals (Section 21.3). Further details of glass transition values are given by Fennema (1996) and are described in Chapter 1.

### Table 21.2  Examples of glass transition values of foods

<table>
<thead>
<tr>
<th>Food</th>
<th>Glass transition temperature (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruits and fruit products</td>
<td></td>
</tr>
<tr>
<td>Apple</td>
<td>(-41) to (-42)</td>
</tr>
<tr>
<td>Banana</td>
<td>(-35)</td>
</tr>
<tr>
<td>Peach</td>
<td>(-36)</td>
</tr>
<tr>
<td>Strawberry</td>
<td>(-33) to (-41)</td>
</tr>
<tr>
<td>Tomato</td>
<td>(-41)</td>
</tr>
<tr>
<td>Grape juice</td>
<td>(-42)</td>
</tr>
<tr>
<td>Pineapple juice</td>
<td>(-37)</td>
</tr>
<tr>
<td>Vegetables</td>
<td></td>
</tr>
<tr>
<td>Sweetcorn, fresh</td>
<td>(-15)</td>
</tr>
<tr>
<td>Potato, fresh</td>
<td>(-12)</td>
</tr>
<tr>
<td>Pea, frozen</td>
<td>(-25)</td>
</tr>
<tr>
<td>Broccoli head, frozen</td>
<td>(-12)</td>
</tr>
<tr>
<td>Spinach, frozen</td>
<td>(-17)</td>
</tr>
<tr>
<td>Desserts</td>
<td></td>
</tr>
<tr>
<td>Ice cream</td>
<td>(-31) to (-33)</td>
</tr>
<tr>
<td>Cheese</td>
<td></td>
</tr>
<tr>
<td>Cheddar</td>
<td>(-24)</td>
</tr>
<tr>
<td>Cream cheese</td>
<td>(-33)</td>
</tr>
<tr>
<td>Fish and meat</td>
<td></td>
</tr>
<tr>
<td>Cod muscle</td>
<td>(-11.7 \pm 0.6)</td>
</tr>
<tr>
<td>Mackerel muscle</td>
<td>(-12.4 \pm 0.2)</td>
</tr>
<tr>
<td>Beef muscle</td>
<td>(-12 \pm 0.3)</td>
</tr>
</tbody>
</table>

Adapted from Fennema (1996).

21.1.3 Volume changes
The volume of ice is 9% greater than that of pure water, and an expansion of foods after freezing would therefore be expected. However, the degree of expansion varies considerably owing to the following factors:

- moisture content (higher moisture contents produce greater changes in volume)
- cell arrangement (plant materials have intercellular air spaces which absorb internal increases in volume without large changes in their overall size (for example whole strawberries increase in volume by 3.0% whereas coarsely ground strawberries increase by 8.2% when both are frozen to \(-20^\circ C\) (Leniger and Beverloo, 1975)))
the concentrations of solutes (high concentrations reduce the freezing point and do not freeze – or expand – at commercial freezing temperatures)
the freezer temperature (this determines the amount of unfrozen water and hence the degree of expansion)
crystallised components, including ice, fats and solutes, contract when they are cooled and this reduces the volume of the food.

Rapid freezing causes the food surface to form a crust and prevents further expansion. This causes internal stresses to build up in the food and makes pieces more susceptible to cracking or shattering, especially when they suffer impacts during passage through continuous freezers. Details of the effect of freezing rate on the cracking resistance of different fruits are described by Sebok et al. (1994).

21.1.4 Calculation of freezing time
During freezing, heat is conducted from the interior of a food to the surface and is removed by the freezing medium. The factors which influence the rate of heat transfer are:

- the thermal conductivity of the food
- the area of food available for heat transfer
- the distance that the heat must travel through the food (size of the pieces)
- the temperature difference between the food and the freezing medium
- the insulating effect of the boundary film of air surrounding the food (Chapter 1)
- packaging, if present, is an additional barrier to heat flow.

It is difficult to define the freezing time precisely but two approaches are taken. The effective freezing time measures the time that food spends in a freezer and is used to calculate the throughput of a manufacturing process whereas the nominal freezing time can be used as an indicator of product damage as it takes no account of the initial conditions or the different rates of cooling at different points on the surface of the food.

The calculation of freezing time is complicated for the following reasons:

- differences in the initial temperature, size and shape of individual pieces of food
- differences in the freezing point and the rate of ice crystal formation within different regions of a piece of food
- changes in density, thermal conductivity, specific heat and thermal diffusivity with a reduction in temperature of the food.

Removal of latent heat further complicates the unsteady-state heat transfer calculations (Chapter 1), and a complete mathematical solution of freezing rate is not possible. For most practical purposes an approximate solution based on formulae developed by Plank (equation (21.1) is adequate. This involves the following assumptions:

- freezing starts with all water in the food unfrozen but at its freezing point, and loss of sensible heat is ignored

1. The time required to lower the temperature of a food from an initial value to a pre-determined final temperature at the thermal centre.
2. The time between the surface of the food reaching 0°C and the thermal centre reaching 10°C below the temperature of the first ice formation.
heat transfer takes place sufficiently slowly for steady-state conditions to operate
the freezing front maintains a similar shape to that of the food (for example in a
rectangular block the freezing front remains rectangular)
there is a single freezing point
the density of the food does not change
the thermal conductivity and specific heat of the food are constant when unfrozen and
then change to a different constant value when the food is frozen.

