The relevance of vehicle design and handling techniques to the cold-chain process of food preservation

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More than the economics of transport and materials handling has to be considered in vehicle design and handling techniques for refrigerated foods. Those concerned with transporting and handling refrigerated products are very directly involved in food processing, especially when preservation of food is by the 'cold-chain' process. Their involvement in the processing aspects can never be secondary to their better understood functions of physical distribution. To suggest that their prime function is other than food processing would imply a poor understanding of how food is preserved by the cold chain.

As others have said: 'The traditional weak links in different cold chains are the transport operations' (Meffert 1978) and 'The transfer from one refrigerated enclosure to another . . . is frequently a weak link in the freezer chain' (Lorentzen 1973).

Research in Australia by Irving and Sharp (1976) showed that the average temperatures of frozen foods rise 4.5 K in the summer and 3.5 K in the winter, while the foods are being transferred from distribution cold store to retailer. A German investigation showed a 5.5 K rise (Wenck 1977) in a similar operation. These average temperature gains are higher than many authorities have anticipated in designing their preservation process. The unfortunate fact is that a number of deliveries involve greater temperature rises, resulting in the product arriving at retail outlets at temperatures higher than $-15\,^{\circ}C$.

The contemporary idea of a satisfactory freezer-chain process of food preservation (Sanderson-Walker 1978*a*) envisages the product being held in primary stores for long-term storage at -26° to $-29\,^{\circ}C$, and then progressing through the chain to secondary stores, distribution stores and ultimately to retail display cabinets into which it should be loaded at a temperature no higher than $-15\,^{\circ}C$.

This idea is consistent with the freezer-chain's reputation for being the food preservation process that offers the consumer the best quality product at the least cost with the lowest energy input (Sanderson-Walker 1978*a*).

Because the principle of time-temperature-tolerance allows higher storage temperatures in stores where storage time is shorter, storage temperatures after primary storage can be planned to increase as products progress through the freezer chain, provided there is a corresponding reduction in storage time in the higher temperature stores. The heat gain in the transfer from store to store will have a bearing on the intermediate store's required temperature. To make the best use of this permissible temperature increase from one end of the chain to the other, it is necessary to consider how temperature rises could occur and where the greatest cost-benefit to the total process can be derived from an acceptable heat gain.

The processing involved between primary storage and the retail cabinet occurs in freezer stores of various classifications, in transport between the various classes of stores and to the retail outlet, and in materials handling in and out of vehicles.

Today the operations and design of freezer stores for their particular purpose are such that none of the temperature increase should be attributed to storage (Hughes, unpublished data). In fact they would have some potential for temperature recovery. However, if temperature recovery has to be more than approximately 2 K, quality could possibly be affected by the product pumping out some of its moisture content in the recooling process.

With today's know-how, it is no problem to have vehicles designed to maintain product temperatures. If, however, the storage and handling procedures can be satisfactorily managed so that there is some heat loss available to the transport function, there is a possibility that some equipment could be designed to reduce transport cost by making use of this available heat loss in the freezer-chain process, but still maintaining the required high quality standards (Haughey 1971; Hughes 1976*a*; Anon. 1978; Lorentzen 1979).

The same possibilities may also occur for cold chains operating at higher temperatures, e.g. for dairy foods, fresh fruit and vegetables. The economical design of transport vehicles is very dependent on the establishment of adequate materials handling standards relative to temperature gain.

Handling techniques

Factors affecting temperature rise during handling include:

- initial temperature of the product;
- temperature of the operating environment during handling;
- time the product is exposed to the environment – the longer the operation, the greater the variation in temperature between individual items of cargo;
- conditions of heat transfer from the environment: air velocity, thermal radiation, and condensation;
- thermal properties of the product;
- thermal and airflow resistance of the packaging; and
- geometry of the cargo unit being handled; particularly important is the extent of unitization.

It is difficult to produce a theoretical estimate of heat losses during the loading and unloading of vehicles (Lorentzen 1973). However, Meffert (1978) has supplied a 'nomograph for the selection of safe exposure times of frozen meats'. Among other items, this highlights the very different temperature readings at different points of measurement within the carton. If there is a temperature rise, there will be very high readings at the exposed corners and edges of the cargo.

Londahl (1977) advises that, 'At an ambient temperature of +15 °C, the centre temperature of a consumer pack of spinach increases from –25 ° to –2 °C within 1 h. With 10 consumer packs in a master carton, the outer packs reach –10 °C after 1 h. The others reach –10 °C after another 1.5 h. In a pallet load of spinach the outer packs reach –15 ° after 1 h, whereas the centre packs have not increased more than 1 °C'. Haughey (1971) has shown that 'Maximum product temperatures occur (after loading into insulated but not refrigerated containers) on the top row and are only attained by a small proportion of the cargo'.

Similarly, Hufschmid (unpublished data) has shown that even under heavy cloud and relatively cool ambient conditions, 8 to 9 °C, temperature readings of the most exposed cartons during the loading of 12t vegetables in 50 min can rise to –4 °C from the original store temperature of –24 °C. In the same load, temperature readings representing the majority of the cargo showed little or no temperature rise. He further reported that the refrigerating plant on the container was required to work only intermittently after the initial 3h operation, the thermostat being regulated by return air temperature at –25 °C. The cartons with high temperature readings on loading, however, did not recool to –24 °C until 7 h after loading, as the return air was affected by the cooler products at the bottom of the stow.

It is because of this potential for high temperature rise and wide variations in the temperature of the product during loading and unloading and the extended period required to stabilize load temperatures in transport, that in order to improve the economics and quality of the cold chain emphasis must be put on the speed of loading and unloading and on the environment conditions, particularly where the destination is a retail outlet with limited recooling capacity.

For the freezer chain, the following techniques and concepts are either in use, or being considered, in order to minimize heat gain in frozen foods during handling. Many of these have applications with respect to other refrigerated products.

Refrigerated docks

Meffert (1978) presented a table of comparisons between loading environments, e.g. port doors, loading bank (i.e. a roofed dock with no walls or refrigeration) and yard loading. The benefits of refrigerated docks diminish if they are not designed to give a good air seal with transport equipment.

Port doors

A port door is placed in the side of the cold store. This is not an extension refrigerated to a temperature higher than the cold store. The trailer fits snugly against its padded seal. It is designed to make the cargo space of the trailer a part of the low temperature environment so that all handling takes place at store temperatures. Sanderson-Walker (1978*b*) has set out the advantages of this technique in comparison with loading docks.

Unitizing of cargo:

- on pallets for use with conventional forklifts;
- on slip sheets – the handling time is 15% greater than when pallets are used, but greater product weight is often available in transport. The economics of this technique depend on the amount of utilization that can be made by the shipper, and also the receiver, of the required special equipment. There are a number of advantages that should be considered (Bard 1977; Bouma 1980; Johnson 1980);
- unit 'push from pallet', as used for loading cartonned meat. This method requires hand unloading (Chua 1977);
- unit 'lift from pallet' (Chua 1977) requiring specially designed in-house pallets to suit regular carton dimensions. Again, unloading is not utilized. Chua (1977) advises loading rates for cartonned meat into export containers as follows. Average of hand-loaded methods: 3.5 t per man-hour; push from pallet: 21 t per man-hour; and lift from pallet: 45 t per man-hour.

Methods to stop unit loads interlocking during transport include stretch wrapping with plastic film or net and shrinkwrapping with plastic film when it is not economic to instal stretch wrapping.

These techniques also assist in stabilizing loads where various carton dimensions are involved. They assist security, stock control and identification of consignments during delivery. The greatest contribution of these techniques to the freezer chain is where they can reduce unloading times for vehicles. This is important when there are multiple drops from large vehicles and where there is no temperature-controlled receiving facility.

They also help offset thermal gains during the loading operations. Haughey (1971) advises in reference to frozen lamb carcasses: 'The addition of a Polythene bag over the normal stocknet wrap reduced surface temperature rise during loading, but had little effect thereafter'.

Carts, trolleys, and roll pallets

Three- or four-wheel equipment that can be loaded without mechanical assistance in and out of vehicles is used extensively for distribution to retail outlets, or where the size of the order for each item is small. As they have two or three upright sides, the load, even if it involves outer cartons of a number of different size, is stacked within the base dimensions of the cart, and thus the problems of pallet overhang and carton toppling are avoided as these can lead to difficulties for distributors with unsupported pallet loads.

Because they are an additional item carried by the vehicle, carts can limit the weight and volume of cargo carried. The economics of using such a cart requires the design to be coordinated with that of the store and the vehicle. Generally, when empty, carts will fold up to give reduced dimensions, which are satisfactory for back loading and storage. A further reduction in product handling occurs when there is sufficient product volume to allow the cart to be incorporated in the retailers' selling fixtures.

Crates and baskets

Crates or baskets may also be stacked to form cargo units, either on conventional pallets, or with the use of dolleys to form a cart. Such baskets can also be designed to allow retail display. Like carts, baskets require good management for efficient utilization. The best application of baskets is where the manufacturer aims to eliminate his outer carton cost and stacks the retail pack directly into a basket. Another important application is where the retailer finds it uneconomic to hold case (outer carton) quantities of a variety of lines.

A distributor using baskets claims he can select and handle a product in less than case quantities at costs comparable with distributors using the case as the smallest unit. For small outlets, this permits a greater variety of stock, reduced refrigerated space and stock being less time in the relatively high temperature of the retail cabinet. The uniformity of dimensions and the structural qualities aid materials handling.

Unless the basket is designed for the purpose of offering insulation, materials handling must recognize the loss of the heat- and draught-insulating capacity of the outer cartons. Some basket designs, which are coordinated with consumer-pack design, can reduce the temperature gain during price marking in the retail store – often the greatest single cause of heat gain in the total freezer-chain process (Runyan *et al.* 1978). Used in conjunction with covers (see below) such baskets appear to offer considerable economic and quality benefits.

A materials handling system built into the vehicle

Not only does this system reduce the time involved in the more precise forklift operation inside the vehicle, as well as the need for low mast-height forklifts, which do not suit the stacking height requirements involved for economic storage, but it also eliminates much wear and tear arising from the use of forklifts inside the vehicle. An advantage of this system is that it can transport two pallets side by side to and from the rear door. This reduces unloading problems caused by interlocking. Such a unit has been devised to operate on a two-tier basis, thus doubling the number of pallets that can be carried – a feature of benefit when carrying light products in outer cartons with poor structural strength, or when carrying pallets of necessarily low height.

This equipment reduces product exposure to ambient temperatures not only on the dock, but also in the vehicle during the loading or unloading operations. The loading or unloading rate exceeds 120 pallets per h. This speed of operation also considerably reduces the effect of door openings during 'part load' deliveries. Being engineered into the vehicle, the system is most economical when employed on work requiring the greatest number of loadings and unloadings in a week.

Insulated covers

The reflecting aluminium cover (Londahl 1977) does not impinge greatly on the transport load. If it is to be used for full thermal capacity in the vehicle, air spaces of 20 mm are required adjacent to the aluminium surfaces. Their best application is where there is considerable radiant heat and in many instances this constitutes the greatest heat load (Richards 1977).

A relatively inexpensive and rugged material has been developed that has properties which should reduce the low utilization life reported by Londahl (1977). Covers and rugs with loose insulating filling are expensive, take time to apply and require space that may not be available in the vehicles. However, they have been shown to be used economically in transport when products at different temperatures are being handled (Karitas 1978).

Carton sizes

Rationalization of carton sizes (Anon. 1979) is a desirable objective in order to:

- make maximum use of the load-unitizing device, e.g. pallets, carts, etc.;
- avoid toppling and allow for faster mechanical handling;
- prevent overhang of pallets – particularly important for fast loading when the internal width of the vehicles permits only 75 mm tolerance for irregular stacking, bulging, etc., as well as airflow;
- reduce carton bulge which can cause pallet overhang, not necessarily at the base; and
- permit less heat exposure during price marking.

Many countries are taking firm action to reduce the number of sizes of outer cartons involved in distribution (Patton 1979).

Small insulated containers

Loading of products in the cold store into small insulated containers (Palmer 1977; Karitas 1978; Runyan *et al.* 1978) is another worth-while procedure. The external measurements of these containers do not generally exceed 1150 x 1150 x 1550 mm. The U.S. Department of Agriculture found that in some instances such containers proved to be expensive, but no product quality criteria were introduced into what amounted to economic evaluations. Small insulated containers are used extensively in Europe and America in the final stages of the distribution chain, where they can be used similarly to carts and have better thermal characteristics than insulated covers. They are particularly useful where small deliveries are concerned because they overcome the problem of rising temperatures caused by vehicle door openings (Penney and Phillips 1967; Soukup 1975) where products of different temperatures are carried (Karitas 1978), and when receiving takes place under unfavourable conditions. They can be used for a reasonable period to hold stock before it is placed in retailers' or institutional fixtures. Adequate knowledge and suitable techniques exist today to ensure that materials handling is no longer the problem child of the freezer chain (Hughes 1975).

Although some of the handling techniques described involve capital outlay, there are many instances where they may be economic and provide better quality in the process. The extent to which they can reduce temperature loss on transfer allows consideration of cost reduction techniques in transport.

Vehicle design

Three major criteria dominate the design of vehicles for the cold-chain process. These are legal requirements relating to the dimensions and gross weights of vehicles, transport costs of refrigerated products and thermal requirements of the cargo.

The legal requirements set the limits within which the economic and thermal factors of design can be considered. Changes in legal requirements can have a massive influence on the economic factors, especially now that greater longevity is being obtained from the expensive equipment involved.

Over the last 10 years, there have been major productivity achievements in the transport of refrigerated foods within Australia. The Australian measure of cost inflation, the Consumer Price Index, has risen 156% over the last 10 years. The capital cost of equipment and the running costs of refrigerated transport, taken as a group, have risen by approximately the same amount. At the end of 1979, the Australian refrigerated carrier was charging very much the same as he did 10 years ago, namely 3 to 3.5 cents t^{-1} km^{-1}. (4.8 to 5.6c per ton mile). Furthermore, he is offering a palletized service in vans with better thermal characteristics. As a result, product heat loss from store to store has been reduced. Thus the road refrigerated transport industry in Australia has effectively improved the quality of its cold-chain process and reduced 'real' costs by approximately 60%. Vehicle design and the recognition of materials handling efficiency have been significant among a number of contributions to these remarkable improvements in productivity and quality. They have also similarly contributed to improvements in other modes of transport within Australia, particularly in the cartage of frozen products from Tasmania to the mainland.

