Proceedings of the

# Strathleven Centenary Symposium

on

# Refrigeration

held on 26 and 27 February 1980

# Strathleven Centenary Symposium

**In November 1879 the S.S. *Strathleven* left Sydney with a cargo of frozen meat and butter which was discharged in good condition in London in February 1880 — the first successful overseas shipment of frozen food.**

**In view of the importance of this shipment as a technological innovation that had immediate effects on world trade in foodstuffs, the CSIRO Division of Food Research with part sponsorship by the Meat and Allied Trades Federation of Australia held the *Strathleven Centenary Symposium on 'Food Refrigeration'* at CSIRO Division of Applied Physics, West Lindfield, N.S.W. on 26 and 27 February 1980.**

**About 200 people attended the Symposium at which 19 papers were presented by speakers from Australia and overseas. The titles and authors of the papers are listed below and the full texts (where available) are included in this combined issue of the Quarterly:**

*The President of the Symposium was Dr J. H. B. Christian, Chief, CSIRO Division of Food Research, and the Organizing Committee consisted of J. F. Kefford (Chairman), G. Fisher (Secretary), Mrs K. H. Adams, Dr B. D. Patterson, K. C. Richardson, Dr A. K. Sharp, Dr J. R. Vickery, Dr D. J. Walker and G. J. Walker.*

Refrigeration of meats and meat products

# Muscle biology and refrigeration: problems past, present and future

By C. L. Davey

Meat Industry Research Association, New Zealand

## Introduction

It was an historical inevitability that many major developments in meat technology relating to refrigeration would be made in Australia and New Zealand. A century ago, both countries saw their salvation in the export of meat preserved by freezing and have concentrated on developing meat science and technology around such refrigeration practice. There was always a readiness to apply the latest biochemical and microbiological knowledge to the investigations and this led to a rich harvest of ideas in modern meat technology.

The early endeavours developed in parallel with the knowledge of muscle tissue and basic microbiology being obtained, particularly at the British Food Investigation Board's Low Temperature Station at Cambridge in England. Cambridge was at that time the centre of much of the world's innovative biochemistry relating to muscle. Australia and New Zealand therefore naturally maintained active links with currents in muscle research through the Low Temperature Station.

As part of a well-devised strategy, a series of important investigations was initiated in the 1930s. Although interrupted by the war, they were reinstated in the late 1940s and assumed special importance once the bulk meat-purchasing agreements with Britain were cancelled, and Australia and New Zealand found themselves in a relatively unprotected meat trade.

By way of respect for the earlier workers such as J. R. Vickery, W. A. Empey, W. J. Scott, E. Griffiths, N. E. Holmes, R. A. Lawrie, A. Howard, T. Moran and E. C. Bate-Smith, who laid the foundations of much modern meat technology, I would advise all aspiring meat scientists to read about their undertakings. Indeed, it is from their work into environmental factors affecting meat quality that many of today's modern processing formulae are derived.

In the light of such knowledge, what more can science give? No more perhaps than the advantage of knowing why, so that further invention can occur at greater pace.
One cannot doubt in this regard that a better knowledge of animal breeding and nutrition, of disease eradication and of microbial control have added to our confidence in meat as a wholesome food. Assuming that meat can be made so, then toughness is its least-wanted feature. Knowledge of muscle was not sufficiently advanced at the time of the earlier investigations that its relation to toughness could be taken into consideration. Through a lack of knowledge of *rigor mortis* (the change of state that converts live muscle into meat) and of the detailed features of muscle structure and function, major emphasis was placed on live animal factors such as age, nutritional regime and pre-slaughter stress as determinants of meat toughness.

The present review emphasizes the relationship between muscle physiology, especially related to *rigor mortis*, and the toughness of meat. The relationship, being close, offers novel ways of processing meat to achieve consistent tenderness. Special attention is given to the results obtained with ox *Musculus sternomandibularis* which has been used over many years as an experimental tissue at the New Zealand Meat Research Institute. Although this muscle has a high content of connective tissue, it is uniformly structured with most of its fibres lying parallel to the axis of the muscle. It therefore lends itself well to scientific study.

### Changes in muscle *post mortem*

*Rigor mortis*

Modern meat science originated largely from the early Cambridge work through studies into the biochemistry and physiology of *rigor mortis*. With the observation by Russian workers in 1939 that myosin (the major contractile protein of muscle) could enzymatically dephosphorylate adenosine triphosphate (ATP), the source of free energy for muscular contraction, the link between structure and contraction was firmly established. The observation immediately prompted a systematic investigation into the development of rigor.

After an animal dies its skeletal muscles live on for a period. If well oxygenated and supplied with nutrients, excised muscle strips can remain in an active, *pre-rigor* condition for many days. They can be stimulated to contract and do work, and like rubber are reversibly extensible. If starved of oxygen, they enter *rigor mortis* some minutes or hours *post mortem* and become nonexcitable. They lose their rubber-like extensibility to become quite rigid. In resting, living muscle the concentration of ATP is quite low (5 to 10 $\mu$mol $g^{-1}$. It would disappear by dephosphorylation within a few minutes after death if not actively replenished. *Post mortem* synthesis of ATP occurs through transfer of phosphate from the muscle store of creatine phosphate, and to a lesser degree through glycolysis of the carbohydrate stores. Balance between dephosphorylation and resynthesis can be sustained as long as creatine phosphate lasts. From then on, resynthesis depends largely on glycolytic transfer reactions. Since these alone cannot keep pace with breakdown, the level of ATP in muscle falls and rigor develops (Bendall 1973).

From studies of rabbit, ox, sheep, horse and whale muscle it becomes clear that the underlying biochemical changes are likely to be the same in all mammalian species, with the complete disappearance of ATP and creatine phosphate and, as the product of glycolysis, the appearance of lactic acid (up to 100 $\mu$mol $g^{-1}$). The ultimate concentration of lactic depends on initial carbohydrate stores and therefore on the pre-slaughter condition of the animal, being high in well fed and rested animals, much lower in starved animals, and almost non-existent in those excessively exhausted. The final or ultimate pH of muscle will be related to the accumulation of the lactic acid, being relatively high (about pH 7) in excessively exhausted animals (Bendall 1973).

The temperature of the muscle considerably affects the time course of these events. In the excised *M. longissimus dorsi* of a well fed and rested ox, *rigor mortis* occurs in about 24 h at 7 °C, 16 h at 18 °C and 5 h at 37 °C (Marsh 1954). The *M. longissimus dorsi* of mature sheep takes approximately the same time to go into rigor, but that of lambs only about two-thirds as long (Marsh and Thompson 1958). These times can be much longer (e.g. 50 h at 20–22 °C) in the *M. longissimus dorsi* of some species of whale (Sharp and Marsh 1953). Times may also vary widely among muscles within a carcass. Thus, in beef, *rigor mortis* occurs in about 8 h in the *M. psoas major*, but in about 24 h in the *M. longissimus dorsi* (Tarrant and Mothersill 1977). Starving, excessive pre-slaughter stress, or the death struggle can all drastically reduce these periods.

Imposing a freeze–thaw cycle on pre-rigor muscle from any species dramatically reduces the time to rigor. In thin strips of muscle, which have undergone a freeze–thaw cycle, it takes only 30 min for ATP levels to fall to zero and the pH to the value achieved during normal rigor development (Bendall 1960). Freezing does not stop the slow development of rigor, which, depending upon the temperature, moves to completion over a period of days in the frozen tissue. For example, if pre-rigor carcasses are frozen rapidly and stored at −12 °C, the frozen muscles achieve rigor in 10 to 20 days (Davey and Gilbert 1974*b*). At higher sub-zero temperatures the rate of rigor development is more rapid (Behnke *et al.* 1973).

*Muscle shortening* post mortem

When held without restraint in a horizontal position an excised, pre-rigor muscle usually shortens slightly to an 'equilibrium length'. At temperatures above about 20 °C the muscle shortens further during rigor development. This rigor or heat shortening is small at 20 °C (< 5% of the equilibrium length) but rises to as much as 50% at 40 °C. Locker and Hagyard (1963), in attempting to reduce muscle shortening to a minimum, developed rigor in ox *M. sternomandibularis* at about 2 °C. Quite contrary to expectation the muscles shortened to as little as half their

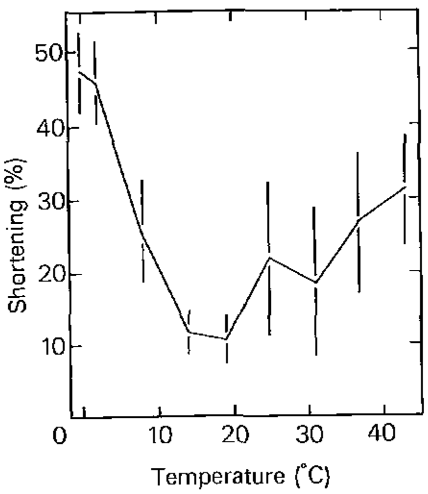


**Fig. 1.** Mean ultimate shortenings of excised ox *M. sternomandibularis* stored at various temperatures during rigor develpment. (From Locker and Hagyard 1963.)

equilibrium length in 24 h (Fig. 1). The shortening increased with falling temperature and decreased if chilling was delayed.

Cold shortening is extremely slow and develops only about 5% of the power of physiological contraction, but it is similar to normal contraction in that it involves ATP dephosphorylation, the rate of which increases markedly in muscles working against a load (Newbold 1966). The power developed in shortening increases with muscle growth (Davey and Gilbert 1975*a*). Cold shortening occurs in beef, sheep and turkeys, and less intensely in pigs (Locker *et al.* 1975). Although also occurring in the rabbit, it has been shown to be confined to that animal's red muscles such as the *M. semitendinosus*.

Unrestrained muscle also shortens if it goes through 'thaw rigor'. Although the power developed is only about a quarter of that observed during a muscle twitch, shortening can be as high as 80% (Jungk *et al.* 1967). Active thaw shortening can occur in muscles frozen at any point short of full rigor development.

To what extent can cold and thaw shortenings occur in muscles that are still attached to the skeleton? A few muscles, such as those of the neck, are severed during carcass dressing and so will shorten as much as unrestrained muscle, others, notably the *M. longissimus dorsi*, remain attached to the skeleton but are still likely to shorten because their constituent fibres terminate in flexible subcutaneous connective tissue. Even muscles fixed absolutely at both ends may exhibit shortened sections if portions are subjected to a differential chilling rate. In restrained ox *M. sternomandibularis* insulated at both ends and held at 2 °C, a zone of marked shortening will occur in the rapidly chilled central region, with concomitant stretching at the two insulated ends (Marsh and Leet 1966).

The mode of carcass hanging affects the shortening potential of intact muscles. Back-leg suspension, for example, leaves many major back and hind-leg muscles slack which allows them to shorten in response to cold (McCrae *et al.* 1971). Holding pre-rigor carcasses in a standing posture during chilling to 0 °C largely overcomes shortening potential (Davey and Gilbert 1973). Presumably a natural, standing posture imposes uniform tension on most fibres of a muscle, while in addition the skeleton restrains opposing muscles more or less equally.

*Stimulation of rigor development*

It is economically advantageous for the processor to accelerate *rigor mortis* in meat animals. This is possible in several ways. Rigor times can be reduced by starvation and stress; of course, on humane grounds such procedures cannot be contemplated (Bendall 1973). It has been shown that the same effect can be achieved by raising the temperature of freshly slaughtered lambs to 45 °C, when rigor develops in about 2 h (Davey and Gilbert 1973). In these conditions heat shortening occurs in those muscles that are not restrained by the skeleton. Rigor develops in about the same time if pre-rigor muscle is subjected to a brief period of very high pressure (Bouton *et al.* 1977).

A more elegant stimulation to provoke rapid rigor development can be achieved with electricity. The physiologist has often used electrical stimuli to develop early rigor in small muscles, without any attempt to define optimum electrical conditions. Harsham and Deatherage (1951) were the first researchers to use electrical stimulation as a means of hastening both the fall of pH and rigor onset in the musculature of freshly slaughtered beef animals. Ingram and Ingram (1955) used the concept in a study of microbial growth rates in relation to rigor development in horse muscle. Hallund and Bendall (1965) showed that a brief period of post-mortem stimulation increased the glycolytic rate in pig muscles. De Fremery and Pool (1960) with chickens, and Carse (1973) with lambs, stimulated carcasses with the specific aim of studying the relationship between rates of post-mortem rigor development and meat tenderness. Recent work in New Zealand sets out the relationship between stimulation parameters and physiological responses. Stimulation for about a minute induces an immediate fall in pH ($\Delta$pH) and almost doubles the rate (dpH/dt) at which the muscle pH subsequently declines towards its ultimate (Chrystall and Hagyard 1976; Chrystall and Devine 1978; see Fig. 2).

The highest $\Delta$pH, about 0.7 pH units, is achieved by stimulating ox *M. sternomandibularis* a few minutes after death. The values for $\Delta$pH reduce progressively as stimulation is delayed, and approach zero if the muscle pH has fallen naturally to 6.2 before stimulation. Stimulation with less than 50 V is effective when administered within 20 min of death, because during that time the stimulus acts both indirectly, through the nervous reticulation, and directly through the muscle itself. After 20 min, indirect stimulation becomes increasingly less effective because nerves transmit less as they lose vitality, and higher voltages (up to 300 V) are then required to cause $\Delta$pH values greater than 0.5. Pulse frequency is the other controller of $\Delta$pH: stimulation frequency should be in the range 5 to 15 pulses sec$^{-1}$. The use of alternating pulses slightly increases $\Delta$pH values, and will prevent polarization at electrode clamps.

In the minute of stimulation the muscle pH falls to about pH 6.5, the creatine phosphate concentration falls to zero, and glycogen and ATP concentrations fall respectively by about 30% and 50%. Using the most effective set of stimulation parameters, the time from death to *rigor mortis* is reduced to about 2 h in lamb muscles and about 4 h in ox muscles.

*Muscle aging*

The development of *rigor mortis* is the most obvious post-mortem change that muscle undergoes, but other, slower, changes also occur. Any rigor muscle eventually loses its rigid condition and becomes more flaccid. The terms 'resolution of rigor' or 'meat aging' are used to describe this change. 'Aging' is as distinctive as rigor development, and can be quantified by measuring the longitudinal extension characteristics of muscle (Fig. 3). Pre-rigor muscle stretches easily if it is loaded lightly (5 to 15 kPa) and the extension reverses with little hysteresis.

Rigor muscle, in contrast, is unyielding but can be irreversibly and fully extended by much larger loads of more than 200 kPa. Aged muscle reverts to being easily stretched but, as with rigor muscle, the extension is an irreversible one. Extension is limited in all three cases to roughly twice equilibrium

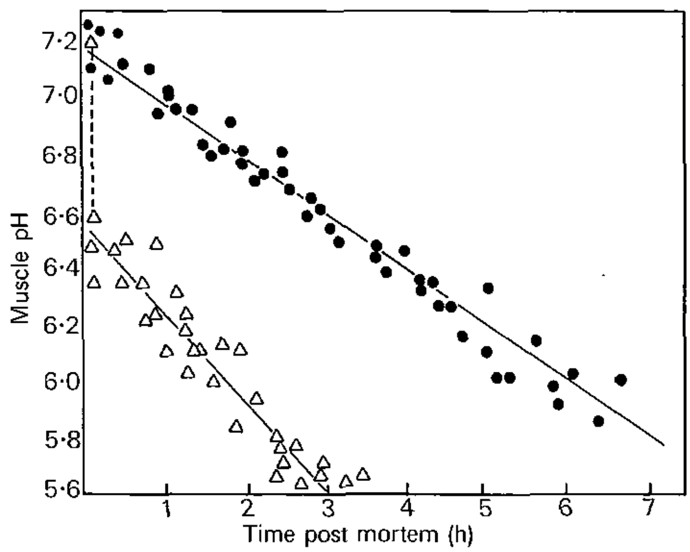


**Fig. 2.** Post-mortem acceleration of pH decline in ox *M. sternomandibularis* caused by electrical stimulations ●, unstimulated control stored at 35 °C; △, stimulated for 1 min, then stored at 35 °C. Dotted vertical line represents $\Delta$pH due to the stimulation treatment. Slope of regression lines represent dpH/dt for each treatment. (Courtesy Dr B. B. Chrystall and Dr C. E. Devine.)

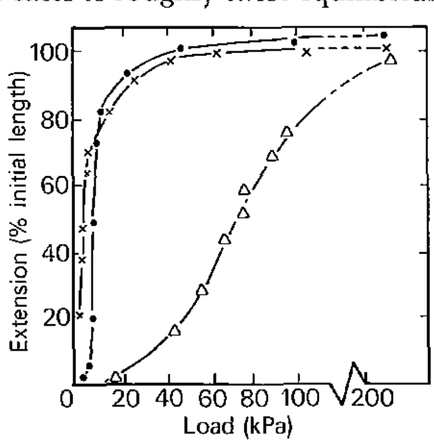


**Fig. 3.** Extension–load curves for strips of ox *M. sternomandibularis*. ×, pre-rigor muscle; △, rigor muscle, held at 15 °C for 30 h *post mortem*; ●, aged muscle, held at 15 °C for 90 h *post mortem*. (After Davey and Dickson 1970.)

length, indicating that connective tissue has become the load bearer at full stretch (Davey and Dickson 1970). The changes observed during muscle aging have been reviewed recently by Dutson (1974), Goll *et al.* (1974), Asghar and Yeates (1978), Goll (1978) and Davey and Winger (1979).

**Meat toughness and its measurement**

Major physical and structural changes accompany heat denaturation of muscle tissue, making difficult any simple interpretation of cooked meat toughness in terms of the fine structure of muscle. A recent review brings together many of the diverse observations that attempt to reveal such a relationship (Davey and Winger 1979).

*Assessment of toughness*

While a panel of trained tasters can be given an appropriate scoring scale on which to assess the toughness of cooked meat, mechanical shear devices (tenderometers) are used to remove the subjectivity which is always inherent in human tasters. Toughness (or the converse, tenderness) is measured on a tenderometer as the force required to cleave a standard cross-section of cooked meat across the muscle fibres. All shear measurements reported in this review have been obtained with the MIRINZ tenderometer (Macfarlane and Marer 1966) which applies a constantly increasing shearing load across the meat sample. At a load determined by the toughness of the meat, a sharp yielding point is indicated on a load-deformation curve. Force scores (FS) are measured on an arbitrary scale of 150 units, each unit being approximately equivalent to a force of 1.7 kPa.

As the tenderometer wedge shears the cooked sample, the muscle fibres, membranes, and connective tissue part, although connective tissue sometimes remains compressed against the base plate of the tenderometer. Despite this, the yielding point correlates well with taste panel scores. The relationship between FS values and panel score is not linear (Fig. 4). Many correlations have led us to regard cooked meat as very tender at shearing values below FS 25, tender from FS 25 to FS 40, and undesirably tough as the score rises much above FS 40 (McCrae *et al.* 1971; Davey and Gilbert 1975*b*).

*Development of cooking toughness*

Increasing cooking temperature produces two distinctly separate phases of toughening (Fig. 5; Davey and Gilbert 1974*a*). Between 40 and 50 °C there is loss of myosin solubility, which presumably indicates denaturation in the contractile system of the muscle, and the meat changes from red to brown.

The second phase, between 65 and 75 °C, is

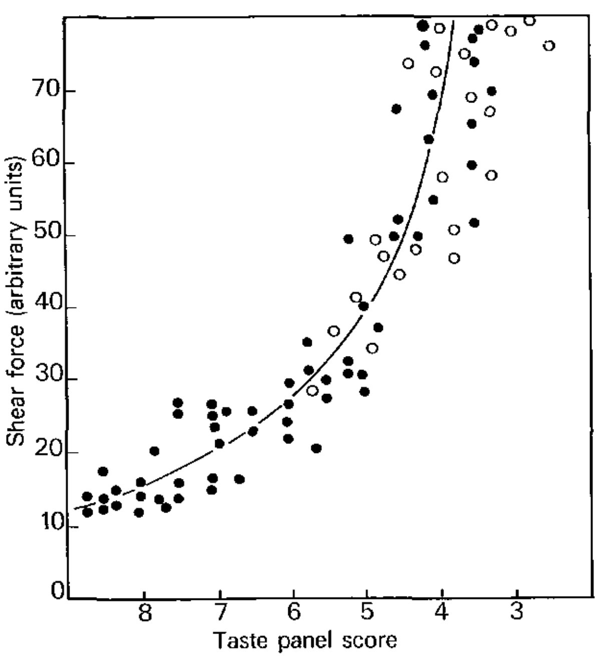


**Fig. 4.** Relationship between sensory and objective measurements of cooked ox muscles. Tenderness measured by a MIRINZ tenderometer. ●, *M. longissimus dorsi*; O, *M. sternomandibularis*. (From Davey and Gilbert 1975*b*.)

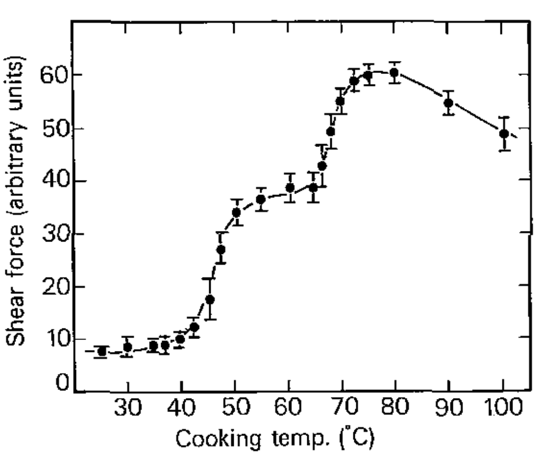


**Fig. 5** Increase in the toughening of ox *M. sternomandibularis* with increasing cooking temperature. Muscle samples cooked in a water bath, at prescribed temperature, for 40 min. (From Davey and Gilbert 1974*b*.)

associated with a 25–30% shrinkage along the muscle fibres through denaturation of connective tissue. As the cooking is prolonged and the cooking temperature rises above 75 °C, the toughening associated with this shrinkage is largely overcome (Davey *et al.* 1976). This is probably a consequence of the breakdown of unspecific structural elements within the muscle fibres as well as of the collagen melting. This conversion of collagen to gelatine destroys the mechanical strength of the connective tissue almost entirely.

The animal's age at slaughter determines the heat stability of cross-linkages in the collagen and hence the rate at which they are destroyed by cooking. In *M. sternomandibularis* of 3-day-old calves, for instance, force scores fall to their lowest after 5 h cooking, while 12 h and 20 h cooking give maximum tenderness from 1½-year-old ox and the meat of 7-year-old bulls. Once collagen has been lost, animal maturity has little influence on residual tenderness, force scores then varying from FS 28 to FS 34 across the age range of animals normally slaughtered.

*Muscle shortening and toughness*

The fact that muscle can enter *rigor mortis* at different levels of shortening is of great importance to the meat technologist. Muscle shortening during the early post-mortem period affects cooked meat toughness to a remarkable degree (Locker 1960). The force required to shear cooked *M. sternomandibularis* rises steeply as the muscle shortening approaches 40% (Marsh and Leet 1966). At shortenings between 40% and 60% the toughness undergoes a sharp decline. A prominent toughness peak therefore exists in the cooked muscle, with its maximum at 40% shortened (Fig. 6). Cold or thaw shortening arising at any stage in the development of rigor produces the same relationship, and the peak appears in the force score/shortening relationship of *M. sternomandibularis* from animals of any age (Davey and Gilbert 1975*b*). It is concluded that the most significant cause of toughness in cooked meat is the shortening of pre-rigor muscle induced by low temperatures, with animal maturity being a secondary cause.

Keeping meat for a number of days before cooking to tenderize it has always been a part of our culinary culture. Apparently, the tenderizing from such aging begins at about the time the muscles enter rigor. The force scores of unshortened *M. sternomandibularis* held at 15 °C fall from about FS 65 to 25 over a period of 2½ days, with an additional decline to FS 15 on storing for 8 days. The shearing values of muscle shortened by 35% also fall during 2½ days of storage at 15 °C, but their initial value is FS 95 and the minimum they fall to is only FS 75 (Davey *et al.* 1967). Two significant conclusions arise from these studies. Firstly, there is a limit to the degree of tenderizing it is possible to achieve by aging and, secondly, shortening drastically reduces this degree of tenderizing. The effect of maximal aging on the shortening/toughening relationship is shown in Fig. 7. The total loss of tenderizing in the samples shortened by 40%, shown in Fig. 7, is

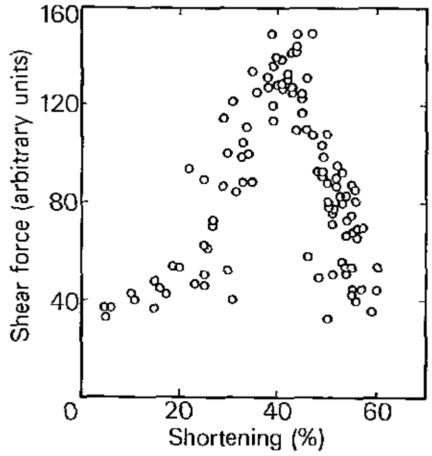


**Fig. 6.** Influence of pre-rigor muscle shortening on shear force of cooked *M. sternomandibularis*. (From Marsh and Leet 1966.)

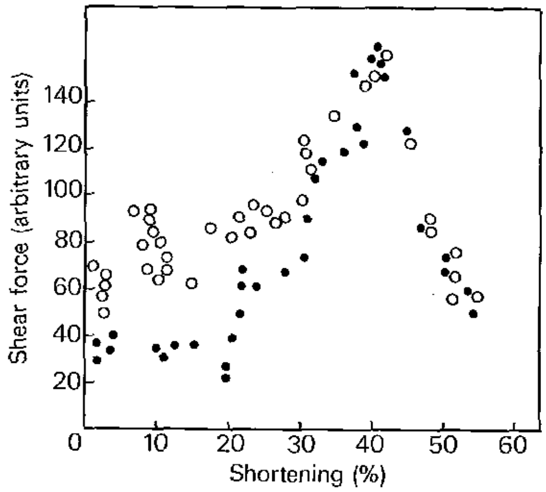


**Fig. 7.** Influence of pre-rigor muscle shortening on muscle aging. O, rigor muscle at different shortenings; ●, aged muscle at different shortenings. Aging was carried out by storing rigor muscle at 15 °C for 4 days. (After Davey *et al.* 1974.)

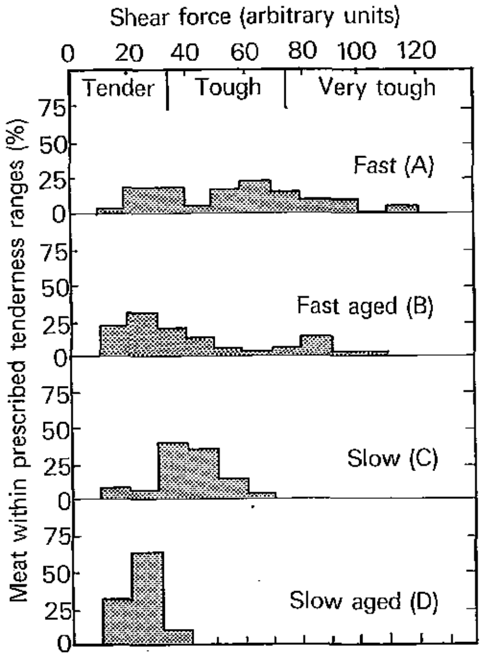


**Fig. 8.** Relationship between shortening and force score for rigor and for aged beef *M. longissimus*. Rigor samples (A and C) were exercised at 18 h *post mortem*, then cooked and analyzed. Aged samples (B and D) were held for an additional 48 h at 15 °C, then cooked and analyzed. Samples Fast A, and Fast Aged B were obtained from rapidly chilled sides. Samples Slow C, and Slow Aged D were obtained from relatively slowly chilled sides (see text). (After Davey 1971.)

not apparently a characteristic of all muscles, although high shortenings do reduce the tenderizing achieved by aging in all the muscles so far studied (Herring *et al.* 1967).

Current understanding of the relationship between meat toughness and muscle shortening is based largely on experiments with ox *M. sternomandibularis*. Are these results applicable to the whole carcass? The large bulk of a beef carcass makes it difficult to chill rapidly, so large-scale studies have been undertaken to determine whether the commercial chilling of beef sides is ever likely to be rapid enough to toughen saleable muscles. An experiment has recently been conducted (Davey 1971) in which the right sides of prime ox carcasses were chilled over 18 h to a deep leg-muscle temperature of 17 °C, while the left sides were chilled in the same time to 7 °C. The tenderness of *M. longissimus dorsi* from the thoracic region of both halves of a carcass is illustrated in Fig. 8. Some 80% of the *M. longissimus dorsi* from the sides chilled rapidly to 7 °C was unacceptably tough.

Even after aging, the force scores of half the samples remained above FS 35. In contrast, the muscle from the side chilled slowly to 17 ° was moderately acceptable, and after aging was very tender. Similar results have been obtained with muscles from young bulls, from cows and from calves; in all these animals toughness increases with an increasing rate of chilling in dressed sides (Buchter 1972). More recently, Martin *et al.* (1977) have examined the effect of stress and glycolytic rate on toughness development in rapidly chilled beef sides. They confirmed the work already cited and further demonstrated that toughness from cold shortening is reduced in muscles that go into rigor early.

Marsh *et al.* (1968) described the effect on the tenderness of *M. longissimus* from chilling and freezing lamb carcasses before *rigor mortis* had set in. Loins from carcasses frozen with little post-mortem delay were tough, about 50% having force scores over 40. On the other hand, loins from lamb carcasses subjected to a delay (24 h, 15–20 °C) and then frozen were all very tender.

## Meat technology applications

### *Processing limits*

We can now make the following observations. These, although simple in themselves, are based on many years of detailed research.

- The major cause of toughness in cooked meat is the rapid chilling of muscle in the pre-rigor phase.
- Toughness is largely avoided if pre-rigor carcasses are either:
  (*a*) chilled in a standing posture,
  (*b*) allowed to go into *rigor mortis* before chilling, or
  (*c*) maintained for a brief period at 35–45 °C before chilling.
- Tenderness can be increased by aging rigor muscle, although the shortening of the muscle reduces its capacity to age.

Processing specifications designed to overcome the effects of rapid pre-rigor chilling or freezing have been developed for both beef and lamb carcasses. They require that carcasses or sides be 'conditioned', i.e. allowed to go into rigor at relatively high temperatures (Locker *et al.* 1975). Rapid chilling arose as a commercial practice partly to combat bacteria, so these specifications also prescribe standards of hygiene and of humidity control to retard microbial growth. The additional tenderizing gained by aging can then form part of the process, but as it is extremely time-consuming it is at present used only where it bestows a definite economic advantage, being favoured for grilling cuts of beef and lamb carcasses.

*Carcass posture and toughness*

Mention has been made of the fact that cold shortening is minimized by chilling lamb carcasses in a standing posture. Does this approach have possibilities in large-scale processing? Results from unorthodox suspension of beef carcasses show that it could have. In beef sides suspended from the aitch bone of the pelvis with the fore and hind legs hanging forward roughly at right angles to the backbone, the tenderness of the *M. longissimus dorsi*, *M. semimembranosus* and *M. biceps femoris* was increased, and for *M. longissimus dorsi* especially, this increased tenderness was apparent in the aged cuts (Herring *et al.* 1965).