The freezing time for cubes of food is calculated using:

\[ t_f = \frac{\lambda \rho}{\theta_f - \theta_a} \left[ \frac{L}{6} \left( \frac{1}{h} + \frac{x}{k_1} \right) + \frac{L^2}{24k_2} \right] \]

where \( t_f \) (s) = freezing time, \( L \) (m) = length of the cube, \( h \) (W m\(^{-2}\)K\(^{-1}\)) = surface heat transfer coefficient, \( \theta_f \) (°C) = freezing point of the food, \( \theta_a \) (°C) = temperature of the freezing medium, \( \lambda \) (J kg\(^{-1}\)) = latent heat of crystallisation, \( \rho \) (kg m\(^{-3}\)) = density of the food, \( x \) (m) = thickness of the packaging, \( k_1 \) (W m\(^{-1}\)K\(^{-1}\)) = thermal conductivity of the packaging, \( k_2 \) (W m\(^{-1}\)K\(^{-1}\)) = thermal conductivity of the frozen zone, 6 and 24 are factors which represent the shortest distance between the centre and the surface of the food. Other shapes require different factors; these are 2 and 8 for a slab, 4 and 16 for a cylinder and 6 and 24 for a sphere. Derivation of the equation is described by Earle (1983).

Equation (21.1) may be rearranged to find the heat transfer coefficient as follows:

\[ h = \frac{L}{6} \left[ \frac{t_f(\theta_f - \theta_a)}{\lambda \rho} - \frac{Lx}{6k_1} - \frac{L^2}{24k_2} \right] \]

Other equations produced by different research workers are described by Jackson and Lamb (1981). The many assumptions made using these equations lead to a small under-estimation of freezing time when compared with experimental data. More complex formulae which give closer approximations have been described by a number of workers including Cleland and Earle (1982).

**Sample problem 21.1**

Five-centimetre potato cubes are individually quick frozen (IQF) in a blast freezer operating at \(-40^\circ C\) and with a surface heat transfer coefficient of 30 W m\(^{-2}\) K\(^{-1}\) (Table 21.3). If the freezing point of the potato is measured as \(-1.0^\circ C\) and the density is 1180 kg m\(^{-3}\), calculate the expected freezing time for each cube. If the cubes are then packed into a cardboard carton measuring 20 cm \( \times \) 10 cm \( \times \) 10 cm, calculate the freezing time. Also calculate the freezing time for IQF freezing of 2.5 cm cubes.

(Additional data: the thickness of the card is 1.5 mm, the thermal conductivity of the card is 0.07 W m\(^{-1}\) K\(^{-1}\), the thermal conductivity of potato is 2.5 W m\(^{-1}\) K\(^{-1}\) (Table 1.5) and the latent heat of crystallisation 2.74 \( \times \) 10\(^5\) J kg\(^{-1}\).)

**Solution to Sample problem 21.1**

To calculate the expected freezing time of each cube, from equation (21.1), for an unwrapped cube,

\[ t_f = \frac{(2.74 \times 10^5)1180}{-1 - (-40)} \left[ \frac{0.05}{6} \left( \frac{1}{30} + 0 \right) + \frac{0.05^2}{24 \times 2.5} \right] = 2648 \text{ s} = 44 \text{ min} \]
21.2 Equipment

The selection of freezing equipment should take the following factors into consideration: the rate of freezing required; the size, shape and packaging requirements of the food; batch or continuous operation, the scale of production, range of products to be processed and not least the capital and operating costs.

Freezers are broadly categorised into:

- mechanical refrigerators, which evaporate and compress a refrigerant in a continuous cycle (details are given in Chapter 19) and use cooled air, cooled liquid or cooled surfaces to remove heat from foods
- cryogenic freezers, which use solid or liquid carbon dioxide, liquid nitrogen (or until recently, liquid Freon) directly in contact with the food.

An alternative classification, based on the rate of movement of the ice front is:

- **slow freezers** and **sharp freezers** (0.2 cm h\(^{-1}\)) including still-air freezers and cold stores
- **quick freezers** (0.5–3 cm h\(^{-1}\)) including air-blast and plate freezers
- **rapid freezers** (5–10 cm h\(^{-1}\)) including fluidised-bed freezers
- **ultrarapid freezers** (10–100 cm h\(^{-1}\)), that is cryogenic freezers.

All freezers are insulated with expanded polystyrene, polyurethane or other materials which have low thermal conductivity (Chapter 1, Table 1.5). Recent developments in computer control, described in Chapter 2, are incorporated in most freezing equipment to monitor process parameters and equipment status, display trends, identify faults and automatically control processing conditions for different products.

21.2.1 Cooled-air freezers

In **chest freezers** food is frozen in stationary (natural-circulation) air at between −20°C and −30°C. Chest freezers are not used for commercial freezing owing to low freezing rates (3–72 h), which result in poor process economics and loss of product quality (Section 21.3). **Cold stores** are used to freeze carcass meat, to store foods that are frozen by other methods, and as hardening rooms for ice cream. Air is usually circulated by fans.
to improve the uniformity of temperature distribution, but heat transfer coefficients are low (Table 21.3).