By the standards of Europe and the U.S.A., the Australian market for new refrigerated trailers is very small. Single orders in either of these two overseas markets may exceed Australia's total national requirements. If the 20% growth rate of the industry (Hughes 1976*a*) has been maintained since 1976, it is probable that the total number of refrigerated trailers purchased in 1980 will not exceed 200.

Although this small market results in higher costs, the small orders give the trailer builder considerable scope to cooperate with the transport operator to develop new concepts in design and materials handling. The most significant Australian developments in the past have been the high thermal quality and longevity of the fibreglass-reinforced, plastic, chassisless, trailers, followed by the 38-mm-wall vehicle designed to be pallet compatible (Hughes and Wilkinson 1973).

More recently we have seen:

- the 'Jumbo' trailer, incorporating a system of stacking pallets in two tiers to suit the handling requirements of products which have insufficient carton strength to stack to the available cubic capacity of the trailers;
- the 'Piggins' system of materials handling built into the trailer, allowing an operational two tier system and extremely fast loading (14 min for 40 pallets) and unloading (19 min) (Piggins 1979).
- as a result of the structural requirements of the Jumbo trailer – designed initially for non-frozen products – a further reduction in wall insulation operating in conjunction with high capacity refrigeration equipment, the reliability of which has now become well accepted; and
- a refrigerating plant that has a higher refrigerating capacity and a flat profile evaporator, giving further potential for the use of trailers with reduced wall insulation.

If the refrigerated transport industry is to continue to reduce real costs and improve its processing technique, it is most important that Australian vehicle builders continue to use the opportunity to innovate that small orders afford. There are areas of better understanding of the cold-chain process, new materials and greater acceptance of improved handling techniques that permit the exploration of new vehicle-design considerations.

Operating without a refrigerating system en route

Lorentzen (1979) has described work that has been proceeding since 1973 and has also provided theoretical substantiation relating to the satisfactory transport of frozen products on hauls up to 3.3 days by rail, where the load itself supplied the refrigeration needs during transport. He concluded that 'Such a procedure is perfectly possible in practice and could give considerable savings in transport costs'. Hughes (1976*b*) has referred to the need to operate with satisfactory loading and unloading practices to obtain the best results.

If vehicles could operate in this manner cost savings would be:

- reduced vehicle equipment costs since there is no refrigerating system, including tanks, etc., and no front wall reinforcement:
- no intrusion by the refrigeration system into the load area and a reduced requirement for air-flow space over the top of the cargo, hence allowing greater cubic capacity in the vehicle and better utilization for non-refrigerated cargoes on return trips;
- substantial reduction in vehicle weight per cubic metre of cargo carried;
- reduced energy costs per kg carried, owing to reduced vehicle weight, and no refrigeration plant motor to operate;
- no refrigerating system maintenance; and
- no risk to cargo caused by mechanical or operator failure with respect to refrigerating systems and temperature settings.

It would be surprising if these savings in refrigerated transport costs did not amount to 15%.

Lorentzen (1979) reported a complicated three-dimensional pattern in the first part of the heating cycle – typically 10–12 h. This pattern could have its basis in the temperature differences between cartons significantly and insignificantly exposed during loading, and the ambient atmosphere left in the container after loading. The effect of both of these factors can be reduced by attention to handling methods.

Haughey (1971) clearly showed that control of loading and unloading procedures was significantly more effective in minimizing temperature rise than other possible measures, such as lower store temperatures, container precooling, air recirculation within the container and additional packaging material. After temperature equilibration, heat leakage caused a net temperature rise from 0.5° to 2°C per day. Haughey's loading was done outside the cold store at rates of *c.* 12 th^{-1}. We should be confident that loading practices available today can eliminate the heat load he experienced on loading which was equivalent to a 24–36-h temperature leakage through the container.

If it is required to reduce temperature loss further during transport, pre-trip refrigeration can be supplied after the doors are closed, in a manner similar to that suggested by Callé (1979), or by the use of other one-shot techniques such as carbon dioxide in the form of dry-ice or snow. Although Callé, in principle, relates these systems to storage, he does recognize the capacity to reduce temperature by depot-based mechanical refrigeration plants, or cryogenic systems connected to the stationary container or vehicle. Differing circumstances will cause either the mechanical or cryogenic gas concept to be the more economical.

If a trip in a vehicle without a refrigerating system is to involve a time span and conditions whereby the temperature loss is estimated to be greater than that which is available from the plan of the cold-chain process, there is the possibility that similar *en route* temperature reduction facilities could be economically established on well-used routes. Their capacity would be limited to an understanding that temperature reduction of frozen foods should not exceed 2 K. Haughey (1971) found that with a typical clip-on unit, the average temperature reduction throughout a container stow of lamb carcasses was 0.2K h^{-1}.

The most appropriate application of methods of transport without a mobile refrigeration system, and where heat gain during handling can be controlled to efficient levels, is where products are being transferred from long-term storage temperatures lower than –26°C to stores where storage times do not require such a low temperature, e.g. –21° to –24°C. It should be noted that

$-29\,^{\circ}C$ is most often recommended for long-term storage. If such a temperature can contribute to reduced transport costs, it can be attained in the outloading store, in most instances, with relatively small increase in storing costs compared with the transport savings.

Features of vehicle design that will help the success of this potential cost saving include:

- minimum air leakage (see below);
- adequate arrangements for appropriate wall air flow;
- recognition that insulation should be greatest in the roof (Haughey 1971) and floors of road vehicles;
- protection from radiation of the top layers of the load (see below);
- development of an air-circulation system that will give greater uniformity of temperature (Lorentzen 1979). Possibilities of using convection caused by varying insulation thicknesses in different surfaces (e.g. walls and floors) can be considered. Another low cost concept involves the use of a small wind turbine activated by the vehicle in motion to drive an internal fan;
- design of quick coupling and uncoupling fittings to suit a depot refrigeration system, most probably involving the rear doors on the vehicles. Preferably the design would permit either mechanical or cryogenic gas refrigeration, as different depots may employ different systems.

There may be some concern whether the experience of Lorentzen (1979) and Haughey (1971) can be reasonably translated to operations such as those described by Hughes (1976*b*) where thin walls (38 mm) are necessary for palletization. When considering this position, one must recognize that, notwithstanding the reduced side wall thickness, the mean insulation thickness of the 11-mm thin wall vehicle described by Hughes (84 mm) is slightly greater than that used by Haughey (76 mm). Appropriate construction methods available today (Hughes and Wilkinson 1973) do not require an allowance of more than 8½% for deterioration in insulation between a new and used vehicle. Lorentzen (1979) and Haughey (1971) advised that heat leakage will come mainly through the roof, and the van under consideration has this required extra roof insulation, as well as greater floor insulation. Moreover, the procedure described by Hughes is still operating.

The heat gain of product in the vehicle may be calculated as follows:

$$\text{Product heat gain} = \frac{\text{vehicle heat leakage}}{\text{cargo weight} \times \text{product specific heat}}$$

When heat leakage from the vehicle is 22 WK^{-1}, the weight of cargo is 18 000 kg, the specific heat of the cargo is 2100 $Jkg^{-1}K^{-1}$ (frozen fish) and the temperature differential between the cargo and the ambient is ΔT, the temperature rise of the cargo is:

$$(22 \times \Delta T)/(18\,000 \times 2100)\ \mathrm{K\,s^{-1}},$$
$$\text{i.e. } 0.051\Delta T\ \mathrm{K/24\ h}.$$

Thus if the average temperature differential is 50 K, the temperature rise is 2.55 K per day.

Because the specific heat increases considerably as temperature rises, this example based on fish is conservative in this aspect. In many of the hauls, night time temperatures predominate and the temperature differential will not be as high as 50 K. Furthermore, the product can be cooled at receiving stores by 2 K without quality deterioration. There is an improvement in the thermal characteristics of a body if there is no refrigeration plant which offers a significant heat bridge (Haughey 1971). There is also potential to reduce the actual heat leakage from 22 WK^{-1} closer to the theoretical assessment of 16.5 WK^{-1} (Hughes and Wilkinson 1973). The Australian thin wall for the Australian 1165-mm pallet is not as thin as the thin wall required for the European pallet (1200 mm) and thus the Australian thin-wall vehicle has a temperature rating of *c.* 0.40 $Wm^{-2}K^{-1}$ which is better than the 0.55 available in Europe (Clement 1978).

It may also be possible to transport perishable products with more critical temperature requirements without a refrigeration plant if the loading temperatures were at the allowed minimum, thus using the much cheaper stationary refrigeration rather than the very expensive mobile refrigeration to pull down the temperature under adverse conditions. Heat of respiration would, as a result, be less significant.

Low air leakage vans without refrigerating systems would be ideal for the application of controlled atmosphere (C.A.) techniques in transport. It is understood that the best results are obtained with C.A. road operations when a professional approach to temperatures is adopted at the point of loading.

There is clearly a need to examine the temperature plan for the cold-chain process for both frozen and higher temperature products in order to allow cost and energy savings that should flow from the elimination of vehicle refrigerating systems in many of the transport operations.

Reduction of air leakage

In the U.S.A. 'it is estimated that unnecessary air leakage in refrigerated transport represents an energy loss as high as 70 million gallons of diesel fuel per year' (Anon. 1978). The immensity of the problem can be understood when one recognizes that fuel represents possibly less than 50% of the costs involved.

The pressure differences causing air leakage were identified by Anon. (1978) as being due to: differences between the temperature inside and outside the vehicle (6 Pa); the necessary pressure to provide forced draught air circulation (up to 375 Pa); vehicle motion, which creates a pressure difference between the front and rear of the vehicle (*c.* 300 Pa at 95 kmh^{-1}); and the effect of wind. He also noted that even when there is no direct air leakage from the inside of the vehicle to the outside, construction of vehicles is frequently such that there is no vapour barrier on the external wall. Consequently, there is exchange of air within the insulation which can produce moisture condensation in the insulation.

'Experience has shown that with proper construction, leakage is not a consequence of lack of care, but is inherent to the mode of construction' (Anon. 1973). Major problems arise, especially as the life of road vehicles increases and when sheet metal techniques of construction and securing wall panels are adopted. Two methods of construction are now used frequently outside North America to overcome these problems. One is the use, as a core material, of structural expanded polyvinylchloride (PVC) which has the thermal properties of polyurethane but does not suffer the same thermal deterioration. Skins of aluminium or fibreglass are laminated to the core material. Joining floor to walls to roof etc., involves no metal connections as rabbeted joints of the skinned core with a thin layer of low conductivity adhesives give the required structural strength. The other technique is the use of fibreglass reinforced plastic skins and reinforcements in conjunction with polyurethane insulation (Hughes and Wilkinson 1973).

Measurement of air leakage in a static position does not properly assess the operational situation. Nor does measurement on a new vehicle give an adequate indication of the air leakage after the vehicle has been operating for some time. To identify air leakage properly, an 'over-the-road' test must be applied. Following on from work done by CSIRO (Sharp *et al.* 1976; Sharp, personal communication), a simple technique using tracer gases may now be developed to determine a vehicle's air leakage under actual operational conditions. This will allow effective air leakage tests as a maintenance management tool, as well as a guide to better design.

Areas of air leakage that require attention in addition to the basic construction method, include floor drains, refrigeration unit seal, roll-up door seals, and door seals (Anon. 1978). It is unlikely that thermal improvement in vehicles can be achieved unless operational air leakage characteristics of vehicles in service are regarded as being of major importance.

Transport refrigeration design

If a refrigeration plant is required in a vehicle, its design must take into account capital and operating costs, energy costs and source, maintenance costs, environmental factors, weight and versatility.

Recent developments that have been discussed are as follows.

- A profile of the evaporator section of the refrigeration plant that allows uniform unitizing methods (Clement 1978; Bennahmias 1979).
- Hydraulic drive for the compressor and air circulation, thermo-electric cooling and vortex tubes (Meffert 1979).
- A number of developments involving eutectic plate-type refrigeration (Adler 1979).
- Obtaining air circulation without constant operation of direct diesel engine driven refrigeration systems which, after product temperature is pulled down, is often not necessary to meet cold-chain requirements. Anon. (1978) using apparently conservative data, e.g. diesel fuel at 60c per gallon, calculated that if the refrigerating equipment were required to cope only with the heat gain through the body of the

vehicle and the heat of respiration, and if air circulation was not powered by the heavy refrigerating system, the present fuel savings over the life of a commonly used refrigeration unit would amount to $US6600. Savings in Australia would be expected to be considerably greater.

- Use of controlled atmosphere techniques to reduce heat of respiration and consequently demand on the refrigeration plant (Anon. 1977).
- An absorption refrigeration system operated by the exhaust gases of the vehicle (Mei *et al.* 1979).
- Use of the refrigerating characteristics involved in the expansion of such fuels as LPG to be used subsequently as the motive fuel for the vehicle; the boiling temperature of propane is $-42\,^{\circ}$C (Ibl 1974; Grechuta 1975; Jäger 1975).
- Increasing the capacity of the refrigeration system so that vehicle costs can be reduced by using materials of stronger structural characteristics but reduced thermal characteristics. This applies particularly where weight is not the major consideration, where cubic capacity, and specifically width, is of significance, where a number of door openings is expected and where loading temperatures are unreliable.

Insulation with expanded PVC

In several European countries manufacturing costs involving expensive expanded PVC are such that finished vehicles cost no more than vehicles manufactured by other methods. Because of its many favourable qualities, it is likely that expanded PVC will play a very significant role in the future of refrigerated transport.

This material permits simple vehicle manufacturing techniques with low capital outlay, light vehicle weights, good air leak characteristics and the use of either metal or fibreglass reinforced plastic skins. Expanded PVC has closed cell structure which eliminates nearly all weight gain caused by moisture absorption, and provides strong bonding of skins. Thus if skins are adhered correctly there is little chance of delamination from core failures. Vehicle manufacturers guarantee there will be no loss of insulating properties for extended periods. Expanded PVC also has high resistance to shearing which can cause internal cracks in traditional insulating materials and lead to heat leaks and problems associated with air leaks. Less deterioration may be expected as a result of impact and accident damage.