Both cold and thaw shortening are largely overcome by freezing in the standing posture; the immediate freezing of lambs with little loss of tenderness is a distinct processing possibility. The benefit of improved tenderness coupled with the technical simplicity of hanging carcasses or sides from the pelvic region provides a sound foundation for the practical processing of beef and lamb. Although the standing posture presents storage difficulties, these can be overcome for lamb by drawing the fore and hind legs into a crouching or kneeling position while the carcass still has its pre-rigor flexibility. Rigor is complete after 20 days at −12 °C and the cuts, whether cooked, frozen or thawed, are uniformly tender. A simple mechanical alteration of carcass shape and a period of controlled frozen storage are all that is required.

*Electrical stimulation of the carcass*

Accelerating rigor development to a useful degree in beef carcasses or sides can be achieved by electrical stimulation within 30 min post-slaughter. The hook suspending the back leg of a side is convenient for one electrode, while a pin inserted into the neck or fore-leg functions as the other. Although Bouton *et al.* (1978) successfully tested stimulation voltages of less than 100 V, voltages greater than 500 V are normally used to overcome impedance at the electrodes and ensure that every muscle is adequately stimulated. Judged from pH falls in a wide selection of muscles, stimulation applied through these electrodes is evenly distributed throughout the side. A side of beef bends on stimulation and the foreleg and shoulder arch towards the hind leg. After about 40 s the muscles begin to tire and the side slowly relaxes, although it remains in a slight tetanus until the stimulation is stopped some 20 to 40 s later. In contrast, a stimulated carcass's forelegs lift to the position they would take up in a standing animal. The commercial advantages of electrical stimulation of beef are a reduction in the possibility of cold shortening, boning-out of rigor cuts 5 h from slaughter, and in packing and chilling hot-boned, pre-rigor meat. This last might seem to be no advantage, as loss of restraining skeletal attachments could be expected to toughen the cuts. However, even at rapid rates of chilling and freezing, toughness does not develop in the boned-out cuts since *rigor mortis* intervenes (Gilbert *et al.* 1977).

Because of their smaller mass, lamb carcasses lose their heat more rapidly than beef during chilling or freezing and so are more prone to cold or thaw shortening. In New Zealand, automatic systems have been developed for their stimulation. In one on-line system the hind-leg hook and gambrel serve as one electrode, while a V-shaped electrode with its point rubbing across the back of the carcass just below the shoulders serves as the other. The carcasses on the killing chain move across the rubbing electrode for a period of 1½ min. Before chilling or freezing, the stimulated carcasses are held for about 2 h at 7 °C to 10 °C to develop rigor, and for longer if they are to be aged. Some New Zealand meat-processing plants have the capacity to stimulate as many as 20 000 carcasses each day. Meat treated in this way can be cooked from the frozen state and be acceptably tender.

**Further developments**

As our knowledge of the muscle cell advances further, it should be possible to relate muscle structure more closely to meat toughness. The further characterization of collagen will reveal the part that connective tissues play in tenderness. In this respect the reason for the quality difference between grilling and stewing cuts is probably related to the amounts of their connective tissue. Since a carcass is composed mostly of lower grade cuts, research directed to their upgrading is obviously useful.

Because electrical stimulation of the carcass avoids most of the toughening caused by rapid chilling and freezing and is so simple, alternatives appear superfluous. Now that research has obviated the confusions introduced by processing toughness, systematic attention can be given to the alleviation of toughness related to such live-animal factors as breed, growth rate, maturity and stress.

### References


Asghar, A., and Yeates, N. T. M. (1978). *CRC Crit. Rev. Food Sci. Nutr.* 10, 115–45.

Behnke, J. R., Fennema, O., and Cassens, R. G. (1973). *J. Agric. Food Chem.* 21, 5–11.

Bendall, J. R. (1960). *In* 'The Structure and Function of Muscle', vol. 3, ed. G. H. Bourne, pp. 227–74. (Academic Press: New York and London.)

Bendall, J. R. (1973). *In* 'The Structure and Function of Muscle', 2nd ed., ed. G. H. Bourne, vol. 2, pp. 243–309. (Academic Press: New York.)

Bouton, P. E., Harris, P. V., Macfarlane, J. J., and O'Shea, J. M. (1977). *Meat Sci.* 1, 307–18.

Bouton, P. E., Ford, A. L., Harris, P. V., and Shaw, F. D. (1978). *J. Food Sci.* 43, 1392–6.

Buchter, L. (1972). *In* 'Chilling: Why and How, Symposium No. 2', 4.51–4.54, Meat Res. Inst., Langford.

Carse, W. A. (1973). *J. Food Technol.* 8, 163–6.

Chrystall, B. B., and Devine, C. E. (1978). *Meat Sci.*, 2, 49–58.

Chrystall, B. B., and Hagyard, C. J. (1976). *N.Z. J. Agric. Res.* 19, 7–11.

Davey, C. L. (1971). *Food Technol. N.Z.* 6, 31–3.

Davey, C. L., and Dickson, M. R. (1970). *J. Food Sci.* 35, 56–60.

Davey, C. L., and Gilbert, K. V. (1973). *J. Food Technol.* 8, 445–51.

Davey, C. L., and Gilbert, K. V. (1974*a*). *J. Sci. Food Agric.* 25, 923–30.

Davey, C. L., and Gilbert, K. V. (1974*b*). *J. Sci. Food Agric.* 25, 931–8.

Davey, C. L., and Gilbert, K. V. (1975*a*). *J. Sci. Food Agric.* 26, 755–60.

Davey, C. L., and Gilbert, K. V. (1975*b*). *J. Sci. Food Agric.* 26, 953–60.

Davey, C. L., Kuttel, H., and Gilbert, K. V. (1967). *J. Food Technol.* 2, 53–6.

Davey, C. L., Niederer, A. F., and Graafhuis, A. E. (1976). *J. Sci. Food Agric.* 27, 251–6.

Davey, C. L., and Winger, R. J. (1979). *In* 'Fibrous Proteins: Scientific, Industrial and Medical Aspects,' eds D. A. D. Parry, and L. K. Creamer. (Academic Press: London.)

De Fremery, D., and Pool, M. F. (1960). *Food Res.* 25, 73–87.

Dutson, T. R. (1974). Proc. Meat Ind. Res. Conf., A.M.I.F., 99–107.

Gilbert, K. V., Davey, C. L., and Newton,. K. G. (1977). *N.Z. J. Agric. Sci.* 20, 139–43.

Goll, D. E. (1978). Proc. 5th Int. Congr. Food Sci. Technol., Kyoto, Japan.

Goll, D. E., Stromer, M. H., Olson, D. G., Dayton, W. R., Suzuki, A., and Robson, R. M. (1974). Proc. Meat Ind. Res. Conf., A.M.I.F., 75–98.

Hallund, O., and Bendall, J. R. (1965). *J. Food Sci.* 30, 296–9.

Harsham, A., and Deatherage, F. E. (1951). U.S. Pat. 2 544 681.

Herring, H. K., Cassens, R. G., and Briskey, E. J. (1965). *J. Food Sci.* 30, 1049–54.

Herring, H. K., and Cassens, R. G., Suess, G. G., Brungardt, V. H., and Briskey, E. J. (1967). *J. Food Sci.* 32, 317–22.

Ingram, M., and Ingram, G. C. (1955). *J. Sci. Food Agric.* 6, 602–11.

Jungk, R. A., Snyder, H. E., Goll, D. E., and McConnell, K. G. (1967). *J. Food Sci.* 32, 158–61.

Locker, R. H. (1960). *Food Res.* 25, 304–7.

Locker, R. H., Davey, C. L., Nottingham, P. M., Haughey, D. P., and Law, N. H. (1975). *Adv. Food Res.* 21, 157–222.

Locker, R. H., and Hagyard, C. J. (1963). *J. Sci. Food Agric.* 14, 787–93.

Macfarlane, P. G., and Marer, J. M. (1966). *Food Technol.* 20, 135–5.

McCrae, S. E., Seccombe, C. G., Marsh, B. B., and Carse, W. A. (1971). *J. Food Sci.* 36, 566–70.

Marsh, B. B. (1954). *J. Sci. Food Agric.* 5, 70–5.

Marsh, B. B., and Leet, N. G. (1966). *J. Food Sci.* 31, 450–9.

Marsh, B. B., and Thompson, J. F. (1958). *J. Sci. Food Agric.* 9, 417–24.

Marsh, B. B., Woodhams, P. R., and Leet, N. G. (1968). *J. Food Sci.* 33, 12–18.

Martin, A. H., Jeremiah, L. E., Fredeen, H. T., and L'Hirondelle, P. J. (1977). *Can. J. Anim. Sci.* 57, 705–12.

Newbold, R. P. (1966). *In* 'The Physiology and Biochemistry of Muscle as a Food', eds E. J. Briskey, R. G. Cassens, and J. C. Trautman, pp. 213–24. (Univ. Wisc. Press: Madison.)

Sharp, J. G., and Marsh, B. B. (1953). Food Invest. Special Rep. No. 58, D.S.I.R., London.

Tarrant, P. V., and Mothersill, C. (1977). *J. Sci. Food Agric.* 28, 739–49.

# The end of the storage life of refrigerated meat: why does it happen and what can be done about it?

By F. H. Grau and J. J. Macfarlane,
CSIRO Division of Food Research, Cannon Hill, Qld.

Refrigerated fresh meat can, in terms of today's trade, be categorized as:

- chilled carcass meat,
- chilled retail cuts,
- chilled vacuum-packed primal cuts or carcasses of small stock,
- frozen boxed or carcass meat,
- frozen retail cuts.

Usually, the end of storage life occurs because of deteriorative changes in one or more of the quality attributes of meat that render it unacceptable for marketing or eating. For table meats, the most important attributes are appearance, odour, flavour and texture. Typical symptoms of spoilage in the raw product are given in the table. Such deterioration in quality attributes can be brought about by the activity of microorganisms, or by physical or chemical changes independent of microorganisms. Brief comments about these factors follow. The microbial spoilage of vacuum-packaged chilled beef is then discussed in greater detail.

### Microbial spoilage

Microorganisms are the most important cause of spoilage of chilled meats. Therefore efforts to extend the shelf-life of chilled meats are directed at controlling the microbial load on the product. The three methods by which this is done are:

(*a*) limiting contamination,
(*b*) destroying contaminating microorganisms, and
(*c*) reducing the microbial growth rate.

With (*a*), good hygiene in the preparation and production of meat is necessary to ensure the lowest possible number of organisms contaminating the product. The lower the initial contamination, the longer it takes for the organism to reach the numbers required to cause spoilage. This principle was used successfully in the export of chilled beef-quarters to the U.K. in the 1930s. Improvements in slaughter-floor practice brought about a 20-fold reduction in contamination with psychrotrophic microorganisms (Empey and Scott 1939).

The possibilities for application of the second method for controlling the microbial load, i.e. destroying microorganisms on the product, are limited by the necessity to maintain the meat in its fresh-like condition. A hot-water pasteurization process designed at the Meat Research Laboratory (Smith and Graham 1978) to reduce salmonella contamination gives a significant reduction in spoilage organisms. In this process the carcass is in contact with water of at least

Typical symptoms of the end of storage life of raw product.

| Type of storage | Features of the spoiled product |
|---|---|
| Chilled carcasses | Slime, off-odour, colour change in flesh and fat |
| Chilled retail cuts | Browning of lean, slime and off-odour |
| Chilled vacuum-packaged primal cuts | Colour change, persistent off-odour after product removed from package |
| Frozen | Rancid odour, desiccation of surface (freezer burn), colour change |

80 °C for 10 s. Both coliforms and salmonellae on the carcass are reduced in numbers by about 99% and even greater reductions in psychrotrophs will occur. In spite of the contact with hot water, the carcass still has a 'fresh' appearance. The work of Bala *et al.* (1977) and Eustace *et al.* (1979) is also of interest with respect to prolonging the storage life of carcasses. Studies by these workers have shown that treatment of carcasses with acetic acid solutions at temperatures from 25 ° to 60 °C results in at least a 95% reduction in the numbers of contamination organisms.

Terminal processes such as those referred to above for the reduction of the level of contaminating organisms would appear to have more promise for achieving an extension of storage life than attempts to improve slaughter-floor hygiene further. From our observations the mean psychrotrophic contamination of sheep carcasses at the completion of slaughtering and dressing is close to 100 $cm^{-2}$ and it is even less for beef carcasses. The greater contamination of mutton carcasses appears to be related to contamination by organisms from the wool during dressing operations. For mutton carcasses a reduction of 90% in initial contamination could be expected to give a 15–20% extension in the shelf-life of aerobically stored carcasses. A reduction of 99% in contamination could increase shelf-life by about one-third, provided recontamination was avoided. In situations where this increased shelf-life is needed, carcass decontamination may be a practical proposition, particularly as it also reduces salmonella contamination.

However, method (*c*) above, i.e. reducing the microbial growth rate, provides by far the most promise for increasing the shelf-life of meat. This can be readily appreciated when one considers that, as just mentioned, a 99% reduction of the initial flora on mutton carcasses is required to increase the shelf-life by about one-third. On the other hand, only a one-third reduction in the growth rate of the spoilage organism is needed to achieve the same increase in shelf-life.

As the temperature of storage of meat is reduced, the growth rate of contaminating organisms is reduced. The effect of temperature is most dramatic near freezing temperatures. For the organisms most important in the spoilage of fresh meats under aerobic conditions, a reduction in storage temperature from 2 °C to −1 °C reduces their growth rate by about 50% (Scott 1937) and so extends the storage life by about 50%. As the temperature is further reduced, meat begins to freeze, and, as ice is formed, solutes are concentrated in the remaining fluid phase. For an organism to be able to grow on frozen meat it has to be able to tolerate both the lower temperature and the increased solute concentration (i.e. lowered water activity $a_w$). As the temperature is reduced below the freezing point, bacteria are the first of the microbes to cease growing.

Yeasts and moulds are able to grow at somewhat lower temperatures. However, below about −10 °C, conditions are so unfavourable that microbial growth ceases. Microbial problems with meat that has been stored below −10 °C are due to growth that occurred either during preparation of the meat for storage or after it was removed from storage, particularly during thawing. Although there is no microbial growth in meat below −10 °C, enzymes elaborated by the organism before freezing can still be active. For instance, microbial lipases may degrade lipids in frozen meats (Alford and Pierce 1961).

### Physical and chemical changes

In non-frozen meat, storage life is usually limited by microbial spoilage and not by physical and/or chemical changes in the meat itself. The main exceptions occur in situations where the appearance of meat is important, e.g. at the point of sale. The appearance of retail cuts of meat depends largely on the oxidation state of the meat pigment myoglobin (Lawrie 1979). In its oxygenated form this imparts a highly desirable bright red colour to meat. However, although oxygen is needed for the formation of the oxygenated form of the pigment, it also oxidizes myoglobin to the undesirable brown metmyoglobin form. The rate of formation of metmyoglobin is reduced with decrease in storage temperature, but is increased by decrease in oxygen concentration down to about 1%, after which it is decreased again. Maintenance of a desirable bright-red appearance in chilled meat is aided therefore by storing the meat at as low a temperature as practicable, and by using packaging materials that are permeable to oxygen. Mincing, or repeated freezing and thawing of meat, accelerate the formation of metmyoglobin (Ledward and Macfarlane 1971) and this effect is believed to be due, at least in part, to the destruction of naturally occurring enzyme systems in meat that are able to reduce metmyoglobin.

In frozen meat stored below −10 °C, microbial growth no longer occurs and storage life is then limited by the effects of physical and chemical changes. The principal effects are on the structural integrity of the muscle, and on meat colour and flavour.

Probably the greatest effect on structural integrity occurs at the time of freezing, when cell membranes may be damaged as a result of the formation of ice. As a consequence of structural damage, exudation of fluid, i.e. drip occurs when meat is thawed and, in spite of extensive research into ways to avoid its occurrence, it remains a drawback to frozen storage.

Many factors affect drip, e.g. rate of freezing, the size and shape of the piece of meat, pH and the state of contraction of the muscle, but with respect to storage effects, fluctuations in temperature during storage and evaporative losses are important factors. The latter, besides reducing the apparent amount of drip, can result in 'freezer burn' (Kaess and Weidemann 1967), a defect in which the surface becomes sponge-like in structure and has a whitish or amber colour. Packaging of the meat provides a moisture barrier and usually prevents the occurrence of this defect. In clear plastic film, the ice sublimed from meat tissue can crystallize on the packaging material giving an unattractive appearance and the impression of excessive water or ice in the pack.

A product of improved appearance can be achieved by vacuum-packaging in such a way that good contact is maintained between the meat surface and the packaging film. However, as mentioned earlier, if the packaging material is permeable to oxygen, formation of brown metmyoglobin can occur and ultimately detract from the appearance of the product.

The best known flavour deterioration in frozen meat is that caused by oxidation of the lipids in meat. The fats of beef and lamb are relatively resistant to such oxidation, in contrast to the more highly unsaturated fat of pork. Thus, the recommended storage life at −18 °C for beef is 12 months, whereas that for pork is 6 months (I.I.R. 1972). If some of the fats in beef are replaced with more highly unsaturated lipids by manipulation of the animal's diet, beef becomes more susceptible to lipid oxidation (Bremner *et al.* 1976).

Oxidative stability depends not only on the content of polyunsaturated fatty acids, but also on the antioxidant present. Natural antioxidants occur in meat but, particularly when the more unsaturated fats are present, oxidative changes may severely limit storage life. Although the application of antioxidants can greatly improve the oxidative stability of meat, their use is generally not permitted in fresh meats. Control of the rate of lipid oxidation is therefore achieved by reducing the temperature of storage, since the rate of oxidation decreases with decrease in temperature. Oxidation can also be reduced by reducing exposure to oxygen by packing meat in oxygen-impermeable films.

**Vacuum-packaged chilled meat**

Probably the most spectacular development in the meat industry over the last decade has been the growth of the trade in vacuum-packaged, boned-out chilled beef, and the rest of this article discusses, in some detail, the factors that influence the storage life of this product.

For international trade, a longer storage life for chilled meat is required than can be achieved by storage at temperatures near the freezing point. This has stimulated the search for treatments that can be combined with chilled storage to increase storage life. In the early shipments of chilled carcass beef, storage life was extended by allowing water to evaporate from the surface of the carcass, thus reducing surface water activity and hence microbial growth rate.

Microbial growth rate was further reduced by the addition of carbon dioxide to the storage atmosphere. Work done over 40 years ago showed that 10% carbon dioxide in the atmosphere extended the lag phase before microorganisms started to multiply and reduced the growth rate of the normal aerobic psychrotrophic meat-spoilage organisms to about one-half that in air (Scott 1938).

Vacuum-packaging of meat is a more modern means of modifying the gas atmosphere. Within packs of fresh meats carbon dioxide levels of 20% or more are obtained, with the oxygen tension falling to below 1%. The actual concentrations achieved for these gases are dependent on the permeability of the film and the head space within the pack. The combined effect of high carbon dioxide and low oxygen tensions is to restrict very severely the growth of the normal aerobic flora and, concurrently, the development of putrefactive odours. Vacuum-packaging of fresh meat results in the appearance of a different, more slowly growing microbial flora – a flora predominantly of lactic acid bacteria but also containing significant numbers of other organisms such as *Microbacterium thermosphactum* and *Enterobacteriaceae*.

The flora developing on vacuum-packaged meat is determined by both the pH of the meat and the permeability of the packaging film to oxygen. When lww pH meat, e.g. about 5.6, is packed in films of very low oxygen permeability, the growth of *M. thermosphactum* (Campbell *et al.* 1979), *Enterobacteriaceae* and *Yersinia enterocolitica* is severely inhibited. Growth of these strains increases with increase in the oxygen permeability of the packaging film. When the pH of the meat is 6.0 and above, all these strains grow even when films of low permeability to oxygen are used.

The respective roles of these strains in mixed culture in causing spoilage is somewhat uncertain. However, in pure culture studies, *M. thermosphactum* and members of the *Enterobacteriaceae* if present in sufficient numbers can cause spoilage, and their increased growth in high pH meat is likely to be a factor in the poorer keeping quality of vacuum-packed high pH meat. The growth of *Y. enterocolitica* is important since some strains are pathogenic. However, it is not yet clear what role, if any, their presence on vacuum-packaged meat has in human illness.

Vacuum-packed high pH meat is also susceptible to spoilage by *Altermonas putrefaciens* (Nicol *et al.* 1970; Gill and Newton 1979). The ability of this organism to grow is very dependent on the pH of the meat. Below about pH 5.8 its growth is severely inhibited. On meat whose pH is 6.0 and above, growth of this organism results in the production of hydrogen sulfide from cysteine. Under the low oxygen tensions found in vacuum-packed meat, hydrogen sulfide reacts with myoglobin to produce the green-coloured sulphmyoglobin. Spoilage is typified by a greenish discolouration of the fat and of the weep, and by the odour of hydrogen sulfide.

A shelf-life of over 10 weeks can be obtained for meat of the usual ultimate pH (5.4–5.6). However, deterioration of even sterile vacuum-packaged chilled meat eventually occurs. After 4 months storage, liverish off-flavours develop (Smith, private communication). These off-flavours develop independently of microorganisms and may be the result of degradative processes in the meat itself or may be the result of oxidative processes from slow diffusion of oxygen through the packaging film.

In meat vacuum-packaged in film of low oxygen permeability the meat is purple owing to the myoglobin being kept in the reduced state. In order to produce the highly sought after bright red coloration of meat, flushing of the vacuum pack with a variety of gas mixtures of carbon dioxide with oxygen has been proposed. However, in the presence of the high oxygen tensions needed to maintain the red colour of the muscle, microbial growth is not controlled as well as it is with meat packed in film of low oxygen permeability. The use of carbon monoxide (1%) has been suggested recently as a means of maintaining meat with red colour as well as inhibiting microbial growth. It is too early yet to decide if such levels of carbon monoxide will give a shelf-life equal to or better than normal vacuum-packed meat.

**Possible relationships between microbial growth and spoilage**

Glucose is the constituent of meat that is usually degraded first during microbial growth. An exception to this is the acinetobactermoraxella group of organisms which are unable to utilize glucose. As the glucose is used at the meat surface, glucose continues to diffuse from the underlying tissue so that a concentration gradient of glucose is established. Eventually the rate of glucose diffusion falls below the rate of utilization and then other constituents such as amino acids, lactate and glucose-6-phosphate are degraded (Gill and Newton 1978). The formation of microbial proteases is repressed until late in the growth phase so that spoilage is usually well advanced before protein is attacked. However, the ability to degrade protein appears to be necessary to enable organisms to penetrate to any significant depth below the surface of the meat (Gill and Penney 1977). Fats can be attacked by extra cellular lipases formed by *Altermonas putrefaciens* and acinetobacter strains (Barnes and Melton 1971).

Because the end products formed by the

microbes depend on both the type of organism and the particular substrate degraded, the characteristics of the spoilage can vary. For example, lactic acid bacteria degrade glucose to lactate, or to lactate, acetate and carbon dioxide, whereas acetylmethylcarbinol is a major end product of glucose utilization by *Microbacterium thermosphactum* under aerobic conditions. The end products formed by *Enterobacteriaceae* from glucose can include all of these. Micrococci can decarboxylate amino acids to form amines. Pseudomonads can produce amonia from amino acids. *Altermonas putrefaciens* can produce hydrogen sulfide from cysteine.

A number of methods for evaluating microbial spoilage or for predicting the remaining shelf-life of stored meats have been suggested. Counts of the number of viable organisms can be correlated reasonably well with spoilage for some products stored under certain specified conditions. For example, when chilled fresh meat is stored aerobically under moist conditions, off-odours and slime formation correlate reasonably well with the total aerobic count measured at temperatures between 0° and 25°C. However, even with this product off-odours are produced at lower counts if the pH of the meat is high. The glucose content of muscle is related to the ultimate post-rigor pH. Meat whose ultimate pH is 6.0 or more will have little if any detectable glucose, whereas meat of about pH 5.5 will contain 100–200 $\mu$ glucose $g^{-1}$. On high pH meat, the small amount of glucose is depleted when the bacterial count is low, and amino acids are attacked at a lower population of organisms than in low pH meat. As a consequence, off-odours are detectable on spoiling high pH meat at bacterial counts that are at least 10-fold lower than those required for detectable off-odour production from low pH meat (Newton and Gill 1978).

For many other meat products, including vacuum-packed fresh meat, there appears to be no clear correlation of total bacterial count with spoilage. Spoilage may be delayed past the time when the maximum bacterial count is reached. This may be due to the spoilage flora being only a fraction of the total count, or a high microbial population may be required for a period of time before sufficient end-products are produced by the organisms for a change to be detectable.

Other methods for detecting incipient spoilage of meats have been proposed, e.g. time taken for the reduction of various dyes such as resazurin and methylene blue, the pH of the meat, its water-holding capacity, ammonia concentration, titratable acidity or alkalinity, and the production of D-lactate (Ingram and Dainty 1971; Sinell and Luke 1978). None of the methods proposed is suitable for all meats since they can at best detect the activity of only some groups of microorganisms. Some of the methods, for instance, pH and water-holding capacity, suffer from the defect that considerable variation in the measured parameter occurs between muscles even before any microbial growth has occurred. For some others, significant changes in the measured parameter occurs only when spoilage is well advanced.

### References


Alford, J. A., and Pierce, D. A. (1961). Lipolytic activity of microorganisms at low and intermediate temperatures. III. Activity of microbial lipases at temperatures below 0°. *J. Food Sci.* 26, 518.

Bala, K., Stringer, W. C., and Naumann, H. D. (1977). Effect of spray sanitation treatment and gaseous atmospheres on the stability of prepackaged fresh meat. *J. Food Sci.* 42, 743.

Barnes, E. M., and Melton, W. (1971). Extracellular enzymic activity of poultry spoilage bacteria. *J. Appl. Bacteriol.* 34. 599.

Bremner, H. A., Ford, A. L., Macfarlane, J. J., Ratcliff, D., and Russell, N. T. (1976). Meat with high linoleic acid content: Oxidative changes during frozen storage. *J. Food Sci.* 41, 757.

Campbell, R. J., Egan, A. F., Grau, F. H., and Shay, B. J. (1979). The growth of *Microbacterium thermosphactum* on beef. *J. Appl. Bacteriol.* 47, 505.

Empey, W. A., and Scott, W. J. (1939). Investigations on chilled beef. Part I. Microbial contamination acquired in the meatworks. Counc. Sci. Ind. Res. Bull. No. 126.

Eustace, I. J., Powell, V. H., and Bill, B. A. (1979). Vacuum-packaging of lamb carcasses: Use of acetic acid to extend chilled storage life. CSIRO Meat Res. Rep. No. 3/79.

Gill, C. O., and Penney, N. (1977). Penetration of bacteria into meat. *Appl. Environ. Microbiol.* 33, 1284.

Gill, C. O., and Newton, K. G. (1978). The ecology of bacterial spoilage of fresh meat at chill temperatures. *Meat Sci.* 2, 207.

Gill, C. O., and Newton, K. G. (1979). Spoilage of vacuum-packaged dark, firm, dry meat at chill temperatures. *Appl. Environ. Microbiol.* 37, 362.

I.I.R. (1972). 'Recommendations for the Processing and Handling of Frozen Foods', 2nd ed. (Int. Inst. Refrig.: Paris.)

Ingram, M., and Dainty, R. H. (1971). Changes caused by microbes in spoilage of meats. *J. Appl. Bacteriol.* 34, 21.

Kaess, G., and Weidmann, J. F. (1967). Freezer-burn as a limiting factor in the storage of animal tissue. *Food Technol.* 21, 143A.

Lawrie, R. A. (1979). 'Meat Science', 3rd ed. (Pergamon: Oxford.)

Ledward, D. A., and Macfarland, J. J. (1971). Some observations on myoglobin and lipid oxidation in frozen beef. *J. Food Sci.* 36, 987.
Newton, K. G., and Gill, C. O. (1978). Storage quality of dark, firm, dry meat. *Appl. Environ. Microbiol.* 36, 375.
Nicol, D. J., Shaw, M. K., and Ledward, D. A. (1970). Hydrogen sulfide production by bacteria and sulfmyoglobin formation in prepacked chilled beef. *Appl. Microbiol.* 19, 937.
Scott, W. J. (1937). The growth of microorganisms on ox muscle. II. The influence of temperature. *J. Counc. Sci. Ind. Res.*, 10, 338.
Scott, W. J. (1938). The growth of microorganisms on ox muscle. II. The influence of 10 per cent carbon dioxide on rates of growth at $-1\,^\circ$C. *J. Counc. Ind. Res.*, 11, 268.
Sinell, H. J., and Luke, K. (1978). D(–)- Lactat als parameter für die mikrobielle Belastung von vacuumverpackten Brühwursterzeugnissen. Proc. 24th European Meeting of Meat Res. Workers CII, 1.
Smith, M. G., and Graham, A. (1978). Destruction of *Escherichia coli* and salmonellae on mutton carcasses by treatment with hot water. *Meat Sci.*, 2, 119.

## Refrigeration of meats and meat products

# Hot boning of meat: refrigeration requirements to meet microbiological demands

By L. S. Herbert and M. G. Smith

### Introduction

A large proportion of the one million or so tonnes of meat exported from Australia in 1978 was in the form of lean beef pieces, frozen in 27-kg packs in fibre-board cartons. Smaller quantities of frozen or chilled primal cuts, mostly bone-out, were also exported. Frozen carcasses, which, since the *Strathleven* shipment and for 75 years thereafter, were virtually the only form of export meat now represent only a very small proportion of the total trade.

### Boning procedures

*Chill-boning*

In an export abattoir, producing 3000 cartons per day, the following procedures are typical for mixed trimmings. Beef carcasses are dressed into sides on the slaughter floor and approximately 1 h after slaughter, enter a chiller. For a further 24 h, the sides are chilled with refrigerated air, at an air velocity of about 1 m $s^{-1}$ and air temperature initially around $0\,^\circ$C, rising to $7\,^\circ$ or $8\,^\circ$C at the end of the chilling period. The sides, in which all the meat is below about $10\,^\circ$C, are transferred from the chiller into a marshalling area, and then into a boning room, both air conditioned at $10\,^\circ$C or lower. Sides are boned, trimmed, and sliced in the boning room, and the boneless meat packed into 152-mm deep fibre-board cartons lined with polyethylene film. Cartons are closed and moved into the loading bay of an air-blast freezer. They are then loaded into the freezer and subjected to 48 h of cooling by air at about $-12\,^\circ$C or lower before being unloaded from the freezer, stacked on pallets and moved into a cold-store at $-20\,^\circ$C.

The salient points of the present procedures are, firstly, that hot beef sides are moved as quickly as possible into the chiller so that bacterial growth at the meat surfaces is minimized by temperature reduction and by surface drying. Secondly, that no further cutting occurs until the side is chilled throughout to $10\,^\circ$C or less, at which temperatures pathogenic mesophiles, in particular *Salmonella* organisms, grow slowly, if at all. However, present procedures are time consuming and labour and capital intensive, e.g. the sides cannot be boned for at least 24 h after slaughter and hence extended holding periods in chillers over weekends and holidays are involved. Multiple handling in and out of chillers requires considerable manual labour. Chillers and refrigerated corridors are expensive to build and maintain, and they require large amounts of expensive electrical energy.