A major problem with cold stores is ice formation on floors, walls and evaporator coils, caused by moisture from the air or from unpackaged products in the store. For example, air at 10ºC and 80% relative humidity contains 6 g water per kg of air (see Section 15.1). If air enters the cold store through loading doors at a rate of 1000 m$^3$ h$^{-1}$, 173 kg of water vapour enters the store per day (Weller and Mills, 1999). This condenses to water and freezes on the cold surfaces, which reduces the efficiency of the refrigeration plant, uses up energy that would otherwise be used to cool the store, creates potential hazards from slippery working conditions and falling blocks of ice, and requires frequent defrosting of evaporator coils. A desiccant dehumidifier, described by Weller and Mills (1999), overcomes these problems by removing moisture from the air as it enters the store and thus reduces ice formation, reduces the size of compressors and fans, and energy needed to maintain the store temperature.

Table 21.3  A comparison of freezing methods

<table>
<thead>
<tr>
<th>Method of freezing</th>
<th>Typical film heat transfer coefficients (W m$^{-2}$ K$^{-1}$)</th>
<th>Typical freezing times for specified foods to −18ºC (min)</th>
<th>Food</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still air</td>
<td>6–9</td>
<td>180–4320</td>
<td>Meat carcass</td>
</tr>
<tr>
<td>Blast (5 m s$^{-1}$)</td>
<td>25–30</td>
<td>15–20</td>
<td>Unpackaged peas</td>
</tr>
<tr>
<td>Blast (3 m s$^{-1}$)</td>
<td>18</td>
<td>–</td>
<td>Hburgers, fish fingers</td>
</tr>
<tr>
<td>Spiral belt</td>
<td>25</td>
<td>12–19</td>
<td>Hburgers, fish fingers</td>
</tr>
<tr>
<td>Fluidised bed</td>
<td>90–140</td>
<td>3–4</td>
<td>Unpackaged peas</td>
</tr>
<tr>
<td>Plate</td>
<td>100</td>
<td>75</td>
<td>Fish fingers</td>
</tr>
<tr>
<td>Scraped surface</td>
<td>–</td>
<td>0.3–0.5</td>
<td>1 kg carton vegetables</td>
</tr>
<tr>
<td>Immersion (Freon)</td>
<td>500</td>
<td>10–15</td>
<td>170 g card cans of orange juice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>Peas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4–5</td>
<td>Beefburgers, fish fingers</td>
</tr>
<tr>
<td>Cryogenic (liquid nitrogen)</td>
<td>1500</td>
<td>1.5</td>
<td>454 g of bread</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9</td>
<td>454 g of cake</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2–5</td>
<td>Hburgers, seafood</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5–6</td>
<td>Fruits and vegetables</td>
</tr>
</tbody>
</table>


In blast freezers, air is recirculated over food at between −30ºC and −40ºC at a velocity of 1.5–6.0 m s$^{-1}$. The high air velocity reduces the thickness of boundary films surrounding the food (Chapter 1, Fig. 1.3) and thus increases the surface heat transfer coefficient (Table 21.3). In batch equipment, food is stacked on trays in rooms or cabinets. Continuous equipment consists of trolleys stacked with trays of food or on conveyor belts which carry the food through an insulated tunnel. The trolleys should be fully loaded to prevent air from bypassing the food through spaces between the trays. Multipass tunnels contain a number of belts, and products fall from one to another. This breaks up any clumps of food and allows control over the product depth (for example a 25–50 mm bed is initially frozen for 5–10 min and then replicated to 100–125 mm on a second belt).

Air flow is either parallel or perpendicular to the food and is ducted to pass evenly over all food pieces. Blast freezing is relatively economical and highly flexible in that
foods of different shapes and sizes can be frozen. The equipment is compact and has a relatively low capital cost and a high throughput (200–1500 kg h$^{-1}$). However, moisture from the food is transferred to the air and builds up as ice on the refrigeration coils, and this necessitates frequent defrosting. The large volumes of recycled air can also cause dehydration losses of up to 5%, freezer burn and oxidative changes to unpackaged or individually quick frozen (IQF) foods. IQF foods freeze more rapidly, enable packaged foods to be partly used and then refrozen, and permit better portion control. However, the low bulk density and high void space causes a higher risk of dehydration and freezer burn (Section 21.3).

_Belt freezers_ (spiral freezers) have a continuous flexible mesh belt which is formed into spiral tiers and carries food up through a refrigerated chamber. In some designs each tier rests on the vertical sides of the tier beneath (Fig. 21.3) and the belt is therefore ‘self-stacking’. This eliminates the need for support rails and improves the capacity by up to 50% for a given stack height. Cold air or sprays of liquid nitrogen (Section 21.2.4) are directed down through the belt stack in a countercurrent flow, which reduces weight losses due to evaporation of moisture. Spiral freezers require relatively small floor-space and have high capacity (for example a 50–75 cm wide belt in a 32-tier spiral processes up to 3000 kg h$^{-1}$). Other advantages include automatic loading and unloading, low maintenance costs and flexibility to freeze a wide range of foods including pizzas, cakes, pies, ice cream, whole fish and chicken portions.