To circumvent the high price of expanded PVC as an insulant, it is possible to design using two insulants. PVC may be used to the required extent where its specific qualities are needed, and polyurethane where the structural requirement is not as great as the insulating requirement, i.e. expanded PVC may be used for its structural qualities and polyurethane to augment the insulation. The roof of the thin-wall vans is a particular example where PVC and polyurethane could be used together.

Insulation against radiant heat

A number of authors have referred to the need to provide better insulation against radiant heat (Soukup 1975; Lorentzen 1979; Haughey 1971). Soukup believes it is more important for delivery vehicles than for long-distance vehicles. The recent development of durable and relatively inexpensive materials with low emmissivity suggests they could be used with advantage on some internal surfaces of vehicles. Such materials, if properly applied and well maintained, are potentially able to eliminate 95% of the radiant heat entering the vehicle through the treated surface. Radiant heat in some conditions can constitute a significant proportion of the heat load on a vehicle.

Door openings in vehicles

If there is no method of preventing the free flow of air in and out of a vehicle when the doors are open, heat gain can be extensive and it will take some time for a refrigeration plant to recool, especially in a part-loaded vehicle (Soukup 1975). Moreover, accumulation of ice on the evaporators will make refrigeration less effective.

With a 4.365-m body containing a 2.5 t payload at $-15\,^{\circ}$C, Soukup (1975) found that for a 3-min delivery operation the use of a secondary door device reduced the total quantum of heat gained during a door opening by *c.* 90%, reduced the surface temperature rise of the most exposed cargo from 24 K to 1 K, and reduced the recooling time, to bring all cargo to $-15\,^{\circ}$C in order to make a satisfactory second delivery, from 40 min to 7 min.

Multi-stop vehicles cannot make deliveries at reasonably uniform temperatures unless some method is adopted to prevent the unrestricted interchange of air when doors are opened. Secondary doors, bulkheads, strip curtains, insulating rugs, and insulated containers are all devices used to restrict the effect of door openings. The best solution will be designed when the temperature policy and handling methods of the shipper and the receiver are incorporated in the total transport plan.

In order to restrict the effect of door openings further, Spiess *et al.* (1977) recommend that the door-opening time be reduced by having orders pre-packed in the depot and loaded to match the sequence of the drops, which should be organized where practical so that small orders are delivered at the beginning of the journey.

Conclusion

From the foregoing, one should be able to discern the potential for transport and materials handling to overcome their reputations of being the weak links in the cold-chain process. There is a lot to suggest that better recognition of the cost and quality significance in these functions may point towards a basis for designing more economical cold-chain processes.

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Transport and storage of refrigerated foods

Air transport: experience and future developments

By Milton Lalas

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In the 100 years since the S.S. *Strathleven* successfully carried 40 tons of frozen meat and butter to the U.K., we have seen vast progress in transportation. Visibly the most impressive progress has been in the air, where the mode was only a vague dream 100 years ago; present speed and range was not forecast even 40 years ago and size was not foreseen 15 years ago. As a matter of interest, the *Strathleven's* cargo of frozen goods is about equivalent to the payload of the Qantas Boeing 747 aircraft.

To date, the large advances have been in numbers of passengers carried, but cargo is now receiving attention by air carriers. Expansion of cargo carriage is rapid, although the total quantities are still a small proportion of world totals.

The special feature of air transport is speed — even the most distant airport is no more than 22 h away from any other airport. Between major airports the time is no more than 12 h provided we are prepared to pay the special premium for supersonic travel. It is this feature of speed that is especially attractive to passengers and shippers of goods, and enables airlines to utilize the payload capability of their vehicles. Apart from other advantages, speed eases the problem of delivering perishables to their destination in good condition.

Perishable cargo and air transportation

The amount of cargo transported by air is increasing year by year, although total quantities are small compared with surface transport. Nevertheless, they are impressive because of the productivity of aircraft as transportation vehicles. For instance, a Qantas 747 can make more than 10 return trips to the U.K. in the time taken for a ship to travel one way.

Cargo of every variety is carried by air, but considering only perishable goods, quantities carried in 1979 were: chilled meat, 1350 t to the U.S.A. and the Middle East; chilled fish, 1150 t to Europe and the Orient; frozen lobster tails, 300 t to the U.S.A.; live eels, 200 t to Europe; and fruit and vegetables, 1340 t to Europe and the Orient.

Required environmental control varied from low temperature (−18 °C and below) for frozen goods, through chilled conditions (about 0 °C), to cool surroundings for general perishables such as eels, fruit and vegetables; for these goods, smells and spoilage result from exposure to heat.

This paper describes the methods of providing the required environmental control for low temperature and chilled conditions during air transport. Because of the speed of travel, conditions must be held for no more than 24 h, thus enabling special methods to be developed for safe carriage.

Firstly, however, I shall indicate how Qantas fits into the commercial world, and outline the payload capacity of the Boeing 747 aircraft operated by Qantas.

Qantas and the Boeing 747

Qantas Airways, in its 60th year of operation, flies 19 Boeing 747 aircraft from Australia to the U.K., Europe, Asia, New Zealand, the Pacific Islands, U.S.A. and Canada. With assets of over $750 000 000, and contracted aircraft purchases in 1980 and 1981 of $320 000 000, Qantas is one of Australia's largest organizations, rating perhaps 10th behind the giants such as Telecom, BHP and the State Electricity Commissions. On a world scale we are dwarfed by overseas airlines, the largest being some ten times our size; nevertheless, Qantas still rates about 20th in size and operations.

Quantifying our aircraft, the 747 cruises at 500 knots or 900 km per h. At take-off ex-Sydney for Honolulu, the aircraft weighs 365 t, fuelled for an 11-h flight; it carries up to 440 passengers, typically 35 t with their baggage, plus 14 t cargo. Our 17 passenger aircraft carry all baggage and cargo in the lower holds; for increased cargo capacity, two of the Qantas fleet are 'Combis' with the aft main deck compartment carrying cargo instead of 152 passengers and the payload comprising typically 24 t of passengers and 25 t of cargo.

Aircraft cargo and environmental control

The main bulk of Qantas cargo is carried in light-weight equipment with a 2438 x 3175 mm base. Some netted cargo is carried, but more and more use is being made of rigid containers 1525 mm high for lower holds, and 2440 mm and 3050 mm on the 'Combi' main decks. These containers have walls and ceiling either of 4.76 mm fibreglass or 1.02 mm aluminium alloy.

Containers are exposed to a wide range of conditions:

- temperatures at airports on our routes range up to 40 °C (summer in Sydney, Honolulu and Bahrein) and down to −5 °C (winter in London and Frankfurt). In flight, lower holds stabilize at 5 °C on long flights; the main deck rapidly stabilizes at 20 °C; and
- pressures vary between sea level values of 100 kPa and a 1.52 km equivalent, or 80 kPa on most flights.

Temperature-sensitive cargo is protected from exposure by insulated containers, and immersion in a cold envelope provided by the sublimation of dry-ice. This arrangement is quite amenable to analysis by heat-flow calculations, and actual tests have shown that the cargo can be delivered at its destination at much the same temperature as that when it was originally loaded into the container.

Analysis has shown, and tests have confirmed that it is vital to provide an air

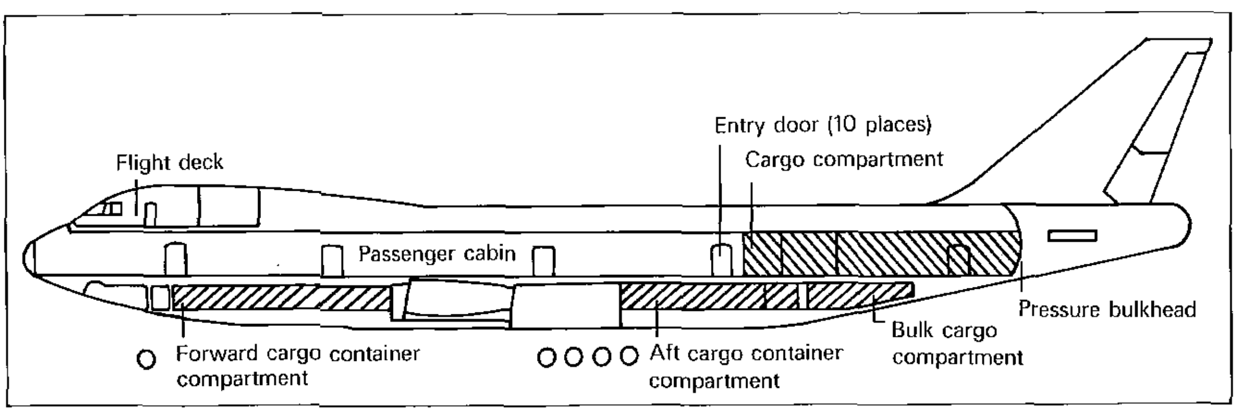

Fig. 1. Cargo compartments in a Qantas 747—238B 'Combi'.

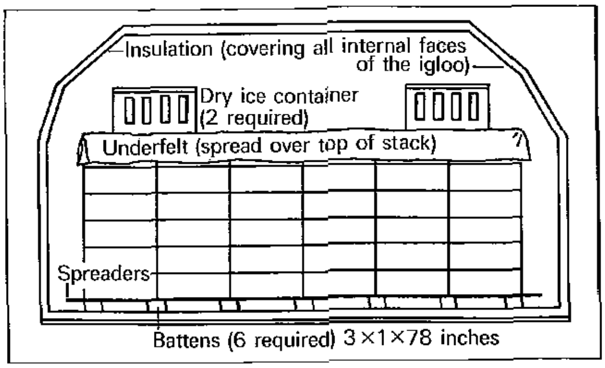

Fig. 2. Carriage of meat cartons in an insulated container.

space right around the cargo, maximizing contact between the cargo and the chilled surrounding envelope. We achieve this by loading on commercial-type pallets on the base of the container and leaving space between cargo, walls and ceiling.

Typically, containers are insulated with 50 mm polystyrene foam on the floor, four walls and ceiling. About 4 t nett cargo is loaded in each container, and 100 kg dry-ice is loaded on top, and insulated from the cargo. On a Sydney–San Francisco flight, a total time of 18 h, the cargo arrives with about 25 kg of dry-ice — a safety margin which allows for any delay en route.

Qantas has studied active temperature control, and has purchased refrigerated containers. These are kept in reserve for use only when extremely sensitive cargo is carried, since the passive system described above has been found satisfactory for chilled and frozen foods. However, some details of these containers may be of interest. The container is 3050 x 2440 x 1525 mm, with 50 mm foam polystyrene insulation protected by fibreglass skins. The refrigeration system is a Cold Cycle unit, using a 'cold-sink' of dry-

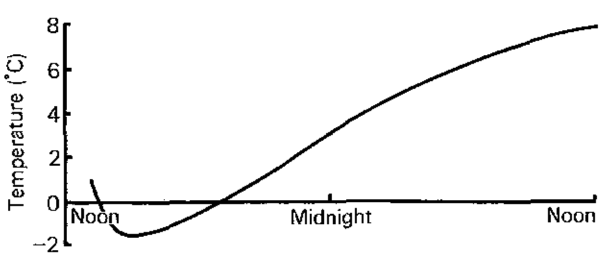

Fig. 3. Temperature control by dry-ice refrigerated and insulated S.A.K. container. (Outside temperature, 22 °C (average); inside temperature, 9 °C to start, 8 °C at finish; weight of dry-ice, 55 kg to start, 14 kg at finish.)

ice to chill and pump Freon R502 in a normal refrigeration cycle; the 'cold-sink' of carbon dioxide is also utilized to drive an air fan, circulating chilled air around the cargo and back to the refrigerator. The cargo hold itself is sealed to exclude carbon dioxide and so the cargo is not subjected to an atmosphere of carbon dioxide. Temperature control can be set to two levels, and has been proved by test using rapid-response thermocouples to maintain the following limits: chilled cargo, 0 °–7 °C; frozen cargo, not exceeding −15 °C.

Temperature limits and monitoring methods

Temperature limits specified for carriage of frozen and chilled cargo vary from nation to nation and authority to authority. These limits must be specified by food authorities, but, as an engineer, I would like to make the following observations.

Chilled food

Most nations specify 0° to 4 °C for chilled meats, although one (Cyprus) specifies −1.4° to −1.1 °C and one (West Germany) specifies +7 °C maximum for meat and +3 °C maximum for offal.

We have found that these limits are too narrow to be observed in practice, although 'proof' can be obtained by 'detuning' the method of measurement — this is discussed below.

I would suggest that 0° to 7 °C is attainable.

Frozen food

Most nations specify maximum temperatures, although some further increase is allowed for short periods (loading, unloading, etc.), e.g. −10 °C for fresh frozen meat, −12 °C for offals and −18 °C for deep frozen meat and offals. Qantas works to −18 °C as an overall maximum temperature, as the difference between these three temperatures is hardly attainable in practice. Incidentally, these temperatures are suspiciously close to soft conversions of 14 °F, 10 °F and 0 °F which might have been set originally because these appeared appropriate.

Temperature measurement

Following our study of portable self-contained instruments to record temperatures, we have chosen the Swiss Haenni Thermograph. This gives a rapid response to temperature changes and provides an accurate record of conditions.

Our study revealed an instrument which, we were told, is widely used in food shipment to monitor temperatures in case of dispute. However, we deemed this quite unsuitable for our purposes. The instrument's sensor was insulated from the environment being measured. In our check we stabilized the instrument at room temperature (about 20 °C), then placed it in a domestic refrigerator: 1 h later the thermograph reading was still 4 °C above the temperature of the refrigerator.

With such a 'detuned' instrument, it would appear that any required temperature could be stabilized by bringing goods to the correct temperature in a refrigerator over a period of about 5 h. Subsequently, a temperature trace would be obtained showing very narrow temperature limits during cargo carriage — this almost without respect to the actual temperatures experienced. In fact the outside layers could be exposed to +30° and +40 °C excursions, and these would record as mild blips if the exposure were no more than about half an hour or so.