*Hot boning*

Hot boning has been proposed (Visser 1977; Cuthbertson 1979) as an alternative processing procedure, in order to reduce capital, labour and energy costs associated with present chill-boning procedures. It is envisaged that dressed sides would be sent either directly, or following a short (2–3 h) period of chilling, to an air-conditioned boning room, where the meat would be removed from the carcass while still hot. Hot meat pieces would then be packed into cartons and frozen.

Several large-scale trials of various aspects of hot boning have been carried out in Australia and overseas in the past 15 years, and techniques for working with hot meat, not set in *rigor mortis*, have been evolved. One of the most important results of these trials has been the demonstration that some 2–3% increase in the yield of saleable beef is realized, where sides are hot boned rather than cold boned, partly owing to a reduction in evaporative weight loss, and partly to more meat being removed from the bones. This is possibly the most important advantage of hot boning. Many of the other claimed advantages such as reduced refrigeration requirements and lower capital costs in handling and chilling equipment, are at best marginal, and may not be realized at all in commercial applications.

The potential of hot boning for increased yield is widely recognized, but so far no Australian abattoir has adopted hot boning for all, or even a considerable part of its production. A major factor inhibiting adoption has been uncertainty concerning the cooling procedures required to preserve the microbiological status of meat that has been cut and handled while still hot and wet, then packed into cartons for cooling and freezing. It is necessary to ensure that bacteriological quality is not inferior to that of meat produced by conventional chill-boning procedures, especially with regard to food poisoning organisms such as salmonellas.

**Microbiological considerations**

Pieces of hot-boned meat are likely to have become contaminated with bacteria during boning and they can remain for some hours under conditions suitable for bacterial growth during usual procedures for cooling and freezing. Laboratory tests have shown that in hot-boned meat pieces near the centre of a 152-mm deep carton frozen under normal blast freezer conditions, salmonella counts can increase by a 1000-fold or more.

Recommendations (Grau and Herbert 1974) about the rate of cooling needed to avoid bacterial growth on hot-boned meat pieces, *viz.* that the meat should be cooled to 7 °C or lower within 3 h of slaughter (2 h of commencing boning) and then frozen within a further 10 h, have been used for several years as the basis for a code of practice for hot boning in the Australian Meat Industry. Since these cooling rates are virtually impossible to achieve under normal commercial conditions, a number of alternative procedures for freezing have been proposed. These include the use of cartons less than 152 mm deep, plate freezing of meat packed in metal moulds, rapid chilling of carcasses before boning-out, and the addition of 'dry ice' to the centre layers of the cartons during packing. In an extensive program of laboratory work recently completed, the microbiological problems of hot boning have been defined in much greater detail.

Fig. 1 shows a typical curve for the growth rate of mesophilic bacteria in blended meat at 25 °C. During the lag phase there is no increase in bacterial count. The individual cells are adjusting to a new environment, and synthesizing the enzymes required to take advantage of the nutrients now available.

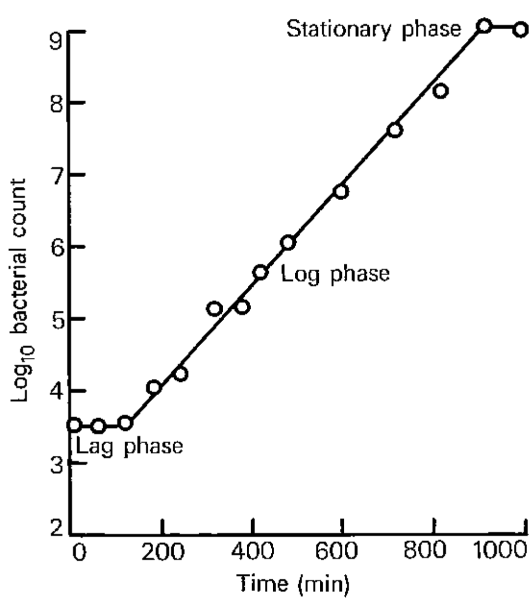


**Fig. 1.** Growth of *E. coli* in blended meat at 25 °C.

After a period of time, which varies depending on such factors as temperature and the nature of the substrates available, the cells begin to increase in size and divide by binary fission. This gives a logarithmic increase in the number of cells with time and, consequently, is known as the log phase of growth. Fig. 1 indicates that meat can be held at 25 °C for about 2 h, i.e. until the end of the lag phase, and there will be no increase in bacterial count. This desirable 'no-growth' situation will be stabilized if the meat is cooled immediately to below 8 °C. Rapid cooling to below 8 °C of blended meat samples on which bacteria are growing, in the lag or early lag phases of growth, results in substantial 'die-off' of bacteria, and a *decrease* in bacterial count — a phenomenon previously reported by Meynall (1958).

Blended meat samples were adjusted to an initial temperature of 25 °C, and then cooled to 8 °C at different rates under conditions similar to those at the centre of a block of meat. The increase in the number of organisms for each rate of cooling was determined and the results plotted as $\log_{10}$ [Increase in number of cells] against Time in minutes to cool to 8 °C (Fig. 2). The initial decrease in bacterial count is clearly shown in Fig. 2 which indicates that the counts start to increase above the count at time zero only after 280 min. (4.5 h).

During our experiments we have found no differences in the growth rate on meat of

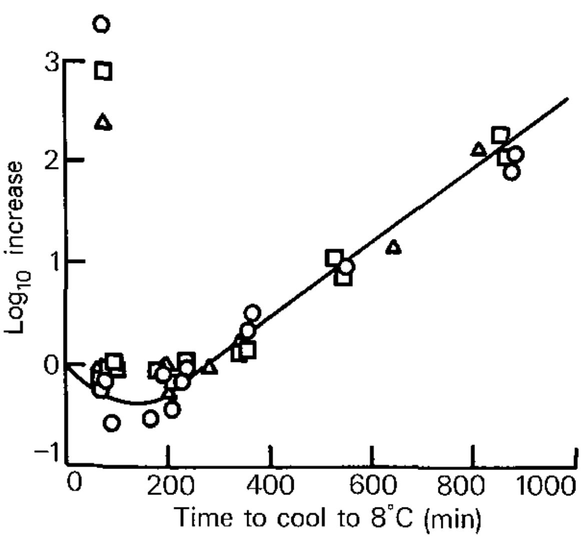


**Fig. 2.** Increase in numbers of cells of mesophilic organisms in blended meat samples cooled from 25 °C to 8 °C. O, *naturally occurring coliform organisms;* □, *Escherichia* coli; Δ, *Salmonella typhimurium*.

Table 1. Growth of *E. coli* on fresh meat*

| Approximate initial temp. (°C) | Calculated increases $\log_{10}$ count | Experimental increases $\log_{10}$ count | Difference |
|---|---|---|---|
| 35 | 2.36 | 2.29 | +0.07 |
| 25 | 2.35 | 2.43 | −0.08 |
| 15 | 1.21 | 1.16 | +0.05 |

*Average of 10 experiments.

*Escherichia coli*, *Salmonella* organisms, or the coliform organisms which normally are present on sheep and cattle carcasses, and we regard the results obtained with each as interchangeable. For example, at 25 °C (Fig. 2) no increase in the number of *E. coli*, *Salmonella typhimurium*, or natural coliform organisms was found providing the meat was chilled to below 8 °C within about 285 min.

Similar experiments were done in which the initial temperatures of blended meat samples were set at 10°, 15°, 20°, 25°, 30°, 35° or 40 °C, and with the aid of a computer, a mathematical equation was obtained for $\log_{10}$ [Increase in *E. coli* count] as a function of initial temperature and Time to cool to 8 °C. Unfortunately, when tests were made on fresh meat (as distinct from blended meat) it was found that, although the increase of organisms initially in a log phase of growth could be calculated accurately from these equations, this was not true for organisms initially in a lag phase of growth.

Further experiments showed that this was because the organisms had an extended lag phase on fresh meat. This is probably due to non-specific inhibitory substances, such as complement and perhaps some hormones, oozing from the surface of freshly cut meat. When this extra lag phase time was taken into account, the following equation was computed for *E. coli*, initially in the lag phase of growth, growing on a fresh meat surface.

$$\log_{10}(I) = 0.53 - 1.02(T/10) - 1.91(t/1000) + 2.11[(T/10) \times (t/1000)] + 1.44(T^2/1000) + 0.002(t^2/1\,000\,000). \quad \text{(Equation 1)}$$

where $I$ is the increase in *E. coli* count, $T$ is the initial temperature of the meat (°C), and $t$ is the time to cool to 8 °C (min).

In Table 1, calculated *E. coli* count increases are compared with the increases actually obtained by bacteriological plate counts and very good agreement is seen to be obtained.

An increase in $\log_{10}$ (count) of 0.3, i.e. a doubling of cell numbers, representing one division of the organisms initially present, has been used as the allowable maximum for

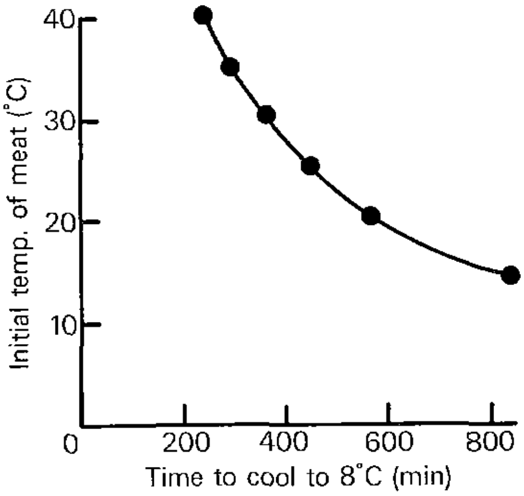


**Fig. 3.** Cooling rates for meat required to prevent increase in numbers of mesophilic bacteria.

bacterial growth. Times to cool to 8 °C from various initial temperatures, corresponding to a doubling of cell numbers, have been calculated from equation 1 and are plotted in Fig. 3. In practice, blocks of meat cooled from the outside at such a rate that *all* the meat is at 8 °C or lower in the times indicated in Fig. 3, will contain only a small central element in which the count could have doubled. Outer layers will have cooled more rapidly, ensuring that there will be a less than two-fold increase, or a decrease, in count in most of the meat in the block. We consider therefore that for the whole block satisfactory control of microbiological growth will have been achieved.

Fig. 3 summarizes our recommendations for the safe handling of meat after hot boning, *viz.* that meat shall be cooled to 8 °C or below within 4 h of commencing boning when the initial temperature of the boned meat is 40 °C, rising to 6 h when the initial temperature is 30 °C and 9.5 h when it is 20 °C. It is now necessary to consider how these cooling rates can be achieved under commercial conditions.

### Cooling and freezing of meat blocks

*Size of block.* The North American market for manufacturing meat is geared to handle 27.2-kg blocks of frozen meat, about 152 mm deep. Recent proposals for standardization of carton sizes (Chua 1978) envisage a standard block of meat 520 by 340 mm by 167 mm deep, weighing 27.2 kg. There are, however, no technical reasons why meat should not be frozen in blocks of lesser depth if, for example, cooling requirements cannot be met in the standard block.

*Role of cartons.* The polyethylene film bag and fibre-board carton serve to hold the block of meat together before freezing, and to give protection against damage and ingress of dirt once the block is frozen. Cartons are not required for structural support of the frozen block. For instance, it would be possible to freeze meat inside polyethylene bags in aluminium moulds. The frozen blocks would be ejected from their moulds, stacked on pallets and could then be covered with 'jumbo cartons' to form convenient unitized loads for shipment.

*Types of freezer.* Air-blast freezers are very commonly used for freezing cartons of meat. For production rates greater than about 1500 cartons per day (40 t meat), meatworks generally install automatic air-blast freezers (Herbert and Lovett 1979) to minimize labour costs associated with manually charged and discharged batch freezers. Plate freezers (Lovett and Herbert 1979) have been installed for cartons in a few abattoirs. They are more efficient thermally than air-blast freezers, can cool and freeze more rapidly, and produce frozen blocks which are flat top and bottom and hence easily stacked in cold stores and containers. Their more general acceptance by the Australian meat industry awaits the development of a large capacity machine with automatic loading and unloading.

### Achievement of recommended cooling rates

The time for temperatures at the centre of blocks of regular geometry to cool to 8 °C may be most conveniently predicted by means of the charts published by Dalgleish and Ede (1965). When the cooling medium is at a temperature lower than the freezing point of meat (1.5 °C or lower) actual cooling rates will be considerably lower than predicted, firstly because the latent heat evolved as the meat freezes substantially increases the total amount of heat to be removed and, secondly, because a temperature arrest occurs in the outer zones of meat at the onset of freezing, causing a reduction in temperature driving force between outer zones and centre. However, frozen meat has a higher thermal conductivity than unfrozen meat, so that heat transfer rates in frozen outer zones will be increased, resulting in partial compensation for the two factors reducing cooling rates. Comparison of predicted times to cool to 8 °C with some actual times from

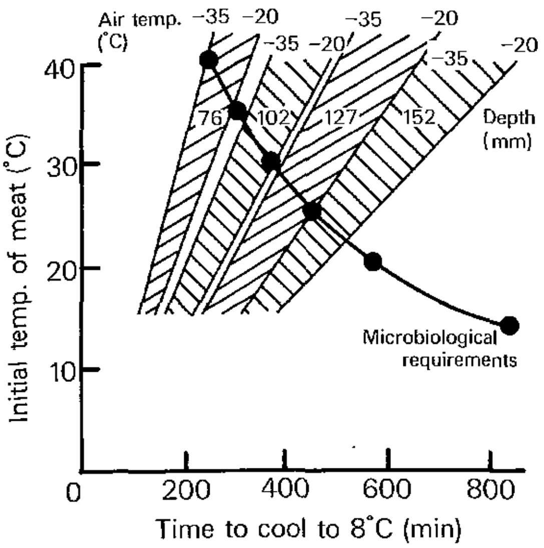


**Fig. 4.** Cooling rates for meat in cartons in air blast freezers.

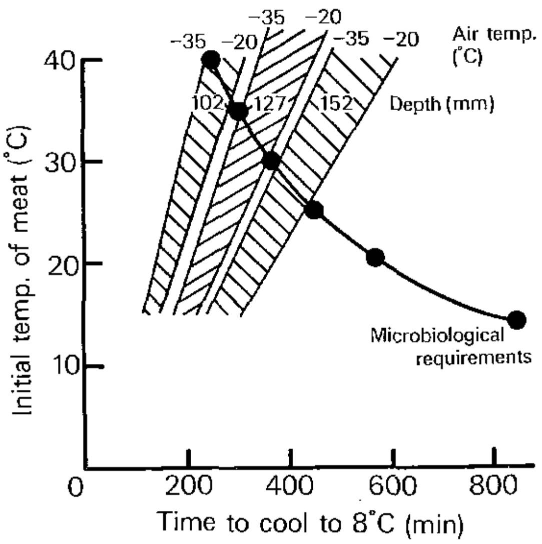


**Fig. 5.** Cooling rates for meat in moulds in air blast freezers.

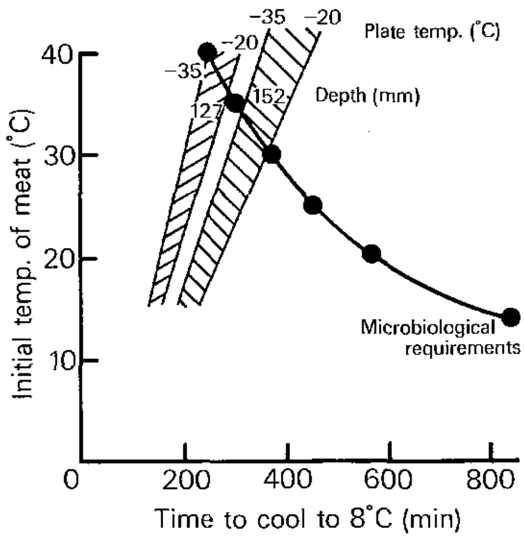


**Fig. 6.** Cooling rates for meat in moulds in plate freezers.

meat-freezing experiments suggest that predicted times should be multiplied by 1.5 to give actual times, and this factor has been used in the calculation of the times plotted in Figs 4, 5 and 6.

Times for centre temperatures to fall to 8 °C have been calculated for three different systems of cooling.

1. hot meat packed in polyethylene film inside fibreboard cartons, cooled and frozen in an air-blast freezer (block depths 76, 102, 127 and 152 mm); air temperatures –20° to –35 °C; heat transfer coefficient 13 $Wm^{-2}K^{-1}$.
2. hot meat packed in polyethylene film in carton-sized aluminium moulds, cooled and frozen in an air-blast freezer (block depths 102, 127 and 152 mm); air temperatures –20 to –35 °C; heat transfer coefficient 33 $Wm^{-2}K^{-1}$.
3. hot meat packed in polyethylene film in carton-sized aluminium moulds cooled and frozen in a plate freezer (block depths 127 and 152 mm); air temperatures –10° to –35 °C; heat transfer coefficient 3000 $Wm^{-2}K^{-1}$.

Thermal properties of warm meat pieces, containing about 10% fat by weight, were assumed to be: thermal conductivity 0.47 $Wm^{-1}K^{-1}$, density 1033 $kg^{-3}$, specific heat 3.4 $kJkg^{-1}K^{-1}$.

In Figs 4, 5 and 6, calculated times for centre temperatures to fall to 8 °C have been plotted against the initial temperature of the hot meat in the three situations described above. Also plotted on each figure is the curve of microbiological requirements, i.e. cooling time against initial temperature derived from microbiological considerations (Fig. 3). From these figures, it can be seen that satisfactory cooling rates are obtained under cooling conditions represented by points in the hatched areas below and to the left of the curve for microbiological requirements. Points above and to the right of this curve represent unsatisfactory cooling rates. Thus, in Fig. 4, we see that for cartons 152 mm deep in an automatic air-blast freezer, satisfactory cooling rates are obtained only if the meat enters the carton below 25 °C when cooling air is at –35 °C, and below 22 °C when cooling air is at –20 °C. If

Table 2. Maximum initial meat temperatures for satisfactory cooling rates in different freezing systems

| Freezing system | Coolant temp. (°C) | Initial meat temp. (°C) | Refer to |
|---|---|---|---|
| Air-blast freezer, | –20 | 22 | Fig. 4 |
| cartons | –35 | 25 | (system 1) |
| Air-blast freezer, | –20 | 26 | Fig. 5 |
| moulds | –35 | 29 | (system 2) |
| Plate freezer, | –20 | 30 | Fig. 6 |
| moulds | –35 | 34 | (system 3) |

the meat enters the carton at 35 °C or higher, satisfactory cooling rates would be achieved only in cartons having a depth of 75 mm or less.

Where, because of customer requirements, meat must be cooled and frozen in 152 mm deep blocks, then it must be packed at or below the temperatures detailed in Table 2 for the three different systems of freezing described above (systems 1, 2 and 3).

An abattoir engineer, who is considering hot boning followed by freezing of the hot-boned meat in a given type of freezer, can obtain from Table 2 the temperature at which meat must be packed into cartons or moulds in order to achieve the cooling rates required to give satisfactory control of growth of mesophilic bacteria. The time of chilling required before boning in order to ensure that the meat is packed at or below the required temperature may then be estimated. Sufficient evidence should now be available to prove to local and overseas health authorities that, providing abattoirs can meet the required cooling rates, hot-boned meat is microbiologically as good as meat produced under the present methods of chill boning.

## References


Chua, H. M. (1978). Carton size rationalisation. Div. Food Res., CSIRO, (Aust.) Meat Res. Rep. No. 6/78.

Cuthbertson, A. (1979). Hot boning. Innovations and techniques in modern meat processing. *Meat* 52, 63-73.

Dalgleish, N., and Ede, A. J. (1965). Charts for determining centre . . . temperatures in regular geometric solids during . . . cooling, NEL Rep. No. 192, (Min. Technol; Glasgow.)

Grau, F. H., and Herbert, L. S. (1974). Note on freezing of hot-boned meat in cartons. Proc. Meat Res. Inst. Symp. No. 3, 'Meat freezing — Why and How', pp. 26.1–2.

Herbert, L. S., and Lovett, D. A. (1979). New measurements of cooling times in blast freezers. *Aust. Refrig. Air Cond. Heat.* 33, 8–14.

Lovett, D. A., and Herbert, L. S. (1978). Design methods for carton freezers. Div. Food Res., CSIRO, (Aust.) Meat Res. Rep. No. 12/78.

Meynall, G. G. (1958). The effect of sudden chilling on *Escherichia coli*. *J. Gen. Microbiol.* 19, 380–9.

Visser, K. (1977). The plate freezing and handling of pre-rigor and post-rigor frozen hot-boned meats. Proc. 19th Meatworks Conv., Country Meatworks Assoc. N.S.W., Casino.

Refrigeration of meats and meat products

# Present and future trends in freezing technology

By R. W. Davies

Canterbury Frozen Meat Co. Ltd, New Zealand

Refrigeration is the most widely used means of meat preservation and, in the commercial sense as we understand it, it is 100 years old. However, the considerable in-depth studies and research needed to understand its effects on meat have been undertaken only during the last two decades or so. In discussing the future of meat preservation by refrigeration, this paper has no dramatic conclusion to draw but offers an appreciation of the results of research and of their industrial application. New Zealand's major meat export is sheepmeat in the carcass form; of lesser importance is beef in cartoned form. The emphasis of research and its application has naturally been in the area of lamb and sheep and it is on the basis of this work that this paper has been written.

### Historical

In the early half of this century, reasonably tender and acceptable meat was produced. This was achieved in the main by hanging overnight after slaughter and then freezing by still-air freezers. These conditions were close to ideal. The cooling floor was a large railed area with natural ventilation consisting of louvred walls to allow the natural air flow to cool the carcass. Of course, there was no temperature or microbiological control and the results varied accordingly. Freezing and storage temperatures were largely set by experience.

Following the Second World War and particularly during the 1950s, rapid or blast freezing was developed and with it tougher meat. This toughness was due to chilling or freezing before *rigor mortis* had set in, which brought about the now well-understood cold shortening and thaw shortening. Changes of this sort were brought about by the commercial pressures to process meat more economically, and it also became clear that regulations governing the handling of meat were going to become more stringent. In lamb processing then, we saw the change from slaughtering one day, hanging overnight, and then slow freezing for 3 days before placing in cold storage – a turnround of 4 days – reduced to slaughter and sort to grades on the cooling floor on one day, blast freeze overnight, and place in cold storage the next day – a turnround of 1 day. The reduction in turnround time to 1 day obviously gave better utilization of costly facilities and consequent economies, but also a less tender product. To process meat from slaughter to cold storage on a 24-hour basis is now almost axiomatic in the industry, and consequently technological development to improve the quality of the product has evolved around the 24-hour cycle.

### Meat regulations

Probably the most dramatic effect on meat processing in the last decade or so has been the introduction in the U.S.A. of the Wholesome Meat Act in 1967, and in the E.E.C. of the Intra-Country Directive, and more particularly the Third Country Directive which has an immediate effect on Australia and New Zealand. Because New Zealand's economy is much more reliant upon meat export than is the Australian economy, the effect on New Zealand has been much more severe. The investment required to upgrade processing facilities in the last 10 years is probably in the range $200–400 million. The attitude taken by the U.S.A. and the E.E.C. is that if you wish to export to us then you must observe our requirements even though you may not agree with some of them. To obtain change in the very large bureaucratic organizations involved is a very formidable task and time consuming. The emphasis of the American regulations is upon facilities and processing methods, whereas those of the E.E.C. tend more to the microbiological side and meat temperatures.

The significant factors to emerge in the last 10 years in meat refrigeration are the removal of wooden constructions from chillers and freezers and eventually from cold stores, the comprehensive recording of temperatures, the introduction of the cold-chain concept and the specification of temperatures, e.g. 7 °C meat temperature for boning and −18 °C for storage.

### The Market Place

Chilled meat has enjoyed a better reputation than the frozen product owing mainly to less toughness – generally chilling procedures are able to avoid cold shock, aging takes place easily at chill temperatures and the meat has a better visual appearance.

While these factors do not seem to have presented a great problem in marketing, they will be much more significant in the future. With increasing costs of transport to overseas markets (by far the greatest cost increase in meat production) and the increasing competitiveness of other foods, the quality and presentation of our meat products will have to improve to hold their market position. An example of a practice that does meat little good is that of the housewife who, having bought fresh meat from her butcher, takes it home and freezes it in the belief that she is getting a good tender product. It may be that this meat has been thawed from a frozen pack which may have had cold shortening, in which case it will be tough, or it may be that it has been on display for some time and its remaining shelf life is very short. Neither alternative will enhance the image of meat.

### Research

In New Zealand, research and development into the tenderness of meat has received very great attention in the last 10 years at our Meat Research Institute, the particular emphasis, of course, being on lamb. The results of this research, that of the CSIRO's Meat Research Laboratory, and others have been well publicised in the technical literature and it is not proposed to review them in detail here.

The significant steps in these developments that have affected refrigeration technology, or may do so in the future, are:

- conditioning and aging;
- altered posture hanging;
- accelerated conditioning and aging.

The conditioning and aging process is reliable and requires a basic 3-day cycle. On the first day after slaughter, the meat is placed in a chiller under the correct conditions of temperature and humidity to promote conditioning; on the second day it is held in the chiller to allow aging, and on the third day it is blast frozen. This may be compared with conventional carcass processing in which slaughter is carried out during the day and blast freezing that night. As can be imagined, if a whole works' kill was to be conditioned and aged, very large additional refrigerated facilities would be necessary. These, together with additional labour, would make the process uneconomic. Additional costs can be absorbed where special markets are prepared to pay a premium for meat so treated, but these markets are not large.

Altered posture hanging is merely a method of relaxing the muscles of the carcass by hanging it so that the leg muscles are in a natural position and are not taking the strain of the weight of the carcass or of their own weight in an unnatural position. This process, while producing some benefit, was not widely used because of the additional labour costs in getting the animal into its correct posture. Moreover, there are numerous technical difficulties in fitting the carcass in its changed shape into existing mechanical handling systems and refrigerated areas such as blast freezers and cold stores.

The development of the accelerated conditioning and aging process has been carried to a stage where many plants have introduced accelerated conditioning as part of their routine slaughter process. However, they have yet to include routine aging to chilling and/or freezing of the carcasses.

The foregoing remarks deal mainly with lamb and sheep; developments with beef carcasses have followed similar lines, although they are not so advanced in practice. It is apparent from recent literature that some beef plants overseas have introduced accelerated conditioning of beef as a routine method of production.

### Present technology

The present state of the art in the main line processing stream of a works operation has been almost totally influenced by the commercial demand to produce quickly and economically. The impact of meat regulations is very recent as is the considerable research that has been undertaken. Where a high quality meat is required for a special market then this has been taken out of the main stream production at a convenient point and processed before being chilled or frozen as required.

The type and size of refrigerated facilities is, of course, dependent on what is being processed and for what purpose.

A typical New Zealand freezing works is very much more oriented to export than is its Australian counterpart. If a works with a peak kill of, say, 9000 lambs and sheep per day and 300 cattle per day can be said to be typical, then you would expect to find refrigerated facilities as follows.

*Sheep and lambs*

- A cooling floor with a working capacity of 3000–5000 carcasses which, if not refrigerated now, most probably will be in the future; it can hold a proportion of the kill overnight and chill to a deep-bone temperature of about 10°C.
- Some chillers to deal with local trade and specially treated parcels such as conditioned and aged meat; the number and capacity of these chillers would vary widely depending on requirements, but could contain up to 2000 carcasses.
- Carcass blast freezing with a capacity of between 10 000 and 14 000 lamb equivalents (a sheep requires 1½ lamb equivalents of space in a freezer) depending on the mix of sheep and lamb.
- Offal freezing as required, either as plate freezers or carton freezers.
- Possibly a lamb-cutting and sheep-boning room conditioned at 10°C. Cartons from this would most likely be frozen in the beef carton freezer.

*Beef*

- Chillers with a capacity of between 700 and 900 sides, some probably equipped for aging where specially required.
- A boning room conditioned to 10°C perhaps with some small chillers attached for aging cuts.
- Carton blast freezing with a capacity in the range 2000–3000 cartons per day.

**Cold storage**

New Zealand cold stores usually range from 43 000–86 000 $m^3$ gross capacity with the refrigeration plant much more sophisticated than in Australian counterparts because more carcasses are stored in stockinette. The use of stockinette as a carcass covering requires particular care in the air-distribution system to avoid desiccation. Older stores used pipe grid systems, which gave the absolute minimum of air movement, but suffered from the problem of defrosting. The removal of ice from pipe grids, which can grow from the original 44.5 mm diameter to 200 or 230 mm, is a labour intensive exercise and can only be undertaken when the product is not stored below the grids. Because of this, and opposition by regulatory bodies, current stores are constructed with ducting systems for air in and air out, in an endeavour to reproduce air movements within the store as near as possible to those of the original grid stores.

When compared with an Australian works of similar capacity the much greater investment in refrigerated space in a New Zealand works will be apparent. Recent surveys of chillers and blast freezers both for carton and carcass freezing have revealed some very wide variations in air flow over the product to be processed. In some instances these variations have been as great as from 0.5 to 15 m $s^{-1}$ in one room. Obviously under these conditions fine control of the refrigerated environment and of the quality of the product processed is not possible. This fault is the natural result of commercial competition — the pressure to provide the cheapest possible solution to a given problem and acceptance by a company that these conditions produced a reasonably saleable product. This has, of course, been the situation up to date.

**The future**

The future requirements of refrigeration technology will be governed by the same factors that have brought us to the present situation: commercial requirements, regulatory requirements, meat-processing developments and research, but they will have changed emphasis. However, it is not possible to discuss the likely development of refrigeration technology until the processing requirements for which it is to be used in the future are known.

*Commercial requirements*

The necessity to produce a product at the cheapest cost, consistent with quality, will continue, with increasing emphasis on two aspects of production — on quality, particularly tenderness and presentation, and on the cost of energy, both in production of the product and in its transportation. As already indicated, the costs of transport and energy are increasing much faster than any other costs in meat production, and it must be remembered that our main markets are on the other side of the world.

*Regulatory requirements*

The increasing demands for hygiene from both the E.E.C. and the U.S.A., with increasing attention to regulations by other importing countries, will direct emphasis into two main areas. One is total introduction of the cold-chain concept, and the other is strict temperature regimes for microbiological protection. We have already seen meat storage and transportation temperatures brought down to $-18\,^\circ C$ and some talk of even lower temperatures is still heard occasionally. It is believed that considerable emphasis will be placed on warehousing techniques with meat, particular attention being given to records of date of production and the historical refrigeration regime to which the meat has been subjected. Present regulations tend to specify temperature plateaux at which the meat should be at various stages in the process, some of these being based on scientific fact, and others being somewhat arbitrary. Development of regulations to take account of time–temperature relationships and the microbiological conditions associated with meat preservation will, it is believed, ultimately form a more satisfactory guide for meat producers to follow. (This aspect will be discussed in the section on research.)

*Processing requirements*

We have seen a very significant change in beef processing, from sides and quarter production to a situation in which almost all beef is boned or cut and cartoned. This has required a total departure from the concept of quarter chillers and freezers to carton freezers and palletized cold stores for cartoned product. Sheep and lamb processing in New Zealand is still very largely based on carcass production, but long-term forecasts suggest there will be an increasing move to cutting and/or boning and packing in cartons. With this in mind, as much flexibility as possible should be built into new refrigeration facilities to allow their simple conversion with changes in the market. Shipping of lamb carcasses is much less economic than the shipping of cut lamb in terms of refrigerated space. With rising energy costs this may well become a very significant factor.

