

**Processing
by the removal of heat**

Chilling | Freezing

PRO

Ch. 19 & 21 of Fellows

General Introduction

- Temperature reduction of foods slows the biochemical & microbiological changes during storage.
- Preservation → sensory characteristics & nutritional value.
- In general, the lower the storage temperature, the longer foods can be stored
- Micro-organisms & enzymes are inhibited at low temperatures, but they are not destroyed.
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- Any increase in temperature can permit the growth of pathogenic bacteria or increase the rate of spoilage of foods.
- Careful control is needed

Chilling

- The unit operation in which the temperature of a food is reduced to between 1°C and 8°C.
- Extend shelf life of fresh & processed foods.
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- Minimal changes to sensory characteristics & nutritional properties of foods
- Chilled foods → convenient, easy to prepare, high quality & 'healthy', 'natural' and 'fresh'.

- Combined with
 - other unit operations (e.g. fermentation or pasteurisation) or
 - control of atmospheric composition of storage
 - to extend shelf life of mildly processed foods.
 - greater preservative effect
- Not all foods can be chilled
 - E.g. tropical, subtropical and some temperate fruits suffer from chilling injury at 3–10°C above their freezing point.

Chilled foods according to storage temperature:

- -1°C to $+1^{\circ}\text{C}$

fresh fish, meats, sausages & ground meats, smoked meats & breaded fish.

- 0°C to $+5^{\circ}\text{C}$

pasteurised canned meat, milk, cream, yoghurt, prepared salads, sandwiches, baked goods, fresh pasta, fresh soups & sauces, pizzas, pastries & unbaked dough.

- 0°C to $+8^{\circ}\text{C}$

fully cooked meats & fish pies, cooked or uncooked cured meats, butter, margarine, hard cheese, cooked rice, fruit juices & soft fruits.

Supply of chilled foods to the consumer

- Sophisticated & expensive distribution systems:
 - chill stores
 - refrigerated transport
 - retail chill display cabinets
 - ownership of domestic refrigerators.
- Precise temperature control & strict conditions of hygiene at all stages → to avoid the risk of food spoilage or food poisoning.
- Low-acid chilled foods → susceptible to contamination by pathogenic bacteria (e.g. fresh & pre-cooked meats, pizzas & unbaked dough)

Fresh foods

- Rate of biochemical changes by micro-organisms or enzymes increases logarithmically with temperature
- Chilling reduces rate of change & retards respiration
- Controlling shelf life of fresh crops in chill storage:
 - type of food and variety or cultivar
 - part of the crop selected
 - condition of the food at harvest
 - temperature of harvest, storage, distribution & retail display
 - relative humidity of the storage atmosphere

Botanical function related to respiration rate and storage life for selected products

| Product | Relative respiration rate | Botanical function | Typical storage life (weeks at 2°C) |
|------------|---------------------------|----------------------------|-------------------------------------|
| Asparagus | 40 | Actively growing shoots | 0.2–0.5 |
| Mushrooms | 21 | | |
| Artichokes | 17 | | |
| Spinach | 13 | Aerial parts of plants | 1–2 |
| Lettuce | 11 | | |
| Cabbage | 6 | | |
| Carrots | 5 | Storage roots | 5–20 |
| Turnips | 4 | | |
| Beetroots | 3 | | |
| Potatoes | 2 | Specialised storage organs | 25–50 |
| Garlic | 2 | | |
| Onions | 1 | | |

From Alvarez and Thorne (1981).

- Respiration rate of fresh fruits is not necessarily constant at a constant storage temperature.
- Remember climacteric/non-climacteric type of fruits?
- Climacteric fruits → a short but abrupt increase in the rate of respiration near to the point of optimum ripeness.

Heat produced by respiration in selected foods

| Food | Heat (W t^{-1}) of respiration for the following storage temperatures | | |
|--------------|---|---------|---------|
| | 0°C | 10°C | 15.5°C |
| Apples | 10–12 | 41–61 | 58–87 |
| Bananas | – | 65–116 | – |
| Beans | 73–82 | – | 440–580 |
| Carrots | 46 | 93 | – |
| Celery | 21 | 58–81 | – |
| Oranges | 9–12 | 35–40 | 68 |
| Lettuce | 150 | – | 620 |
| Pears | 8–20 | 23–63 | – |
| Potatoes | – | 20–30 | – |
| Strawberries | 36–52 | 145–280 | 510 |
| Tomatoes | 57–75 | – | 78 |

Adapted from Leniger and Beverloo (1975) and Lewis (1990).