_Fluidised-bed freezers_ are modified blast freezers in which air at between $-25^\circ C$ and $-35^\circ C$ is passed at a high velocity (2–6 m s$^{-1}$) through a 2–13 cm bed of food, contained on a perforated tray or conveyor belt. In some designs there are two stages; after initial rapid freezing in a shallow bed to produce an ice glaze on the surface of the food, freezing is completed on a second belt in beds 10–15 cm deep. The formation of a glaze is useful for fruit pieces and other products that have a tendency to clump together. The shape and size of the pieces of food determine the thickness of the fluidised bed and the air velocity needed for fluidisation (a sample calculation of air velocity is given in Chapter 1). Food comes into greater contact with the air than in blast freezers, and all surfaces are frozen simultaneously and uniformly. This produces higher heat transfer coefficients, shorter freezing times (Table 21.3), higher production rates (10 000 kg h$^{-1}$) and less dehydration of unpackaged food than blast freezing does. The equipment therefore needs less frequent defrosting. However, the method is restricted to particulate foods (for example peas, sweetcorn kernels, shrimps, strawberries or French fried potatoes). Similar equipment, named _through-flow freezers_, in which air passes through a bed of food but fluidisation is not achieved, is suitable for larger pieces of food (for example fish fillets). Both types of equipment are compact, have a high capacity and are highly suited to the production of IQF foods.

### 21.2.2 Cooled-liquid freezers

In _immersion freezers_, packaged food is passed through a bath of refrigerated propylene glycol, brine, glycerol or calcium chloride solution on a submerged mesh conveyor. In contrast with cryogenic freezing (Section 21.2.4), the liquid remains fluid throughout the freezing operation and a change of state does not occur. The method has high rates of heat transfer (Table 21.3) and capital costs are relatively low. It is used commercially for concentrated orange juice in laminated card–polyethylene cans, and to pre-freeze film-wrapped poultry before blast freezing.
Fig. 21.3  Spiral freezer, self-stacking belt.
(Courtesy of Frigoscandia Ltd.)
21.2.3 Cooled-surface freezers

Plate freezers consist of a vertical or horizontal stack of hollow plates, through which refrigerant is pumped at $-40\degree C$ (Fig. 21.4). They may be batch, semi-continuous or continuous in operation. Flat, relatively thin foods (for example filleted fish, fish fingers or beefburgers) are placed in single layers between the plates and a slight pressure is applied by moving the plates together. This improves the contact between surfaces of the food and the plates and thereby increases the rate of heat transfer. If packaged food is frozen in this way, the pressure prevents the larger surfaces of the packs from bulging. Production rates range from 90–2700 kg h$^{-1}$ in batch freezers. Advantages of this type of equipment include good economy and space utilisation, relatively low operating costs compared with other methods, little dehydration of the product and therefore minimum defrosting of condensers, and high rates of heat transfer (Table 21.3). The main disadvantages are the relatively high capital costs, and restrictions on the shape of foods to those that are flat and relatively thin.

Scraped-surface freezers are used for liquid or semi-solid foods (for example ice cream). They are similar in design to equipment used for evaporation (Chapter 13, Fig. 13.5) and heat sterilisation (Chapter 12) but are refrigerated with ammonia, brine, or other refrigerants. In ice cream manufacture, the rotor scrapes frozen food from the wall of the freezer barrel and simultaneously incorporates air. Alternatively, air can be injected into the product. The increase in volume of the product due to the air is expressed as overrun (see Chapter 1, Section 1.1.1).

Freezing is very fast and up to 50% of the water is frozen within a few seconds (Jaspersen, 1989). This results in very small ice crystals, which are not detectable in the mouth and thus gives a smooth creamy consistency to the product. The temperature is reduced to between $-4\degree C$ and $-7\degree C$ and the frozen aerated mixture is then pumped into

![Fig. 21.4 Plate freezer.](Image)

(Courtesy of Frigoscandia Ltd. and Garthwaite, A. (1995).)
containers and freezing is completed in a ‘hardening room’ (see ‘chest freezers’ above). Further details of ice cream production are given in Chapter 4.

21.2.4 Cryogenic freezers
Freezers of this type are characterised by a change of state in the refrigerant (or cryogen) as heat is absorbed from the freezing food. The heat from the food therefore provides the latent heat of vaporisation or sublimation of the cryogen. The cryogen is in intimate contact with the food and rapidly removes heat from all surfaces of the food to produce high heat transfer coefficients and rapid freezing. The two most common refrigerants are liquid nitrogen and solid or liquid carbon dioxide. Dichlorodifluoromethane (refrigerant 12 or Freon 12) was also previously used for sticky or fragile foods that stuck together in clumps (for example meat paste, shrimps, tomato slices), but its use has now been phased out under the Montreal Protocol, due to its effects on the earth’s ozone layer (further details are given in Chapter 19).

The choice of refrigerant is determined by its technical performance for a particular product, its cost and availability, environmental impact and safety (Heap, 1997). The market for frozen foods is increasingly characterised by shorter product life cycles and hence more rapid changes to the number and type of new products. There is a significant commercial risk if the payback period on capital investment exceeds the product life cycle, unless the equipment is sufficiently flexible to accommodate new products (Summers, 1998). Two advantages of cryogenic freezers, compared to mechanical systems, are the lower capital cost and flexibility to process a number of different products without major changes to the system (Miller, 1998).