**Research**

As already indicated, meat research has produced a more thorough understanding of both the processing requirements and refrigeration technology needed to produce a tender, high quality product. In the present state of the art, this type of production is limited to batch type rather than in-line production, because of the high costs of providing facilities for the latter. Development and refinement of the meat technology involved will move with heavy emphasis on temperature relationships rather than temperature plateaux. It is believed that the development of the refinements and the freezing technology necessary will be assisted greatly with this type of approach. Once it is developed by research it will hopefully be taken up by the regulatory bodies.

In the author's view the most significant research development of recent times is the accelerated conditioning and aging process, especially as applied to sheep and lamb. For the first time, it provides an opportunity to modify current in-line production processes, and with some further technological development it is hoped that all sheep meat will be processed economically to full, accelerated conditioning and aging standards. The Canterbury Frozen Meat Co. Ltd, has attempted to adapt this system to practical in-line production. The work is not yet wholly completed, but the undertaking is mentioned to illustrate some future trends.

The Canterbury Frozen Meat Co. Ltd, like most other New Zealand freezing companies, was faced with hygiene regulations which, among other things, required substantial upgrading of carcass blast freezing facilities. The original facilities consisted of individual rooms holding from 1500–2000 carcasses. These were refrigerated by various coil and fan combinations, some with ducted plenums and some without. The rooms were operated manually with staff loading, sorting and stacking to rails by hand. It was general practice to use these rooms for further sorting between the cooling floor and the final cold storage.

The time at which a blast freezing room was put on to freeze depended on when the room had been filled with the number of grades required. This usually meant that the rooms were closed early the next day, the effective freezing period being from late afternoon until early morning, say, 16 h at best.

Evaluation of the various options open to the company showed that complete replacement of these facilities was the most economic solution. The final choice was an automatic multilevel freezer with individual level refrigeration, divided into bays within each level. Refrigeration was supplied by conventional coil and fan on each level, the air being fed to a pressurized plenum above the carcasses. Considerable attention was given to the design of the plenum in order to ensure that an air flow as uniform as possible was distributed over each carcass. Carcasses were fed into the system at the top level and loaded to gantries automatically spaced. Gantries were used in preference to mechanical conveyance through the freezer, as this meant that the carcass skid was stationary on its rail throughout the freezer and hence problems with rail dirt were minimized. Almost all the mechanical equipment was at each end of the freezer and so could be serviced in the event of breakdown without having to gain access to the middle of the freezer. As each gantry is loaded the whole freezer indexes forward one position, and each gantry is always in the same position relative to the plenum air slots after each movement. Plenum outlets were thus able to be designed so that the air flowed down between each gantry row and was not dissipated by striking obstructions. A typical cross-section and air distribution pattern in this freezer is shown in Fig. 1.

The first of these freezers was commissioned in 1975, and consisted of two units having a total capacity of 18 000 lambs per day. Control of the unit was kept reasonably simple, its ultimate development being dependent on the practical results achieved. The significant advantages that have been gained from this design are:

- the freezer has a full 24-h turnaround as opposed to the original individual rooms with a 16-h maximum turnaround;
- staff are no longer required to work in very low temperatures, except of course, during a breakdown; and
- provision was made in the design to change from carcass freezing to carton freezing in the future should it be required.

As a result of experience gained on the first freezer, a second was designed and constructed with much more sophisticated control. The first freezer handled 12.1 carcasses per kilowatt; the latest handles 15.7 carcasses per kilowatt.

The design philosophy has evolved around the accelerated conditioning and aging process. This consists of passing all carcasses through a stimulation tunnel to give the accelerated conditioning; the tunnel being after the slaughterfloor and prior to the cooling floor. Following stimulation and a holding period of approximately 2 h on the cooling floor, the carcass can then be blast frozen immediately to give a quality known as accelerated conditioning. To achieve full tenderness it is necessary to hold the carcass for a further 6–8 h. As explained earlier, this is done only for special parcels where adequate chiller space is available for the aging part of the process.

In designing the latest blast freezer, an attempt has being made to optimize the time available, i.e. to try to incorporate the aging section in the normal process flow. By studying the freezing characteristics of a carcass, it has been found that the time taken to lower its temperature from the latent heat phase to the finally frozen level of $-18\,^{\circ}C$ may be from 2.5–4 h depending on the weight of the carcass. Adopting 4 h as the maximum time required, and adding a further hour to allow for the defrost cycle of the freezer, means that there is a period available in the 24-h cycle of some 19 h in which to lower the carcass from the temperature at entry to the latent heat phase, of aproximately $-4\,^{\circ}C$. Control therefore of the carcass freezer system has been directed towards maintaining as high a temperature as possible through the early part of freezing to enable aging to take place, and then to end up with a properly frozen, tender carcass at the end of the 24-h period.

In the second tunnel constructed, the refrigeration system was changed (Fig. 2), and concentrated at the bottom level of the tunnel building. With attendant advantages of less structural weight and less refrigeration equipment, and consequent cost savings,

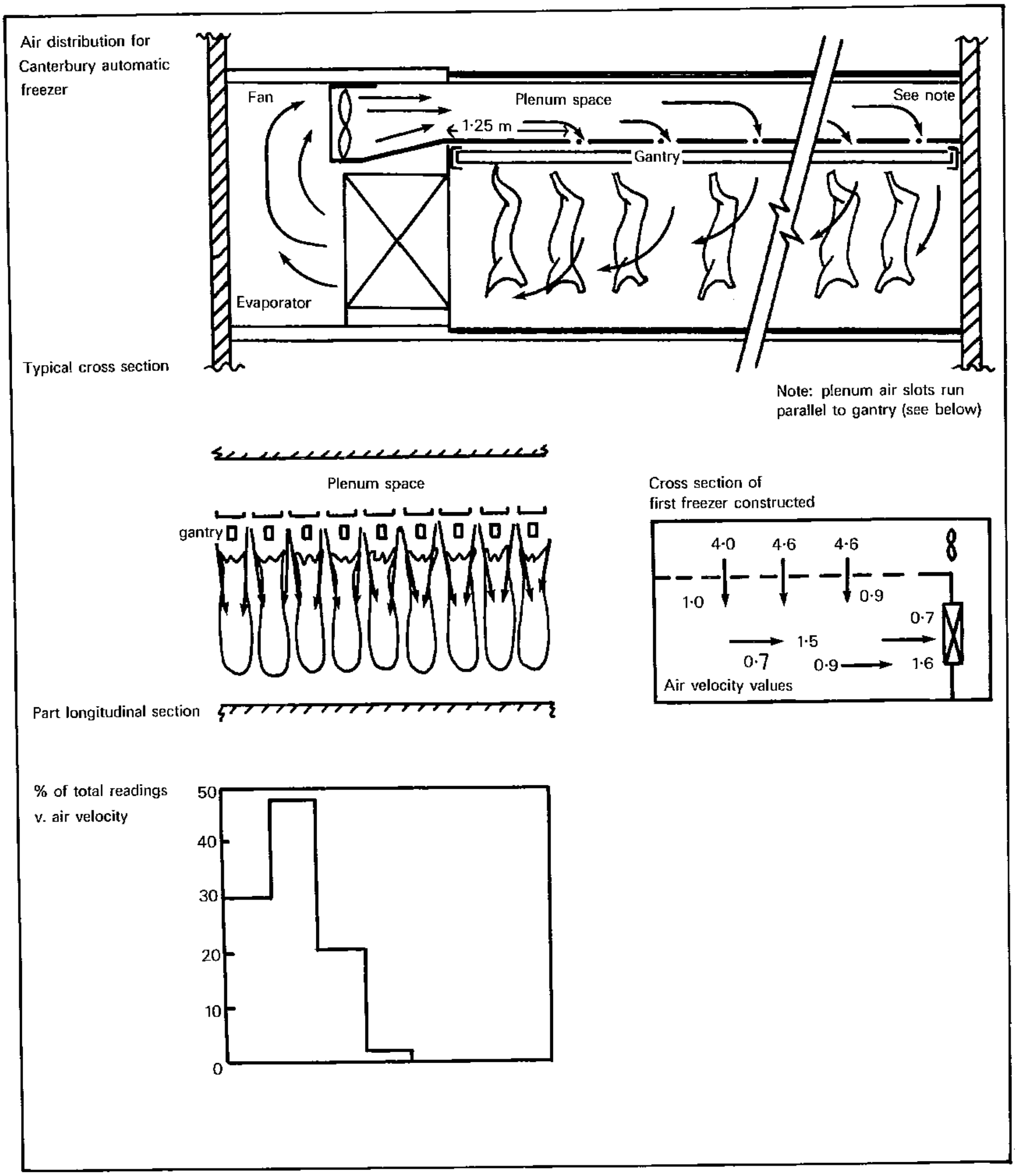


**Fig. 1**. Cross-section and pattern of air-distribution in the automatic freezer at Canterbury, N.Z.

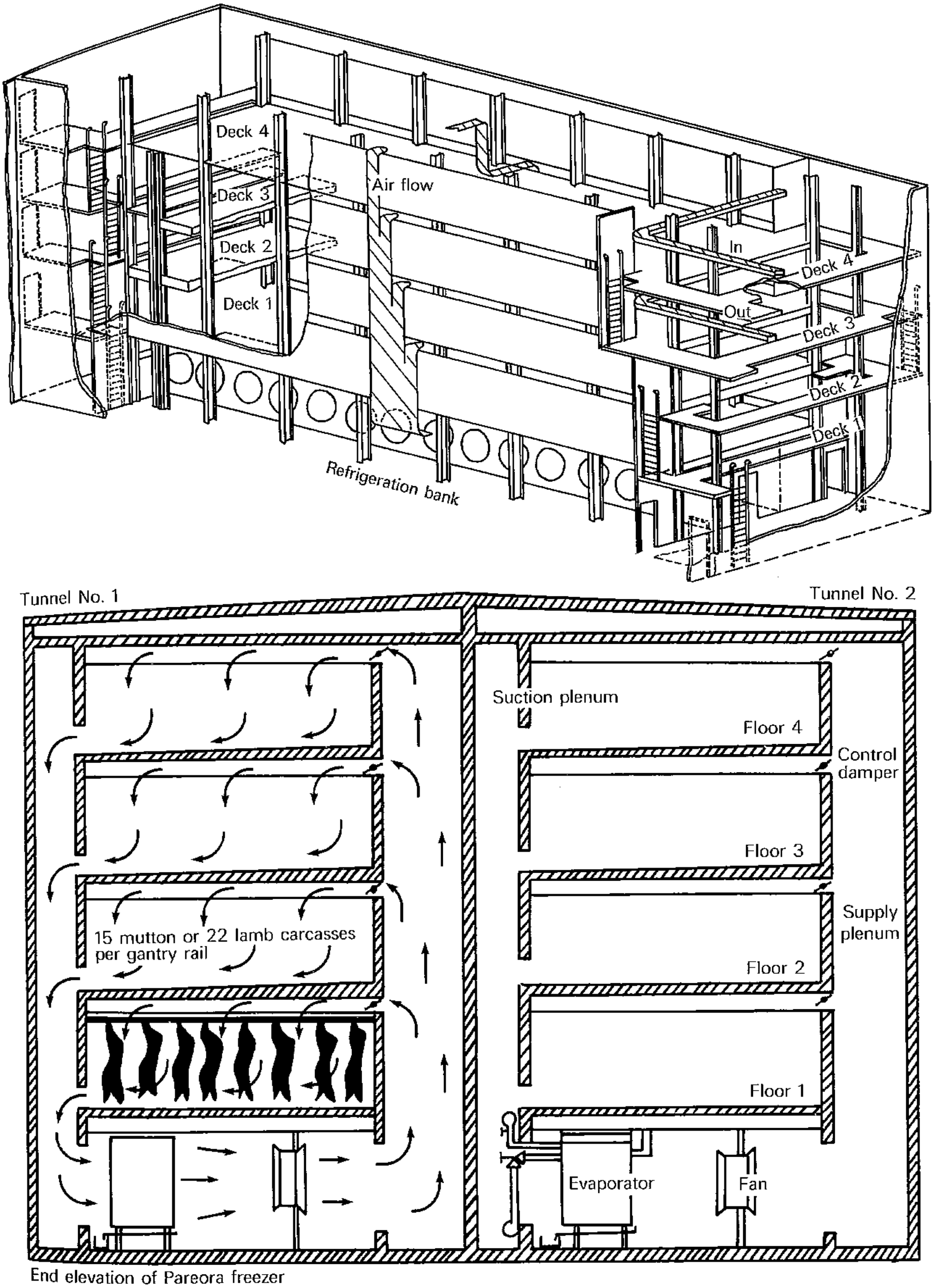


**Fig. 2.** Pictorial view of floors, baffles and end elevation of the Pareora No. 2 freezer.

these two tunnels have a carcass capacity of 6000 lamb equivalents each. The refrigeration control system is by means of air ducts up one side of the tunnel, through a flow control butterfly valve to the plenum above the carcasses, and then exiting from the freezing area to a further vertical plenum and returning to the refrigeration plant. Control of the amount of refrigeration given to carcasses is by means of the butterfly valve which controls the amount of air admitted to each plenum. Over the four floors there are 28 valves, seven in each level, and each valve can be controlled individually. Manual control of such a system is quite inappropriate, and use has been made of a programmable logic controller on each tunnel in a PDP11 computer over the top. In order to establish the parameters for successful control, a theoretical approach was taken using Plank's formula, together with practical tests for confirmation. Considerable assistance was given by MIRINZ and Massey University in this work.

At the point of entry to the freezer, the operator inputs information relating to the type of carcass, its covering and weight range as each line comes forward. As that line progresses through the freezer it is monitored continuously, and each time it enters a bay the amount of refrigeration provided for that bay will be governed by the lightest carcasses present until such time as those carcasses have reached the required temperature. Alternatively, if the bay also has much heavier carcasses present, until such time as it becomes necessary to commence hard refrigeration of the heavy carcasses to ensure that they are adequately frozen at the end of the 24-h period.

This installation has now been running satisfactorily in the manual mode for some 12 months. The computer program for monitoring has now been completed and is undergoing tests. It should be operative towards the end of the present killing season. At that stage, evaluation of the results will show how successful the philosophy has been.

The Pareora development* is the first part of what will ultimately become an integrated system from slaughter right through to cold storage. Like Australia, New Zealand is studying the possibilities of automatic weighing and grading, which undoubtedly will be a computer-based system, and which surely will be extended to sorting procedures and operation of the cooling floor. The necessary input information to the blast freezer will then be obtained directly from the computer operating the cooling floor. This will result in a totally integrated system of control of environment and time, which will maximize the quality and minimize the cost of tender meat production in a direct in-line system. Hopefully, this development will remove the necessity for special parcel markets.

In a paper covering such a wide topic, it is not possible to supply detailed information. Consequently, emphasis has been placed on a brief overview of the history, the current situation and the future, with a particular development being outlined since it may provide a pointer to future technology. Refrigeration will be the major means of meat preservation, in the author's opinion, for at least another 100 years, with developments heavily in the area of quality control of the product through the cold-chain approach from production to the consumer's kitchen. With the aid of the silicon chip, refrigeration control may take some major steps in the 1980s.

*A detailed description of this freezer was presented in a paper at The Engineers Conference of the Council of Public Abattoir Authorities, in Invercargill, New Zealand, in 1978.

# Benefits and problems in the use of low temperatures

By B. D. Patterson
CSIRO Division of Food Research, North Ryde, N.S.W.

Fresh fruits and vegetables are alive, and like all living things are killed by extremes of temperature. Although the lethal extremes are about 40 °C at the upper end and the freezing point of the tissue at the lower end, when living produce is transferred from the farm to the consumer it is advisable to control the temperature more precisely. The reason is that cooling slows down degenerative processes such as fungal growth, softening and excessive loss of water. In addition, as the temperature is lowered, plant parts use their stored reserves more slowly and their effective life is prolonged. Therefore if all plants were equally resistant to chilling temperatures, it would be best to cool them at harvest time to just above their freezing point and keep them at this temperature until they could be used. Unfortunately, many plants, especially those which derive from warm areas of the world, are damaged by chilling temperatures. Below 10 °C the metabolism of these plants is increasingly disrupted and, as a consequence, they deteriorate more quickly than they would at temperatures above the chilling range. Naturally, this sensitivity to chilling affects the conditions for storing fresh fruit and vegetables, as can be seen in Table 1 which shows the minimum storage temperatures for three chilling-sensitive and three chilling-resistant crops. The minimum temperature for storage is about 0 °C for the chilling-resistant species, but for the chilling sensitive species it is 10–12 °C.

### Effect of temperature on storage life

It might be thought that the problem of chilling sensitivity is really rather trivial and could easily be avoided by keeping the temperature of susceptible commodities above the minima shown in Table 1. Nevertheless, the problem is a real one, as can be seen when the effect of temperature on storage life is considered.

In Fig. 1, the effect on storage life of lowering the temperature from 20° to 0 °C is shown for two vegetables, one chilling-sensitive (cucumber) and the other chilling-resistant (brussels sprouts). It shows that relative to their life at 20 °C, sprouts could be kept almost 12 times as long at 0 °C. Such an improvement was not possible for cucumbers, however, because below about 13 °C, their life in storage was actually shortened by further lowering the temperature.

Brussels sprouts and its close relatives among other cole crops (varieties of the

Table 1. Minimum storage temperatures of selected fruits and vegetables

| Species | Origin | Temperature (°C) |
|---|---|---|
| Chilling-resistant | | |
| Broccoli *(Brassica oleracea)* | Europe | 0 |
| Chinese gooseberry (Kiwi fruit, *Actinidia chinensis*) | China | 0 |
| Persimmon *(Diospyros kaki)* | China | −1 |
| Chilling-sensitive | | |
| Mango *(Mangifera indica)* | India | 10 |
| Lemon *(Citrus limon)* | S.E. Asia | 12 |
| Banana *(Musa sp.)* | S.E. Asia | 12 |

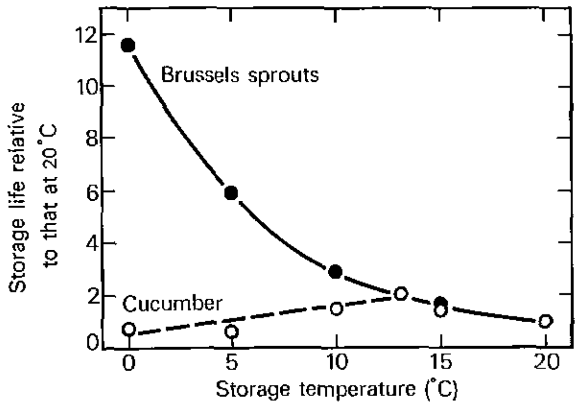


**Fig. 1**. Contrasting effects of temperature on the storage life of brussels sprouts (chilling-resistant) and cucumbers (chilling-sensitive). The life of brussels sprouts (data replotted from Lyons and Rappaport 1959) continues to increase down to 0°C, while that of cucumbers (replotted from Eaks and Morris 1956) decreases below 13°C.

species *Brassica oleracea*) originated from Western Europe and the Mediterranean region (Heywood 1978) which has a winter-growing season. It is therefore not surprising that they are able to survive chilling, and even grow to some extent well below 10°C.

In contrast, the cucumber probably originated in India (Purseglove 1968) where temperatures are higher overall and where chilling temperatures are particularly unlikely during the wet monsoon season.

With these examples in mind, we can define some of the differences between chilling-resistant and chilling-sensitive produce. The tissues of a chilling-resistant plant are preferentially stored at temperatures close to 0°C. At this temperature the rate of metabolism will be slowed and degenerative processes minimized. Conversely, the metabolism of a chilling-sensitive plant will be disrupted at temperatures approaching 0°C, and its storage life will actually be shortened by chilling. Therefore it has to be stored at about 10°C, at which temperature degenerative processes will be much quicker.

While chilling-sensitivity is a serious problem in fruit and vegetable storage, it should not be forgotten that some insect pests are sensitive to chilling, and this sensivity can sometimes be exploited in fruit storage. Work at the Gosford Horticultural Postharvest Laboratory, which is affiliated with this Division, has shown that the Queensland fruit fly will die after a few days at or close to 0°C. This insect is a serious pest of fruit in Australia. Some countries which are potential importers of fresh fruit from Australia, for instance Japan, have stringent quarantine requirements in order to prevent such pests from being introduced. Chemical treatment with ethylene dibromide is currently used to disinfest fruit, but there is some concern that this technique may leave harmful residues. However, if fruit are kept near 0°C for 14 days, all larvae of fruit fly will be killed. Of course, although this technique holds a good deal of promise as an alternative to chemical disinfestation, it is only suitable for fruits that are relatively chilling-resistant.

#### Chilling sensitivity of cultivars and their wild progenitors

The example of brussels sprouts illustrates how the relative resistance to chilling of our domesticated crops derives from that of their wild ancestors. Nevertheless, in the wild, a given species of plant often grows in a range of climates. This is frequently true for the ancestors of our cultivated plants. It might therefore be expected that among predominantly tropical species, those ecotypes that have derived from areas of lowest extremes of temperature would show at least some resistance to chilling. Unfortunately, the human societies which domesticated our food plants did not always domesticate the ecotypes that grew in the coldest areas. They often preferred to settle in the lowlands of the tropics and consequently the degree of chilling-resistance in a fruit or vegetable variety may often be far less than that of its wild parents growing at the coldest part of its range. An exception to this generalization is shown by the avocado, which seems to have been domesticated from several wild sources, some having come from low altitudes in Central America, while others were obtained from high altitudes in Mexico. This appears to be the reason for the difference in chilling-sensitivity of the West Indian varieties (high) and the Mexican varieties (low). While the Mexican varieties are not generally grown, because of their small fruit, they seem to have conferred some chilling resistance on their hybrids, such as the cultivar Fuerte. As a result, there is considerable variation in chilling-resistance between different varieties of avocado. As well as being able to grow in colder areas, the more chilling-resistant varieties are easier to transport to distant markets because ripening can be effectively delayed by cooling below 10°C (Lutz and Hardenburg 1968).

**Application of research**

Genetic and environmental factors appear to interact in determining the degree of chilling resistance of particular fruits and vegetables. Research in this laboratory is aimed at identifying what goes wrong with the metabolism of chilling-sensitive plants near 0 °C and how some conditions allow particular species to avoid chilling damage. Several groups of *predominantly tropical* plants have evolved varieties with much improved chilling-resistance. This is true for such diverse species as passionfruit (Patterson *et al.* 1976), wild tomatoes (Patterson *et al.* 1978), seagrasses (McMillan 1979) and mangroves (McMillan 1975). These four examples of adaptation are all of *predominantly* tropical plants that have evolved varieties able to resist chilling. However, these varieties with greatly improved chilling resistance cannot grow or develop at chilling temperatures any more than can their more sensitive forbears. In this they differ strikingly from plants of families that have evolved in higher latitudes such as the cole crops mentioned earlier. These varieties are able to grow and develop at chilling temperatures, whereas in tropical families adaptation to chilling is much more limited, although nonetheless important to the survival of the plant. At this Division the nature of this adaptation is being investigated; we believe that during chilling, normal metabolism is disturbed and some chemical compounds accumulate which normally would be kept at very low levels. Above a certain level they may actually be poisonous, and kill the tissue.

What is the practical value of knowing which chemical compounds accumulate in the chilled plant? One obvious application is concerned with minimizing the deleterious effects of chilling on stored produce. Our approach to this is, on the one hand, to seek environmental conditions that minimize the expression of chilling sensitivity and, on the other hand, to improve chilling-resistance genetically.

Environmental conditions certainly do influence the expression of chilling injury, probably through an effect on metabolism. The metabolism of green plants varies with the time of the day because during daylight there is a net fixation of carbon dioxide from the air while in the dark there is a net loss again via respiration. Chilling could well have a different effect on different pathways

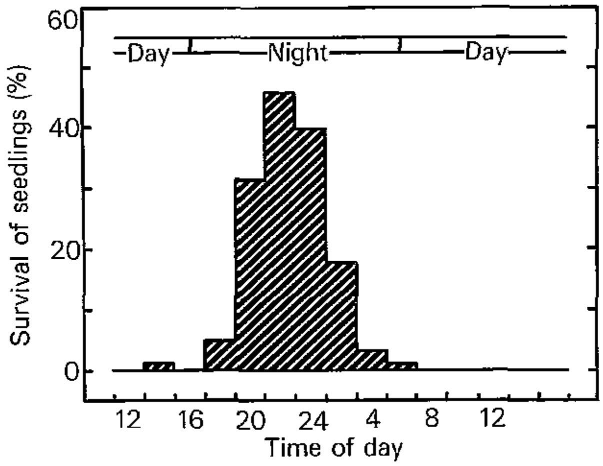


**Fig. 2.** Effect of time of day on the survival of tomato seedlings after chilling stress. (Adapted from Patterson *et al.* 1979.) Tomato seedlings of exactly the same age at the start of the chill were chilled from different times of the day for 6 days when subsequent survival was assessed. Other experiments showed that the time at 0 °C required to kill 50% of the seedlings was 3 days when chilling was started at 7.00 h and 6 days when chilling was started at 22.00 h.

of metabolism so that starting chilling at different times during the day–night cycle might be expected to have different effects. This was indeed found with tomato seedlings (Patterson *et al.* 1979). Fig. 2 shows that when tomato seedlings of matching age were chilled for 6 days, half of them survived when chilling was started at 22.00 h, but all were killed when they were chilled from 7.00 h. Other experiments showed that at 7.00 h the seedlings are about twice as sensitive to chilling as they are at 22.00 h. One interpretation of this result is that the different pathways of metabolism, whose relative contributions vary through the day and night in green tissues, differ in their tendency to produce toxic levels of metabolites at chilling temperatures. The way by which the plant could reduce the rate of metabolism through those pathways that are most critically altered by chilling could therefore repay study.

Several sites within the cell may be affected deleteriously by chilling (Lyons 1973; Hochachka and Somero 1973). One of the sites studied in this laboratory is at the metabolic step catalyzed by the enzyme PEP[A]-carboxylase (Graham *et al.* 1979). This enzyme catalyzes the reaction:

PEP + bicarbonate – oxaloacetate + phosphate

In the plants that we have studied, it is an important enzyme in the processes that lead,

Table 2. Chilling-sensitive horticultural crops and their wild relatives with greater chilling resistance. (Modified with additions from McGlasson *et al.*, 1979)

| Sensitive crop | Tolerant wild or cultivated species | Genetic compatibility |
|---|---|---|
| Guava *(Psidium guajava)* | *P. cattleyanum* | Poor |
| Avocado *(Persea americana)* | Mexican race | Good |
| Papaw *(Carica papaya)* | *C. pubescens* and *C. stipitata* | Poor |
| Tomato *(Lycopersicon esculentum)* | *L. hirsutum* | Good |
| Pepper *(Capsicum anuum)* | *C. pubescens* | Poor |
| Passionfruit *(Passiflora quadrangularis)* | *P. edulis* *P. caerulea* | Promising |
| Pineapple *(Ananas comosus)* | *A. bracteata* | Good |
| Custard apple *(Annona squamosa)* | *A. cherimolia* | Good |
| *Sorghum bicolor* | *S. halepense* | Promising |

for instance, to the synthesis of chlorophyll and many amino acids. In order to catalyze such a chemical reaction, an enzyme must first combine with its substrates which, in this instance, are PEP and bicarbonate. At 20 °C a concentration of PEP of 0.1 mmole per litre is sufficient to give half the maximum rate of catalysis for the tomato enzyme. However, temperature can affect the affinity of this enzyme for PEP, as is shown in Fig. 3. The enzyme from tomato requires about nine times the concentration of PEP at 1.3 °C than it requires at 20 °C in order to give half the maximum rate of catalysis. In other

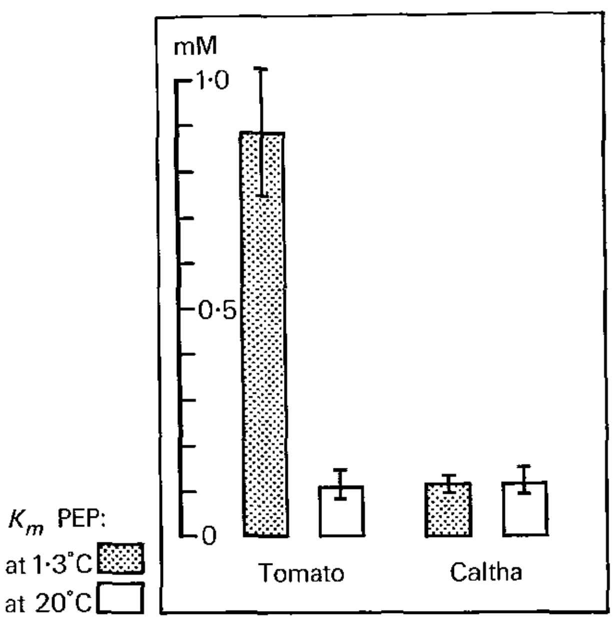


**Fig. 3.** Effect of temperature on the enzyme, PEP-carboxylase, from two plants. (Adapted from Graham *et al.* 1979). In the figure $K_m$ refers to the concentration of PEP required to give 50% of the maximum velocity of the enzyme at that temperature.

words, the tomato enzyme loses its high affinity for the substrate PEP at temperatures approaching 0 °C. Since the concentration of PEP is very low in plant tissues, this result implies that the tomato enzyme will work inefficiently at temperatures approaching 0 °C.

A contrasting result is shown in Fig. 3. for the same enzyme from the alpine plant *Caltha intraloba* which is very resistant to chilling. This plant can grow and develop near 0 °C. It can be seen that its enzyme has about the same affinity for PEP at 1.3 °C as it has at 20 °C. Obviously, in this plant species, PEP-carboxylase is likely to be an efficient catalyst at chilling temperatures.

The example of PEP-carboxylase shows one mechanism by which chilling temperatures can cause imbalances in metabolic pathways. As chilling temperatures are approached, pathways that involve enzymes which lose affinity for substrates will tend to be blocked, while pathways which do not have such temperature-sensitive enzymes are likely to receive a proportionately larger share of metabolites. Eventually, some metabolites are likely to reach levels that are toxic and chilling injury will result.

[A]Abbreviation: PEP = phosphoenolpyruvate.

*Prospects for reducing chilling sensitivity*

If chilling sensitivity could be reduced in crops of tropical origin, refrigerated storage would give proportionately greater benefits. One way that this is likely to be achieved is by plant breeders exploiting the genetic potential of the wild progenitors of cultivated plants. Table 2 shows a list of cultivated plants that are chilling-resistant. Obviously, there is a substantially untapped genetic resource in these wild plants, although in order to able to use it, an efficient selection method for chilling-resistance would be needed. In other words, when the plant breeder has made hybrids between the wild species and the cultivated plant, he must be able to screen very large numbers of seedlings for the inherited ability to resist chilling, so that other unwanted characters can be rejected. In this Laboratory it has been found that some metabolites build up quite specifically in chilling-sensitive varieties. In addition, the nature of chloroplast fluorescence changes (Smillie 1979). By providing plant breeders with a means of measuring these changes after a non-lethal chilling stress, the chilling-resistance of hybrid seedlings could be assessed accurately. In this way the chilling-resistance which is present in the wild relatives of many of our tropical crops could be incorporated into new varieties.