Handling on airports

At present, shipments of cargo requiring refrigeration are brought to airport terminals in refrigerated trucks. Cargo is transferred to aircraft containers at the latest possible time, the container dry-iced to provide the 'cold-sink' and then transferred to the aircraft. Typical times for handling would be as follows.

- Transfer manually from refrigerated truck to container . . . 1 h.
- Period in container before loading on aircraft and closing door . . . 1 h.
- Pull down in aircraft lower holds to 5 °C in 4 to 5 h after departure . . . 4 h.
- Total flight time up to . . . 18 h.
- In container at destination . . . 1 h.
- Transfer from container to refrigerated truck at destination airport . . . 1 h.

Ambient temperatures in this process can reach 40 °C at airports and be down to 5 °C stabilized temperature in flight.

Sometimes, direct transfer from refrigerated truck to aircraft is not possible, or a cargo is transhipped at an intermediate airport with a long period awaiting for connections. When this happens, the cargo is transferred to airport refrigerators large enough to accept whole cargo containers.

Logistics of insulated/refrigerated containers

All transport industries are plagued by a partial one-way flow of goods, resulting in an accumulation of containers at destination, concurrent with a shortage at the originating port. Aircraft cargo transport is especially susceptible to this problem in the case of refrigerated cargo, and this problem is only partially alleviated by the more constant flow of cargo in each direction.

When using our special refrigerated containers (previously detailed) to carry general cargo, we have available an internal capacity of 8.5 m^3 compared with 10 m^3 for a normal cargo container of this size — a loss of 1.5 m^3. This is a serious loss of capacity, but more serious is the weight of 550 kg for refrigerated containers compared with 250 kg for normal containers, an increase of 300 kg. At an overall cost of the order of $100 each year to carry each excess kilogram, this increased weight represents a large cost which must be paid in charges by shippers.

Our solution to this logistics problem has already been mentioned, namely to install temporary insulation in standard containers. Foamed polystyrene without protection is installed at the originating port, and this must be discarded at destination because of soiling. Consequently the full cargo volume is available for the return service. At about $500 per container, a weight of 50 kg and with the insulation carried one way only, costs are considerably less than they would be if the more sophisticated units were used because these incur the weight penalty both ways, apart from the loss of cargo capacity on the return journey.

The future

Ideally, refrigerated containers should be loaded at the originating freezing point and discharged at the user's distribution point. This would require a single, self-contained refrigerated intermodal container for use on road/rail transport and air transport. In fact the Qantas refrigerated container would fulfil this requirement providing dry-ice is replenished at 40-h intervals. However, the prime costs of containers, plus return transport costs to the originating point, would seem to make this quite impractical. I can foresee that the present mode of transport will continue for some time — road transport to the airport, transfer to aircraft containers, then transfer to road transport at the destination airport.

A field which would seem to require some attention is the rationalization on an international level of temperature limits, based on a firm scientific/commercial foundation. Limits must, of course, ensure safe delivery of refrigerated cargo to the destination, but they must also be practical limits, really achievable in commercially viable operations.

Some expert advice seems to be necessary in the field of temperature measurement of refrigerated cargo. With a variety of temperature recording instruments available, there is a choice of units having various response rates to temperature excursions. Qantas believes a rapid response instrument is necessary; however, if we are advised that an instrument with less response is acceptable, our task of providing suitable environmental control is made much easier.

Transport and storage of refrigerated foods

Hypobaric intermodal containers

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Introduction

Hypobaric storage involves placing a fresh agricultural commodity in an environment in which temperature, humidity and total pressure are closely regulated. Also controlled is the rate at which air is changed in the storage area. These four factors act individually and in concert with each other to provide the proper environment for low pressure storage. No expendable materials such as gases or chemicals are required. Only energy to operate the system and a small amount of make-up water for the humidification system are necessary.

These environmental parameters mentioned are important because they affect the storage life of agricultural products.

Temperature

The respiration rate of plant materials and growth of spoilage microorganisms are directly related to temperature — the higher the temperature the greater the respiration rate of plants and the growth rate of bacteria. Chemical and enzymatic processes associated with the spoilage of foods are also greatly affected by storage temperatures. For these reasons it is usually best to store agricultural products at a temperature just above that at which cold damage occurs.

The hypobaric containers employ a 'cold plate' design which provides a more uniform temperature throughout the box than is possible with conventional refrigeration, where it is necessary to set the temperature several degrees higher than the optimum in order to avoid cold damage in the colder locations. A 1 °C difference between the highest and lowest temperature can be expected in a fully loaded hypobaric container.

Oxygen

Microbial growth and the aging processes of fruits and vegetables require oxygen. Oxidation processes, by which fats turn rancid and meat pigments change to unattractive colors, also depend upon a supply of oxygen.

Under low pressure storage, the oxygen level is almost directly proportional to the total pressure, i.e. if you halve the total pressure, you halve the partial pressure of oxygen. At very low pressures it is necessary to correct for the water vapour pressure, when calculating the partial pressure of oxygen. For example, at 667 Pa pressure and 1.1 °C, the storage environment for meat, the partial pressure of oxygen without correction for the vapour pressure would be 21% of 667 Pa or 140 Pa. With the correction, it would be 21% of 667 Pa–587 Pa (vapour pressure of water at 1.1 °C) or 16.8 Pa. By comparison, the partial pressure of oxygen at atmospheric pressure and the same temperature would be 21.2 kPa.

Humidity

One of the problems associated with storage is loss of moisture from the product to the surrounding air and the subsequent reduction in consumer appeal. The Freon-containing coils in conventional refrigerated containers, being several degrees lower than the container ambient air, condense out moisture from the air stream flowing over them. No provision is made to replenish this lost moisture.

By comparison, hypobaric containers rely on their cooled inner surfaces, which are only a degree or so colder than the product, for temperature control. Condensation is held to a minimum and the moisture that is lost through condensation and the vacuum pump exhaust is replenished by the humidification system.

Ventilation

Perishables produce carbon dioxide and other volatile substances which have an adverse effect on their storage life. These gases are present at higher concentrations within the commodity than in the surrounding air. They leave the commodity and travel into the air across the concentration gradient. The rate of movement through the air-filled pores of the commodity depends on the magnitude of the gradient, the total cross-sectional area of the pores and the ease with which gas molecules pass through the air-filled pores (gas mobility). Each of these three factors are influenced by hypobaric storage.

The concentration gradient may be increased by removing the noxious gases

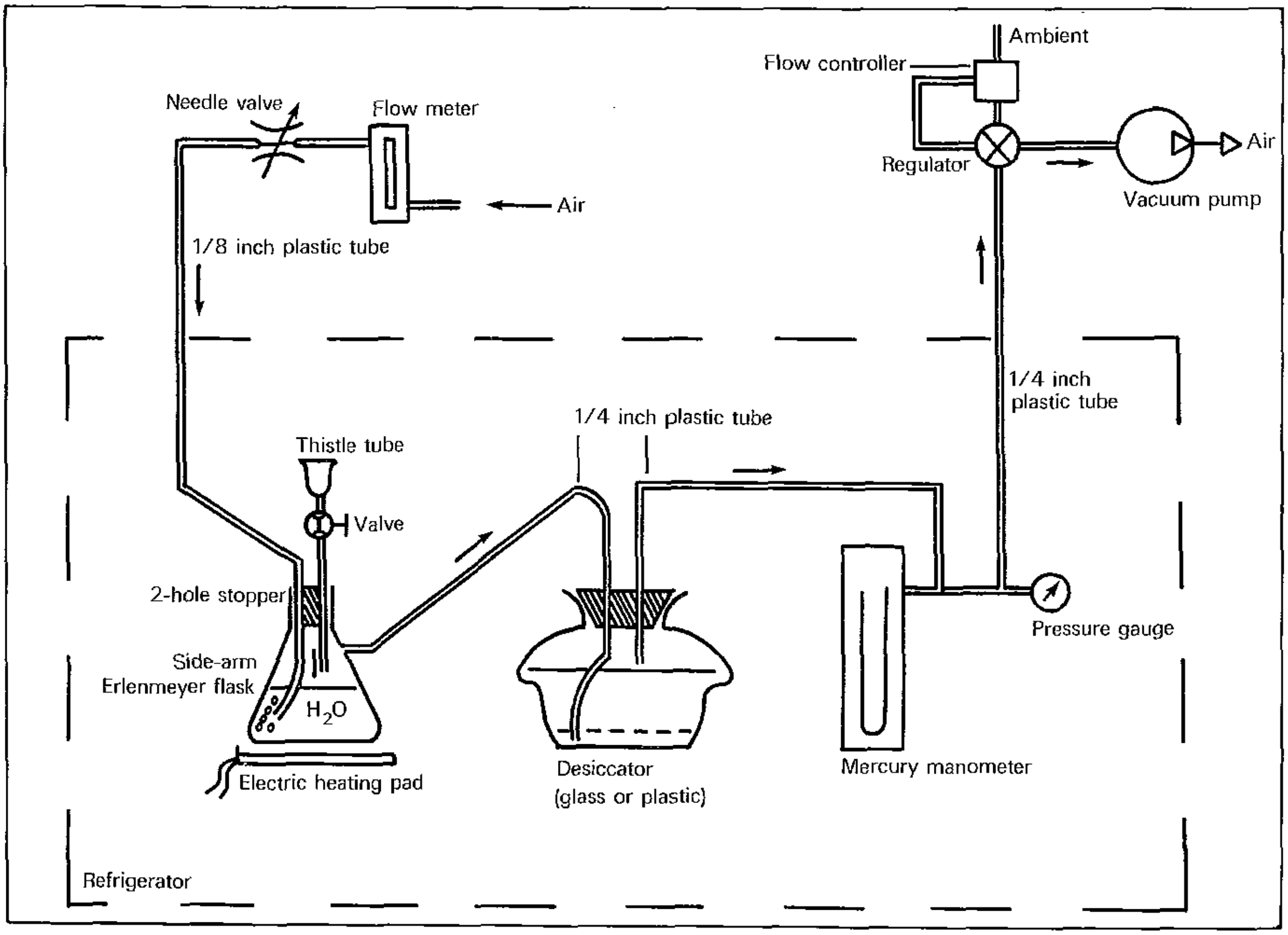

Fig. 1. Typical laboratory hypobaric system.

surrounding the commodity. The vacuum pump runs constantly during storage, providing the ventilation necessary to produce a greater concentration gradient.

The total cross-sectional area of all the pores available for gas exchange may be increased by increasing the humidity of the ambient air. For example, the pore area of an apple peel has been said to double when the relative humidity is increased from 75% to 95% (Fockens and Meffert 1972). Thus hypobaric storage is able to increase the total pore area by providing a higher level of humidity.

Gas mobility increases as the total pressure is lowered. Since there are fewer gas molecules per given volume, each molecule can travel a greater distance before colliding with another. The ability of each molecule of a noxious gas to diffuse through surface openings to the surrounding air is thus increased.

In summary, constant ventilation sweeps away from the surrounding air undesirable gas molecules which are aided in their movement from within the commodity by an increased concentration gradient, greater total surface pore area and greater gas mobility, all of which are inherent in hypobaric systems.

Fig. 2. A 40-foot Grumman Dormavac Intermodal Container.

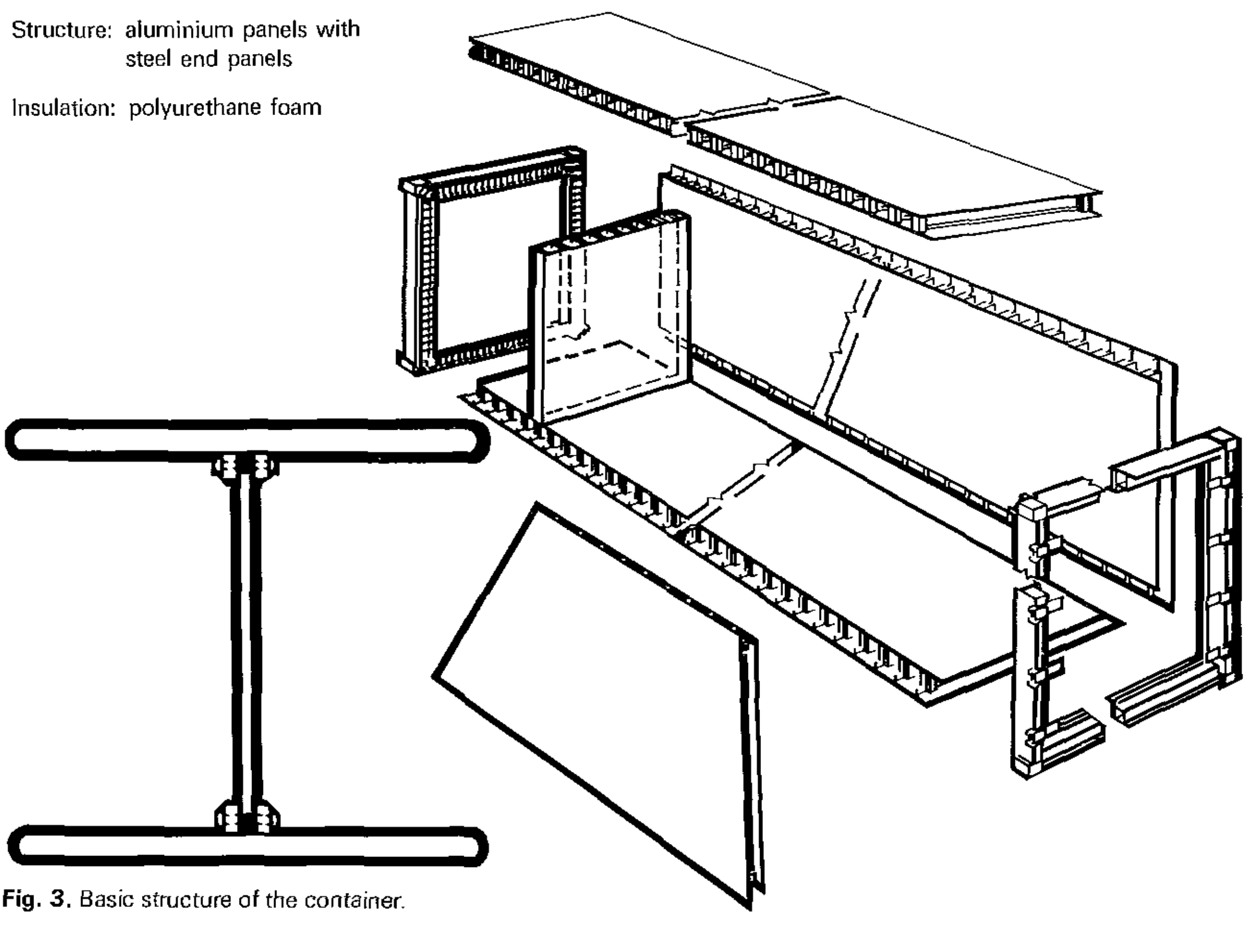

Fig. 3. Basic structure of the container.