Both liquid-nitrogen and carbon dioxide refrigerants are colourless, odourless and inert. When liquid nitrogen is sprayed onto food, 48% of the total freezing capacity (enthalpy) is taken up by the latent heat of vaporisation needed to form the gas (Table 21.4). The remaining 52% of the enthalpy is available in the cold gas, and gas is therefore recirculated to achieve optimum use of the freezing capacity. Carbon dioxide has a lower enthalpy than liquid nitrogen (Table 21.4) but most of the freezing capacity (85%) is available from the subliming solid and the lower boiling point produces a less severe thermal shock. In addition, solid carbon dioxide in the form of a fine snow sublimes on contact with the food, and gas is not recirculated. Carbon dioxide is a bacteriostat but is also toxic, and gas should be vented from the factory to avoid injury to operators. Carbon dioxide consumption is higher than liquid-nitrogen consumption, but storage losses are lower.

Table 21.4 Properties of food cryogens

<table>
<thead>
<tr>
<th>Property</th>
<th>Liquid nitrogen</th>
<th>Carbon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m⁻³)</td>
<td>784</td>
<td>464</td>
</tr>
<tr>
<td>Specific heat (kJ kg⁻¹ K⁻¹)</td>
<td>1.04</td>
<td>2.26</td>
</tr>
<tr>
<td>Latent heat (kJ kg⁻¹)</td>
<td>358</td>
<td>352</td>
</tr>
<tr>
<td>Total usable refrigeration effect (kJ kg⁻¹)</td>
<td>690</td>
<td>565</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>−196</td>
<td>−78.5 (sublimation)</td>
</tr>
<tr>
<td>Thermal conductivity (W m⁻¹ K⁻¹)</td>
<td>0.29</td>
<td>0.19</td>
</tr>
<tr>
<td>Consumption per 100 kg of product frozen (kg)</td>
<td>100–300</td>
<td>120–375</td>
</tr>
</tbody>
</table>

In liquid-nitrogen freezers, packaged or unpackaged food travels on a perforated belt through a tunnel (Fig. 21.5), where it is frozen by liquid-nitrogen sprays and by gaseous nitrogen. Production rates are 45–1550 kg h\(^{-1}\). The temperature is either allowed to equilibrate at the required storage temperature (between \(-18^\circ C\) and \(-30^\circ C\)) before the food is removed from the freezer, or alternatively food is passed to a mechanical freezer to complete the freezing process. The use of gaseous nitrogen reduces the thermal shock to the food, and recirculation fans increase the rates of heat transfer. A newer design of tunnel, with fans located beneath the conveyor to produce gas vortices is described by Summers (1998). This design is said to double the output of conventional freezers of the same length, reduce nitrogen consumption by 20% and reduce already low levels of dehydration by 60%. The temperature and belt speed are controlled by microprocessors to maintain the product at a pre-set exit temperature, regardless of the heat load of incoming food. The equipment therefore has the same efficiency at or below its rated capacity. This results in greater flexibility and economy than mechanical systems, which have a fixed rate of heat extraction (Tomlins, 1995).

Other advantages include:

- simple continuous operation with relatively low capital costs (approximately 30% of the capital cost of mechanical systems)
- smaller weight losses from dehydration of the product (0.5% compared with 1.0–8.0% in mechanical air-blast systems)
- rapid freezing (Table 21.3) which results in smaller changes to the sensory and nutritional characteristics of the product
- the exclusion of oxygen during freezing
- rapid startup and no defrost time
- low power consumption (Leeson, 1987).

The main disadvantage is the relatively high cost of refrigerant (nitrogen and carbon dioxide consumption are shown in Table 21.4).

Liquid nitrogen is also used in spiral freezers (Section 21.2.1) instead of vapour recompression refrigerators. The advantages include higher rates of freezing, and smaller
units for the same production rates because heat exchanger coils are not used. Other applications include rigidification of meat for high-speed slicing (Chapter 4), surface hardening of ice cream prior to chocolate coating (Chapter 23) and crust formation on fragile products such as seafood and sliced mushrooms (Londahl and Karlsson (1991), before finishing freezing in mechanical or cryogenic freezers. Other applications are described by Tomlins (1995).

Immersion of foods in liquid nitrogen produces no loss in product weight but causes a high thermal shock. This is acceptable in some products (for example raspberries, shrimps and diced meat), but in many foods the internal stresses created by the extremely high rate of freezing cause the food to crack or split. The rapid freezing permits high production rates of IQF foods using small equipment (for example a 1.5 m long bath of liquid nitrogen freezes 1 t of small-particulate food per hour).

21.3 Changes in foods

21.3.1 Effect of freezing

The main effect of freezing on food quality is damage caused to cells by ice crystal growth. Freezing causes negligible changes to pigments, flavours or nutritionally important components, although these may be lost in preparation procedures (Chapters 3 and 10) or deteriorate later during frozen storage. Food emulsions (Chapter 4) can be destabilised by freezing, and proteins are sometimes precipitated from solution, which prevents the widespread use of frozen milk. In baked goods a high proportion of amylopectin is needed in the starch to prevent retrogradation and staling during slow freezing and frozen storage.