It is obvious that in applying the results of scientific research to the problems of fruit and vegetable storage, different disciplines must interact. Research on chilling-sensitivity is one such discipline that can produce valuable improvements. Genetic improvement seems to have the greatest potential for success, but for it to be realized rapidly, plant physiologists and biochemists must be able to provide plant breeders with appropriate selection techniques for screening hybrid material.

### References


Eaks, I. L., and Morris, L. L. (1956). Respiration of cucumbers associated with physiological injury at chilling temperatures. *Plant Physiol.* 31, 308–14.

Graham, D., Hockley, D. G., and Patterson, B. D. (1979). *In* 'Low Temperature Stress in Crop Plants: The Role of the Membrane', eds J. M. Lyons, J. K. Raison and D. Graham. (Academic Press: New York.)

Heywood, V. H. (1978). 'Flowering Plants of the World'. (Oxford University Press: Oxford.)

Hochachka, P. W., and Somero, G. N. (1973). 'Strategies of Biochemical Adaptation'. (W. B. Saunders Co.: Philadelphia.)

Ingraham, J. L. (1973). *In* 'Temperature and Life', eds H. Precht, J. Christopherson, H. Hensel and W. Larcher. (Springer Verlag: New York.)

Lutz, J. M., and Hardenburg, R. E. (1968). The commercial storage of fruits, vegetables and florist and nursery stocks. U.S. Dep. Agric. Handbk. No. 66, p. 26.

Lyons, J. M. (1973). *Annu. Rev. Physiol.* 24, 445–66.

Lyons, J. M., and Rappaport, L. (1959). Effect of Temperature on respiration and quality of brussels sprouts during storage. *Proc. Am. Soc. Hortic. Sci.* 73, 361–6.

McGlasson, W. B., Scott, K. J., and Mendoza, D. B. (1979). The refrigerated storage of tropical and subtropical products. *Int. J. Refrig.* 2, 199–206.

McMillan, C. (1975). *In* 'Proc. Int. Symp. Biol and Managmt of Mangroves', eds G. E. Walsh, S. C. Snedaker and H. J. Teas. (Univ. Florida: Gainesville.)

McMillan, C. (1979). *Am. J. Bot.* 66, 810–19.

Patterson, B. D., Murata T., and Graham, D. (1976). Electrolyte leakage induced by chilling in *Passiflora* species tolerant to different climates. *Aust. J. Plant Physiol.* 3, 435–42.

Patterson, B. D., Paull, R. E., and Graham, D. (1979). *In* 'Low Temperature Stress in Crop Plants: The Role of the Membrane', eds J. M. Lyons, J. K. Raison and D. Graham. (Academic Press: New York.)

Patterson, B. D., Paull, R. E., and Smillie, R. M. (1978). Chilling resistance in *Lycopersicon hirsutum* Humb. & Bonpl., a wild tomato with a wide altitudinal distribution. *Aust. J. Plant Physiol.* 5, 609–17.

Purseglove, J. W. (1968). 'Tropical Crops: Dicotyledons.' (Longman: London.)

Smillie, R. M. (1979). *In* 'Low Temperature Stress in Crop Plants: The Role of the Membrane', eds J. M. Lyons, J. K. Raison and D. Graham. (Academic Press: New York.)

## Refrigeration of fruits and vegetables

# Atmosphere composition as an aid to refrigeration

By N. L. Wade

N.S.W. Department of Agriculture (located at CSIRO Division of Food Research, North Ryde, N.S.W.)

The rate of deterioration in quality of fresh produce can often be substantially reduced by the use of controlled atmospheres. Atmosphere control can be used as either an adjunct or alternative to refrigeration. This article discusses the mechanism by which atmosphere control works, existing and potential uses for the technique and reasons for its limited commercial adoption.

Composition of the storage atmosphere can greatly affect the storage behaviour of fresh produce. The oxygen, carbon dioxide and ethylene contents of the atmosphere interact to modify the metabolism of stored produce. Beneficial responses to atmosphere modification include inhibition of the initiation of ripening, retardation of the ripening process, and delayed onset of senescence and physiological or pathological breakdown. Detrimental responses to atmosphere modification include induction of physiological disorders (especially those due to oxygen deficiency or carbon dioxide toxicity), increased susceptibility to disease and development of undesirable flavours.

Atmosphere control entails lowering the oxygen content and/or raising the carbon dioxide content of the air surrounding the produce. It may also be necessary to prevent ethylene from accumulating in the atmosphere. An incidental but important consequence of atmosphere modification is the likelihood of change in the humidity of the store.

Carbon dioxide and ethylene are evolved and oxygen is consumed by all plant organs. When produce is stored under restricted ventilation, atmosphere modification will necessarily ensue. The composition of the atmosphere can be manipulated by passing the storage atmosphere through chemical scrubbers to remove excess carbon dioxide (and ethylene, if required), and by reticulation of externally derived gases into the store. Application of the technique is not restricted, however, to permanent storage buildings. Produce can be treated during transport by either flushing the vehicle with appropriate gases or enclosing the produce in plastic packages which are only moderately permeable to oxygen and carbon dioxide. This latter method is very economical, and can be applied where precise control of atmosphere composition is unnecessary.

### Mechanism of action of atmosphere control

The effects which oxygen, carbon dioxide and ethylene have on fresh produce are complex and not fully understood. Oxygen is a substrate and carbon dioxide a product of respiration. Both compounds directly or indirectly modulate the activities of the respiratory system and a number of other enzyme systems. Air which is depleted in

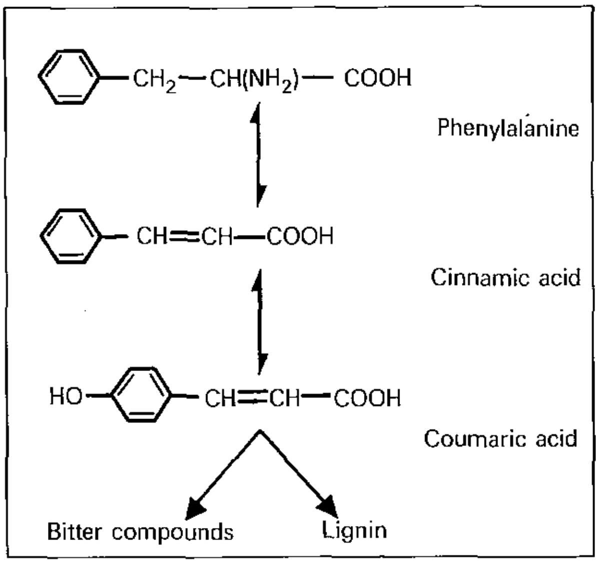


**Fig. 1.** Reactions partially catalysed by the enzyme phenylalanine ammonia lyase.

oxygen and enriched in carbon dioxide reduces the respiratory activity of fresh produce, but there is no valid reason for supposing that a mere reduction in respiration rate will prolong storage life.

Ethylene is a plant hormone, which in minute amounts can affect many facets of cell metabolism, including the initiation of ripening and senescence (McGlasson *et al.* 1978) and the synthesis of phenolic compounds (Abeles 1973). The activity of phenylalanine ammonia lyase, a key enzyme of phenolic metabolism, is increased by ethylene. Pursuant to this increase in enzyme activity is an accumulation of phenolic intermediates which may cause flavour defects, or serve as substrates for lignin synthesis (Fig. 1). Lignification may impair texture. For example, ethylene makes carrots bitter, owing to the accumulation of phenolics, and asparagus toughens when ethylene induces lignification (Table 2). Ethylene has been implicated in the hard-core disorder of sweet potato, which involves a textural defect and tissue discoloration associated with phenolic metabolism. Ethylene is, therefore, generally detrimental to produce, and even its vital role in the ripening process may warrant deferment, so that produce may be sent to market unripe.

A major effect of atmosphere control is the regulation of the ethylene hormonal system. The increase in ethylene synthesis that is associated with the induction of ripening in many kinds of fruit cannot occur if the external oxygen concentration is less than about 7% (Mapson and Robinson 1966). The basal level of ethylene synthesis by unripe fruit is not affected so dramatically by oxygen, but is nonetheless decreased by low oxygen. The sensitivity of produce to ethylene also decreases at low oxygen concentrations. It is surmised that oxygen must bind or react at or near the site to which ethylene attaches itself in the cell, before ethylene can exert its effect (Fig. 2). When oxygen falls to 3%, the binding of ethylene is reduced to 50% of that in air (Burg and Burg 1967).

Carbon dioxide does not directly affect ethylene synthesis, but it is antagonistic to ethylene. The presence of 10% carbon dioxide abolishes the biological activity of 1$\mu$L/L of ethylene (Burg and Burg 1967). Carbon dioxide is a structural analogue of ethylene, and may competitively displace ethylene from its binding site (Fig. 2). Alternatively, since ethylene is readily oxidized by tissues to carbon dioxide, this compound might act as a feedback or mass-action inhibitor of the oxidation (Beyer 1979).

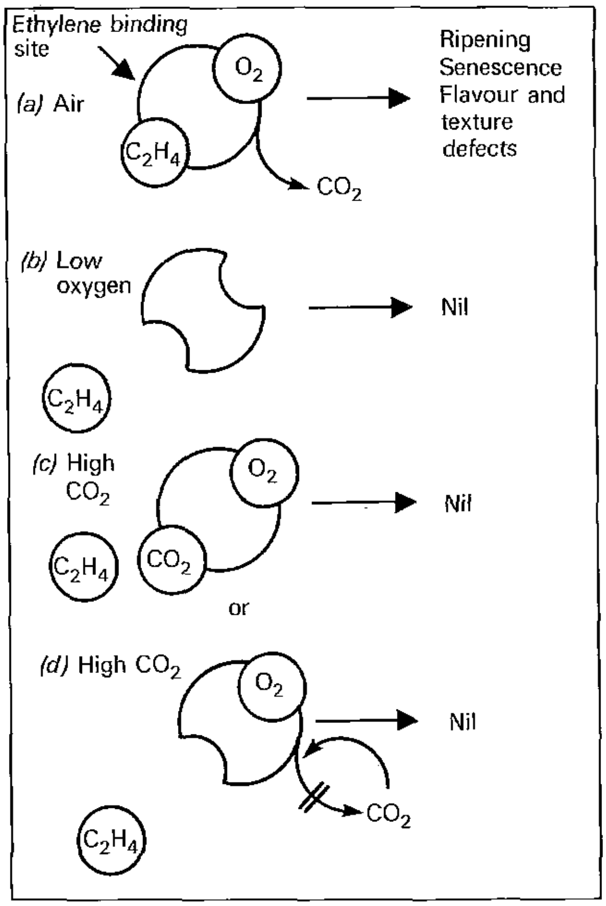


**Fig. 2.** The influence of oxygen and carbon dioxide on the binding of ethylene to its receptor site. In the presence of oxygen, ethylene binds to its receptor and initiates ripening, etc. (*a*). The oxygen is reduced to carbon dioxide. In the absence of sufficient oxygen, ethylene cannot bind (*b*). In the presence of carbon dioxide, ethylene is either displaced from its receptor (*c*) or else cannot bind because oxygen reduction is inhibited (*d*).

Oxygen cannot be completely eliminated from the atmosphere, since it is essential for the maintenance of normal metabolism. Below about 1–3% oxygen, many commodities suffer from oxygen deprivation. Carbon dioxide concentration must be adjusted with due regard to the potentially injurious effects of this gas. Some commodities tolerate only 1% carbon dioxide, whilst others will tolerate 20% or even more (Table 1). Despite the ability of low oxygen and high carbon dioxide atmospheres to reduce ethylene evolution and render produce less susceptible to it, harmful amounts of ethylene can still

Table 1. Selected fruit and vegetables which have shown beneficial responses to atmosphere control (derived from Hardenburg 1969 and Stoll 1974).

| Commodity | Application | Atmosphere Oxygen (%) | Atmosphere Carbon dioxide (%) | Storage temperature (°C) | Beneficial response |
|---|---|---|---|---|---|
| Apples | Storage | 2–3 | 1–8 | –1 to 4 | Extension of storage life |
| Asparagus | Transport | 1–3 | — | 2 | Retardation of disease |
| Bananas, green | Transport | 2 | 5 | 12 | Extension of shelf life |
| Beans, green | Transport | 2–5 | — | 7 | Extension of shelf life; retention of chlorophyll |
| Brussels sprouts | Storage | 2–14 | 4–7 | 0 | Extension of storage life |
| Cabbage | Storage | 1–2.5 | 5 | 0 | Retention of green colour and fresh flavour |
| Capsicum | Storage | 2–3 | 2–5 | 8–13 | Extension of storage life |
| Cauliflower | Storage | 2–16 | 0–10 | 0–1 | White colour of curd preserved; retention of leaf chlorophyll |
| Nectarines | Storage | 1 | 5 | 0 | Extension of storage life |
| Onions, green | Transport | 2–5 | — | 0.5 | Retention of chlorophyll in tops |
| Peaches | Storage | 1 | 5 | 0 | Extension of storage life |
| Pears | Storage | 0.5–2 | 1 | –1 to 0 | Extension of storage life |
| Peas, green | Storage | 5–10 | 5–10 | 0–1 | Extension of storage life |
| Strawberries | Storage, transport | 2 | 0–20 | 0–7 | Extension of storage and shelf life; control decay |

accumulate, and it may be desirable to scrub the atmosphere free from the gas. This can be done with chemical absorbents like potassium permanganate (Scott *et al.* 1970) or with ultraviolet irradiation (Scott *et al* 1971). Another technique is that of low pressure storage, where the produce is stored at a pressure less than one-tenth of normal atmospheric pressure (Burg and Burg 1966). The storage chamber is continuously swept with a bleed of clean external air. The pressure reduction lowers the partial pressures of oxygen and ethylene and increases the diffusivities of these gases, whilst the flushing air removes ethylene from the chamber.

**Applications of atmosphere control**

The benefits of atmosphere control can be realized either at ambient temperature or in cool storage, but the maximum response is usually obtained at cool-storage temperatures. Atmosphere control can be used therefore to derive full benefits from refrigeration or as a substitute for refrigeration. In yet another application, atmosphere control can be used in conjunction with refrigeration at temperatures part way between ambient temperature and the freezing point of the commodity.

*Obtaining maximum benefits from cool storage*

This application is best illustrated by the widely used practice of storing apples at about 0 °C in atmospheres containing about 3% oxygen and 1% or more carbon dioxide (Lutz and Hardenburg 1968). Cool storage by itself enables storage of apples through the winter and spring, but controlled atmospheres are necessary if storage is to persist into the summer. It is customary to apply controlled atmospheres to apples throughout the entire storage period, but some cultivars respond to short, pre-storage treatments with high carbon dioxide. For example, Golden Delicious apples may be treated with 20% carbon dioxide at –1 °C for 10 days before conventional storage at –1 °C in 2.5% oxygen plus 1% carbon dioxide. Apples treated in this way soften less and lose less titratable acidity during 6–7 months' storage than untreated fruit (Couey and Olsen 1975).

*Substituting for cool storage*

The storage biology of some commodities and economic factors may preclude the use of refrigeration. Fresh, warm-climate produce (such as bananas, mangos, pawpaws, tomatoes, pumpkins and citrus) may suffer chilling injury if stored below their critical threshold temperatures. These critical temperatures usually lie between about 10° and 15 °C for warm-climate crops (Lyons 1973). Although these commodities will keep better if stored at 10°–15 °C than at higher temperatures, the development of ripening and senescence is only slightly retarded in this temperature range.

Another factor is cost. Despite the long history of refrigeration in Australia, most

Table 2. Fruit and vegetables subject to injury by ethylene[A]

| Commodity | Atmosphere | Temperature (°C) | Effect of ethylene removal | Reference |
|---|---|---|---|---|
| Asparagus | Air | 20 | Reduced rate of toughening | Haard *et al.* 1974 |
| Bananas | Modified by polyethylene bag | 20 | Initiation of pulp ripening prevented | Scott *et al.* 1970 |
| Carrots | Air | 3 | Development of bitterness prevented | Sarkar and Phan 1974 |
| Citrus e.g. Valencia oranges | Air or 3% oxygen/ 5% carbon dioxide | 10 | Maintenance of normal orange flavour; development of off-flavour prevented; decay reduced | McGlasson and Eaks 1972 |
| Lettuce | Air | 7 | Abolition of 'russet spotting' disorder | Rood 1956 |
| Pears (Williams) | Modified by polyethylene bag | −1 | Incidence of 'brown heart' disorder reduced | Scott and Wills 1974 |
| Sweet potato | Air | 2–22 | Reduced incidence of 'hardcore' disorder, in which areas of the tissue remain firm after cooking | Buescher *et al.* 1975, Timbie and Haard 1977 |

[A]In addition to the commodities listed in the table, artichokes, beans (green), broccoli, cabbage, cauliflower, celery, cucumbers, parsley, parsnips, potatoes, rhubarb, and silver beet may also benefit by removal of ethylene.

fresh produce is not refrigerated. To justify the use of more refrigeration on economic grounds, it would be necessary to establish that the resultant reduction in wastage and deterioration of quality could repay the cost of cooling. Inexpensive atmosphere modification has considerable potential as a means of maintaining the market quality of produce where biological or economic considerations mitigate against cooling. Unripe bananas and some other tropical fruit can be packed in polyethylene bags containing an ethylene absorbent (Scott *et al.* 1970). The metabolic activity of the bananas generates an in-transit atmosphere which is depleted in oxygen and enriched in carbon dioxide. Ethylene evolved by the bananas is absorbed and inactivated. Under these modified atmosphere conditions, the fruit remain green, turgid and unripe at ambient temperature.

An alternative to special packaging may be the administration of a modified atmosphere for a brief period prior to dispatch to market. Treatment of carrots, potatoes and zucchini with high levels of carbon dioxide or low levels of oxygen for a few days at 20 °C reduced the respiratory activity of the produce upon return to air and appeared to improve shelf life (Wills *et al.* 1979).

*Atmosphere control at intermediate temperatures*

Reference has been made to the problem of chilling-sensitive, warm-climate produce. This is an extreme case where injury is occasioned at relatively high temperatures. Other commodities, however, including those of temperate origin, may suffer injury at somewhat lower temperatures which are nonetheless above the freezing point of the tissues. Some cultivars of apple, for example, suffer injury below 3 °–5 °C (Carne 1948). One strategy for storing these apples is to operate the cool store above the critical threshold temperature for injury, whilst redressing the potential loss in storage life by application of a controlled atmosphere.

Instances exist where the injurious effects of cool storage can be deferred or prevented by atmosphere control, permitting the storage temperature to be fixed at just above the freezing point of the produce. Peaches often suffer internal breakdown when stored below about 7 °C for more than 2 or 3 weeks (Lutz and Hardenburg 1968). Under an appropriate controlled atmosphere, storage for 2 or 3 months at 0 °C is possible (Table 1). This phenomenon is not used commercially in Australia, for reasons which will be examined later.

**Examples of commodities responding to atmosphere control**

The storage behaviour of many commodities has been tested under controlled atmospheres, because the technique is simple and the necessary technology has been developed for commercial application. Selected examples of commodities which have displayed marked responses to controlled atmospheres are given in Table 1. This list is not comprehensive and the storage conditions quoted are not recommendations. Many entries in the table are derived from several independent studies using different conditions, and this information has been summarized as the range of conditions examined.

A second table (Table 2) has been compiled listing commodities known to be subject to injury when ethylene accumulates in the atmosphere. Interpretation of this table must allow for the profound moderating effect that temperature has on responses to ethylene. Initiation and development of ripening and accumulation of phenolics are retarded by cool storage at about 0 °C. Ethylene is therefore most active at ambient temperature, but the effects of ethylene removal have been demonstrated at temperatures as low as −1 °C (Table 2). Regard should be paid to the inevitable impairment of ventilation in a cool room and the possibility of dissimilar commodities being stored together. Fruit such as apples, pears and peaches generate large amounts of ethylene and should not be stored with ethylene-sensitive produce.

### Commercial applications of atmosphere control

Apart from the prolonged storage of apples and pears (Fig. 3), atmosphere control is little used in Australia. There are several reasons for this situation:

- Long-term storage is generally not necessary. Most staple commodities are produced in at least one area of Australia in any given month of the year and so can be supplied fresh. Short-season dessert fruit are readily absorbed by the fresh market, and furnish the public with seasonal variety. Processors, however, may benefit from short-term storage to carry them over the period of peak supply when deliveries exceed processing capacity. The advent of mechanical harvesting has aggravated this problem, since crops can be harvested more quickly.
- Knowledge about responses to controlled atmosphere has often been acquired before other limiting factors in storage have been solved. Principal amongst these problems is wastage from disease. Atmosphere control which slows ripening senescence usually has little direct effect on the establishment of infection. The oxygen concentrations used do not prevent infection, although, where high levels of carbon dioxide can be used, some fungistatic effects have been seen. The pioneering studies of Huelin, Tindale and Trout into the controlled atmosphere storage of Australian peaches have lain in abeyance since the 1930s, because of the problem of brown rot infection which was solved only about 10 years ago. When fungicides are used to control brown rot, the astonishing increases in storage life under atmosphere control demonstrated in 1937 can be realized in practice.
- The most pressing requirement of the Australian fruit and vegetable industries in postharvest technology is probably the improvement of the systems for transport and distribution of perishable produce from distant production areas to retail outlets. The postharvest treatments of greatest utility in this regard are those that can be applied by the grower before dispatch to market. Protective treatments with fungicides to control disease and with other chemicals to control various physiological disorders are accepted postharvest technology. On-farm, rapid pre-cooling, especially forced-air cooling, is gaining widespread acceptance. Prompt cooling reduces loss of shelf-life whilst produce is necessarily detained on the farm awaiting transport, and helps keep produce at reasonable temperatures during overnight journeys.

The grower has little control over the environmental conditions experienced by his produce past the farm gate. Suitable refrigerated vehicles, with or without

**Fig. 3.** Delicious apples in bulk bins being removed from controlled atmosphere storage during the summer at Orange, N.S.W.

atmosphere control facilities, are not readily available to the fresh produce industry; and the compressed or liquefied gases used in North America to regulate in-transit atmospheres are very costly. Modified atmospheres created by special packaging, such as enclosure of fruit in plastic bags or liners, is one option open to growers. Although this works well with bananas, the technique cannot be used indiscriminately because of the lack of accurate control of the atmosphere. Hot produce packed in this way can easily suffer from oxygen deficiency or carbon dioxide toxicity.

Supplementing or replacing pre-cooling with brief controlled atmosphere treatments is another potentially useful approach. Such treatments appear to have residual effects on the produce which improve shelf-life. Conditions of treatment could be controlled to prevent the produce being harmed, although care with large stacks of hot produce would be required. Any restriction of ventilation through large stacks could cause overheating and generation of harmful atmospheres.

### Conclusion

Atmosphere control used in conjunction with or instead of refrigeration is a potentially useful postharvest treatment for many commodities. By manipulating the oxygen and carbon dioxide contents of the storage atmosphere, synthesis of ethylene by produce can be reduced and the susceptibility of the produce to ethylene lowered. In some instances, accumulation of ethylene in the atmosphere must also be prevented. When the ethylene metabolism of fresh produce is interfered with in these ways, unripe fruit will not ripen until returned to air and the rate of ripening is reduced in fruit that has started to ripen. Undesirable changes in phenolic metabolism which lead to flavour and textural defects are prevented. The onset of tissue senescence and loss of product quality are delayed.

Controlled atmospheres may be used in conjunction with cool storage to derive maximal storage life, or as an alternative to refrigeration where biological or economic factors intervene. In a compromise application designed for chilling-sensitive produce, storage temperature is raised to a biologically safe point and atmosphere control is used to compensate for the loss in life which would otherwise ensue.

The response of many commodities to atmosphere control has been determined, and many beneficial effects have been observed. Few commodities are, however, stored or transported with the aid of atmosphere control. A major technical problem in Australian postharvest horticulture is the transport of fresh produce from growing areas to terminal markets. Protective chemical treatments and rapid precooling are being introduced to solve this problem. Atmosphere control has a potential application in this area by either short pre-transit treatments or continuous in-transit treatments.

### References

Abeles, F. B. (1973). 'Ethylene in Plant Biology', p. 202. (Academic Press: New York and London.)

Beyer, E. M., Jr. (1979). Effect of silver ion, carbon dioxide, and oxygen on ethylene action and metabolism. *Plant Physiol.* **63**, 169-73.

Buescher, R. W., Sistrunk, W.A., and Brady, P.L. (1975). Effects of ethylene on metabolic and quality attributes in sweet potato roots. *J. Food Sci.* **40**, 1018-20.

Burg, S. P., and Burg, E. A. (1966). Fruit storage at subatmospheric pressures. *Science* **153**, 314-5.

Burg, S. P., and Burg, E. A. (1967). Molecular requirements for the biological activity of ethylene. *Plant Physiol.* **42**, 144-52.

Carne, W. M. (1948). *In*, 'The Non-Parasitic Disorders of Apple Fruits in Australia', p. 53. Counc. Sci. Ind. Res. (Aust.) Bull. No. 238.

Couey, H. M., and Olsen, K. L. (1975). Storage response of 'Golden Delicious' apples after high-carbon dioxide treatment. *J. Am. Soc. Hortic. Sci.* **100**, 148-50.

Haard, N. F., Sharma, S. C., Wolfe, R., and Frenkel, C. (1974). Ethylene induced isoperoxidase changes during fiber formation in postharvest asparagus. *J. Food Sci.* **39**, 452-6.

Hardenburg, R. E. (1969). Summary tables of controlled atmosphere recommendations. *In* 'Controlled Atmospheres for the Storage and Transport of Horticultural Crops', eds. D. H. Dewey, R. C. Herner, and D. R. Dilley, pp. 122-131. (Dep. Hortic. Michigan State Univ.: East Lansing, Michigan, U.S.A.)

Lutz, J. M., and Hardenburg, R. E. (1968). 'The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks'. Agric. Handbk. No. 66 (U.S. D.A.: Washington, D.C.)

Lyons, J. M. (1973). Chilling injury in plants. *Annu. Rev. Plant Physiol.* **24**, 445-66.

Mapson, L. W., and Robinson, J. E. (1966). Relation between oxygen tension, biosynthesis of ethylene, respiration and ripening changes in banana fruit. *J. Food Technol.* **1**, 215-25.

McGlasson, W. B., and Eaks, I. L. (1972). A role for ethylene in the development of wastage and off-flavours in stored Valencia oranges. *HortScience* **7**, 80-1.

McGlasson, W. B., Wade, N. L., and Adato, I. (1978). Phytohormones and fruit ripening. *In* 'Phytohormones and Related Compounds — A Comprehensive Treatise', eds. D. S. Letham, P. B. Goodwin, and T. J. V. Higgins. Vol. II, pp. 447-93 (Elsevier/North Holland Biomedical Press: Amsterdam.)

Rood, P. (1956). Relation of ethylene and post-harvest

temperature to brown spot of lettuce. *Proc. Am. Soc. Hortic. Sci.* 68, 296-303.
Sarker, S. K., and Phan, C. T. (1974). Effect of ethylene on the qualitative and quantitative composition of the phenol content of carrot roots. *Physiol. Plant.* **30**, 72-6.
Scott, K. J., and Wills, R. B. H. (1974). Reduction of brown heart in pears by absorption of ethylene from the storage atmosphere. *Aust. J. Exp. Agric. Anim. Husb.* 14, 266-8.
Scott, K. J., McGlasson, W. B., and Roberts, E. A. (1970). Potassium permanganate as an ethylene absorbent in polyethylene bags to delay ripening of bananas during storage. *Aust. J. Exp. Agric. Anim. Husb.* 10, 237-40.
Scott, K. J., Wills, R. B. H., and Patterson, B. D. (1971). Removal by ultra-violet lamp of ethylene and other hydrocarbons produced by bananas. *J. Sci. Food Agric.* 22, 496-7.
Stoll, K. (1974). A review paper on the storage of vegetables in controlled atmospheres. *Bull. Int. Inst. Refrig.* 54, 1302-24.
Timbie, M., and Haard, N. F. (1977). Involvement of ethylene in the hard core syndrome of sweet potato roots. *J. Food Sci.* 42, 491-3.
Wills, R. B. H., Wimalasiri, P., and Scott, K. J. (1979). Short pre-storage exposures to high carbon dioxide or low oxygen atmospheres for the storage of some vegetables. *HortScience* 14, 528-30.

**Refrigeration of fruits and vegetables**

# Genetic approaches to extend the storage life of fruits and vegetables

By E. C. Tigchelaar

Department of Horticulture, Purdue University, West Lafayette, U.S.A.

Deterioration and death is an unhappy fate which all living organisms ultimately experience. Longevity is a genetically determined attribute which loses its selective advantage when an organism's capability to reproduce and perpetuate its kind has been completed. As a consequence, most living systems deteriorate rapidly following completion of their reproductive function. Senescence of annual plants is a dramatic example of such a 'genetically programmed death'.

In higher plants, marked differences in longevity occur within different tissues. In many perennial plants, new leaves and fruit are 'born and die' during a single season, while the life span of the tree itself may be many years. Annual crops, in contrast, complete their single reproductive cycle in a span of several weeks or months, producing seed which reinitiates the cycle when climatic conditions are favourable. These extremes in longevity are consequences of the evolutionary process by which natural selection moulds the genetic makeup to fit the environment. Longevity is of little evolutionary significance unless it is accompanied by an increase in reproductive capacity or fitness to survive in a particular environment.

The seed frequently shows the greatest longevity of any tissue because of its role in continuing the life cycle and evolutionary progress of the organism. Other tissues, which do not directly contribute to perpetuation of the organism, commonly deteriorate rapidly when maturation is complete. Tissues such as fruit serve a temporary function in distribution of seed and, as a consequence, longevity of such tissues is not of critical importance to the evolutionary survival of that organism.

Storability varies widely from crop to crop as well as among different varieties of a particular commodity. This variation, which is potentially useful in crop improvement, will be the focus of discussion in this paper.

### Factors influencing storage or shelf life

Studies with many perishable commodities have shown wide crop as well as varietal differences in storage life. In most instances the precise cause for storability differences is not known. Several factors may contribute to enhanced storage life. These include:

- Tolerance to mechanical injury during harvest and handling.
- *Reduced* water loss and desiccation.
- *Resistance* to storage pathogens.
- *Absence of* physiological storage disorders.
- High chilling requirements which delay sprouting in storage.
- Variation in susceptibility to chilling injury.
- Physiological and/or biochemical differences.

Few direct attempts have been made to exploit variability in storage life in applied breeding programs. As a general rule, plant breeders examine the storage potential of a new cultivar during the final stages of evaluation and testing and/or following release. Seldom is a concerted effort made to select for storability during the development phase of variety improvement. This is presumably because of the difficulty of accurately measuring storage life and the complexity of factors which contribute to influence the period and conditions under which a commodity can feasibly be held. In addition, the genetic and physiological basis for differences in storage life is poorly understood. More fundamental information on the causative factors contributing to improved storage life is required before it will be possible to exploit effectively variability in this characteristic by means of applied breeding programs.