- Undesirable changes to some fruits & vegetables when temperature is reduced < a specific optimum for the individual
→ *chilling injury*
- E.g. internal or external browning, failure to ripen & skin blemishes
- Apples (< 2–3°C), avocados (< 13°C), bananas (< 12–13°C), lemons (< 14°C), mangoes (< 10–13°C), melons, pineapples and tomatoes (each < 7–10°C).
- May include an imbalance in metabolic activity
→ over-production of metabolites → toxic to the tissues.

Optimum storage conditions for some fruits and vegetables

| Food | Temperature (°C) | Relative humidity (%) | Storage life (days) |
|-------------|------------------|-----------------------|---------------------|
| Apricot | -0.5-0 | 90 | 7-14 |
| Banana | 11-15.5 | 85-95 | 7-10 |
| Bean (snap) | 7 | 90-95 | 7-10 |
| Broccoli | 0 | 95 | 10-14 |
| Carrot | 0 | 98-100 | 28-42 |
| Celery | 0 | 95 | 30-60 |
| Cherry | -1 | 90-95 | 14-20 |
| Cucumber | 10-15 | 90-95 | 10-14 |
| Eggplant | 7-10 | 90-95 | 7-10 |
| Lemon | 10-14 | 85-90 | 30-180 |
| Lime | 9-10 | 85-90 | 40-140 |
| Lettuce | 0-1 | 95-100 | 14-20 |
| Mushroom | 0 | 90 | 3-4 |
| Peach | -0.5-0 | 90 | 14-30 |
| Plum | -1-0 | 90-95 | 14-30 |
| Potato | 3-10 | 90-95 | 150-240 |
| Spinach | 0 | 95 | 10-14 |
| Strawberry | -0.5-0 | 90-95 | 5-7 |
| Tomato | 4-10 | 85-90 | 4-7 |
| Watermelon | 4-10 | 80-90 | 14-20 |

Adapted from Farrall (1976), Frazier and Westhoff (1988), Duckworth (1966), Kader *et al.* (1998) and Yang (1998).

- In animal tissues, aerobic respiration rapidly declines when the supply of oxygenated blood is stopped at slaughter.
- Anaerobic respiration of glycogen to lactic acid
→ the pH of the meat to fall & the onset of *rigor mortis*.
- Cooling during anaerobic respiration to produce required texture & colour of meat & to reduce bacterial contamination.
- Undesirable changes caused by cooling meat before rigor mortis has occurred
→ *cold shortening*.

- To chill fresh foods
→ remove sensible heat (*field heat*) & heat generated by respiratory activity.
- Production of respiratory heat at 20°C & atmospheric pressure



- Size of refrigeration plant & processing time to chill a crop are calculated using unsteady-state heat transfer methods

- Assumptions to simplify calculations

E.g.

- the initial temperature of a food is constant & uniform throughout the food,
- the temperature of the cooling medium, respiratory activity & all thermal properties of the food are constant during cooling.

Processed foods

Micro-organism (temperature range for growth):

- thermophilic
min: 30–40°C, optimum: 55–65°C
- mesophilic
min: 5–10°C, optimum: 30–40°C
- psychrotrophic
min: 0–5°C, optimum: 20–30°C
- psychrophilic
min: 0–5°C, optimum: 12–18°C

- Chilling prevents growth of thermophilic & many mesophilic.
- Microbiological concerns
 - number of pathogens can grow
 - during refrigerated storage < 5°C or
 - as a result of any increase in temperature (temperature abuse).
- Some species can grow to large numbers or are sufficiently virulent to cause poisoning
E.g. *Aeromonas hydrophilia*, *Listeria* spp,
Yersinia enterocolitica, some strains of *Bacillus cereus*, *Vibrio parahaemolyticus* & enteropathogenic *Escherichia coli*.
- GMP → during the production of chilled foods.