There are important differences in resistance to freezing damage between animal and plant tissues. Meats have a more flexible fibrous structure which separates during freezing instead of breaking, and the texture is not seriously damaged. In fruits and vegetables, the more rigid cell structure may be damaged by ice crystals. The extent of damage depends on the size of the crystals and hence on the rate of heat transfer (Section 21.1.1). However, differences in the variety and quality of raw materials and the degree of control over pre-freezing treatments both have a substantially greater effect on food quality than changes caused by correctly operated freezing, frozen storage and thawing procedures. Details of the changes to meats are described by Devine et al. (1996) and changes to vegetables are described by Cano (1996).

The influence of freezing rate on plant tissues is shown in Fig. 21.6. During slow freezing, ice crystals grow in intercellular spaces and deform and rupture adjacent cell walls. Ice crystals have a lower water vapour pressure than regions within the cells, and water therefore moves from the cells to the growing crystals. Cells become dehydrated and permanently damaged by the increased solute concentration and a collapsed and deformed cell structure. On thawing, cells do not regain their original shape and turgidity. The food is softened and cellular material leaks out from ruptured cells (termed ‘drip loss’). In fast freezing, smaller ice crystals form within both cells and intercellular spaces. There is little physical damage to cells, and water vapour pressure gradients are not formed; hence there is minimal dehydration of the cells. The texture of the food is thus retained to a greater extent (Fig. 21.6(b)). However, very high freezing rates may cause stresses within some foods that result in splitting or cracking of the tissues. These changes are discussed in detail by Spiess (1980).
21.3.2 Effects of frozen storage

In general, the lower the temperature of frozen storage, the lower is the rate of micro-biological and biochemical changes. However, freezing and frozen storage do not inactivate enzymes and have a variable effect on micro-organisms. Relatively high storage temperatures (between −4°C and −10°C) have a greater lethal effect on micro-organisms than do lower temperatures (between −15°C and −30°C). Different types of micro-organism also vary in their resistance to low temperatures; vegetative cells of yeasts, moulds and gram-negative bacteria (for example coliforms and Salmonella species) are most easily destroyed; Gram-positive bacteria (for example Staphylococcus aureus and Enterococci) and mould spores are more resistant, and bacterial spores (especially Bacillus species and Clostridium species such as Clostridium botulinum) are virtually unaffected by low temperatures. The majority of vegetables are therefore blanched to inactivate enzymes and to reduce the

Fig. 21.6 Effect of freezing on plant tissues: (a) slow freezing; (b) fast freezing.
(After Meryman (1963).)
numbers of contaminating micro-organisms (Chapter 10). In fruits, enzyme activity is controlled by the exclusion of oxygen, acidification or treatment with sulphur dioxide.

At normal frozen storage temperatures (−18°C), there is a slow loss of quality owing to both chemical changes and, in some foods, enzymic activity. These changes are accelerated by the high concentration of solutes surrounding the ice crystals, the reduction in water activity (to 0.82 at −20°C in aqueous foods) and by changes in pH and redox potential. The effects of storage temperature on food quality are shown in Fig. 21.7. If enzymes are not inactivated, the disruption of cell membranes by ice crystals allows them to react to a greater extent with concentrated solutes.

The main changes to frozen foods during storage are as follows:

- **Degradation of pigments.** Chloroplasts and chromoplasts are broken down and chlorophyll is slowly degraded to brown pheophytin even in blanched vegetables. In fruits, changes in pH due to precipitation of salts in concentrated solutions change the colour of anthocyanins.
- **Loss of vitamins.** Water-soluble vitamins (for example vitamin C and pantothenic acid) are lost at sub-freezing temperatures (Table 21.5). Vitamin C losses are highly
temperature dependent; a 10°C increase in temperature causes a sixfold to twentyfold increase in the rate of vitamin C degradation in vegetables and a thirtyfold to seventyfold increase in fruits (Fennema, 1975b). Losses of other vitamins are mainly due to drip losses, particularly in meat and fish (if the drip loss is not consumed).

- **Residual enzyme activity.** In vegetables which are inadequately blanched or in fruits, the most important loss of quality is due to polyphenoloxidase activity which causes browning, and lipoxygenases activity which produces off-flavours and off-odours from lipids and causes degradation of carotene. Proteolytic and lipolytic activity in meats may alter the texture and flavour over long storage periods.

- **Oxidation of lipids.** This reaction takes place slowly at −18°C and causes off-odours and off-flavours.

These changes are discussed in detail by Fennema (1975a, 1982, 1996) and Rahman (1999).

**Recrystallisation**

Physical changes to ice crystals (for example changes in their shape, size or orientation) are collectively known as *recrystallisation* and are an important cause of quality loss in some foods. There are three types of recrystallisation in foods as follows:

1. **Isomass recrystallisation.** This is a change in surface shape or internal structure, usually resulting in a lower surface-area-to-volume ratio.
2. **Accretive recrystallisation.** Two adjacent ice crystals join together to form a larger crystal and cause an overall reduction in the number of crystals in the food.
3. **Migratory recrystallisation.** This is an increase in the average size and a reduction in the average number of crystals, caused by the growth of larger crystals at the expense of smaller crystals.