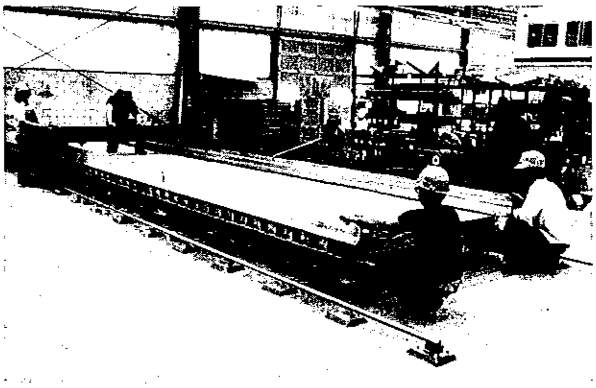

Fig. 4. Special 'I'-beam sections being welded into 40-foot panels.

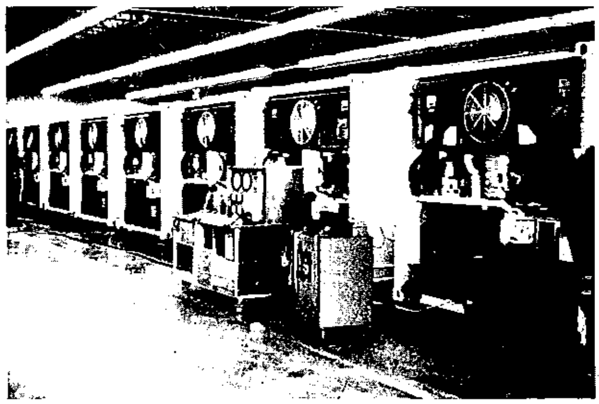

Fig. 6. Completed unit ready for final test.

Hypobaric systems

Fig. 1 shows how low pressure conditions may be achieved by means of small-scale laboratory equipment. All low pressure systems are basically the same, no matter the size. A conventional refrigeration unit maintains the desired temperature. An air-tight container capable of withstanding an external force of one atmosphere is evacuated by a constantly running pump. Pressure is controlled by a standard, off-the-shelf vacuum regulator. Metered, humidified air is bled into the storage chamber.

The commercially available, 40-foot intermodal container (Fig. 2) looks like any 40-foot refrigerated container and is made by the Dormavac Division of Grumman Allied Industries, Inc. of Long Island, New York. The basic areas in which the Dormavac container differs from other containers are in the structure and in the environmental system.

The container has been certified to the standards of the American Bureau of

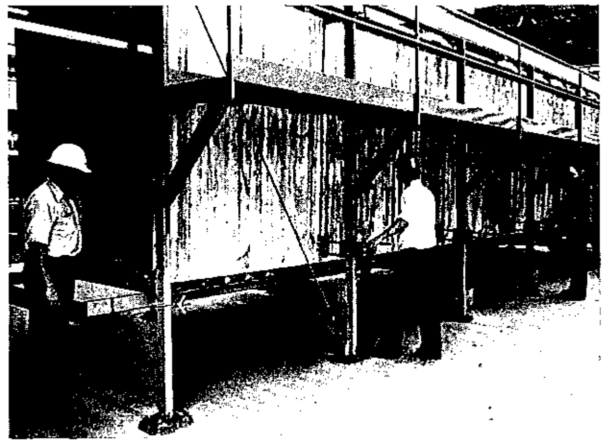

Fig. 5. Panels being joined in a mating jig.

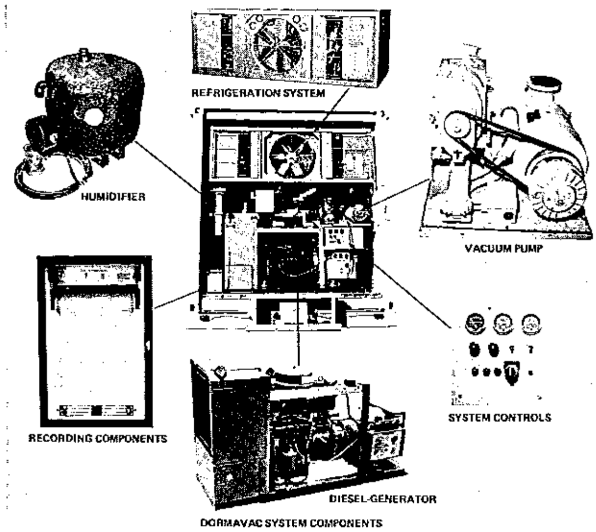

Fig. 7. Components of the mechanical system.

Shipping as well as meeting all of the criteria of the International Organization for Standards (ISO) and American National Standard ANSI MH 5.1–1971, with a safety factor of 1.5 times the design limit load. The structural strength was naturally a problem owing to the enormous forces on the walls when the interior is near vacuum. Keeping the wall thickness to a minimum to allow maximum cargo space was essential. Aluminum was chosen as the principal structural material primarily because of weight and a special 'I' beam was designed (Fig. 3). It consists of two extruded aluminum flanges and a fiberglass pultrusion web for thermal insulation. These 'I' beams are assembled and welded 54 to a side to form a 40-foot panel which becomes a side, floor or ceiling. Fig. 4 shows the 'I' beam sections being welded to make a panel. Fig. 5 shows the panels being joined in a mating jig and Fig. 6 shows completed units ready for test.

The mechanical system (Fig. 7) includes a standard York refrigeration unit modified slightly to accommodate the Freon-glycol heat exchanger, a vacuum pump, system controls, a generator driven by a Perkins diesel motor, and a humidifier boiler. Almost all items are standard, off-the-shelf items.

The water/glycol lines welded to the inner surfaces turn the walls, floor, ceiling and door into 'cold plates' which remove heat evolved from the product in addition to the heat which enters the box through the walls. This arrangement is shown in Fig. 8.

The vacuum/water subsystem is shown in Fig. 9. All but a very small percentage of the water in the air exhausted from the hypobaric container is recovered in the water-seal vacuum pump and after purification is returned to the boiler for reuse.

Test results

Many experiments have been conducted over the past 4 years by the Grumman Dormavac laboratory to evaluate the ability of hypobaric systems to extend the storage life of agricultural products. A variety of laboratory-sized chambers and, in some instances, 40-foot Dormavac containers were used in these studies. Following are some of the commodities tested and the results achieved.

Apples

A full container of Empire apples were picked at the preclimacteric stage and stored successfully for 239 days at 5.3 kPa, −1.1 to −0.6 °C and 95–98% relative humidity. They were still at the preclimacteric stage upon removal from the Dormavac. Fig. 10 shows the internal concentration of ethylene during the post-storage ripening period (Dilley, unpublished data). It is apparent that the fruit remains in the preclimacteric condition

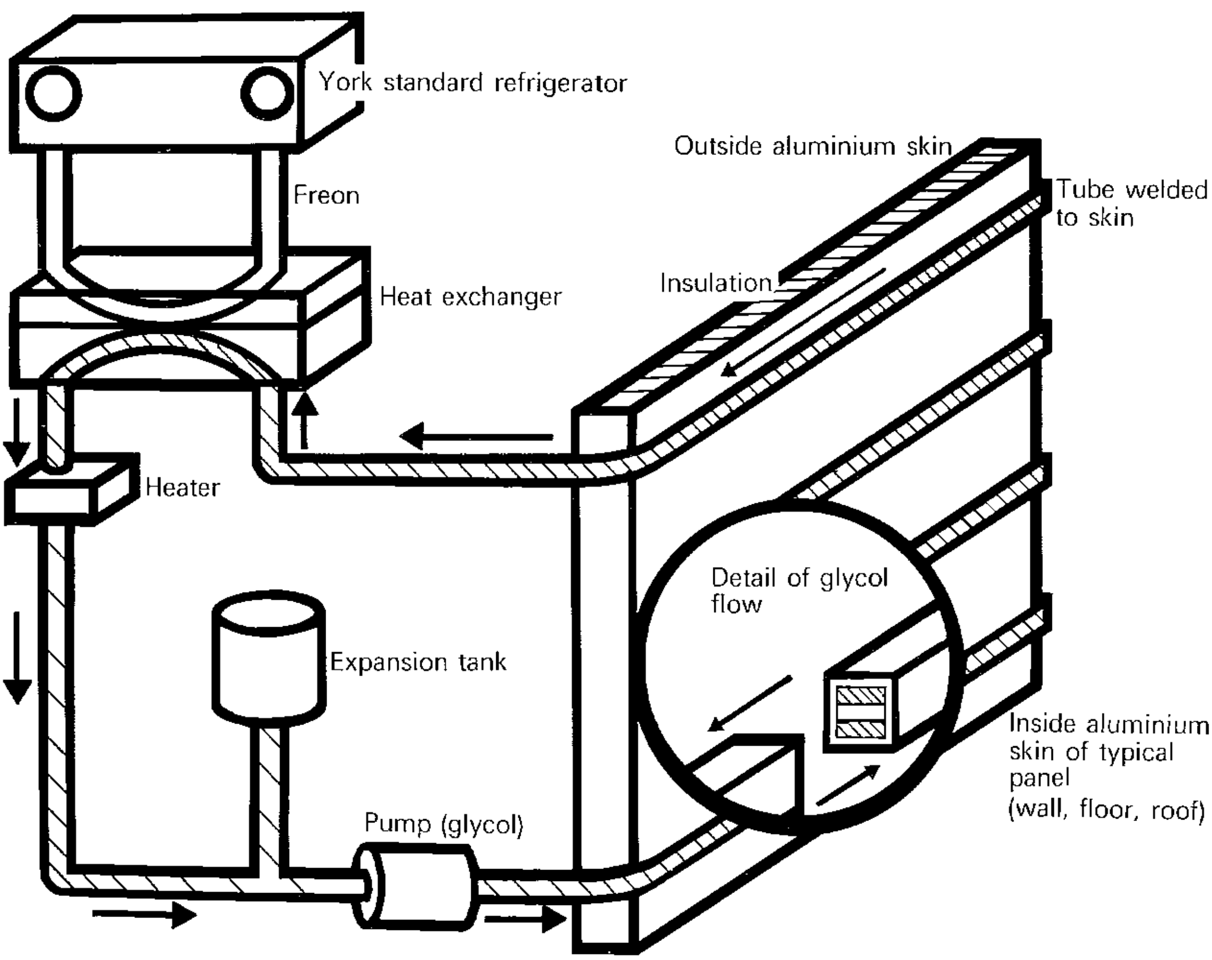

Fig. 8. Refrigeration subsystem.

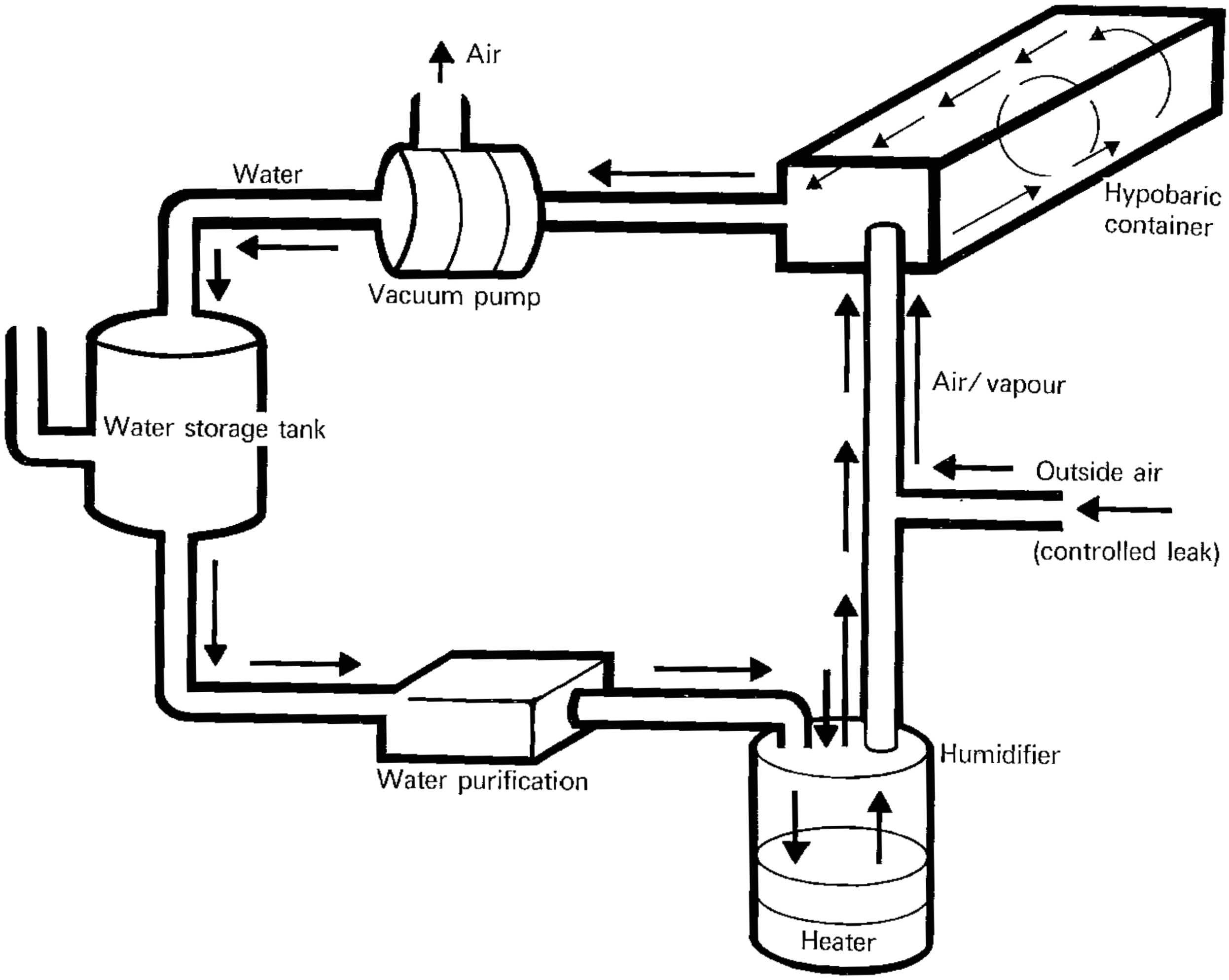

Fig. 9. Vacuum–water subsystem.

throughout the storage period, yet ethylene production proceeds at the normal rate once the fruit is removed for ripening. Especially significant is the fact that, although ethylene synthesis returns to normal following storage, the fruit's ability to respond to ethylene is impaired. It has been demonstrated that the time required for ripening of apples is extended after storage under hypobaric conditions (Dilley, personal communication). This delay in ripening can be used to advantage in the distribution of the product.