Pathogenic or spoilage bacteria in high-risk chilled foods

| Micro-organism | Source | Minimum growth temperature (°C) | Type of infection/spoilage and incubation period | Typical high-risk foods |
|--|---|---------------------------------|--|---|
| Pathogens | | | | |
| <i>Aeromonas hydrophilia</i> | Fresh or brackish water | 1–5 | Diarrhoea, vomiting, fever (12–36 h) | Most commonly from water but also raw milk, poultry, lamb, cheese, shellfish |
| Enteropathogenic <i>Escherichia coli</i> | Intestinal tract of humans and warm blooded animals | 4–7 | Six types of illness including intestinal haemorrhage and toxic reaction (6–36 h) | Meat, poultry, fish, vegetables, Brie and Camembert cheeses, water, radish, alfalfa sprouts |
| <i>Vibrio parahaemolyticus</i> | Inshore marine waters | 5–10 | Gastro-enteritis, abdominal cramps, nausea, fever, wound infection (12–36 h) | Raw, improperly cooked or re-contaminated fish and shellfish, water |
| <i>Bacillus cereus</i> | Soil, cereal, vegetable and meat surfaces | 4–10 | Two types: diarrhoeal illness or emetic nausea and vomiting (12–36 h) | Cereal or spice containing products |
| <i>Yersinia enterocolitica</i> | Pigs | –1–7 | Fever, diarrhoea, severe abdominal pain, vomiting, joint pain (24–36 h) | Lamb, pork, seafoods, milk, tofu, chitterlings (raw pork intestine) |
| <i>Campylobacter jejuni</i> | Water, milk, poultry | 20 | Diarrhoea, muscular pain, headache, vomiting (48–120 h) | Milk, milk products, seafood, water |
| <i>Salmonella enteritidis</i> | Poultry, cattle, other animals | 5.2–6 | Nausea, vomiting, high fever, abdominal pain (6–48 h) | Eggs, poultry, milk, meats, gravies |
| <i>Clostridium botulinum</i> | Ubiquitous, especially soil, water | | 7 types of toxin: blurred vision, vomiting, diarrhoea, progressive difficulty in swallowing, respiratory failure. Up to 70% fatal (12–36 h). | Canned vegetables and other low acid foods, smoked fish |
| Group I | | 10 | | |
| Group II | | 3.3 | | |
| <i>Staphylococcus aureus</i> | Cattle, other animals, processing equipment | 6 (10 for toxin) | Vomiting, nausea, diarrhoea, headache, collapse, wound infection (2–4 h) | Milk, dairy products, cooked meats, seafoods |

| Micro-organism | Source | Minimum growth temperature (°C) | Type of infection/spoilage and incubation period | Typical high-risk foods |
|---|--|---------------------------------|---|--|
| <i>Clostridium perfringens</i> | Soil, dust, vegetation, raw, dried and cooked foods | 12 | Acute diarrhoea, nausea but little fever or vomiting (8–24 h) | Raw meats, poultry, fish, dairy products, dried foods, soups, spices, pasta |
| <i>Listeria monocytogenes</i> | Ubiquitous (soil, healthy humans or animals, food processing surfaces) | –0.4–3 | Gastro-enteritis. Individuals having compromised immune systems are especially vulnerable (24–96 h) | Milk, seafoods, ready-to-eat sandwiches and salads, especially those containing meat, coleslaw, soft cheeses |
| Spoilage micro-organisms <i>Brochothrix thermosphacta</i> | – | | Sliminess, off-odours or flavours | Vacuum packed beef, pork, lamb, sliced cured meats, corned beef |
| Lactic acid bacteria | Ubiquitous | 0–5 | Production of either lactic acid, acetic acid, formic acid, ethanol, carbon dioxide | Milk, milk products, meats, fruit juices, vegetables, alcoholic beverages, sugar products |
| <i>Pseudomonas</i> spp | – | –3–0 | Development of bitterness and rancidity, green colouration | Most chilled foods |
| Yeasts (e.g. <i>Candida</i> spp), and moulds (e.g. <i>Mucor</i> spp, <i>Rhizopus</i> spp) | Ubiquitous | <0 | Fermentation by yeasts causing yeasty, fruity or alcoholic off-flavours and odours Visible mould growth, softening, flavour and aroma changes and mycotoxin production | Fruit juices, meat products, vegetables, dairy products |

Adapted from Marth (1998), Frazier and Westhoff (1988), Anon. (1996) and Walker and Betts (2000).