Migratory recrystallisation is the most important in most foods and is largely caused by fluctuations in the storage temperature. When heat is allowed to enter a freezer (for example, by opening a door and allowing warm air to enter), the surface of the food nearest to the source of heat warms slightly. This causes ice crystals to melt partially; the larger crystals become smaller and the smallest (less than 2 μm) disappear. The melting crystals increase the water vapour pressure, and moisture then moves to regions of lower

<table>
<thead>
<tr>
<th>Product</th>
<th>Vitamin C</th>
<th>Vitamin B₁</th>
<th>Vitamin B₂</th>
<th>Niacin</th>
<th>Vitamin B₆</th>
<th>Pantothenic acid</th>
<th>Carotene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beans (green)</td>
<td>52</td>
<td>0–32</td>
<td>0</td>
<td>0</td>
<td>0–21</td>
<td>53</td>
<td>0–23</td>
</tr>
<tr>
<td>Peas</td>
<td>11</td>
<td>0–16</td>
<td>0–8</td>
<td>0–8</td>
<td>7</td>
<td>29</td>
<td>0–4</td>
</tr>
<tr>
<td>Beef steaksᵃ</td>
<td>8</td>
<td>9</td>
<td>0</td>
<td>24</td>
<td>22</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Pork chopsᵃ</td>
<td>+–18</td>
<td>0–37</td>
<td>+–5</td>
<td>0–8</td>
<td>18</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Fruitᵇ</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>18</td>
<td>29</td>
<td>17</td>
<td>16</td>
<td>–</td>
<td>–</td>
<td>37</td>
</tr>
<tr>
<td>Range</td>
<td>0–50</td>
<td>0–66</td>
<td>0–67</td>
<td>0–33</td>
<td>–</td>
<td>–</td>
<td>0–78</td>
</tr>
</tbody>
</table>

+, apparent increase.

ᵃ Storage for 6 months.

ᵇ Mean results from apples, apricots, blueberries, cherries, orange juice concentrate (rediluted), peaches, raspberries and strawberries; storage time not given.

Adapted from Burger (1982) and Fennema (1975b).

<p>| Table 21.5  | Vitamin losses during frozen storage |</p>
<table>
<thead>
<tr>
<th>Product</th>
<th>Loss (%) at −18°C during storage for 12 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beans (green)</td>
<td>52</td>
</tr>
<tr>
<td>Peas</td>
<td>11</td>
</tr>
<tr>
<td>Beef steaksᵃ</td>
<td>8</td>
</tr>
<tr>
<td>Pork chopsᵃ</td>
<td>+–18</td>
</tr>
<tr>
<td>Fruitᵇ</td>
<td>–</td>
</tr>
<tr>
<td>Mean</td>
<td>18</td>
</tr>
<tr>
<td>Range</td>
<td>0–50</td>
</tr>
</tbody>
</table>

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vapour pressure. This causes areas of the food nearest to the source of heat to become dehydrated. When the temperature falls again, water vapour does not form new nuclei but joins onto existing ice crystals, thereby increasing their size. There is therefore a gradual reduction in the numbers of small crystals and an increase in the size of larger crystals, resulting in loss of quality similar to that observed in slow freezing.

Cold stores have a low humidity because moisture is removed from the air by the refrigeration coils (see psychrometrics in Chapter 15). Moisture leaves the surface of the food to the storage atmosphere and produces areas of visible damage known as freezer burn. Such areas have a lighter colour due to microscopic cavities, previously occupied by ice crystals, which alter the wavelength of reflected light. Freezer burn is a particular problem in foods that have a large surface-area-to-volume ratio (for example IQF foods) but is minimised by packaging in moisture-proof materials (Chapter 24). The causes of dehydration during freezing and frozen storage are discussed in detail by Norwig and Thompson (1984).

Temperature fluctuations are minimised by:

- accurate control of storage temperature (±1.5°C)
- automatic doors and airtight curtains for loading refrigerated trucks
- rapid movement of foods between stores
- correct stock rotation and control.

These techniques, and technical improvements in handling, storage and display equipment, have substantially improved the quality of frozen foods (Jul, 1984).

Storage life

There is some confusion and lack of precise information on the storage life of frozen foods, caused in part by the use of different definitions. For example a European Community directive states that frozen storage must ‘preserve the intrinsic characteristics’ of foods, whereas the International Institute of Refrigeration defines storage life as ‘the physical and biochemical reactions . . . leading to a gradual, cumulative and irreversible reduction in product quality, such that after a period of time the product is no longer suitable for consumption . . . ’. Another definition by Bogh-Sorensen describes practical storage life (PSL) as ‘the time the product can be stored and still be acceptable to the consumer’ (Evans and James, 1993). These definitions differ in the extent to which a product is said to be acceptable and rely heavily on the ability of taste panellists to detect changes in flavour, aroma, etc. that can be used to measure acceptability.