The comparison of taste, firmness and total soluble solids between hypobaric and controlled atmosphere apples is seen in Table 1. These hypobaric apples were stored for a total of 12 months after which they were still judged marketable.

Foliage cuttings

A laboratory test was conducted to determine whether several varieties of unrooted foliage cuttings could be stored for 23 days under hypobaric conditions. A secondary objective was to determine the optimum storage pressure. Although this symposium is concerned with the preservation of food, this experiment is mentioned here because hypobaric storage might possibly be employed to preserve food crop cuttings and rooted plants.

The results, as shown in Table 2, indicate that cuttings can be stored successfully under hypobaric conditions and that 4.0 kPa is probably the most suitable pressure. Table 3 shows the percentage of stored cuttings which were subsequently successfully rooted, thus providing further proof that 4.0 kPa is the optimum pressure for the storage of the varieties of cuttings tested.

Pork

A 20-foot experimental hypobaric container was used to determine the effect of low pressure storage on pork loins. A secondary objective was to determine

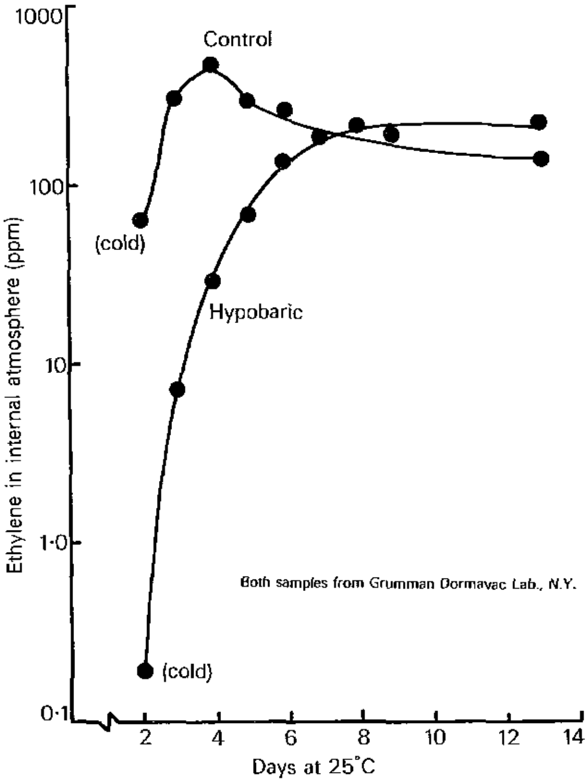

Fig. 10. Ethylene synthesis in Empire apples during ripening at 25 °C following hypobaric storage.

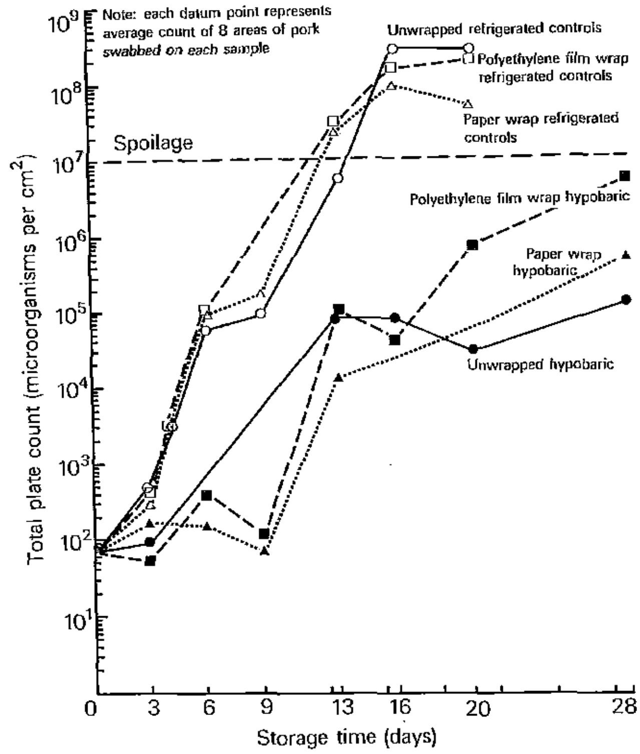

Fig. 11. Total plate count per cm^2 of pork loin surfaces.

whether pork should be wrapped and, if so, the most desirable wrapping material. In Fig. 11 total plate counts shown by pork stored under hypobaric conditions are compared with those of control loins (Jamieson 1979). An increase in storage life under low pressure storage is indicated, as is the advantage of paper wrap over polyethylene wrap.

Further tests on pork were conducted in Taiwan with a 40-foot Dormavac intermodal container. After 13 days of storage, the control meat had either reached the borderline of spoilage or had already spoiled. Meat stored under hypobaric conditions, regardless of treatment, had significantly lower bacterial counts. In Table 4 the plate counts for the various cuts of pork stored under each of the test conditions are listed.

Lamb

The first experiment to investigate the feasibility of storing lamb under hypobaric conditions was conducted jointly by the

Table 1. Comparison of firmness, total soluble solids and panel evaluation between hypobaric and controlled atmospheric apples.

Storage period (days)	Firmness (kPa) Hypobaric	Firmness (kPa) Controlled atmosphere	Total soluble solids (%) Hypobaric	Total soluble solids (%) Controlled atmosphere	Taste panel rating[A] Hypobaric	Taste panel rating[A] Controlled atmosphere
142	120	93.8	13.0	11.8		
142 + 6 days of shelf life	99.3	92.4	12.7	11.6		
158	112	80.7	13.6	12.3	31.3	41.2
158 + 4 days of shelf life	91.7	79.3	13.4	11.9		
239					38.4	46.5

[A] Rating scale: 23.5 perfect apple, 60 unacceptable.

Table 2. Evaluation at 12, 20 and 23 days of cuttings stored under hypobaric conditions

Variety	Pressure (kPa)	12 days storage	20 days storage	23 days storage
Green Peperomia	2.7	a.r.[A]	a.r.	Fresh and green
	4.0	a.r.	a.r.	Fresh, green, crisp
	5.3	a.r.	a.r.	Green but sl. limp
	101.3	Fresh	Fresh	Very dry, brown and brittle
Philodendron Cordatum	2.7	a.r.	a.r.	Fresh and green
	4.0	a.r.	a.r.	Fresh, green, crisp
	5.3	a.r.	a.r.	Green, sl. limp
	101.3	Beginning to dry out, brown edges & spotting	Dead or dying	Leaves paler green very limp
Marble Queen Pothos	2.7	a.r.	a.r.	Fresh and green
	4.0	a.r.	a.r.	Fresh, green, crisp
	5.3	a.r.	a.r.	Green, sl. limp
	101.3	Beginning to dry out, brown edges & spotting	Dead or dying	Leaves dry, some completely brown
Golden Pothos	2.7	a.r.	a.r.	Fresh and green
	4.0	a.r.	a.r.	Fresh, green, crisp
	5.3	a.r.	a.r.	Some brown spotting green, sl. limp
	101.3	Beginning to dry out, brown edges & spotting	Dead or dying	Leaves very limp, brown, 40% dried, brown spotting
Aphelandra	2.7	a.r.	a.r.	Limp
	4.0	a.r.	a.r.	Fresh, green, crisp
	5.3	a.r.	a.r.	Very limp
	101.3	Beginning to dry out, brown edges & spotting	Dead or dying	Leaves very dry, brown and brittle

[A] As received.

Table 3. Percentage of cuttings which were successfully rooted after planting

After being planted in soil for 4 weeks:
2.7 kPa: *c.* 80% rooted and survived
4.0 kPa: *c.* 100% rooted and survived. Grew at same rate as fresh cut cuttings
5.3 kPa: *c.* 73% rooted and survived
Control
101.3 kPa: all cuttings died.
Fresh
cuttings: *c.* 100% rooted and survived.

Armour Research Laboratory and Grumman Dormavac. A full container of fresh lamb was stored for 36 days and, after bacterial counts and organoleptic evaluations were made, the meat was sold at the going market price for fresh lamb. Shortly after that, a full container of lamb was transported from San Angelo, Texas, to Teheran. Although the trip took 42 days, the lamb was approved for sale as fresh by the Iranian Meat Institute and by other health-related agencies. Eight additional hypobaric containers carrying lamb from

Table 4. Total plate counts of various cuts of fresh pork after hypobaric storage for 13 days at 0 °C to 1 °C (Log number of bacteria per cm^2)

Test conditions	Bacon		Ham		Loins	
	Hypobaric	Controls	Hypobaric	Controls	Hypobaric	Controls
Paper wrapped, precooled	5.28	8.42	5.23	5.85	3.66	8.96
Polyethylene wrapped, precooled	5.91	8.34	3.89	7.66	3.20	8.08
Paper wrapped	4.15	7.49	5.46	7.68	3.97	7.81
Polyethylene wrapped	4.20	7.63	5.04	7.40	–	7.83

Initial count: bacon, 4.45; ham, 4.51; loins, 3.72.
Controls stored at 101.3 kPa, 0–1 °C.
Hypobaric samples stored at 1.3 kPa, 0–1 °C, 95% R.H.

Table 5. Total plate counts on meat after 40 days of hypobaric storage (reported in log numbers of bacteria per cm^2).

	670 Pa	800 Pa	930 Pa
Carcass, thighs	6.19	6.89	7.41
Carcass, ribs	7.80	4.67	6.11
Paper-wrapped ribs	5.82	6.71	6.85
Paper-wrapped loin	6.17	7.49	7.15
Paper-wrapped leg	5.30	6.87	7.55
Saran-wrapped breast	6.30	7.11	7.72
EVA[A]-wrapped breast	7.02	7.60	7.47
Average	6.37	6.76	7.18
Storage temp.: −1.1°C			

[A]Ethylene-vinyl acetate copolymer.

Australia to Iran could not be serviced by Grumman personnel because of political turmoil in Iran at the time. The containers malfunctioned causing a large proportion of the meat to spoil.

Laboratory efforts to improve the storage of meat, in general, led to the discovery that pressures lower than 1.3 kPa, the setting used in all full-container tests, gave better storage life. In one such experiment the relative effect of 670 800 and 930 Pa on bacterial growth was investigated. Table 5 shows the improvement in the suppression of bacterial growth as the pressure is lowered.

Other Commodities

Several additional agricultural products have been stored both experimentally and on a commercial basis. Full container loads of papaya have been shipped to both the east and west coasts of the United States. A full load of mangoes was shipped from Mexico to Japan. A container of fresh pork was shipped from South Dakota to Hawaii. A full container of potted tropical plants was shipped from Hawaii to Seattle. All of these products were commercially marketed as top-grade, fresh produce.

Laboratory studies to determine optimum storage parameters under hypobaric conditions have been completed on lettuce, strawberries, limes, sweet peppers, tomatoes, avocados, honeydew melons, ear corn, radishes, pineapple, broccoli, cauliflower, ferns, carnations, mushrooms, organ meats and fish.

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Developing a frozen seafood industry in Australia

By. J. F. Black

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We are remembering in this Symposium the first shipment of frozen meat to the United Kingdom in November 1879. The frozen seafood industry in Australia, ironically, began in reverse, with a shipment of prepared fish products from the United Kingdom to Australia in 1958, shortly after the introduction to the retail trade of products of the then new technology, quick frozen foods, which this year is 50 years old. A lot has happened since the late 1950s, and before dealing specifically with the development of supermarkets and consumer interest in frozen seafood, it must be stated that the wheel has turned and in some areas there is now substantial production in Australia and export of frozen seafoods.

In 1978–79 the value of the Australian lobster catch was estimated at $77 million, and the total export value of lobsters and prawns rose to a record of $214 million. The total fisheries' production was $268 million, thus leaving $54 million for the domestic market, very little of which was frozen. That dollar value covered wetfish, scallops, abalone, oysters and tuna, and consequently a further $88 million worth of frozen seafoods, primarily pre-packaged fish fillets and value-added product, was imported to satisfy the domestic demand.

For a country surrounded by water, we are not great fish eaters compared with other nations. The latest statistics from the Australian Bureau of Statistics show the total apparent consumption of fish in 1976–77 was 7 kg per head, of which only 4 kg was fresh or frozen. In comparison, the total meat consumption, including poultry, was 123.5 kg per head. Currently, the trend in fish consumption is up but we have a long way to go.

Referring again to the $88 million worth of imports, I read in October 1979 where the Government of New South Wales had decided to invest heavily in a fish-handling facility in the Wollongong–Pt Kembla area on the expectation that fishermen in the South Coast area could catch more fish to replace part of the imports. This, to my mind, is one of the greatest fallacies of the Australian fishing industry.

In 1972 I became involved with a proposed fishing group who had been told that my company sold a lot of seafood products. They came to see me and discussed the size of their vessels, the varieties of fish that they would catch, and how frequently they would land the catch; and that side of the venture looked encouraging. However, when it was further explained that my company sold fish products in packets, the conversation momentarily died, and then I was told, 'We can only catch the fish — you have to do the rest.' The 'rest' involves enormous expenditure. It requires a factory, filleting and skinning equipment, a complete processing line, freezing facilities, packaging lines and a large amount of cold storage. 'Why,' I asked, 'would my company want to do all that when a simple Telex to the United Kingdom, Canada, Japan, Europe or South Africa would land on my door-step packaged products ready for immediate delivery to the supermarket and, most importantly, already accepted by the consumer?'