- Shelf life of chilled processed foods:
 - type of food
 - degree of microbial destruction or enzyme inactivation achieved by the process
 - control of hygiene
 - barrier properties of the package
 - temperatures during production chain

Cook–chill systems

Chilled foods (by the class of microbial risk)

- Class 1; raw or uncooked ingredients: salad or cheese as RTE foods; chill-stable raw foods: meat, fish, etc.
- Class 2; products made from a mixture of cooked & low risk raw ingredients
- Class 3; cooked products that are then packaged
- Class 4; products that are cooked after packaging, incl. ready-to-eat-products-for-extended-durability (REPFEDs) → shelf life 40+ days

REPFED also = refrigerated-pasteurised-foods-for-extended-durability.

‘cooking’ → heat process results in a min. 6*D* reduction in target pathogens

- After preparation, cooked–chilled foods are portioned & chilled within 30 min of cooking.
- Chilling to 3°C should be completed within 90 min & food should be stored at 0–3°C.
- In the cook–pasteurise–chill system, hot food is filled into a flexible container, a partial vacuum is formed to remove oxygen and the pack is heat sealed.
- Then pasteurised to min. 80°C for 10 min at the thermal centre, followed by immediate cooling to 3°C.
- Shelf life of 2–3 weeks.

Equipment

Classification (method used to remove heat):

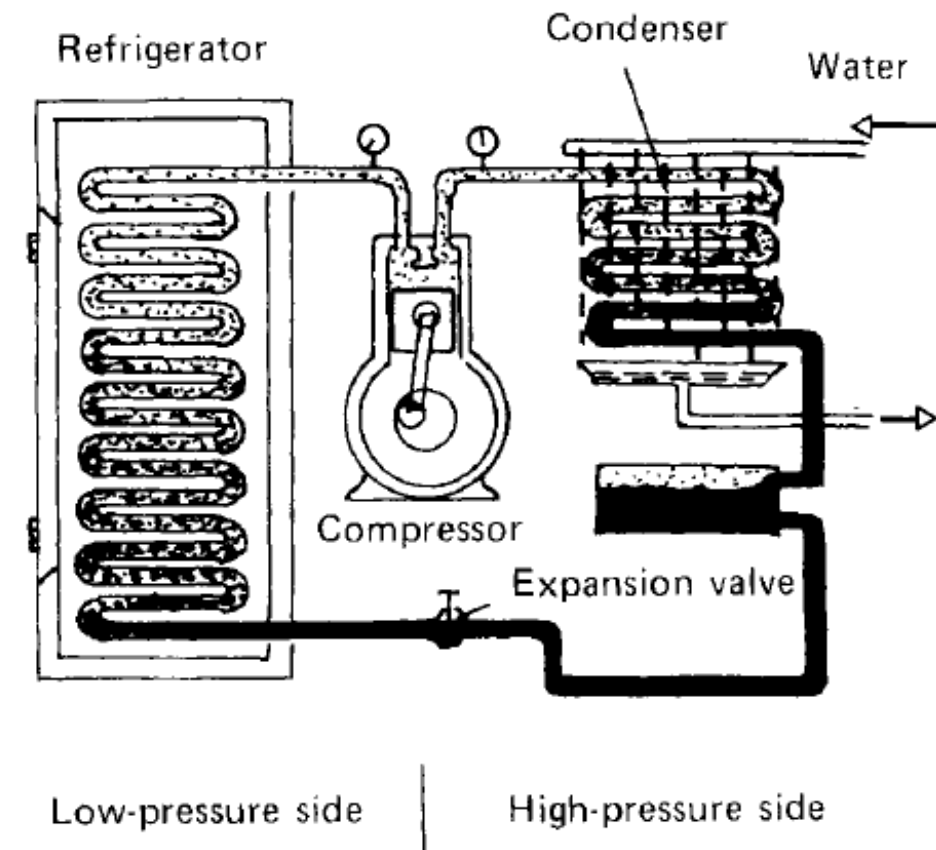
- mechanical refrigerators
 - cryogenic systems.
-
- all should lower the temperature of the product as quickly as possible through the critical warm zone (50–10°C) where maximum growth of micro-organisms occurs.