**Genetics and breeding for improved storage life**

Recent efforts to enhance storage life and quality genetically have proven successful in several highly perishable crops (Janick and Moore 1975). Generally, the primary effort has been focused on genetic resistance to storage diseases or physiological disorders which limit the storage life of a particular commodity. Examples in three major perishable crops will serve to illustrate the possibilities of utilizing genetic variation to improve shelf and storage life.

*Apples*

A wide range of variation in storability exists among apple cultivars (Table 1). As a general rule, early season varieties store poorly, whereas late cultivars store well; however, several exceptions to this rule occur. This apparent association between earliness and inferior storability may reflect a lack of selection and concern for good storage life in early cultivars destined for immediate consumption without storage or, conversely it may imply a physiological association between early maturation and rapid deterioration.

Variation also occurs in susceptibility to physiological storage disorders (Table 1). Certain of these disorders are unique to particular cultivars and appear to result from genetic defects which limit 'fruit longevity'. Recent studies have demonstrated the importance of calcium nutrition to the incidence of several storage disorders (Faust *et al.* 1969) and the feasibility of developing cultivars which are efficient accumulators of calcium to minimize these storage disorders is being explored (Faust *et al.* 1971).

Tolerance to mechanical damage and bruising during harvest and handling is a critical attribute affecting commercial storage life. Susceptibility of the scab-resistant cultivar, Sir Prize, to harvest bruising has seriously reduced its potential as a storage variety (Dayton *et al.* 1977).

Shrivelling and desiccation may contribute to losses during improper storage or product display. The cuticular waxes of the apple fruit appear to play an important role in restricting water loss during storage,

Table 1. Storage season and susceptibility to storage disorders among certain apple cultivars (After Childers 1978)

| | | Susceptibility to storage disorders | | | | |
|---|---|---|---|---|---|---|
| Variety | Cold storage season (days) | Water core | Scald | Soft scald | Bitter pit | Others |
| Transparent | 0 (90) | Medium | None | None | None | — |
| Gravenstein | 0–30 (90) | Slight | Slight | None | Severe | — |
| Wealthy | 0–30 (90) | Slight | Medium | Medium | Slight | — |
| Cortland | 90–120 (150) | Slight | Medium | Slight | Slight | — |
| McIntosh | 60–90 (150) | None | Slight | None | Slight | Brown core |
| G. Delicious | 90–120 (150) | Slight | Slight | Severe | None | Shrivelling |
| N. Spy | 120–150 (180) | Slight | Slight | None | Severe | 'Spy spot' |
| Ben Davis | 120–150 (240) | Slight | Medium | — | Slight | — |

Table 2. Ripening characteristics of fruits heterozygous for *rin* ($^+rin$) and *nor* ($^+nor$) and the double mutant hybrid ($^+rin\ ^+nor$)

| Ripening characteristic | $^+rin$ | $^+nor$ | $^+rin\ ^+nor$ |
|---|---|---|---|
| Time from anthesis to respiratory peak | Delayed 2–3 days | Delayed 4–5 days | Delayed 8–10 days |
| Respiratory climacteric | Delayed, magnitude similar to normal | Delayed, magnitude 50–60% of normal | Delayed, magnitude 20–25% of normal |
| Associated rise in $C_2H_4$ production | Delayed, 35–50% of normal | Delayed, 25–50% of normal | Delayed, 20–25% of normal |
| Shelf life | Normal | 2-3 times normal | Very long |
| Pectinesterase activity | Normal | Normal | ? |
| Polygalacturonase activity | 25–60% of normal | 25–40% of normal | 10–15% of normal |
| Carotenoid accumulation | Delayed and attenuated | Delayed and attenuated | Delayed and reduced |
| Fruit quality | | | |
| a) pH | Normal[A] | Normal[A] | Normal[A] |
| b) titratable acids | Normal[A] | Normal[A] | Normal[A] |
| c) soluble solids | Normal[A] | Normal[A] | Normal[A] |

[A]Tigchelaar, unpublished data.
Adapted from (Tigchelaar *et al.* 1978)

transport and marketing. These surface waxes have also been implicated in certain storage disorders (Faust and Shear 1972) and both quantity and arrangement of wax platelets affect its function in enhancing storability and shelf life. Several scab-resistant breeding lines with heavy cuticular wax exhibit a remarkable shelf life (Dayton *et al.* 1977) implying a function for these surface waxes in retaining storage quality.

*Sweet corn*

Quality of sweet corn deteriorates rapidly during storage and handling, primarily as a result of losses in sugar content. This loss in sweetness, which results from the hydrolysis of sucrose to ultimately form starch, is catalysed by several enzymes, each of which is genetically controlled. Recent work to elucidate the genetic control of starch biosynthesis has identified genes which retard the conversion of sugars to starch, thereby enhancing storage and shelf-life quality. The starch-deficient maize brittle-1 ($bt_1$), which produces only 30% of the normal quantity of starch (Tsai *et al.* 1970) contains low activity of the enzyme sucrose UDP glucosyl transferase. This enzyme functions to hydrolize sucrose for starch synthesis (Tsai 1974). Tsai and Glover (1974) have combined $bt_1$ with the sugary-1 (*su*) gene and report substantial improvement in postharvest retention of sucrose and desired textural qualities. Use of other genetic mutants affecting starch biosynthesis are being explored in a similar way to improve sweet corn storage life (Ferguson *et al.* 1979).

*Tomatoes*

Tomato fruit is a highly perishable, chilling injury susceptible commodity which has a very limited storage and/or shelf life, particularly when harvested mature. As a consequence, fruit destined for storage or shipment to distant markets is commonly harvested immature and ripened artificially during packing, in transit, or at the market destination.

Studies on the genetic extension of tomato storage and shelf life was prompted by fundamental research on a group of mutations which, in essence, prevent ripening from occurring or severely retard its progress. Three such mutants (ripening inhibitor (*rin*); non-ripening (*nor*) and never ripe (*Nr*)) have been identified and characterized. Virtually all of the obvious changes commonly associated with tomato ripening (colour development, softening, respiratory increases, and ethylene production) are inhibited or severely delayed and, as a consequence, mutant fruit can be held for very long periods without the serious deterioration which occurs in normal ripening cultivars. A detailed survey of the genetics and physiology of these mutants has been published recently (Tigchelaar *et al.* 1978*a*).

Attempts to exploit the remarkable shelf life of these unusual variants by inducing normal ripening has proven largely unsuccessful. Some stimulation of carotene pigment synthesis by treatment with ethylene in combination with high oxygen occurs (Frenkel and Garrison 1976). However colour, texture and flavour were not considered acceptable for commercial use (Buescher 1977).

The *rin* and *nor* genes are recessive mutants which, when crossed with normal ripening parents, produce hybrids which ripen acceptably. Critical comparisons of the ripening behavior of these mutant hybrids with their normal ripening parents, reveal, however, that many features of the ripening process are altered in $F_1$ hybrids (Table 2). A 2-3-fold increase in shelf life occurs in hybrids of the *nor* mutant and further improvements in shelf life result with hybrids which are heterozygous for both mutant genes. These improvements in storage life seem to be associated with a genetic attenuation of the ripening rate (Buescher 1977; Ng and Tigchelaar 1977; Tigchelaar *et al.* 1978*b*).

Recent research has attempted to quantify quality changes in normal and *nor* mutant hybrid fruit during storage 'on and off' the plant. These studies suggest that changes in fruit pH, total acidity and colour occur more slowly during ripening of hybrid fruit on the vine (Grazzini, unpublished data). No consistent pattern of change in soluble solids occurred during 'on vine' storage. Postharvest changes in these attributes of quality follow a similar pattern. However, shelf life and the attainment of acceptable quality depend upon the stage of maturity at harvest. Hybrid fruit do not attain acceptable colour if harvested immature. Cooperative research efforts in Australia and the U.S. are presently under way to establish the feasibility of utilizing these novel genetic variants and to define pre- and post-harvest treatments required to maximise their quality and shelf life. Other mutants with potential for further enhancing storage life have been identified and described, and a 'long keeping' cultivar for home garden use was offered commercially in 1979. Similar long-storing types have apparently been used for many years in home gardens in southern Italy (Palmieri *et al.* 1975).

## Summary and conclusions

Genetic variability for improved storage and shelf life exists in many perishable fruit and vegetable crops and offers opportunities for reducing postharvest losses by genetic means. For certain crops, the possibility exists of genetically prolonging the time a commodity can be held under conventional storage conditions. Of possibly greater importance is the potential to exploit this variability in order to reduce postharvest losses in developing countries, where storage facilities are limited and large losses of perishable fruits and vegetables occur during transit and marketing.

Progress toward enhanced storability will require greater emphasis in selecting for storage life during variety development and a clear definition of the individual components which contribute to enhanced shelf life. Fundamental genetic and physiological studies in several crops are providing the 'blueprint' for future design of cultivars with improved storage life.

## References


Buescher, R. W. (1977). Factors affecting ethephon-induced red color development in harvested fruits of the *rin* tomato mutant. *HortScience* **12**, 315–6.

Buescher, R. W., and Tigchelaar, E. C. (1977). Utilization of *nor* tomato hybrids for extending storage life and improving processed quality. *Lebensm-Wiss + Technol.* **10**, 111–3.

Childers, N. F. (1978). Storing apple. *In* 'Modern Fruit Science', pp. 238–73. (Horticultural Publications: New Brunswick, NJ, 08903.)

Dayton, D. F., Mowry, J. B., Williams, E. B., Janick, J., Emerson, F. H., Hough, L. F., and Bailey, C. (1977). Scab resistant apples. *HortScience* **12**, 434.

Faust, M., Shear, C. B., and Williams, M. W. (1969). Disorders of carbohydrate metabolism of apples. *Bot. Rev.* **35**, 169–94.

Faust, M., Shear, C. B., Oberle, G. B., and Carpenter, G. T. (1971). Calcium accumulation in fruit of certain apple crosses. *HortScience* **6**, 542–3.

Faust, M., and Shear, C. B. (1972). Fine structure of the fruit surface of three apple cultivars. *J. Am. Soc. Hortic. Sci.* **97**, 351–5.

Ferguson, J. E., Dickinson, D. B., and Rhodes, A. M. (1979). Analysis of endosperm sugars in a sweet corn inbred (illinois 677A) which contains the sugary enhancer (*se*) gene and comparison of *se* with other corn genotypes. *Plant Physiol.* **63**, 416–20.

Frenkel, C., and Garrison, S. A. (1976). Initiation of lycopene synthesis in the tomato mutant *rin* as influenced by oxygen and ethylene interactions. *HortScience* **11**, 20–1.

Janick, J., and Moore, J. N. (1975). 'Advances in Fruit Breeding'. (Purdue Univ. Press: West Lafayette, IN, 47907.)

Ng, T. J., and Tigchelaar, E. C. (1977). Action of the non-ripening (*nor*) mutant on fruit ripening of tomato. *J. Am. Soc. Hortic. Sci.* **102**, 504–9.

Palmieri, S., Sozzi, A., Gorini, F. L., and Soressi, G. P. (1975). Influenza die geni *Nr* e $nor^2$ su qualita e conservabilita del pomodoro (*L. esculentum* Mill.). *Ann. Ist. Valoriz. Technol. Prod. Agr. Milano.* **6**, 1–12.

Tigchelaar, E. C., McGlasson, W. B., and Buescher, R. W. (1978*a*). Genetic regulation of tomato fruit ripening. *HortScience* **13**, 508–13.

Tigchelaar, E. C., McGlasson, W.B., and Franklin, M. J. (1978*b*). Natural and ethephon stimulated ripening of $F_1$ hybrids of the ripening inhibitor (*rin*) and non-

ripening (*nor*) mutants of tomato (*Lycopersicon esculentum* Mill.). *Aust. J. Plant Physiol.* 5, 449–56.
Tsai, C. Y., Salamini, F., and Nelson, O. E. (1970). Enzymes of carbohydrate metabolism in the developing endosperm of maize. *Plant Physiol.* 46, 299–306.
Tsai, C. Y. (1974). Sucrose–UDP glucosyl-transferase of maize endosperm. *Phytochemistry* 13, 885–91.
Tsai, C. Y., and Glover, D. V. (1974). Effect of the brittle-1 sugary-1 double mutant combination on carbohydrate and postharvest quality of sweet corn. *Crop Science* 14, 808–10.

**Refrigeration of fruits and vegetables**

# Mineral composition of fruit and vegetables in relation to storage life

By I. B. Ferguson

Plant Diseases Division, DSIR, Auckland, New Zealand.

It has been firmly established that there are connections between the mineral contents of fruit and vegetables and their quality during storage at low temperatures. Much recent research into the cold storage of produce has been involved with mineral composition, not only in relation to the occurrence of specific storage disorders, but also with the relationships of mineral composition to general quality. Although most of these relationships are still poorly understood at the physiological and biochemical level, it is becoming evident that they can be used in the food industry as important indicators of potential quality.

The possibilities for using mineral content in quality assessment are best illustrated by the relationship between the calcium content of apple fruit and the storage disorder, bitter pit. The association of calcium with the occurrence of this disorder has been shown by the ability of calcium treatment to reduce the incidence of bitter pit (e.g. Jackson 1962), and by the close relationship found between calcium content of the fruit flesh and the development of bitter pit during storage (e.g. Perring 1968; Martin *et al.* 1975; Ferguson *et al.* 1979). Although several other relationships between mineral content and quality of cold-stored fruits and vegetables will be mentioned, it is the calcium–bitter pit relationship that has been most studied and is beginning to prove useful on a commercial basis.

The following discussion is divided into three parts. The first deals with the known relationships between mineral content and fruit and vegetable quality. The second part deals with the definition or characterization of these relationships and leads onto the third part which is a discussion of how such relationships can be useful in assessing quality in commercial systems.

### Relationships between mineral content and storage quality

There is a distinction between a mineral-related disorder and a relationship involving mineral content and general quality. Disorders have usually been identified by response of the fruit or vegetable to treatment with a particular mineral nutrient, e.g. bitter pit in apples and black-heart in celery can be prevented by raising the calcium levels of the tissue. The relationship involving general quality is one where certain levels of minerals can be identified in relation to minimum or optimum fruit or vegetable quality. This relationship is less easily identified, but possibly will become of greater importance.

*Disorders*

Mineral-related disorders that occur most frequently usually involve calcium. They have been summarized often (e.g. Shear 1975) and Table 1 sets out the more important of them. Although they can be divided into those that develop post-harvest such as bitter pit and breakdown, and those that develop pre-harvest on the plant, there is a similarity in symptom expression. Most symptoms involve tissue collapse followed by browning or corking. Calcium has a predominant role in such disorders, probably for two reasons. The first is that the calcium contents of fruit are generally low in comparison with other plant tissue because of the low rates of movement of calcium in the phloem (Bollard 1970). The second is that calcium can affect whole-fruit metabolism, and hence, senescence. For example, high calcium tissue levels have been associated with reduced respiration in apples (Bangerth *et al.* 1972; Faust and Shear 1972; Bramlage *et al.* 1974), avocados (Tingwa and Young 1974) and tomatoes (Wills and Tirmazi 1979), although in the latter fruit, other divalent cations were often as effective.

There are very few storage disorders that have been convincingly related to tissue contents of other elements. However, general deficiency symptoms are known in fruit and some examples are given in Table 2. Most of these occur on the plant before harvest, but they should not be ignored when considering storage disorders. For example, the boron corking disorders bear many similarities to calcium-related corking in pip-fruit. The magnesium-related disorder in grapes, *Stiellähme*, which is a fruit stalk necrosis, appears to be related to problems in internal mobilization of magnesium — in many ways similar to calcium-related problems in fruit (Schimansky 1977; Rizotto 1977).

As a general principle, the tissue contents of potassium and magnesium tend to be effective in the opposite direction to that of calcium. Where potassium and magnesium are high, calcium tends to be low, and the tissue more susceptible to storage disorders such as bitter pit and breakdown. However, there do not appear to be any specific storage disorders related directly to these nutrients.

Nitrogen and phosphorous have been shown to affect storage quality directly; low phosphorous and high nitrogen content of the flesh of apple being associated with increased low-temperature breakdown (Tiller *et al.* 1959; Letham 1961, 1969*a,b*; Johnson and Yogaratnam 1978). The results are important in that these authors have demonstrated a direct response, manifest in fruit tissue content, to fertilizer dressings of nitrogen, phosphorus and potassium. This means that the timing and quantity of fertilizer applied, particularly of nitrogen, will be critical in producing a fruit able to withstand low-temperature storage. The physiological causes of breakdown associated with low phosphorus contents are not clear. Letham (1961, 1969*a*) found that low phosphorous resulted in smaller cell size and reduced respiration, and the involvement of phosphorus in membrane lipids would also point to the association of phosphorus with membrane permeability.

The disorders can be arranged according to the nature of the symptom. This is done in Table 3, and the most noticeable feature is that cell collapse and tissue breakdown is predominant; the primary symptoms of most mineral-related disorders are those of physical breakdown. Another feature of the symptoms is that calcium disorders can be divided into discrete tissue breakdown as with bitter pit, and more general breakdown, such as low-temperature, or senescent breakdown. This may reflect what I believe to be a dual effect of calcium in apple tissue. One effect is related to whole-fruit respiration rates, where increased calcium will slow down respiration and associated metabolism. The other effect is a specific one, where localized areas of calcium deficiency may be remedied by calcium application.

Table 1. Disorders related to the calcium content of tissue

| Fruit or vegetable | Disorder |
|---|---|
| Apple | Bitter pit |
| | low-temperature breakdown |
| | Watercore |
| | Cork spot |
| Pear | Cork spot |
| | Black-end |
| Plum | Fruit cracking |
| Cherry | Fruit cracking |
| Mango | Soft nose |
| Tomato | Blossom-end rot |
| Capsicum | Blossom-end rot |
| Celery | Black-heart |
| Brussels sprouts | Internal browning |
| Lettuce | Tip burn |

Table 2. Some mineral deficiencies manifest in fruit tissue

| Fruit | Deficient mineral | Symptom |
|---|---|---|
| Apple | B | Corking |
| Citrus | B | Lumpy rind |
| Apricot | B | Corking |
| Citrus | Cu | Gumming |
| Plum | Mn | Cracking |
| Citrus | P | Coarseness |
| Grape | Mg | Shrivelling |
| Grape | Zn | Distortion |

Table 3. Mineral-related disorders in terms of symptom expression

| Symptom | Disorder | Mineral |
|---|---|---|
| Corking | Cork spot in apples and pears | Ca, B |
| Pitting — discrete cell break-down | Bitter pit and lenticel blotch in apples | Ca |
| General tissue breakdown | Blossom-end rot in tomatoes | Ca |
| | Low-temperature breakdown in apples | Ca, P |

*General quality*

There are a number of general features which have been related to mineral levels in fruit and vegetable tissue. Not all of these are related to storage quality in that many, such as colour, are present at harvest. A few examples are given in Table 4; most have been found by altering the nutrient supplies to the growing fruit.

As in specific disorders, calcium appears to be related to physical parameters such as firmness, rather than to flavour or colour. One of the strongest relationships shown is that between organic acids and potassium. Potassium is the major base in the fruit, the most mobile and abundant cation, and there is a distinct relationship between pH regulation, organic acid levels and potassium content (Tomkins 1954). Fruits such as chinese gooseberry (known locally as kiwi fruit) with high acid levels, also tend to have high mineral ion levels (Heatherbell 1975; Ferguson 1980). It is likely that there is a close relationship between the levels of acids and cationic bases such as potassium throughout the development of the fruit. Fertilizer treatments have also been shown to alter titratable acidity in apple (Letham 1969*a*); acidity increased with the amount of potash fertilizer applied.

**Characterization of mineral content/storage quality relationships**

We can define these relationships at two levels. One is where an explanation is sought for the physiological or biochemical basis of a mineral-related condition, e.g. the search for the effect of calcium on membrane permeability with respect to bitter pit or breakdown; this will not be discussed further. The other has to do with the degree of precision with which a relationship can be identified and described. For example, once calcium was related to bitter pit, a lot of time

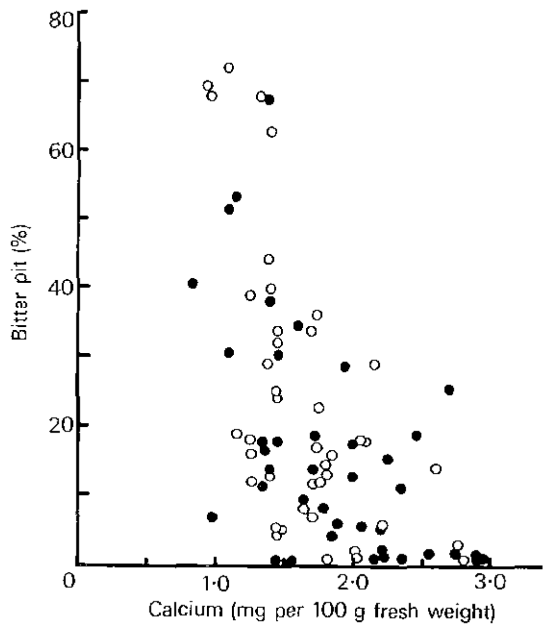


**Fig. 1**. Distribution of bitter pit in relation to calcium content of Cox apple fruit as measured in plugs of cortical tissue. Each point represents a separate orchard or large block in an orchard. o, 1978, ●, 1979.

was spent on determining which tissue analysis would present the best relationship. Thus leaves, whole fruit, fruit peel, fruit flesh, etc. have been analysed with respect to subsequent development of bitter pit (Drake *et al.* 1966; Perring 1968; Turner *et al.* 1977). Results have shown consistently that the calcium content of fruit provides the best fit, and the cortical flesh, where bitter pit develops, has shown to be the best fruit tissue to analyse (Turner *et al.* 1977).

This simple relationship between flesh calcium and bitter pit has formed the basis of a system set up to predict the potential incidence of bitter pit in orchards in New Zealand. The relationship obtained from large numbers of orchards over 2 years, is illustrated in Fig. 1. A feature of the relationship is that it is triangular or wedge-shaped rather than strictly linear, but it is apparent that, generally, low calcium corresponds to high pit and high calcium corresponds to low pit. The region of non-linearity is almost solely occupied by points representing fruit with low calcium levels, but low incidence of pit. This sort of distribution illustrates the problems associated with seeking precision in defining a relationship. To obtain better associations, attempts have been made to involve other nutrients such as potassium or magnesium, or potassium/calcium or other cation ratios (e.g. van der Boon *et al.* 1968; van Lune and van Goor 1979), or to involve non-mineral factors such as fruit weight, where we know that larger fruit are more susceptible to pit and have lower calcium contents (e.g. Martin *et al.* 1975).

But can we expect better relationships to be obtained? In this particular case, probably not unless we pick parameters closer to the causes of the development of the disorder. It is unlikely that this lies in potassium content since that is probably a corollary of the factors governing transport into the fruit. Neither are we likely to be satisfied with fruit weight alone since it reflects only concentration. This season, we are expanding the calcium/bitter pit prediction system to include an index of fruit maturity. Maturity by itself is related to the development of bitter pit (Reid *et al.* 1978), and it is possible that the low calcium/low pit fruit are more mature than others in the same low calcium region of the distribution.

In attempts to relate mineral content to other disorders of economic importance, there is even less precision. With low-temperature breakdown, the calcium and phosphorus relationships have been shown to occur with regard to ameliorating treatments (Bangerth *et al.* 1972; Johnson and Yogaratnam 1978), but a close relationship has been more difficult to define. And despite good evidence for the involvement of calcium and phosphorus, workers in some parts of North America have been unable to define adequately the critical factor in breakdown in McIntosh apples that has appeared in the last 10 years. Because of this lack of precision, the use of critical nutrient levels, or threshold values have been little used in fruit disorders, as compared with use in leaf analysis. The exception is with calcium and bitter pit where agreement is being reached in different countries on the levels of calcium in the flesh below which bitter pit is likely to occur (Perring and Sharples 1975; Turner *et al.* 1977).

**Usefulness of mineral content/storage quality relationships**

Inability to get a perfect straight line should not prevent these relationships from being used. There are at least two commercial systems operating in different countries that use mineral content of apples as a factor in assessing quality and potential quality in cold storage. The differences in approach reflect two ways that analysis can be used: as a factor in overall quality assessment, and as a means of specifically predicting a potential level or risk of disorder.

British workers incorporate mineral levels, particularly those of calcium and potassium, in an assessment of potential storage quality, which also includes firmness, colour, bruising, etc. In addition, they have set levels of potassium, calcium, magnesium, phosphorus and nitrogen which they regard as optimum for long-term storage (Waller 1980). Their recommendations are based on relationships between fruit firmness and nitrogen and phosphorus; breakdown and phosphorus and calcium; bitter pit and calcium, potassium and magnesium; coreflush and potassium. They also include mineral levels that are associated with susceptibility to *Gleosporium* rotting. Waller (1980) has also listed prediction ratings and storage indices based on mineral analysis.

In New Zealand, we have concentrated on calcium and bitter pit, and have instituted a system of calcium analysis of plugs of the apple fruit cortical tissue in order to enable us to offer a prediction of the likely incidence of bitter pit in any one block of trees or orchard (Ferguson *et al.* 1979). We are not attempting to define a one-for-one

Table 4. Mineral content and general fruit quality

| Mineral (high levels) | Effect | Tissue | Reference |
|---|---|---|---|
| Calcium | Increases firmness | Berry fruit | Neal (1965)<br>van Buren and Peck (1963) |
| Potassium | Increases acidity | Berry fruit<br>Grape | Ballinger and Kushman (1969)<br>Abdalla and Sefick (1965) |
| Potassium | Improves colour | Peach | Stembridge *et al.* (1962) |
| Phosphorus | Decreases acidity | Grape<br>Citrus | Abdalla and Sefick (1965)<br>Bar-akiva *et al.* (1968) |
| Phosphorus | Alters colour | Berry fruit<br>Citrus | Eaton (1971)<br>Bar-akiva *et al.* (1968) |

relationship between calcium content and bitter pit incidence in any one orchard, and Fig. 1 shows that such a relationship is not the case. We are more concerned to identify orchards of high risk and low risk, and this can be done with low margins of error. The system now accommodates a large proportion of export Cox's Orange Pippins.

The success of either type of system will depend on a number of criteria. The first, of course, is reliability. There is good agreement in the levels of fruit calcium that can be related to varying degrees of incidence of bitter pit. Whilst this depends on the particular part of the fruit analysed, levels tend to be similar to work in the U.S.A., Holland, U.K. and New Zealand. Also, the levels have been shown to be consistent between districts and in different seasons (Turner *et al.* 1977). We should not expect to have to alter critical levels themselves, but would expect to take other factors such as climate, fruit maturity, etc. into account when assessing the effectiveness of level in any one year. This does not mean that the relation between pit and calcium will alter. An example is in the New Zealand system where the fruit is analysed 3 weeks before commercial harvest. If we find or expect the fruit size to increase dramatically in the intervening 3 weeks, we would expect pit development to be greater than if the fruit size changed only slightly.

Another criterion is simplicity. This may be open to argument, but complex index systems, unless computerized and tending to be all-embracing, probably will not provide more accurate predictive systems — at least not until we have located the critical factors of development of most disorders to a greater extent. Speed is also important, especially if some action is to be taken before harvest or marketing. A further criterion is the standardization of analytical methods, which include tissue sampling.

What can actually be done with data from such systems? We believe that the simple relationship between calcium content of the fruit and the development of bitter pit is sufficient to enable fruit to be treated in storage according to predicted risk. This means that, for example, high risk fruit should be released, perhaps on the home market, after minimum storage time and it should not be allowed to undergo long-term storage, as with our normal export fruit. Post-harvest treatments could also be more selective in that only high risk fruit really need be treated.

The principle of this sort of system should be expanded, as is done in the U.K., to the point where we aim for optimal mineral levels in fruit. This is common in general plant nutrition. Leaf mineral content is used extensively for diagnosis of a deficiency, but as well, levels associated with optimal growth and yield have frequently been established. We should be doing the same for optimal quality — both of fresh and stored produce. This applies particularly to pip-fruit where we now have sufficient information. We should be able to recommend optimal mineral contents for the quality we desire, and then aim our horticultural practices to achieve them.

There are two basic ways of running a system of production and marketing. One is to take the product and construct a system of harvesting, handling and storage to suit the characteristics of the product. The other is to attempt to manipulate the product to the requirements of an often too inflexible handling and marketing system. We usually operate at a point between these two extremes, but I think that currently we are tending far too strongly in the direction of trying to fit the fruit into the system. We tend to harvest fruit, not at the optimum maturity for storage, but perhaps because we aim to get it onto the market before a competitor. We store fruit not so that it should reach a suitable level of quality for the consumer, but so that we can hope that it will survive a long boat trip and then be released according to market requirements.

Some modern horticultural practices could run counter to the requirements of quality. For example, there is evidence that some herbicides may reduce calcium uptake from the soil by the fruit tree (Faust and Korcak 1978), yet the use of herbicide strips is now a widespread practice and its popularity may increase since it appears that less nitrogen fertilizer is required with herbicide strip management (e.g. Atkinson and White 1980). Another example is that a high level of applied nitrogen fertilizer still common in many orchards, will produce fruit more susceptible to low-temperature breakdown (e.g. Tiller *et al.* 1959). The preference of some markets for large fruit also runs counter to efforts to reduce the incidence of bitter pit, which is greater in large fruit.

There must be a limit to the way we can

manipulate fruit. Rather than multiply the variety and extent of post-harvest treatments, we should be working towards producing and selecting the best fruit, i.e. fruit that requires a minimum of post-harvest treatments. But how often does storage quality play an important role in the selection and breeding of new varieties of fruits? There is a danger that the ready acceptance of short-term treatments, which are seen as panaceas for particular problems, will diminish the importance of producing good quality fruit in the first place. One example is that the increasing use of post-harvest treatments for bitter pit control is tending to take the emphasis away from the grower producing the best fruit by his horticultural practices, which includes calcium spraying. This is where the value of using the relationship between mineral content and storage quality becomes most apparent. We now have a means of assessing, at the time of harvest, the potential quality of fruit destined for storage.

### References


Abdalla, D. A., and Sefick, H. J. (1965). Influence of nitrogen, phosphorus, and potassium levels on yield, petiole nutrient composition and juice quality of newly established Concord grapes in South Carolina. *Proc. Am. Soc. Hortic. Sci.* **87**, 253–8.

Atkinson, D., and White, G. C. (1980). Some effects of orchard soil management on the mineral nutrition of apple trees. *In* 'Proc. the conf. Min. Nutr. and Fruit Quality of Temperate Zone Fruit Trees'. (Canterbury: U.K.) (In Press).

Ballinger, W. E., and Kushman, L. T. (1969). Relationship of nutrition and fruit quality of Wolscott blueberries grown in sand culture. *J. Am. Soc. Hortic. Sci.* **94**, 329–35.

Bangerth, F., Dilley, D. R., and Dewey, D. H. (1972). Effect of postharvest calcium treatments on internal breakdown and respiration of apple fruits. *J. Am. Soc. Hortic. Sci.* **97**, 679–82.

Bar-akiva, A., Hiller, V., and Patt, J. (1968). Effect of phosphorus and chicken manure on yield, fruit quality and leaf composition of grapefruit trees. *Proc. Am. Soc. Hortic. Sci.* **93**, 145–52.

Bollard, E. G. (1970). The physiology and nutrition of developing fruits. *In* 'The Biochemistry of Fruits and their Products', vol. 1, ed A. C. Hulme, pp. 387–425. (Academic Press: London and New York.)