Going back to the title of this paper, 'Developing a Frozen Seafood Industry in Australia', I must emphasize that before you can develop an industry, you must be sure you have a market and a marketable product. This Symposium commemorates the shipping of frozen meat to the United

Kingdom 100 years ago. A further 50 years elapsed until in 1928 an American mining engineer, named Clarence Birdseye, developed the art of quick freezing and in March 1930 commenced successful retail selling in Springfield, Massachusetts. There is a World Congress in Monte Carlo in June 1980 to celebrate the commercial viability of frozen foods around the world, and 1980 is 50 years after the introduction of Birds Eye frozen foods. I make no apology that the brand name, Birds Eye, will appear often in the remainder of this paper, for it was this name that was to start the development of frozen foods and subsequently a frozen seafood retail market here in Australia.

First Frozen Fish

Production of frozen vegetables began in Australia in 1949 but market acceptance of these products was slow. Possibly the limited range that was on offer was one reason for this. Frozen foods were launched in Melbourne with a product range covering a few vegetables and fruits — frozen seafoods were unheard of. Frozen Fish Sticks were introduced to the United States market early in the 1950s with the first volume sales recorded in 1953. Production began in the United Kingdom in 1955 with the name changed to Fish Fingers, but it was not until 1958 that Birds Eye Fish Fingers were imported into Australia from the United Kingdom. The raw material, cod, was identical with the United Kingdom's product but the breading complied with Australian regulations.

Consumers knew nothing of Fish Fingers: I recall working in small self-service stores on Saturday mornings, and with my Sales Manager on the public address system I would stand beside a very small freezer display cabinet and offer with each purchase of a 12-oz packet of Birds Eye Peas and a 10-oz packet of Birds Eye Beans, one free 6-oz packet of Fish Fingers. That was the start of developing a consumer market for a frozen seafood product. The range and number of brands gradually increased and the volume of sales rose making it viable to merchandise and advertise.

Failure first

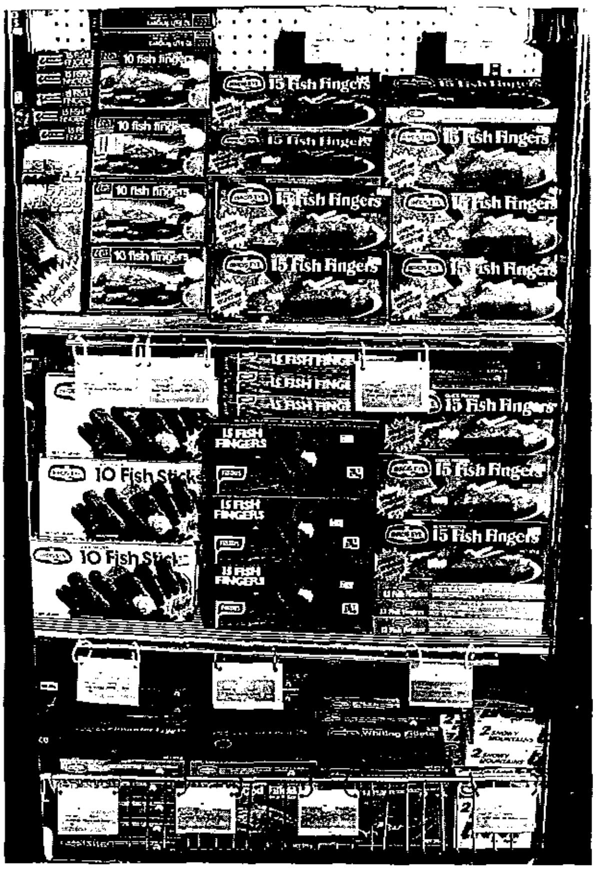
Earlier I mentioned Australia's export of prawns to a value exceeding $100 million. Years ago, I approached prawn exporters for a supply of export rejects which, when further processed, could be offered in consumer packs through supermarkets at fairly consistent year-round prices as against the massive peaks and very occasional troughs in the price of fresh prawns. In 1976 one major exporter decided there was market potential in the consumer area and put out packs of prawn meat, breaded prawns, and prawn cutlets, but under his own unknown label. This turned out to be a disaster, and following a quick management decision they decided to co-pack for Birds Eye. This line of seafood turned over more than $1 million in the first 6 months, and the total retail market of local prawns processed within Austalia would today have a turnover value of $5–6 million. Expansion of the market in the last year has been slowed down by a poor prawn season, but for all concerned the market remains viable if continuity of supply can be maintained.

Turning back to development, it was most unfortunate that the joint venture set up by Southern Ocean Fisheries and British United Trawlers in Albany, West Australia, went into bankruptcy so quickly. The study appeared sound: utilization of trawlers previously lying idle in Hull and Grimsby; the establishing of a modern processing plant at the water-side in Albany; and all the necessary equipment available for processing and packing for both catering and consumer markets. In addition, the joint venture company held a substantial order from Birds Eye for three varieties of fish fillets in consumer packs. There was quite a lot of publicity by Birds Eye announcing that Australian fish fillets would be sold in lieu of the imported product and that the standard, consistency of quality and price would be more than comparable to the imported product.

The end result was unfortunate. Not enough fish were caught of the right type or quantity to support the venture, and $7 million was lost in less than 2 years. This experience has shown that extreme care, including a complete feasibility study, particularly of fish type and continuity of supply, has to be assured before any money is invested, and most importantly there must be a market.

Future for frozen fish

What then is going to happen in 1980? Two companies, Safcol in Millicent, South Australia, and Edgell in Kelso, New South Wales, are building plants for value-added



Typical freezer display of frozen packaged seafoods in a Supermarket.

seafoods. The South Australian plant is primarily for fish fingers, while Edgell plan an extensive range of value-added products that will replace part of the current imports. Consumers will detect no difference as the same species of raw material will be drawn from existing overseas suppliers, but as fish blocks, not in the retail packaged form. The fish blocks are sized to an international standard giving us the flexibility to import from many overseas sources. The Kelso operation will cut or chop the blocks into portions which will then be breaded or battered and packaged.

Initially, all fish blocks will be imported, but here now is the opportunity for facilities such as at Wollongong and elsewhere on the Australian coast to catch fish, fillet them, press them into moulds, freeze and pack for possible sale to a local industry. I say possible sale, and stress again that we have established a market but must continue to offer to the consumer a product that appears and tastes identical to that which they have been purchasing over the last 20 odd years. The Australian raw material must match the quality and the consistent standard of the imported product, and be comparable in price.

I mention this specifically at a Symposium organized by CSIRO, as I see the fishing industry looking for further scientific help and guidance to ensure that their raw material is suitable. Gem fish could be a possibility, also blue grenadier.

The joint venture with the Polish company, Dalmore Trading, who intend to fish in the Antarctic region could also have potential.

Back finally to the supermarket. The photograph gives some idea of the marketing aids that we are using right now in one supermarket chain in New South Wales, and in March/April over 1000 supermarkets will be similarly merchandised.

In summary, demand has been established for frozen packaged seafoods. Some products are already being supplied from Australian resources; some products will be marketed from imported blocks with the value-added components of breading, battering, and packaging, coming from Australian resources; and at long last there is an opportunity to use Australian raw material, provided it can conform to the specifications that I have outlined.

Microbiological problems associated with refrigerated poultry

By T. A. McMeekin and C. J. Thomas
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Recently there has been a consumer trend away from frozen food products to equivalent fresh material and this is reflected in the ratio of production of frozen and fresh poultry. The latter are said to have superior sensory characteristics in addition to being more easily handled by the consumer.

With frozen poultry, microbiological problems do not occur until the defrosting and culinary stages of preparation. However, with fresh poultry the problem of microbiological spoilage places constraints on both the processor and retailer. The purpose of this paper is to examine the microbiological aspects of spoilage of chill-stored poultry and the following topics will be discussed:

- psychrotrophic microorganisms;
- contamination of the product with psychrotrophs;
- development and metabolism of psychrotrophs on the carcass; and
- evaluation of spoilage and prediction of shelf life.

The last topic is most relevant to this session of the Symposium. However, some consideration of the others is worth while as it is necessary to have a knowledge of the organisms involved and the mechanisms of contamination and spoilage if a product with an adequate shelf life is to be obtained.

Psychrotrophic microorganisms

The organisms of significance in the spoilage of chill-stored meats are the psychrotrophs. These are defined as those that grow well at refrigeration temperatures but have temperature optima greater than 20 °C (Eddy 1960). Within the group, a great number of genera are represented, but only a few are of importance in the spoilage of chill-stored poultry. These are *Pseudomonas*, *Alteromonas*, *Moraxella* and *Acinetobacter*. At temperatures close to 0 °C the pseudomonads will dominate on aerobically stored carcasses since they exhibit faster growth rates than their competitors. However, if the temperature rises then *Acinetobacter*, *Moraxella* and psychrotrophic enterics may also be recovered as part of the microflora present at spoilage (Barnes and Thornley 1966) (Table 1). Other work with beef, however, suggests that the pseudomonads continue to dominate at all temperatures up to 15 °C (Gardner 1965).

The spoilage association which develops on vacuum-packaged poultry differs from that on aerobically stored carcasses. The strictly aerobic *Pseudomonas* species are inhibited, the new set of ecological conditions favour the development of facultative and anaerobic organisms, and *Lactobacillus*, *M. thermosphactum*, *A. putrefaciens* and enteric types form a significant part of the spoilage association (Ogilvy and Ayres 1951; Wells *et al.* 1958; Shrimpton and Barnes 1960).

Contamination

Psychrotrophs may enter the processing plant on the feet and feathers of the bird or are added to the carcass from water used during processing. If cleaning practices are improperly carried out then large numbers of psychrotrophs may build up on plant and equipment (Mead 1976).

Several workers have enumerated psychrotrophs at various stages on the processing line and have reported that, after scalding, carcasses are virtually free from psychrotrophic contamination (Barnes 1960; Clark 1968; Notermans *et al.* 1977; Thomas

Table 1. Changes in the kinds of spoilage organisms on chickens stored at 1°, 10° and 15°C. (From Barnes and Thornley, 1966)

		Distribution of groups (%)												
Treatment	Total count at 20°C (nos/cm^2)	Total no. of strains	Micrococci	Gram +ve rods (catalase +ve)	Gram +ve rods (catalase −ve)	Streptococci	*Flavobacteria*	*P. putrefaciens*	*Enterobacteriaceae*	*Aeromonas* (pigmented)	*Pseudomonas* (non pigmented)	*Pseudomonas*	*Acinetobacter*	Unidentified
Initial	9.5×10^4	58	50	14	—	—	14	—	8	—	2	—	7	5
1°(10–11d)	6.0×10^7	40	—	—	—	—	—	19	3	—	51	20	7	—
10°(3–4d)	5.7×10^7	80	4	—	4	6	—	4	15	4	21	12	26	4
15°	6.2×10^7	69	—	4	2	8	—	4	27	6	9	2	34	4

Table 2. Incidence of contaminants on carcasses and in processing water at various stages of processing. (Data from Thomas (1979) represent mean of 8 samples.)

Sample	Viable count (22°C)	Number of psychrotrophs	Psychrotrophs (%)
Non-processed skin[A]	3.25×10^5	1.47×10^2	4.5
Scald water[B]	2.4×10^4	< 0.45	0
Fresh scald input	2.15×10^3	< 8	0.5
Fresh plucker input	1.02×10^3	9.6	1.0
Plucked carcass skin	3.08×10^5	2.38×10^2	0.07
Eviscerated carcass skin	1.44×10^5	5.08×10^2	0.35
Ice	6.80×10^3	7.70×10^2	11.3
Immersion washer water	4.07×10^5	2.39×10^3	5.8
Washed carcass skin	2.63×10^5	9.68×10^2	3.6
Immersion chiller water	1.97×10^5	6.59×10^3	5.3
Immersion chiller skin	7.58×10^4	5.55×10^3	7.3

[A]Water and ice counts: nos/ml.
[B]Skin counts: nos/16 cm^2.

1979). Subsequently, numbers increase with further processing and Knoop *et al.* (1971), Lahellec *et al.* (1972) and Thomas (1979) implicated immersion washer and chiller water as the major source of these organisms. The data of Thomas (1979) is shown in Table 2. These inputs resulted in carcasses with $\simeq 5 \times 10^2$ psychrotrophs cm^{-2} of skin which represents $< 10\%$ of the viable count at 20°C. This confirms the estimate of Barnes

(1976) which indicated that psychrotrophs varied from 1% to 10% of the viable count at 20 °C.

Although the literature contains a great deal of information on numbers and types of organisms at various stages of processing and much effort has been put into reducing levels of contamination, fundamental information is lacking on the mechanisms of contamination of meat surfaces. The first efforts to define the parameters important in contamination were made by Notermans and Kampelmacher (1974, 1975) for the immersion chilling part of the process. These workers concluded that contamination was a time-dependent process and that motile bacteria 'attached' much more readily to chicken skin than non-motile bacteria. Subsequently, Notermans and coworkers have reported similar findings for various other substrates including chicken muscle ± fascie (Firstenberg-Eden *et al.* 1978; Notermans *et al.* 1979). From a similar series of experiments, McMeekin and Thomas (1978) concluded that the time effect had a negligible influence on the level of contamination in comparison with the effect of the bacterial concentration of the chiller water. The relationship between bacterial retention and suspension concentration was linear with slopes of log/log plots close to unity. The important consideration from a practical point of view is to prevent a build up of contamination at any point during the immersion chilling process, as this will be reflected by proportionately increased numbers on the carcass.

Thomas (1979) further attempted to explain the mechanism of contamination by a microscopic examination of the relationship between contaminant microorganisms and chicken skin. The major points of interest to arise from this were as follows:

- scalding and plucking procedures removed the skin epidermis and exposed dermal tissue to colonization by microbial contaminants;
- the microtopography of the skin and a liquid film present on the skin surface were implicated as major factors in contamination; and
- these features also explain the ineffectiveness of carcass decontamination procedures.