Equipment: Mechanical refrigerators

Basic elements:

- an evaporator,
 - a compressor,
 - a condenser,
 - an expansion valve.
-
- Components of refrigerators are frequently constructed from copper as the low thermal conductivity → high rates of heat transfer and high thermal efficiencies.

- A refrigerant circulates between 4 elements of refrigerator,
- changing state from liquid to gas, & back to liquid



Mechanical (compression–expansion) refrigerator.
(After Patchen (1971).)

- Properties of refrigerants:
 - a low boiling point & high latent heat of vaporisation
 - a dense vapour to reduce compressor size
 - low toxicity & non-flammable
 - low miscibility with oil in compressor
 - low cost.
- Ammonia
 - excellent heat transfer properties
 - is not miscible with oil
 - toxic & flammable
 - causes corrosion of copper pipes.
- Carbon dioxide
 - nonflammable & non-toxic
 - operating pressures > ammonia.

- Halogen refrigerants (chlorofluoro-carbons or CFCs)
 - all non-toxic & non-flammable
 - good heat transfer properties
 - lower costs than other refrigerants
 - interaction with ozone in the earth's atmosphere?
- Newer, ozone-friendly HCFCs are being developed.
- Main refrigerants now used: Freon-22 & ammonia

Properties of refrigerants

| Refrigerant | | Boiling point | Latent heat | Toxicity | Flammability | Vapour density | Oil solubility |
|-------------|---------------------------------|---------------------|------------------------|----------|--------------|-----------------------|----------------|
| Number | Formula | (°C) at 100 kPa | (kJ kg ⁻¹) | | | (kg m ⁻³) | |
| 11 | CCl ₃ F | 23.8 | 194.2 | Low | Low | 1.31 | Complete |
| 12 | CCl ₂ F ₂ | -29.8 | 163.54 | Low | Low | 10.97 | Complete |
| 21 | CHCl ₂ F | -44.5 | 254.2 | Low | Low | 1.76 | Complete |
| 22 | CHClF ₂ | -40.8 | 220.94 | Low | Low | 12.81 | Partial |
| 717 | NH ₃ | -33.3 | 1328.48 | High | High | 1.965 | <1% |
| 744 | CO ₂ | -78.5 (sublimes) | 352 | Low | Low | 60.23 | <1% |

- Chilling medium may be air, water or metal surfaces.
- Air chillers (e.g. *blast chillers*)
 - use forced convection to circulate air at ca. 4°C at high speed (4 ms⁻¹)
 - reduce boundary films thickness to increase rate of heat transfer.
 - also used in refrigerated vehicles, but food should be adequately chilled when loaded onto the vehicle

- *Eutectic plate systems*
- Another type of cooling → refrigerated vehicles, esp. for local distribution.
- Salt solutions (e.g. KCl, NaCl, or NH_4Cl) are frozen to their eutectic temperature (from -3 to -21°C)
-
- air is circulated across the plates, to absorb heat from the vehicle trailer.
- plates are regenerated by re-freezing in an external freezer.

- Retail chill cabinets use chilled air which circulates by natural convection.
- Large stores may have a centralised plant to circulate refrigerant to all cabinets.
- The heat generated by the condenser can also be used for in-store heating.

Other methods of cooling

- Foods with a large surface area (e.g. lettuce) are washed and ***vacuum cooled***.
- Food is placed in a large vacuum chamber
- Pressure is reduced to appr. 0.5 kPa.
- Cooling takes place as moisture evaporates from the surface (a reduction of appr. 5°C for each reduction of 1% in moisture content).

- Direct immersion in chilled water (***hydrocooling***)
- to remove field heat from fruit & vegetables,
- cheese is often cooled by direct immersion in refrigerated brine.