The use of PSL and to a lesser extent, the concept of high-quality life (HQL), is used to establish storage life. PSL is defined as ‘the time that a statistically significant difference (P<0.01) in quality can be established by taste panellists’. These methods therefore measure the period that food remains essentially the same as when it was frozen. This should not be confused with a storage life that is acceptable to consumers as foods may be acceptable for three to six times longer than the PSL or HQL. Examples of PSL for meats and HQL for vegetables, stored at three temperatures are shown in Table 21.6.

The main causes of loss of storage life are fluctuating temperatures and the type of packaging used. Other factors, including type of raw material, pre-freezing treatments and processing conditions are discussed in detail by Evans and James (1993). Temperature fluctuation has a cumulative effect on food quality and the proportion of PSL or HQL lost can be found by integrating losses over time. Time-temperature tolerance (TTT) and product-processing-packaging (PPP) concepts are used to monitor
and control the effects of temperature fluctuations on frozen food quality during production, distribution and storage (Olsson, 1984; Bogh-Sorensen, 1984).

Coloured indicators are being developed to:

- show the temperature of food (for example, liquid crystal coatings which change colour with storage temperature)
- indicate temperature abuse (for example wax melts and releases a coloured dye when an unacceptable increase in temperature occurs)
- integrate the time–temperature combination that a food has received after packaging and to give an indication of the remaining shelf life (Fig. 21.8).

In the last category, indicators may contain a material that polymerises as a function of time and temperature to produce a progressive, predictable and irreversible colour change. In another type, a printed label contains diacetylene in the centre of a ‘bull’s eye’, with the outer ring printed with a stable reference colour. The diacetylene gradually darkens in colour due to combined time and temperature and when it matches the reference ring the product has no remaining shelf life. An example of a time–temperature integrator, based on an enzymic reaction which changes the colour of a pH indicator, is described by Blixt (1984) and Selman (1995) has reviewed developments in this area. More recently a bar code system has been developed that is applied to a pack as the product is dispatched. The bar code contains three sections: a code giving information on the product identity, date of manufacture, batch number, etc. to identify each container uniquely. A second code identifies the reactivity of a time–temperature indicator and the third section contains the indicator material. When the bar code is scanned by a hand-held microcomputer, a display indicates the status and quality of the product with a variety of pre-programmed messages (for example: ‘Good’, ‘Don’t use’ or ‘Call QC’). A number of microcomputers can be linked via modems to a central control computer, to produce a portable monitoring system that can track individual containers throughout a distribution chain.

<table>
<thead>
<tr>
<th>Product</th>
<th>Practical storage life (PSL) (months)</th>
<th>High quality life (HQL) (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−12ºC</td>
<td>−18ºC</td>
</tr>
<tr>
<td>Beef carcasses</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Ground beef</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Veal carcasses</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Lamb carcasses</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Pork carcasses</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Sliced bacon</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Chicken, whole</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td>Turkey, whole</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Ducks, geese, whole</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Liver</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 21.6 Storage life of meats measured by PSL and vegetables measured by HQL.

From Guadagni (1968) and Evans and James (1993).
21.3.3 Thawing

When food is thawed in air or water, surface ice melts to form a layer of water. Water has a lower thermal conductivity and a lower thermal diffusivity than ice (Chapter 1) and the surface layer of water therefore reduces the rate at which heat is conducted to the frozen interior. This insulating effect increases as the layer of thawed food grows thicker. (In contrast, during freezing, the increase in thickness of ice causes heat transfer to accelerate.) Thawing is therefore a substantially longer process than freezing when temperature differences and other conditions are similar.

During thawing (Fig. 21.9), the initial rapid rise in temperature (AB) is due to the absence of a significant layer of water around the food. There is then a long period when the temperature of the food is near to that of melting ice (BC). During this period any cellular damage caused by slow freezing or recrystallisation, results in the release of cell constituents to form drip losses. This causes loss of water-soluble nutrients; for example beef loses 12% thiamine, 10% riboflavin, 14% niacin, 32% pyridoxine and 8% folic acid (Pearson et al., 1951) and fruits lose 30% of the vitamin C. Details of changes to foods during thawing are described by Fennema (1975a).

In addition, drip losses form substrates for enzyme activity and microbial growth. Microbial contamination of foods, caused by inadequate cleaning or blanching (Chapters 3 and 10) has a pronounced effect during this period. In the home, food is often thawed using a small temperature difference (for example 25–40°C, compared with 50–80°C for commercial thawing). This further extends the thawing period and increases the risk of contamination by spoilage and pathogenic micro-organisms. Commercially, foods are often thawed to just below the freezing point, to retain a firm texture for subsequent processing.

Some foods are cooked immediately and are therefore heated rapidly to a temperature which is sufficient to destroy micro-organisms. Others (for example ice cream, cream and frozen cakes) are not cooked and should therefore be consumed within a short time of thawing.

When food is thawed by microwave or dielectric heaters (Chapter 18), heat is generated within the food, and the changes described above do not take place. The main considerations in thawing are:

- to avoid overheating
- to minimise thawing times
- to avoid excessive dehydration of the food.
Commerically, foods are thawed in a vacuum chamber by condensing steam, at low temperatures by warm water (approximately 20°C) or by moist air which is recirculated over the food. Details of the types and method of operation of thawing equipment are described by Jason (1981).

21.4 Acknowledgements

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21.5 References