Boon, J. van der, Das, A., and Schreven, A. C. van (1968). Control of bitter pit and breakdown by calcium in the apples Cox's Orange Pippin and Jonathan. *Agricultural Research Report* 711, (Centre Agric. Publ. and Docum.: Wageningen.)

Bramlage, W. J., Drake, M., and Baker, J. H. (1974). Relationships of calcium content to respiration and postharvest condition of apples. *J. Am. Soc. Hortic. Sci.* **99**, 376–8.

Buren, J. P. van, and Peck, N. H. (1963). Effect of calcium level in nutrient solution on the quality of snap bean pods. *Proc. Am. Soc. Hortic. Sci.* **82**, 316–21.

Drake, M., Weeks, W. D., Baker, J. H., Fields, D. L., and Olanyk, G. W. (1966). Bitter pit as related to calcium level in Baldwin apple fruit and leaves. *Proc. Am. Soc. Hortic. Sci.* **89**, 23–9.

Eaton, G. W. (1971). Effect of N, P and K fertilizer applications on cranberry leaf nutrient composition, fruit colour and yield in a mature bog. *J. Am. Soc. Hortic. Sci.* **96**, 430–3.

Faust, M., and Korcak, R. (1978). Effect of herbicides on calcium uptake by apple seedlings. *In* 'Plant Nutrition 1978'. Proc. 8th Int. Colloq. on Plant Analysis and Fertilizer Problems, pp. 123–30. Eds A. R. Ferguson, R. L. Bieleski, I. B. Ferguson. DSIR Information Ser. No. 134, Wellington. 123–130.

Faust, M., and Shear, C. B. (1972). The effect of calcium on respiration of apples. *J. Am. Soc. Hortic. Sci.* **97**, 437–9.

calcium and potassium. *N.Z. J. Agric. Res.* **12**, 642–9.

Lune, P. van, and Goor, B. J. van (1979). Extractability of calcium from apple fruit and apple leaf tissue and the occurrence of bitter pit. *J. Hortic. Sci.* **54**, 327–31.

Martin, D., Lewis, T. L., Cerny, J., and Ratkowsky, D. A. (1975). The predominant role of calcium as an indicator in storage disorders in Cleopatra apples. *J. Hortic. Sci.* **50**, 447–55.

Neal, G. E. (1965). Changes in the cell walls of strawberries during ripening. *J. Sci. Food Agric.* **16**, 604–11.

Perring, M. A. (1968). Mineral composition of apples. VII. The relationship between fruit composition and some storage disorders. *J. Sci. Food Agric.* **19**, 186–92.

Perring, M. A., and Sharples, R. O. (1975). The mineral composition of apples. Composition in relation to disorders of fruit imported from the Southern Hemisphere. *J. Sci. Food Agric.* **26**, 681–9.

Reid, M. S., Ferguson, I. B., and Bateup, C. B. (1978). Progress in the fight against bitter pit. *Orchardist N.Z.* **51**, 299–302.

Rizzotto, N. (1977). Untersuchungensergebnisse über die Bekampfung der Sticllähme. *Mitt. Hoeheren Bundeslehr-Versuchsanst. Wein-Obstbau, Klosterneuberg* **27**, 187–90.

Schimansky, C. (1977). Orientierande Untersuchungen über den Transport von Magnesium, Calcium and Kalium in die Fruchtstande von Rebpflanzen nach Kurzzeitapplikation von $^{28}$Mg, $^{45}$Ca und $^{86}$Rb. *Mitt. Hoeheren Bundeslehr-Versuchsanst. Wein-Obstbau, Klosterneuberg* **27**, 181–4.

Shear, C. B. (1975). Calcium-related disorders of fruits and vegetables. *Hortscience* **10**, 361–5.

Stembridge, G. E., Gambell, C. E., Sefick, H. J., and van Blaricon, L. O. (1962). The effect of high rates of nitrogen and potassium on the yield, quality and foliar mineral composition of Dixigem peaches in the South Carolina sandhills. *Proc. Am. Soc. Hortic. Sci.* **81**, 153–61.

Tiller, L. W., Roberts, H. S., and Bollard, E. G. (1959). The Appleby experiments. N.Z. DSIR Bull. No. 129. (Wellington, New Zealand.)

Tingwa, P. O., and Young, R. E. (1974). The effect of calcium on the ripening of avocado (*Persea americana* Mill.) fruits. *J. Am. Soc. Hortic. Sci.* **99**, 540–2.

Tomkins, R. G. (1954). Unsolved problems in the preservation of food. The influence of cultural conditions on the quality and preservation of fruits and vegetables. *J. Sci. Food Agric.* **5**, 161–7.

Turner, N. A., Ferguson, I. B., and Sharples, R. O. (1977). Sampling and analysis for determining relationship of calcium concentration to bitter pit in apple fruit. *N.Z. J. Agric. Res.* **20**, 525–32.

Waller, W. M. (1980). The use of apple analysis. *In* 'Proc. Conf. on Min. Nutr. and Fruit Quality of Temperate Zone Fruit Trees'. (Canterbury: U.K.) (In Press).

Wills, R. B. H., and Tirmazi, S. I. H. (1979). Effect of calcium and other minerals on ripening of tomatoes. *Aust. J. Plant Physiol.* 6, 221–7.
Ferguson, I. B. (1980). Movement of mineral nutrients into the developing fruit of the kiwifruit (*Actinidia chinensis* Planch.). *N.Z. J. Agric. Res.* (In Press.)
Ferguson, I. B., Reid, M. S., and Prasad, M. (1979). Calcium analysis and the prediction of bitter pit in apple fruit. *N.Z. J. Agric. Res.* 22, 485–90.
Heatherbell, D. A. (1975). Identification and quantitative analysis of sugars and non-volatile organic acids in Chinese gooseberry fruit (*Actinidia chinensis* Planch.). *J. Sci. Food Agric.* 26, 815–20.
Jackson, D. I. (1962). The effects of calcium and other minerals on incidence of bitter pit in Cox's Orange apples. *N.Z. J. Agric. Res.* 5, 302–9.
Johnson, D. S., and Yogaratnam, N. (1978). The effects of phosphorus sprays on the mineral composition and storage quality of Cox's Orange Pippin apples. *J. Hortic. Sci.* 53, 171–8.
Letham, D. S. (1961). Influence of fertilizer treatment on apple fruit composition and physiology. I. Influence on cell size and cell number. *Aust. J. Agric. Res.* 12, 600–11.
Letham, D. S. (1969*a*). Influence of fertilizer treatment on apple fruit composition and physiology. II. Influence on respiration rate and contents of nitrogen, phosphorus, and titratable acidity. *Aust. J. Agric. Res.* 20, 1073–85.
Letham, D. S. (1969*b*). Influence of fertilizer treatment on apple fruit composition and physiology. III. Influence on contents of phosphorus, magnesium,

**Refrigeration of fruits and vegetables**

# Market quality and condition — a cold appraisal

By E. G. Hall*

Consultant in Postharvest Horticulture

This symposium commemorates the first successful shipment of frozen meat from Australia to England 100 years ago in the S.S. '*Strathleven*'. Refrigeration of fruit has a history almost as long. The first shipment of apples to the United Kingdom under refrigeration was from Melbourne in 1888 and such shipments were well-established by the turn of the century. In 1891 the Victorian Department of Agriculture opened the first government cool stores in Melbourne, where butter and meat were frozen for export and local storage, and fruit was accepted for local storage. This was the beginning of cool storage of fruit in Australia (Tindale 1964).

We should remember those far-sighted and tenacious people and companies who, often against apathy or active opposition, pioneered fruit and vegetable cool storage and export in this country. In New South Wales there were the N.S.W. Fresh Food Cold Storage Co., which was in business well before 1900, the Batlow Packing House Co-op., especially under H. V. Smith, the Sydney Municipal Cool Stores under W. J. Williams, the Producers' Co-op. Distributing Society, which started cool storage of apples in Kentucky in 1925, and Walter Barrett in Orange. More recently, Alfred Nugan of Griffith was an innovative pioneer of precooling and quality control of produce for the local market.

In Victoria, the Department of Agriculture built and operated five cool stores for fruit in the fruit-growing districts around Melbourne during the period 1905–1914. These later became the first of the grower-owned co-operative cool stores in Victoria. Among the fruit-growing families who pioneered orchard cool stores the Lawford, Thiele, Petty and Tully families deserve special mention.

In Tasmania the first fruit cool stores were primarily for precooling apples and pears for export. Early operators were Tasmanian Orchardists and Producers, Huonville Cool Stores and Moonah Cool Stores before 1920, and Bender & Co. and Port Huon Growers a little later.

*Formerly, Leader, Fruit and Vegetable Storage Section, Division of Food Research, CSIRO.

In South Australia, as in Victoria, the pioneering initiative was taken by the State Government. The Government Produce Department opened a cool store for fruit in 1909. In the early 1920s growers' co-operative cool stores were established in the fruit-growing areas in the Adelaide Hills, the first being at Gumeracha and Balhannah in 1922.

In Western Australia pride of place must go to H. J. Price of Illawarra Orchards who had a fruit cool store operating in 1913 and remained an innovator all his life. Mt Barker Co-op. started cool storage of apples in 1917, Simper Pty Ltd in 1918, and W.A. Meat Export Works in Fremantle in 1921.

In Queensland there were two worthy pioneers, the apple growers Archibald at Pozieres and Barlow at Applethorpe; their early experiments with 'gas storage' deserve special mention.

Australia also has a long history of fruit cool storage research; pioneering researchers in Departments of Agriculture were Pittman, Elliott and Carne in Western Australia, Carne and Martin in Tasmania, and Empey, soon followed by Tindale of the Victorian Department of Agriculture, and Trout and Huelin of the CSIR working together in Melbourne.

The aim of this paper is to make a plea for better quality control for perishable produce after harvest through active quality control programs. In the title I have used the two terms 'quality' and 'condition', although, for most people, the term quality is all embracing and includes condition factors. Basic quality is largely inherent, being determined during the growth of the crop and by its time of harvest. Condition covers wilting, aging, ripeness, handling damage and postharvest disease and is a function of care after harvest. Quality control after harvest is essentially control of the environment, primarily temperature, and the time factor. The knowledge upon which quality maintenance is based is not new – it goes back to the early days of postharvest horticulture – but it is still not generally appreciated and application is widely lacking.

### What is quality?

The answer to the question, 'what is good quality in fruit and vegetables?' will differ with different kinds of produce, with the position of the recipient in the marketing chain, and especially with the particular end use. Quality is still largely a subjective judgment and perhaps can usefully be defined as that combination of characteristics and properties that gives the commodity value for its desired end use. Thus the term 'quality' may be qualified in various ways so that we have market quality, storage quality, shipping quality, consumer quality, nutritional quality and processing quality.

Quality maintenance is therefore concerned with the condition factors which change with time after harvest. For particular produce, the rate, and often the nature, of the changes depend on the environment, of which the most important component is the temperature.

*External appearance*

The first assessment of quality is generally made on the basis of external appearance. This is a rapid and non-destructive assessment, but is not always indicative of internal quality. Nevertheless, in marketing, appearance is most important, as consumers 'buy with their eyes'; indeed, that is usually all they can do. With experience it is possible by inspection to make reasonably reliable judgments about internal and end-use quality, based on generally consistent relationships with visible characteristics. Factors affecting external appearance are size, shape, colour, freshness (wilting), cleanliness, mechanical damage, and the presence of pests or disease.

*Internal condition*

Important quality factors which the consumer, consciously or unconsciously, tries to assess when buying are eating quality and keeping quality. Eating quality is concerned with the amount of the edible portion (as affected by skin thickness, juice content, and presence of damage or disease), flavour, texture, and nutritional value, although I doubt if the last is seriously considered by most consumers. Keeping quality is important all along the marketing chain. Shelf-life is particularly important to both the retailer and the consumer – 'how long will it keep when I get it home?' is often a major question.

*Price*

Finally there is a mental calculation of cost benefit. What is the best value for money – lower quality at a lower price or higher quality at a higher price? This is often a difficult decision as selling price is often based on size and appearance which may not reflect either eating quality or keeping quality. For many kinds of fruit, fruit of intermediate size is usually better for both eating and keeping than fruit of large size, this is particularly true of apples.

### Quality control

Losses of produce, both by direct destruction and by deterioration of quality and condition, continue to be high in the marketing of fruit and vegetables in Australia, especially in hot weather.

Variable quality of produce received by retailers is a major cause of marketing losses. There is therefore a need for both wholesalers and retailers to recognize market quality defects and their relation to marketing losses. Training programs followed by effective quality control programs by individual operators will reduce these losses. It is time that all Chambers of Fruit and Vegetable Industries took the initiative in organizing training of operators.

Quality control involves two functions. The first is selection of the produce, which is concerned with suitability for the particular market and shipping conditions, considering grade standards and minimum market quality, with maturity always being a major factor. The second is quality maintenance. This requires effective use of available procedures to ensure that quality is maintained throughout the marketing chain. The main benefit will be from minimizing the *time x temperature* factor to give fresh produce a quick and cool journey from the farm gate to the table.

Postharvest quality control starts at harvest; all produce should be protected from heating and brought to the packing house without delay. In the packing house, maturity and condition must be assessed to determine suitable market outlets, or, better still, this selection should be made at or before harvest. Packing house procedures and special treatments must be regularly checked to ensure proper operation and to avoid delays and injury to the produce.

Control of the temperature of the produce is the most important factor in quality control after harvest. It is essential to measure the temperature of the produce at key points in the packing house and throughout the marketing chain. Adequate records of temperatures and times must be kept not only to know what is happening to the produce but also why it is happening.

### Maturity

An understanding of maturity is essential for the successful distribution of fresh fruits and vegetables. It is important to the shipper as it affects many marketing decisions, and it is similarly important to the wholesaler and retailer. It is important to the consumer as it affects eating quality and shelf-life. Reliable determination of maturity is necessary to enable the provision of optimum protective services for the maintenance of quality and condition after harvest.

Maturity indices and maturity standards are needed: to be reliable they must be consistent and practical; to be effective they must be readily understood and uniformly applied. The search for satisfactory maturity indices has been a long one and has not been particularly successful. More research and a lot more application are needed in this difficult area in order to add to the few standards so far usefully in operation.

### Careful handling

In any quality control program the importance of careful handling and safe, non-pressure, packaging must be emphasized to keep mechanical damage to a low level. The effects of mechanical injury in direct loss, more rapid respiration, ripening and aging, and increased decay are well-known, yet avoidable losses by rough, careless handling are still everywhere to be seen.

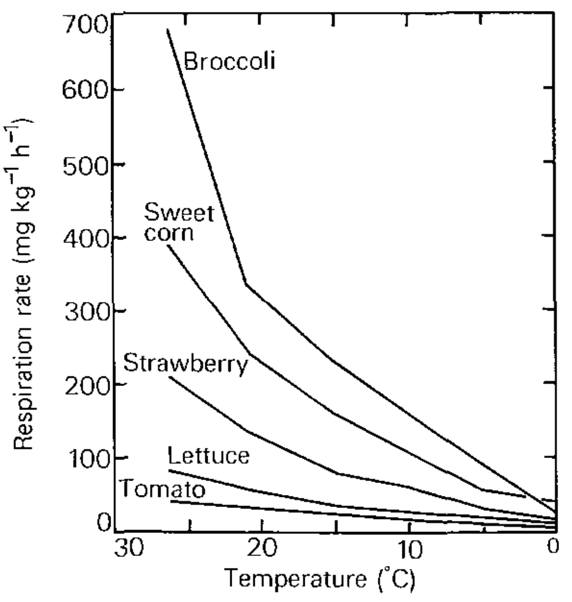


**Fig. 1.** Effects of reduction in temperature on rate of respiration.

The 'why' and 'how' of careful handling must be an important part of operator training.

### Temperature

Despite advances in the knowledge and application of control of the composition of the atmosphere, control of temperature is still the most effective means for quality control after harvest. Lowering the temperature is the most direct and simplest way to retard respiration, ripening and other aging changes in perishable produce (Fig. 1). In the range of temperatures usually experienced, a rise of temperature of 10 deg. C will increase the rate of aging 2–3 times for most kinds of produce. The adverse effect of warming will be greatest for perishable items like sweet corn, green peas, broccoli and strawberries (Fig. 2). For instance, a delay of 2 h under warm conditions between harvesting and cooling could reduce subsequent life by a whole day; it follows that the gains from cooling them are correspondingly great. Temperature has a marked effect on the loss of sugar from sweet corn (Fig. 3) and green peas.

Cooling is a most effective means of controlling rotting after harvest and, furthermore, there is no problem with chemical residues as there may be when fungicides are used. Rot-producing pathogens grow best and most rapidly at temperatures of about 25 °C, but only slowly or not at all at low temperatures. The common green mould will produce a rot in oranges in 3 days at 25 °C, but at 0 °C more than 60 days, and at 5 °C about 25 days are required (Fig. 4).

Ripening must also be considered, especially with fruits like bananas, pears and tomatoes which are harvested unripe. All fruits ripen, ripening is an aging process and its understanding is as important as an understanding of maturity. Most fruits ripen best at a temperature of about 20 °C but there is a considerable range at which different fruits will ripen satisfactorily. Unless fruit is ripened at a suitable temperature, its quality will be poor and it will be unacceptable to the consumer. The ripening of bananas, tomatoes and Williams pears is very sensitive to temperature; bananas for instance will ripen well only within the very narrow range from 18° to 23 °C and Williams pears and tomatoes ripen poorly at temperatures above 30 °C and below 15 °C.

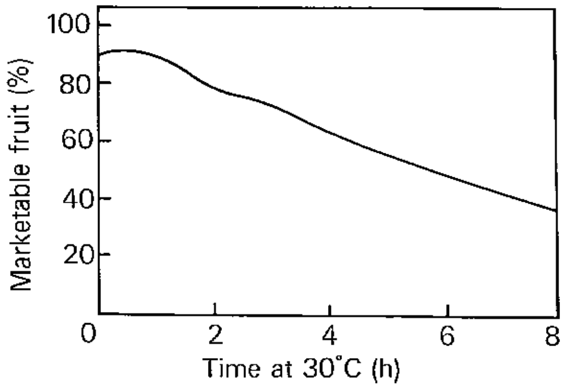


**Fig. 2.** Effect of delay before cooling on quality of Shasta strawberry. (After Mitchell *et al.* 1972.)

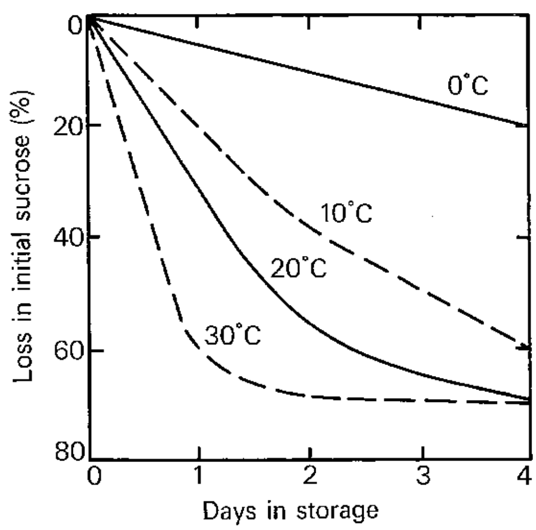


**Fig. 3.** Depletion of sucrose in sweet corn stored at four temperatures. (Adapted from Appleman and Arthur 1919.)

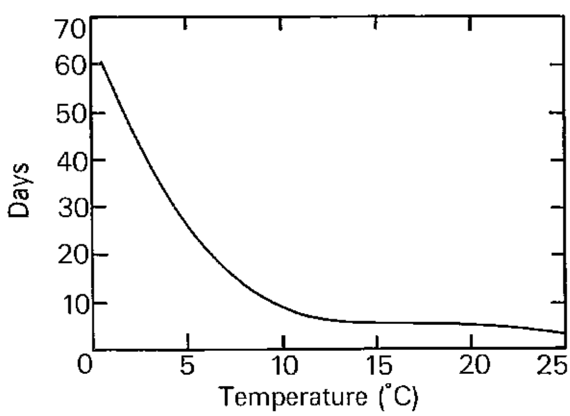


**Fig. 4.** Effect of temperature on the development of green mould in oranges.

Control of ripening temperatures is therefore necessary.

As fruits and vegetables are alive, exposure to extremes of temperature can be very damaging. Because of their high water content they will freeze at temperatures in the range $-2°$ to $-0.5°C$. Moreover, many fruits and vegetables are injured by exposure to cold at temperatures well above their freezing points. The extent of injury depends on the actual temperature, the duration of exposure, and the physiological condition of the produce, maturity being an important factor with fruits. Tropical fruits, tomatoes and cucurbits are particularly sensitive to cold, and in general, exposure to temperatures below $10°C$ should be avoided, except in some instances for initial quick cooling of warm fruit.

During ripening, increased quantities of the physiological gas, ethylene, are produced. As well as playing a key role in stimulating ripening, ethylene accelerates other aging processes such as yellowing of leaves. Climacteric type fruits like apples, pears, stone fruits, tomatoes and avocados produce much more ethylene than non-climacteric fruits like citrus and pineapples. It may therefore be damaging to green vegetables or other fruits in which ripening is *not* wanted (e.g. cucumbers) to be in the same space with ethylene-producing kinds during transport or storage, particularly at higher temperatures. In this respect, apples and passionfruit are especially dangerous because of their very high rates of ethylene production. Such mixed loads should therefore be avoided unless they are to be very well refrigerated and the duration of transport or storage will be short.

**Water loss**

A major factor in loss of quality after harvest is water loss and consequent wilting with loss of 'freshness'. Water loss is also loss of saleable weight and often the main cause of significant loss of profit. The rate of evaporation of water from produce depends primarily on the difference in water vapour pressure between the produce and its surroundings and on the surface/volume ratio of the produce. Leafy vegetables and beans therefore wilt very much faster than round fruits. Relative humidity may be very misleading as a guide to water loss because the drying power of the storage atmosphere depends on the difference between the actual vapour pressure and the saturation vapour pressure; this vapour pressure deficit rises rapidly with increasing temperature, for a given amount of water vapour in the air. Thus at the same relative humidity, perishable produce (in which the air spaces are nearly saturated) will wilt much more rapidly at higher than at lower temperatures. Therefore a major advantage of rapid cooling is reduced water loss.

**Temperature management**

The actual temperature of the product is the most important factor in the successful marketing of perishable produce. Thus 'temperature management is the most important, the most readily available process for controlling the postharvest environment, and proper temperature management is vital throughout distribution' (Kasmire and Mitchell 1978). What does temperature management involve? It starts as soon as the produce is harvested and involves monitoring and controlling produce temperatures throughout the marketing chain.

Whether special cooling is necessary will depend on the kind of produce, the ambient temperatures and the duration of transport and marketing. In warm weather, cooling of very perishable items is a must and most fruits and vegetables will benefit and sell better. Last year, a prominent Queensland grower, who has recently built a cool store and cooling facilities, said that because of the much better retention of quality in precooled broccoli, it will soon be difficult to sell broccoli at any price on the Brisbane market if it has not been properly cooled.

While slow cooling in a cool room is satisfactory for less perishable lines, more perishable kinds require faster cooling. For these, forced air cooling is generally best, particularly if the air is nearly saturated with water vapour. Such a system is almost essential to prevent wilting during cooling of produce with a high surface/volume ratio which therefore loses moisture rapidly, e.g. broccoli, lettuce, green beans, strawberries and cut flowers, and one is operating successfully at Brisbane Markets (Anon. 1979).

Cool storage rooms are an essential part of any cooling facility so that promptly cooled produce can be held at optimum temperatures before marketing. A cool store also provides for the holding of produce for short periods in times of over-supply, or to take advantage of anticipated undersupply.

It is commonly believed that precooling *without continued refrigeration is worse than* no cooling at all. This is not necessarily so; many tests have shown that the amount of deterioration is a function of total time × temperature, i.e. total degree-days.

However, 'sweating' can be a problem. Moisture condensing on the surface of cold produce unloaded from a cool store or transport vehicle into a warm, humid environment is difficult to remove. Its continued presence then provides ideal conditions for the development of decay, once the produce has warmed up. If the 'sweating' is likely to occur, the consignment should be open-stacked to hasten warming, both to reduce the amount of condensation and to facilitate its evaporation.

Unless warming is necessary for ripening, precooled produce should be kept cool. For short journeys, close stowage under cover may suffice; for intermediate journeys close stowage in an insulated vehicle is often satisfactory, but for long journeys proper stowage in a vehicle both insulated and refrigerated is necessary. In the wholesale market, produce can usually be sold quickly, but if not, it should be held under refrigeration. Precooled, very perishable, high value lines should be kept under refrigeration at all times. As the benefits of refrigeration and continued temperature management are being more widely appreciated, more and more wholesalers are installing cool rooms.

For the full benefit to be realized, quality *maintenance by temperature control must* be continued through retailing. The ideal facility for retailing is a cool store from which refrigerated display cabinets are kept stocked with the more perishable produce, but *excluding the very chilling-sensitive kinds* such as bananas. To minimize risk of chilling injury, to reduce 'sweating', and to minimize moisture loss, the cool room should be run at a temperature of 5 °C and a relative humidity of 95%. For this to be possible the room and its refrigeration must be correctly designed. Other measures to improve quality maintenance at the retail level are:

- ▶ Do not overload the cool room; load the produce so as to leave air paths around, under, and through the stack to permit effective cooling.
- ▶ Do avoid the other common fault of over-storage; turn over the stock quickly; especially do not hold very perishable, short-keeping, lines more than 3–4 days (Hall 1973).
- ▶ Do not overload refrigerated display cabinets and maintain a daily turnover of stock in them.
- ▶ Prepack as much as possible; although costly, consumer prepackaging can be economic since it does improve quality maintenance, mainly by reducing handling damage and moisture loss.

**Long cool storage**

Long cool storage is an essential part of the marketing of apples and pears and is extending to other seasonal crops. Cool-store management has an important place in *quality maintenance. Initial cooling must* be rapid, and required temperatures, and gas concentrations in C.A. storage, must be kept as constant as possible.

After initial cooling, variations in air temperatures in different positions in the stack should not exceed 1 °C above or below the nominal temperature, and in any one position variations with time should not exceed 0.5 °C. Uniform conditions can only be achieved if the cool store has been properly designed with adequate insulation and an efficient vapour barrier on the warm side, adequate surface in the cooling equipment, adequate air circulation and efficient air distribution, and if it has been carefully constructed. Here too the common fault of over-storage must be avoided; apples and pears in poor condition because they have been kept too long in cool store are all too common on the market.

In conclusion, I quote a major fruit and vegetable handler and packer who recently said that refrigeration adds 15 to 20% to the market value of perishable produce and 'you should take one-third of that increase in profit'.

It was very pleasing to hear the General Manager of C.O.D. say last year that there is almost an explosion of interest in refrigeration by fruit and vegetable growers and marketers. The industry must aim for a continuous, properly managed 'cold chain' for perishable produce.

**References**

Anon. (1979). Forced air cooling — Brisbane Markets plant. *Queensl. Fruit and Veg. News*, 3 May, 1979.

Appleman, C. O., and Arthur, J. M. (1919). Carbohydrate metabolism in sweet corn. *J. Agric. Res.* 17, 137–52.

Hall, E. G. (1973). Mixed storage of foodstuffs. CSIRO Div. Food Res. Circ. No. 9.

Kasmire, R. F., and Mitchell, F. G. (1978). *In* Perishables Handling, Issue No. 39. Univ. Calif. Co-op. Extn. (Roneo.)

Mitchell, F. G., Guillou, R., and Parsons, R. A. (1972). Commercial cooling of fruits and vegetables. Univ. Calif. Manual No. 43.

Tindale, G. B. (1964). Apple and pear cool storage in Victoria, Part 1. *J. Agric. Vic.* 62, 163–178.

#### Further Reading

Am. Soc. Hortic. Sci. (1978). Relative Humidity — Physical Realities and Horticultural Implications. Spec. insert in *HortScience* 13 (5).

The Commercial Storage of Fruits, Vegetables, Florists and Nursery Stocks. USDA Handbk No. 66, rev. 1977.

Perishables Handling, issue No. 39, Mar. 1978, Univ. Calif. Co-op. Extn.

Recommendations for Chilled Storage of Perishable Produce. (Int. Inst. Refrig.: Paris, 1979.)

Ryall, A. L., and Lipton, W. J. (1972). 'Handling, Transportation and Storage of Fruits and Vegetables. Vol. 1. Vegetables and Melons'. (Avi Publ. Co.: Westport, Conn., U.S.A.)

Ryall, A. L., and Pentzer, W. T. (1974). 'Handling, Transportation and Storage of Fruits and Vegetables and Melons'. (Avi Publ. Co.: Westport, Conn., U.S.A.)

Ryall, A. L., and Pentzer, W. T. (1974). 'Handling, Transportation and Storage of Fruits and Vegetables. Vol. 2. Fruits'. (Avi Publ. Co.: Westport, Conn., U.S.A.)


### Transport and storage of refrigerated foods

# Refrigerated sea transport — recent and future trends


By G. R. Scrine

Shipowners' Refrigerated Cargo Research Association, U.K.


#### Introduction

The end of the 1960s saw a tremendous transition in the services from Australasia to Japan, Europe and the U.S.A., a revolution which, although foreseen and inevitable, was perhaps similar to the pre-war changes in refrigerated ship design when the forced-air cooler came into general use.

#### Conventional refrigerated ships

First of all, for a trade which was traditionally served by refrigerated liner services, one of the more dramatic changes over the past decade has been the demise of the refrigerated cargo liner. This has been supplemented by the omnibus carrier — the tramp reefer which is able to carry refrigerated cargoes in the temperature range from +20° to −30°C and has a refrigeration capacity to cool bananas from +30° to +12°C in a matter of 36 h.

The locker of about 200–300 m³ has disappeared to be replaced by large open 'tween decks, admirable for loading with large quantities of bananas, citrus fruit and deciduous fruit, but which are rather difficult to manage in trades requiring something less than a full deck of one particular cargo. Hence compromise has to be reached with mixed cargoes if the ship is to operate economically.

Some features that have had a considerable effect on the design of the conventional refrigerated ship are rate of air circulation, fresh air ventilation, and palletization.

One should look firstly at the possible reasons for particular rates of air circulation. These are:

- cooling of cargo within a given time scale;
- distribution of air within the cargo space; and
- minimizing temperature gradients within the cargo.

Over the past 40 years air circulation rates in ships and their refrigeration capacity have increased dramatically. Fig. 1 gives some

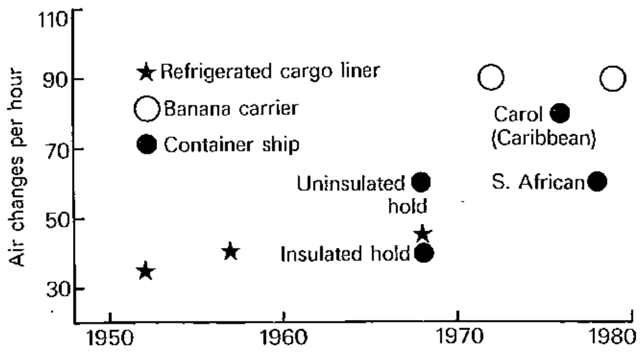


**Fig. 1**. Typical figures for air circulation in various types of ship.

typical values for various types of ships including some of the modern container vessels.