- Re-circulated chilled water used in ***plate heat exchangers*** to cool liquid foods after pasteurisation.

- Liquid & semi-solid foods (e.g. butter & margarine) are cooled by contact with refrigerated, or water-chilled metal surfaces in ***scraped-surface heat exchangers***.

Equipment: Cryogenic chilling

- Cryogen is refrigerant that changes phase by absorbing latent heat to cool the food.
- Cryogenic chillers: solid carbon dioxide, liquid carbon dioxide or liquid nitrogen.
- Solid carbon dioxide
removes latent heat of sublimation (352 kJ kg^{-1} at 78°C)
- Liquid cryogen
remove latent heat of vaporisation (358 kJ kg^{-1} at 196°C for liquid nitrogen; liquid carbon dioxide has a similar latent heat to the solid).
- The gas also absorbs sensible heat as it warms from 78°C (CO_2) or from 196°C (liquid nitrogen) to give a total refrigerant effect of 565 kJ kg^{-1} and 690 kJ kg^{-1} respectively.

- Advantages of carbon dioxide:
 - boiling & sublimation point > nitrogen → less severe effect on the food
 - most of enthalpy (heat capacity) from conversion of solid or liquid to gas.
- Carbon dioxide does not require gas handling equipment to extract most of heat capacity; liquid nitrogen does.
- Main limitation of carbon dioxide, and to a lesser extent nitrogen, is its ability to cause asphyxia.
- Maximum safe limit for operators of 0.5% CO₂ by volume & excess carbon dioxide is removed from the processing area by an exhaust system to ensure operator safety.
- Other hazards associated with liquefied gases: cold burns, frostbite & hypothermia after exposure to intense cold.

- Solid carbon dioxide can be used in the form of 'dry-ice' pellets
- liquid carbon dioxide can be injected into air to produce fine particles of solid carbon dioxide 'snow', which rapidly sublime to gas.
- Both types are deposited onto, or mixed with, food in combo bins, trays, cartons or on conveyors.
- A small excess of snow or pellets continues the cooling during transportation or storage prior to further processing.

- E.g. in older meat processing operations, dry-ice pellets were layered with minced meat as it was filled into containers.
- Lack of uniformity in distribution of pellets resulted in some meat becoming frozen and some remaining above 5°C, which permitted bacterial growth and resulted in variable product temperatures for subsequent processing.
- The use of snow horns to distribute a fine layer of snow over minced meat as it is loaded into combo bins has eliminated these problems and resulted in rapid uniform cooling to 3–4°C.

- Liquid nitrogen is used in freezing & chilling operations.
- For batch chilling, typically 90–200 kg of food is loaded into an insulated stainless steel cabinet, containing centrifugal fans and a liquid nitrogen injector.
- The liquid nitrogen vaporises immediately and the fans distribute the cold gas around the cabinet to achieve a uniform reduction in product temperature.
- highly flexible in operation and suitable for low production volumes or where a large number of speciality products are produced.

- For continuous chilling, food is passed on a variable speed conveyor to an inclined, insulated, cylindrical barrel.
- The barrel rotates slowly and internal flights lift the food and tumble it through the cold nitrogen gas.
- To chill diced meat or vegetables at up to 3 t h⁻¹.
- The gentle tumbling action in a partial vacuum, cooled by nitrogen gas to 2°C, solubilises proteins in poultry meat, which increases their binding capacity and water holding capacity, thus improving later forming and coating operations.

- Other applications of cryogenic cooling:
- sausage manufacture,
carbon dioxide snow removes heat generated during size reduction & mixing & *cryogenic grinding*
cryogen reduces dust levels, prevents dust explosions and improves the throughput of mills.
- In spice milling,
cryogenics prevent the loss of aromatic compounds.

- production multi-layer chilled foods (e.g. trifles and other desserts)
the first layer of product is filled
the surface is hardened with carbon dioxide.
next layer can be added immediately without waiting for the first layer to set.
- cooling & case-hardening of hot bakery products & chilling flour
to obtain accurate & consistent flour temperatures for dough preparation.