With the increasing cost of energy and the present lack of a viable alternative to the vapour compression cycle it is doubtful whether an increase in or a continuation of high air volume is justified for the majority of cargoes. Given that the banana has dominated design requirements for so long, one may ask that attention be given to more rapid means of cooling for a given rate of air circulation, i.e. fewer short circuits. Also, that some means of reducing the metabolic activity of fruit be given priority (see below).

Nevertheless, there has been some standardization in the design of cargo space for this type of ship. Thus most utilize the Stal ductless sytem with perforated floor gratings. This arrangement gives a reasonable distribution of air provided sufficient space is left between the deckhead and the top of the cargo. The squaring-off of cargo spaces to accommodate pallets without leaving short circuits has also been implemented, albeit with some loss of cubic capacity.

It is perhaps of interest to look at the carrying capacity of the refrigerated cargo ship, in particular those that have been built for the banana/charter trade. There has been a consistent demand for ships in excess of 10 000 $m^3$ throughout the past decade, and within the past 7 years the ships exceeding 17 000 $m^3$ have been much in evidence. Fig. 2 illustrates individual ships or types that have been built in recent years.

The demand for service speeds above 22 knots has showed no signs of abating and even the latest vessels built for a well-known European shipowner are also capable of this speed.

*Palletizing*

One other significant change in recent years has been the growing acceptance of palletized perishable cargo; two ships specially built for palletized frozen lamb several years ago have become very successful in the fruit trades from the Middle East, and the modern reefer ship is likely to have carriage of palletized cargoes as a primary design requirement.

Although not all cargoes are palletized, loading and discharging rates of pallet ships are high.

*Automation*

It is, however, in the field of automation that continuing progress has been and continues to be made, though one of the first computer-controlled refrigeration plants was that on the M.V. *Chrysantema* which came into service in 1973.

The potential for full automation has been apparent for many years and from a technological point of view there would appear to be few obstacles. One major problem is the defrosting of air coolers which is labour intensive. The majority of refrigerated cargo ships and container ships have air-circulating systems cooled with brine. It is usual to have at least three brine temperatures available, one for frozen cargo, one for chilled cargo, and one high temperature line for thawing.

Technically, it is not difficult to automate the defrosting process, but some changes in operational procedures may well be required. The advent of the microprocessor, whilst not a universal panacea, could well be the basis of a surveillance and control system to

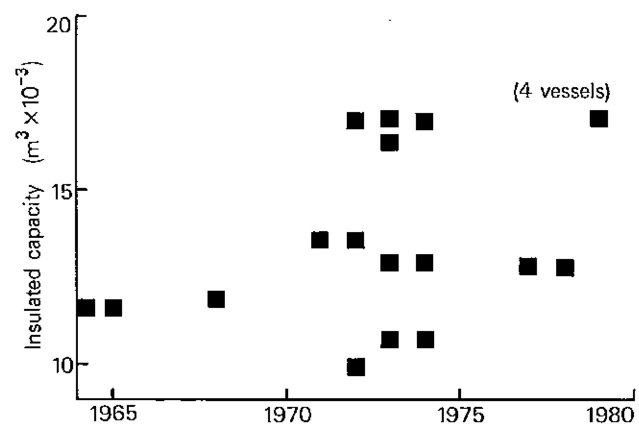


**Fig. 2.** Insulated capacity of refrigerated cargo vessel in tramp reefer operations.

automate this process. Needless to say, a large number of remotely controlled valves will cost considerably more than a manual system.

One other aspect which could never be automated is acceptance of cargo, particularly for the refrigerated cargo ship. Whilst it is still the responsibility of the Master to accept cargo, there is always a need for someone with special knowledge or skills, usually based on experience, to accept or reject perishable cargo.

**Containers and container ships**

The radical changes that took place in 1969/70 on the Australian service have so far lasted for a decade, and there have been some impressive changes in the size of container ship during this period, if not in the method of carrying cargo (see Figs 3 and 4).

Without delving too deeply into the history of containers for the Australia-Europe service, there was inevitably some discussion concerning the choice between the integral container, which in the early 1960s did not perhaps have 100% reliability, and the porthole container. The latter, being coupled to a largely conventional ship's refrigeration system, could be assured of 100% reliability at sea but required rather extensive terminal systems and a well-organized delivery service, if the standards of carriage at sea were not to be lost on land.

Both systems have found a place in the transport field and the greater carrying capacity of the porthole container may win the day, although increasing reliability of mechanical systems, together with a more sophisticated level of control, make the integral container a formidable competitor. The depth of the refrigerated unit has slowly been reduced and the size of the compressor is probably the limiting factor. This trend could give some impetus to smaller compressors running on R502.

The more obvious changes in the porthole container have been seen in the new service between South Africa and Europe, for example:

- An increase in external height from 8 ft to 8 ft 6 in.
- Two types of container: one principally for frozen break bulk cargo such as meat and

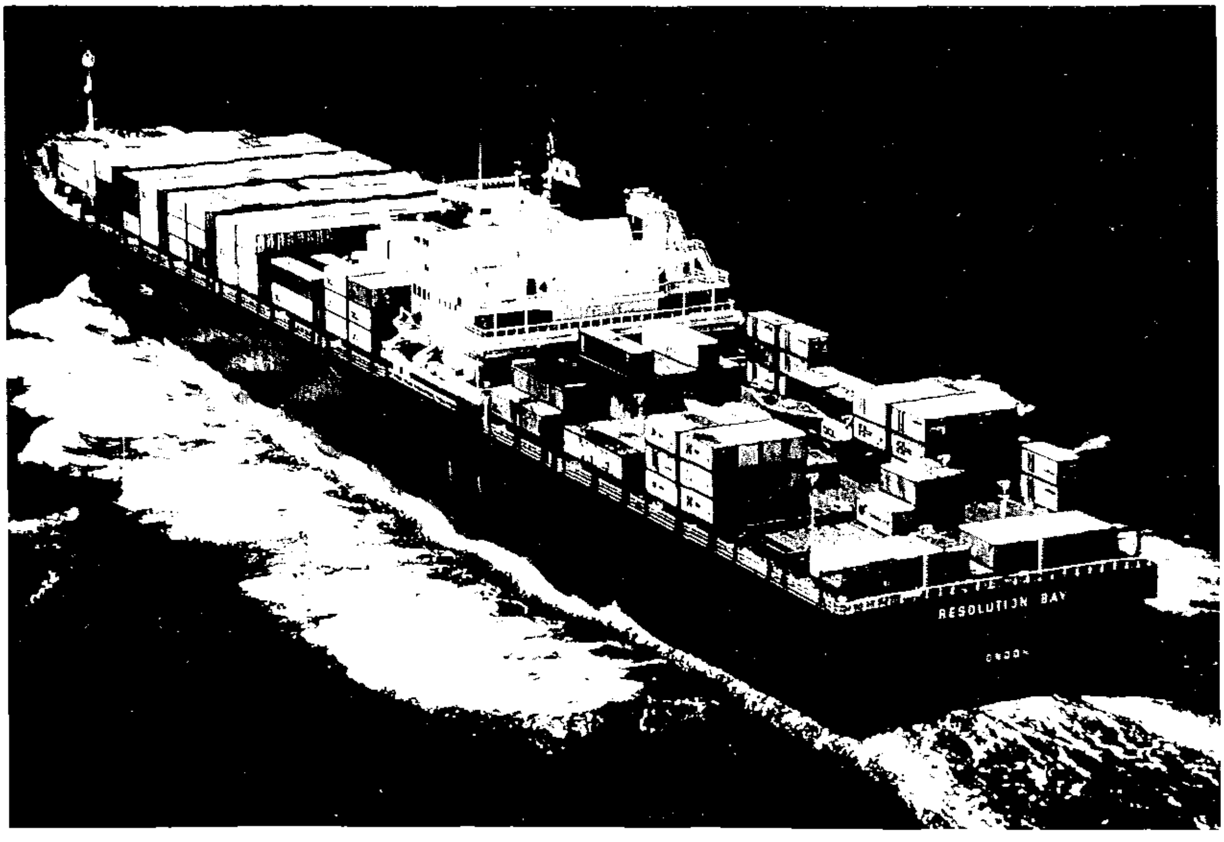


**Fig. 3.** M. V. *Resolution Bay.*

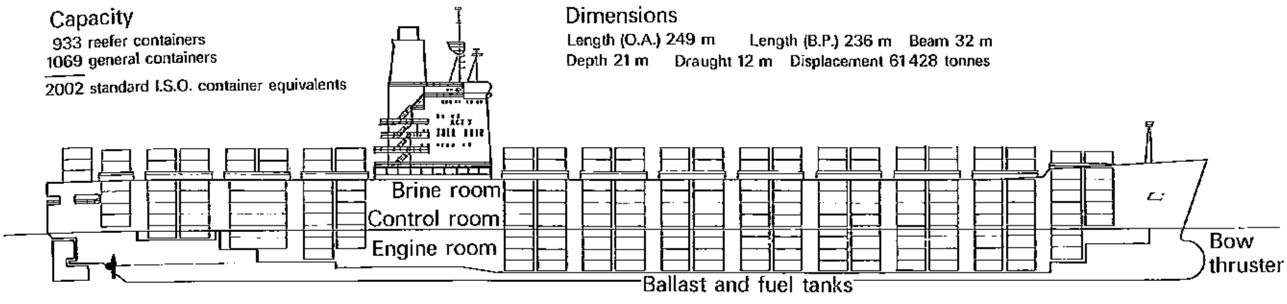


**Fig. 4.** A schematic view of the ACT 7 class of container ship in use between Australia and Europe, and between Australia and the east coast of North America.

frozen packaged food including fish and vegetables; the other, a container with a heat leak considerably in excess of the reefer container, but tailored to accommodate the 1200 x 1000 mm pallet.

- Reduction in the size of air plenums. The chamber which distributes air from the porthole to the floor section is commonly referred to as a plenum chamber. The depth was reduced from 125 mm to around 70 mm without any significant increase in the static pressure required to circulate the same volume of air as in the conventional container. This was largely achieved by 'radiusing' all sharp corners, the most significant being the inlet and outlet portholes, as shown in Fig. 5. Similar techniques have recently been applied to 40-ft porthole containers and a reduction from 150 mm to 100 mm in the plenum depth has been achieved. This has not been achieved without problems – slam closing of the closure plate on these larger containers was a problem for some time. The maximum number of air changes per hour that can be achieved without slam closing is shown in Table 1 for several types of containers.
- Removal of cargo battens. In order to facilitate loading of a predominantly palletized cargo in fruit containers, the side wall battens were discarded with no detrimental effect on cargo temperatures. The frozen containers also had no cargo battens, but were required to use temporary battens for the time being. This seems to be following a trend set some years ago on certain integral containers for the banana services between Central America and the ports in the Gulf of Mexico. These containers also carried frozen meat on the return journey.

**Container refrigeration systems**

The refrigeration plant on board the large container vessels, whilst not dissimilar to that on conventional refrigerated ships, has required a consistent level of reliability both in control and data processing to enable the refrigeration engineer to manage approximately 33 000 m$^3$ cargo space.

There are certainly some advantages in the 'Australia • New Zealand • Europe • Container Service' (ANZECS) type of ship with fewer coolers and controls than the ships in the South African service which have a maximum of nine containers per cooler. It is not surprising therefore to see a three-position switch on the temperature controllers of the latter which bears the following legend: (1) Manual. (2) Automatic. (3) Computer

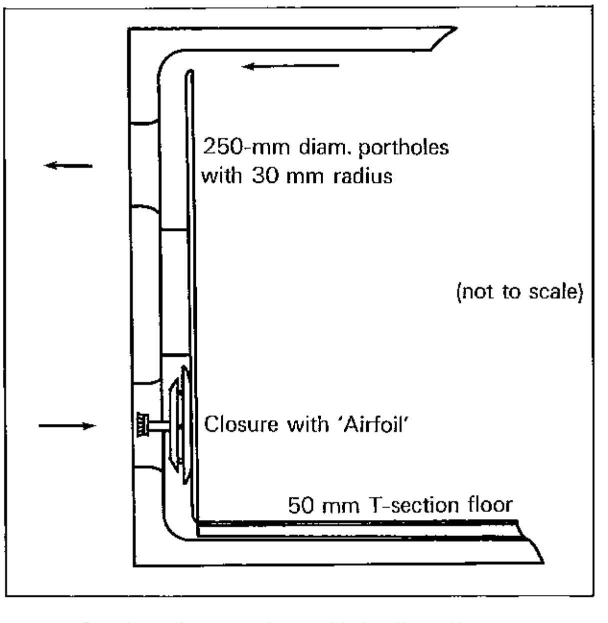


**Fig. 5.** Section of a container with 'radiused' corners.

Table 1. Slam closing of closure valves

| Valve type | Valve plate diam. (cm) | Spring force unit area (g cm$^{-2}$) | Limiting air changes |
|---|---|---|---|
| 40-ft container | 4.15 | 1.39 | 120 |
| S. African container ('radiused' portholes) | 3.36 | 2.23 | 140 |
| 20-ft Australia service | 2.85 | 4.17 | > 140 |
| Modified 20-ft Australia service | 2.85 | 1.98 | 134 |

(inoperative at present).

An interesting new development in refrigerant compressors is the single-screw compressor developed by Hall Thermotank and Grasso (Clarke *et al.* 1975–76). Although it has yet to make an impact on the marine world, it does, according to the designers, offer some advantages in coefficient of performance, presumably resulting from a reduction in the oil cooling load.

One of the improvements in screw compressors during the decade has been the use of an intermediate stage flash gas inlet which, according to one manufacturer's test data, raised the specific capacity by *c.* 30% at an evaporation temperature of –40 °C, and by *c.* 6% at 0 °C (Lundberg 1974–75).

Container refrigeration systems have seen little change in mechanical components, the Coplametic 3-cylinder or Prestcold equivalent being one of the more popular designs in the Australia service. It is, however, in the control field that the greatest changes have taken place. Temperature control is moving into the electronic era. Before long control systems will move into the microchip age as well (Carter and Scrine 1976).

A modulating type of control valve as fitted to new container designs and operated by a multiterm electronic controller is shown in Fig. 6. By utilizing microprocessor systems it is possible to centralize the operation of these units, and within the next decade we could see automatic checking of the unit before loading, as well as automatic fault diagnosis in the field.

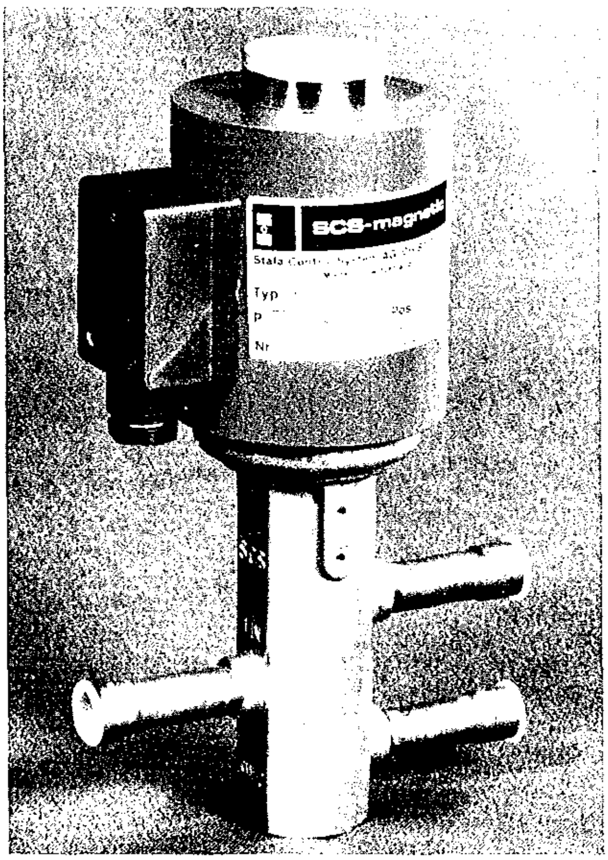


**Fig. 6.** A modulating type of control valve operated by a multiterm electronic controller.

**Liquid gases**

Another development of some note has been the increasing use of liquid nitrogen both as a back-up facility and also as a terminal in its own right. Some new developments on the continent of Europe for both frozen and chilled cargoes suggest that the time has come to look at short-term storage of fruit and vegetables in oxygen atmospheres which may range from 2% to 8%, and with carbon dioxide controlled by the flushing action of nitrogen vapour.

A typical liquid nitrogen terminal system is shown in Fig. 7. Such terminals could be based on a simple system with low initial cost, but to date some have tended to follow the mechanical system layout too closely, and costs per container slot have been relatively high.

**Other types of refrigerated ship**

The tramp reefer is a combination ship which can carry palletized, break bulk cargoes and also integral or porthole containers.

One interesting, if perhaps expensive, concept is the Orenstein and Koppel design which proposes removable decking to convert the ship from a bulk non-reefer to break bulk refrigerated cargo to 40-ft porthole container (Anon. 1978). A model section of this

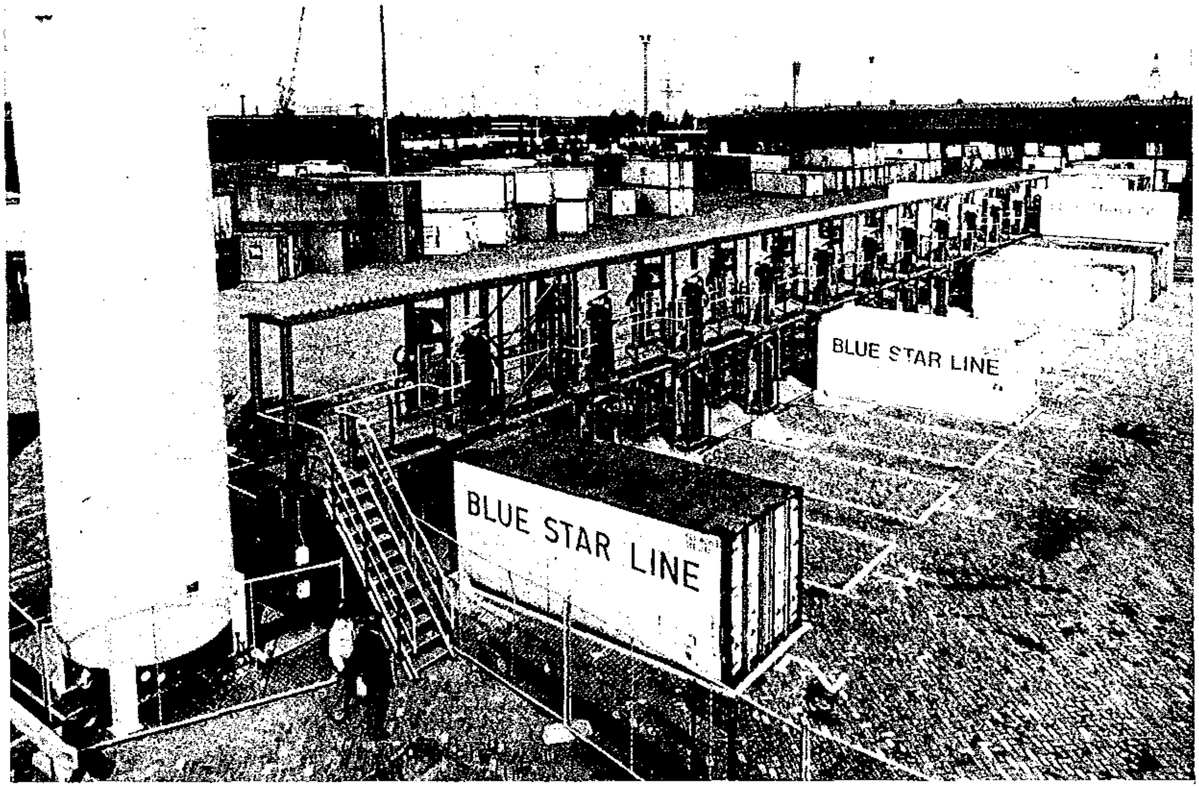


**Fig. 7.** Liquid nitrogen terminal at Rotterdam.

proposed ship is shown in Fig. 8.

The bulk carrier/container vessel has recently made an impact on the container world, albeit mostly in the dry cargo field. However, this type of ship can handle integral containers and will no doubt be used more widely in the future as the operators claim that they are more versatile than the cellular type of ship.

### 'Difficult' cargoes

Finally, a few words about 'difficult' cargoes. On the whole, difficulties usually arise when a cargo is in transit towards the limit of its useful storage life.

One particular problem in containers has been the Ellendale Mandarin which suffered initially from indifferent packaging, and occasionally journey times up to 10 weeks. Adverse temperature distribution has sometimes occurred owing to compacting cartons or puffy fruit, and this has encouraged moulds and other fungal infections.

Other cargoes which can be troublesome, though not necessarily in the Australian service, are avocados, pineapples and, occasionally, plums. Again these are not usually refrigeration problems, but rather ones of administration and handling which increase total journey time, often beyond what was usual in the days of passenger liner services. Another cargo which seems to have suffered somewhat with increasing export volume is the Chinese gooseberry (also known as kiwi fruit) which, although normally good-tempered, has suffered recently from an unacceptable percentage of moulds and rots in spite of exemplary carrying temperatures.

Some operational problems could be reduced given proper pre-cooling and transit facilities, but even in services where such facilities are first-class much can be lost at some stages of the journey. As increasing use of containerization changes conventional operational patterns, it is clear that occasionally well-ordered procedures vary, and this can result in indifferent outturns from time to time.

### Future trends

The future has now become inexorably tied to the cost and availability of fuel oil, and the resulting costs of moving cargoes across the world and refrigerating them in transit.

At present the high cost of propulsion has

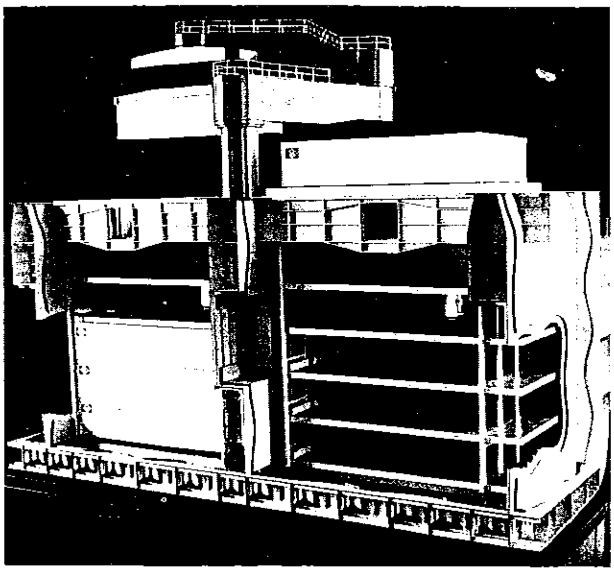

Fig. 8. A model section of a proposed multiple-purpose ship.

led to lower average speeds by the liner container services. Inevitably more cargo is in transit on the high seas at any one time. Probably, therefore, greater emphasis will be put on propulsion efficiency for a given size of ship, and an alternative to the expensive, giant container ship may well appear.

To continue with the theme of saving energy, one could question the wisdom of very low temperatures for some frozen foods which may be only 4 or 5 weeks in transit, when the coefficient of performance of the refrigeration plant is approximately 1.5 and somewhat worse when fans and pumps are included.

Circulation of air can also be very wasteful of energy particularly in some of the integral containers and container ship designs: some improvements can be expected here. To quote one rather extreme example of integral container design we have the following:

| Design | Air Volume ($m^3$/h) | Power input to fan (kW) |
|---|---|---|
| A | 1290 | 0.63 |
| B | 2520 | 0.52 |

Even more striking is the difference in fan power between maximum circulation for cooling fruit and minimum circulation for frozen cargo, and the example below is for a container ship designed to carry about 350 insulated containers.

| | Compressors | Pumps | Fans | Total |
|---|---|---|---|---|
| Cooling (kW) | 808 | 88 | 137 | 1033 |
| Holding (kW) | 448 | 64 | 40 | 552 |

In future, designs of refrigeration plant which show energy savings even with higher initial capital costs could help to contain the costs of transporting cargo; in the present economic climate, however, it is difficult to predict future running costs with any certainty.

There could be some re-assessment of insulation thickness, and installed compressor and fan power, but while the need exists to remove vast quantities of field heat from fruit cargoes there is a limit to the reduction in air volume and refrigeration power, unless pre-cooling facilities improve world wide. A genuine reduction in plant capacity could be made if cooling could be spread over a longer period without detriment to the ultimate storage life of the product concerned.

It is unfortunate that the two heat sinks for condensing refrigerants are air and sea water, both of which are similar in value at sea and which can reach peak temperatures of 30 °C. Were there an abundant and continuous supply of chilled water from absorption units operating from exhaust gases, one could see some improvement in plant output for a given compressor size. Nevertheless, in spite of some successful designs for air-conditioning plants of up to 60 kW output, equipment costs are somewhat greater than sea-water pumps, and waste heat is limited whilst vessels are in port.

### Automation

As mentioned earlier, trends towards further automation will continue and development of microprocessor techniques for sequence control, optimization of plant, and cooling programs could be commonplace in future. Microprocessor techniques could also be extended to such items as air refreshing, measurement of carbon dioxide and other gases, and possibly relative humidity. In recent years a number of rather expensive relative humidity indicators have appeared, although these have yet to be thoroughly tested in service at low temperatures.

### Modified storage atmospheres

As another paper in the Symposium is concerned with hypobaric containers it is not proposed to deal at length with this subject.

Although such equipment has been available for some little time, it has yet to prove itself in the market place. It is recognized that some advantages may apparently be gained by using low pressure storage, which cannot be achieved by other means, for example storage of strawberries and possibly whole, chilled lamb for extended periods.

The use of modified atmospheres is not new, and chilled beef was successfully carried under 10% carbon dioxide for voyages of 50 days without difficulty. It is surprising to read in a recent report from MIRINZ about gas staining of meat with carbon dioxide! Although this was often mentioned by the meat trade in the past, such occurrences were spasmodic, and beef with a good bloom was landed in the U.K. with no sign of staining after several weeks under this gas.

However, it is the mixture of oxygen, carbon dioxide and nitrogen which normally comes under the heading of modified atmosphere. It is unlikely that such atmospheres will make a large impact on the container world, but one should be prepared for them should the need arise. Although the container nominally lends itself to this application, it is not easy to achieve and maintain complete gas tightness. On a small scale, a through flushing technique with the right atmospheric composition could be a workable solution. Any attempt at individual control of carbon dioxide and oxygen is out of the question on a modern ship unless it is fully automated. The costs of providing such services are likely to be high, and one instinctively feels that there will not be a great demand for this type of service in the near future.

### Chemical coatings and film wraps

Much has been written about fungicides, dips, and chemical coatings over the past 30 years, but one feels advances could still be made in the field of chemical coatings or dips. That the refrigeration engineer is limited in what he can provide is well recognized, i.e. control of temperature, atmospheric pressure (in special circumstances) and relative humidity. Reduction in fruit metabolism is normally achieved by reducing its temperature as quickly as possible to a point where heat of respiration is minimal. Nevertheless, a large quantity of energy is required to remove sensible and metabolic heat, and if this could be significantly reduced, say by a factor of 2, it could affect refrigeration plant design, particularly if a slower rate of cooling could be adopted.

For example, an approximate calculation for a tonne of banana cargo is as follows:

| | Normal (3 days cooling) | Treated (6 days cooling) |
|---|---|---|
| Av. sensible heat removal (watts) | 262 | 131 |
| Heat of respiration (av. between 30 °C and 120 °C) (watts) | 95 | 48 |
| Air changes (per h.) | 90 | 40 |
| Fan heat (watts) | 74 | 10.5 |
| Fresh air (watts) | 1.5 | 0.75 |
| Fan heat (watts) | 73 | 36.5 |
| Total watts | 504 | 226 |

Flexible plastic film wraps have been extensively used for both fruit and meat over the past decade, and there is no doubt that they have made up for some possible deficiencies in the surrounding atmosphere, notably low relative humidity. They have been widely used with bananas and pears for a number of years, and the grape is one of the more recent commodities to be protected in this way with encouraging results. One adverse factor, however, is the generally poor heat transfer between product and air, though this is minimized to some extent by using ventilated cartons. Additional wrapping of fruit presents problems as is illustrated by the example for citrus fruit, where the half-cooling time for unwrapped fruit is 24 h, but for wrapped fruit it is 48 h.

Nevertheless, the film wrap has made an important contribution to the carriage of fruit and vegetables and further developments in film permeability rates, together with the use of ethylene absorbents, may occur (McGlasson *et al.* 1979). One cannot necessarily relax other requirements for the carriage of fruit, particularly temperature, except possibly where ethylene absorbents are used, and one may judge the film wrap as an excellent adjunct to normal temperature control.

The use of Cryovac packaging for chilled beef cuts represented a considerable advance in the carriage of such meat, and the current export trade in chilled lamb has renewed interest in such films. Of particular interest is the development of Cryovac techniques for wrapping whole carcasses. The effect on refrigeration requirements is somewhat marginal, although with the carriage of chilled beef cuts, a temperature range from $-2°$ to $2°C$ could be tolerated without adversely affecting the outturn. With chilled lamb cargoes it is necessary to maintain temperatures within a much closer tolerance and variations of $\pm 0.5°$ at $0°$ to $-1°C$ are preferred.

Other techniques of sterilization apart from carbon dioxide, may well affect the export of chilled lamb, in particular. If meat cuts were acceptable in the Middle East, it is certain that they would all be packaged in Cryovac.

One could, however, foresee a greater use of frozen meat cuts as an alternative to the carcass, since this system could increase the weight of meat per container, but for the European market rather than the Middle East, where frozen meat is acceptable only in certain countries.

One may summarize future trends in a few words: some reassessment of the design parameters of refrigerated cargo ships and container ships may well occur, but one cannot foresee any major advances in the efficiency of the vapour compression cycle at present.

In order to have more flexibility, it is quite likely that the container with an integral refrigeration unit will grow in usage, particularly in developing areas that do not have the throughput for a porthole-container system.

Even with the benefit of 10 years' hindsight, it is difficult to envisage the ANZECS type of container ship with 1200 or more integral units; the attendant problems of removing a considerable quantity of rejected heat from the condensing units plus the loss of stowage space in that number of containers are daunting.

Whatever the outcome of trade developments, and it is the trade which usually dictates the type of equipment that is ultimately to be used, the shipowner will doubtless rise to the occasion and provide the appropriate environment in which to carry perishable cargoes.

## References


Anon, (1978). Profile of a new reefer ship design. *Motor Ship* 58, 31–3.

Clarke, R. J., Hodge, J. M., Hundy, G. F., and Zimmern, B. (1975–6). A new generation of screw compressors for refrigeration. *Proc. Inst. Refrig. London* 72, 67–75.

Lundberg, A. (1974–5). A new concept of refrigeration screw compressors. *Proc. Inst. Refrig. London* 71, 27–35.

McGlasson, W. B., Scott, K. J., and Mendoza, D. B. (1979). The refrigerated storage of tropical and subtropical products. Int. J. Refrig. 2, 199-206.

Scrine, G. R., and Carter, W. D. M. (1976). Control of small refrigeration systems. *Bull. Int. Inst. Refrig.* 56*(Annexe-1)*, 469–75.