Chill storage

- Once a product has been chilled, the temperature must be maintained by refrigerated storage.
- Chill stores are normally cooled by circulation of cold air produced by mechanical refrigeration units, and foods may be stored on pallets, racks, or in the case of carcass meats, hung from hooks.
- Transport of foods into and out of stores may be done manually using pallet trucks, by forklift truck or by computer-controlled robotic trucks.

Control of storage conditions

- Fresh products → RH & composition atmosphere.
- adequate circulation of air using fans,
→ control temperature, RH or atmospheric composition.
- for respiring foods; to remove heat;
- for cheese; flavour development takes place during storage.
- when high storage humidities are used for fresh fruits and vegetables → increased risk of spoilage by mould growth if 'dead spots' permit localised increases in humidity.

Temperature monitoring

- is an integral part of quality management & product safety management throughout the production and distribution chain.
- monitoring devices store large amounts of data & integrate into computerised management systems.
- temperature sensors measure air temperatures or product temperatures

Effect on foods

- Little or no reduction in eating quality or nutritional properties → correct storage temperature
- Hardening due to solidification of fats and oils.
- Chemical, biochemical and physical changes during refrigerated storage limit the shelf life of chilled foods.
- E.g. enzymic browning, lipolysis, colour & flavour deterioration & retrogradation of starch

- Lipid oxidation → quality loss in cook–chilled products
cooked meats → oxidised flavour: ‘warmed-over flavour’ (WOF)
- Migration of oils from mayonnaise to cabbage in chilled coleslaw,
- Syneresis in sauces & gravies due to changes in starch thickeners,
- Evaporation of moisture from unpackaged chilled meats & cheeses,
- More rapid staling of sandwich bread at reduced temperatures
- Moisture migration from sandwich fillings.

Loss of vitamins during chilled storage of selected foods

| Food | Losses (% per day) | | | | |
|-----------------------------|----------------------------|----------------------|-------------------------|-------------------------|-----------------------|
| | Ascorbic acid ¹ | Thiamin ² | Riboflavin ² | Pyridoxine ² | Carotene ³ |
| <i>Fruit and vegetables</i> | | | | | |
| Apples | 0.1–0.5 | | | | |
| Brussels sprouts (cooked) | 4.6 | 0.3 | | | |
| Cabbage (white) | 0.1–0.2 | | | | |
| Carrots | 0–0.6 | 0 | 0 | 1.6 | 0.2–0.8 |
| Cauliflower | 0.1–0.2 | | | | |
| French beans | 1.9–10.0* | 0 | 0 | 1.8 | 1.8–2.2 |
| Lettuce | 4.8–9.7* | 4.7 | 5.4 | 2.9 | |
| Oranges | 26.0 | | | | |
| Parsley | 2.2–4.5* | +8.2 | 3.9 | 1.8 | 1.0–3.0 |
| Peas | 1.0–2.0 | | | | |
| Pineapples | 18.0 | | | | |
| Potatoes (boiled) | 10.7 | 1.3 | | | |
| Strawberries | 0 | | | | |
| Spinach (cooked) | 6.4 | | | | |
| Tomatoes | | | | | 41 |
| <i>Meats</i> | | | | | |
| Pork liver (fried) | 10.3 | 0.7 | 0.7 | 0 | |
| Roast pork | | 0.1 | | | |

¹ Storage at 0–2°C and relative humidity 76–98%, storage time: 2–21 days

² Storage at 1°C and relative humidity 50±10%, storage time 3–14 days

³ Storage at 7°C and relative humidity 60–80%, storage time 2–21 days

* Rapid wilting at low storage humidity

Adapted from Ezell and Wilcox (1959 and 1962), Adisa (1986) and Bogнар (1980).

- In cook–chill systems,
- insignificant losses for thiamine, riboflavin & retinol;
- vit. C losses 3.3–16% day⁻¹ at 2°C.
→ variation → differences: chilling time, storage temperature, oxidation & reheating conditions.
- Vit. C losses: cook–pasteurise–chill < cooked–chilled foods
E.g. spinach lost 66% within 3 days at 2–3°C after cook–chilling; 26% loss within 7 days at 24°C after cook–pasteurising–chilling.