Further microscopic work by Thomas (personal communication) may also have resolved the differences between the results of Notermans and Kampelmacher (1974, 1975) and McMeekin and Thomas (1978). The former used carcasses obtained immediately after plucking, whereas the latter used further processed carcasses. Microscopic examination of skin taken after plucking and immersed for various times revealed a progressive swelling related to water uptake. This opened capillary spaces on the surface into which motile bacteria may swim and become entrapped thus explaining the increases in motile types with time of immersion observed by Notermans and Kampelmacher (1974, 1975).

Nevertheless, a fundamental difference remains between the two groups of workers. Notermans and Kampelmacher (1974, 1975) use the term 'attached', which infers an active process on the part of the organisms, whereas McMeekin and Thomas prefer the term 'retained' indicating a passive non-specific process.

Later microscopic work by the Dutch group (Firstenberg-Eden *et al.* 1979) suggested that extracellular polysaccharides were important in the 'attachment' process, but this is refuted by Thomas (1979) who found no evidence for the involvement of polysaccharides in the retention of bacteria on chicken skin.

Development and metabolism of psychrotrophs

Mossel (1971) has drawn a clear distinction between contamination and the development of microorganisms in food. The fate of initial contaminants depends on various factors and for broiler carcasses, temperature of storage is the cardinal factor controlling the rate of spoilage of the carcass. Thus if the carcasses are stored at chill temperatures, the psychrotrophs mentioned above, which have the quickest generation times and shortest lag phases, will rapidly outgrow their competitors.

The layer material on the skin also plays an important role in the development of the microflora. It is from the constituents of this layer that the spoilage flora derive their nutrition and produce the end-products associated with spoilage. Electrophoretic and chromatographic studies have shown that the fluid film contains proteins (particularly serum albumin) and amino acids which provide an excellent growth medium and which are replenished during storage by leakage of material from damaged dermal tissue. Degradation of the actual skin is only rarely observed and then only after the carcass has spoiled. This concurs with work on other meat substrates which indicates that proteolysis of sarcoplasmic and myofibrillar proteins occurs only after spoilage which is a result of the degradation of compounds with low molecular weights. However, the pits observed in the layer material suggest that albumin may be degraded early in the spoilage process.

While substances of low molecular weight are utilized in preference to proteins, it appears that the spoilage flora also show preferential utilization of substrates within the low molecular weight group. Data suggests that the carbohydrate (particularly glucose) fraction of meat is first metabolized and that amino acids are utilized only on exhaustion of the carbohydrate reserve (Gill 1976). This work has so far been reported only for beef (Gill and Newton 1977; Newton and Gill 1978) and there are no data on the precise composition of the layer material on

Table 3. Off-odour producers as a proportion of the psychrotrophic flora on chicken tissues

Days	Breast muscle (%)	Leg muscle (%)	Skin (%)	
0	15[A]	9[B]	11[C]	—[D]
4	26	17	12	—
8	46	17	9	25
12	66	15	13	32
16	80	21	16	42

[A]McMeekin 1975; [B]McMeekin 1977; [C]Daud *et al.* 1979; [D]Thomas 1979.

Table 4. Volatile compounds associated with spoiled chicken breasts stored at 2° or 10°C. (From Freeman *et al.*, 1976)

Hydrogen sulfide	*n*-heptane
Methyl mercaptan	1-heptene
Dimethyl sulfide	Hepadine
Dimethyl disulfide	*n*-octane
Methyl acetate	Acetone
Ethyl acetate	Benzene
Methanol	Toluene
Ethanol	

chicken skin. However, several workers have suggested that preferential utilization of small molecular weight carbohydrates has implications for the keeping quality of meat and may be used to advantage to extend the shelf life of the product (Shelef 1977; Newton and Gill 1978). Once glucose has been depleted the spoilage flora begin to attack amino acids releasing ammonia and other odoriferous by-products. Therefore if additional glucose is available, metabolism of amino acids is delayed.

Much of the work on off-odour production relies on the excision of sterile muscle sections as spoilage substrates which can be inoculated with pure cultures of bacteria or mixtures to provide an indication of spoilage potential. This type of study has allowed characterization of the types and proportion of off-odour producers at various stages of spoilage and the consensus is that off-odours are produced by a consistently small fraction of the flora at any stage of spoilage (Table 3).

Studies on sterile substrates have also revealed the nature of the volatile compounds responsible for spoilage odours (Table 4, Freeman *et al.* 1976). Prominent among these are the volatile sulfides which are derived from the sulfur-containing amino acids methionine and cysteine. An important property of these compounds is that they are detectable at extremely low concentrations and odour thresholds. Characteristics of the three principal sulfides are shown in Table 5 (Herbert 1970).

Several groups of organisms are associated with the production of sulfide-like off-odours in poultry, particularly *Alteromonas putrefaciens* and the fluorescent pseudomonads (Barnes and Thornley 1966; Barnes and Impey 1968; McMeekin 1975, 1977; Daud *et al.* 1979). *A. putrefaciens* is affected by the pH of the substrate (Barnes and Impey 1968) and fails to compete with pseudomonads on breast muscle at pH 5.8 (McMeekin 1975). However, it is favoured in competition with *Pseudomonas* species when chicken carcasses are packed in impermeable films (Barnes and Impey 1968). A flora analysis based on the packaging experiments of Shrimpton and Barnes (1960) was reported by Barnes and Melton (1971). This indicated that carcasses wrapped in permeable polyethylene films spoiled owing to the growth of fluorescent and non-fluorescent pseudomonads, but the flora of carcasses stored in the impermeable film were dominated by *A. putrefaciens* (Table

6). This is to be expected because Thomas (1979) has demonstrated the development of the spoilage association in a liquid film on the skin and Fromm and Monroe (1965) have reported the pH of rinse water to be $\simeq$6.2–6.3. It is also of interest that production of sulfides by this organism could not be delayed by addition of glucose, as under anaerobic conditions it continues to metabolize cysteine even in the presence of glucose.

Evaluation of spoilage and prediction of shelf life

Numerous bacteriological, chemical and physical measurements have been proposed to evaluate the stage of spoilage of poultry, but the majority appear to have little predictive value. However, several attempts have been made to predict the shelf life of aerobically stored flesh on the basis of temperature history (Spencer and Baines 1964; Olley and Ratkowsky 1973a, b).

Spencer and Baines (1964) postulated a linear relationship between temperature and rate of spoilage in the range $-1°$ to $25°$C. This was described by the equation:

$$k_t = k_o(1 + ct),$$

where k_t is the rate of spoilage at temperature $t°$, k_o is the rate of spoilage at temperature $0°$, and c is a constant for linear response.

An alternative hypothesis was proposed by Olley and Ratkowsky (1973*a*). This suggested that the data fitted the Arrhenius equation in

Table 5. Organoleptic descriptions of various concentrations of volatile sulphides. (From Herbert, 1970)

Compound	Concn in aqueous soln (ppb)	Odour description	Concn in naturally spoiling fish muscle after 10 days at 0°C (ppb)
H_2S	40	Slight H_2S (Threshold value)	150
	80	Medium to strong H_2S	
$(CH_3)_2S$	0.50	Slightly sour trace of sulfide (Threshold value)	20
	0.75	Slight cabbage water	
	1.50	Strong sulfidy, byre like	
CH_3SH	0.05	Very slightly sour, (Threshold value)	120
	0.50	Slight cabbage water, leeks	
	2.00	Sharp, strong, stale cabbage water	
	100.00	Metallic, cooked meat, sulfidy	

Table 6. A comparison of the spoilage flora of chickens stored at 7° wrapped in oxygen-permeable film (A) and oxygen-impermeable film (B). (From Barnes and Melton, 1971)

Treatment of carcasses and storage time	Colony count at 1°C (organisms cm^{-2})	Total no. of strains	Distribution of strains				
		Film A[A]					
0 days	2.7×10^4	22	18	58	19	5	
8 days	4.9×10^6	21	5	92	1	3	
12 days	2.8×10^8	28	7	82	3		8
		Film B[B]					
0 days	2.7×10^4	22	5	63	9	19	4
8 days	5.2×10^5	23	12	31	42	3	12
12 days	6.6×10^6	26		3	69		28[C]
14 days	7.5×10^5	27		4	60		36
16 days	5.8×10^7	26		38	51		11

[A]Oxygen-permeable film (polyethylene).
[B]Oxygen-impermeable film (vinylidene chloride — vinyl chloride copolymer).
[C]Cocci, possibly unidentified streptococci.

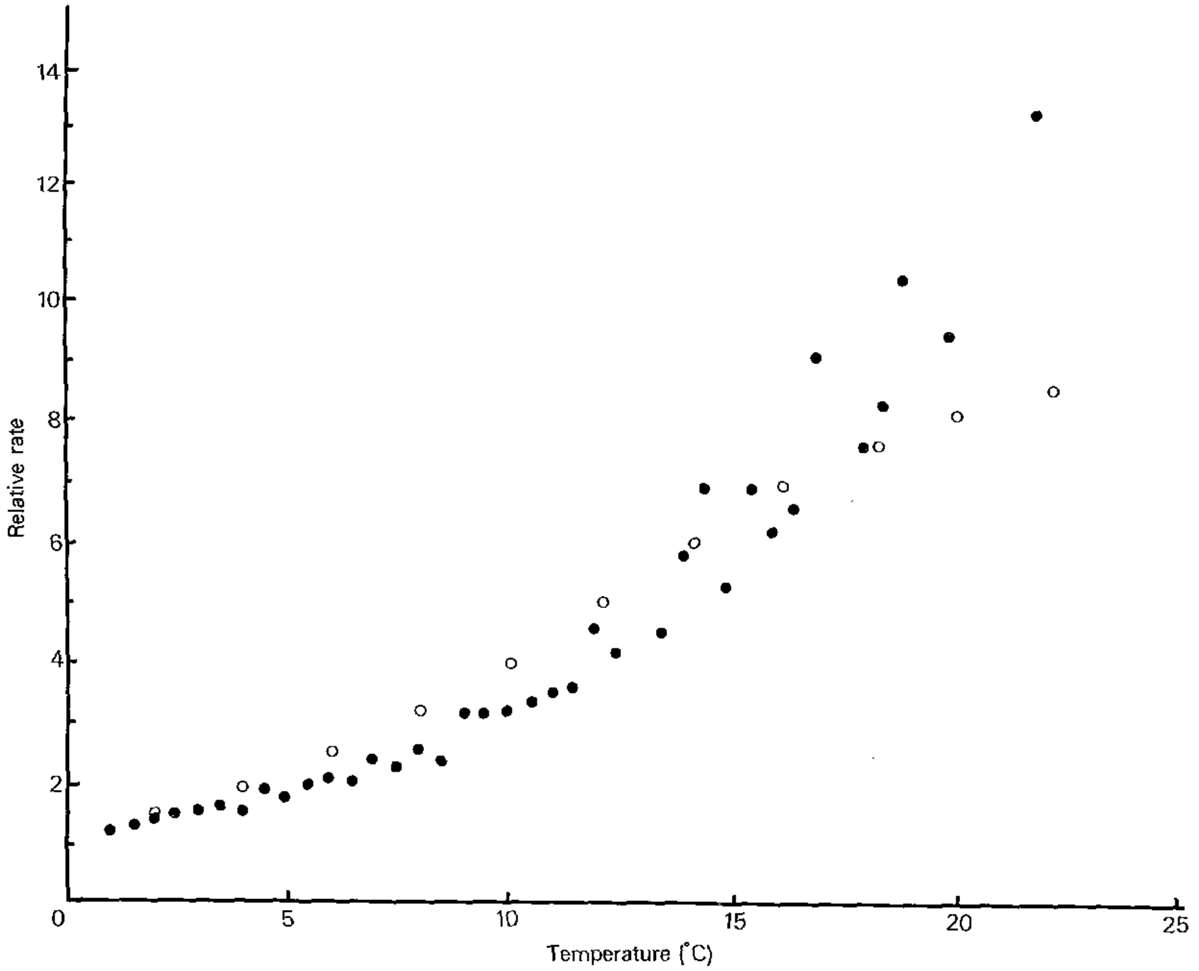

Fig. 1. Mean relative rates (●) of growth and metabolism of poultry storage bacteria (Data of Daud *et al.*, 1978) compared with relative rates (O) predicted by the general spoilage curve of Olley and Ratkowsky (1973*a*,*b*).

which spoilage rate was substituted for reaction rate. A relative spoilage rate curve (the OR curve) was constructed for 0–25 °C (Fig. 1), relative spoilage rate being the ratio of actual spoilage at any temperature to the actual rate at 0 °C.

The majority of the data sets used by Olley and Ratkowsky (1973*a*) in the construction of the general spoilage curve were based on fish spoilage. However, some data on meat and poultry were included and the results of statistical analysis suggested that the relative spoilage rate was fairly constant irrespective of the type of flesh or the nature of the test (chemical, physical, bacteriological or organoleptic).

Subsequently, Daud *et al.* (1978) found that the rate of spoilage of chicken tissues and the rate of development and metabolism of poultry spoilage bacteria as a function of temperature were more accurately described by the Olley and Ratkowsky (1973*a*) predictions than by the Spencer and Baines (1964) equation (Fig. 1). However, at temperatures above $\simeq$ 16 °C the poultry spoilage curve continues to rise and did not show the plateau effect predicted by the OR curve. The continued rise in relative rate in the region 15–25 °C may be expected from a consideration of the effect of temperature on the rate of growth of spoilage pseudomonads. Farrell and Barnes (1964) noted generation times of 2.2 h at 15 °C, 1.4 h at 20 ° and 0.89 h at 25 °. Most of the data in this temperature range refers to relative rates of growth of spoilage organisms and what remains to be proved is that an increased bacterial growth rate is reflected in a proportionately increased spoilage rate. Nevertheless, deterioration at temperatures between 15–25 °C occurs so rapidly that the product would be organoleptically unacceptable within 24 h.

Having determined the relationship

between spoilage rate and temperature it was necessary to have a method of measuring and summing the temperature history of the product. This was provided by an electronic temperature function integrator designed by Nixon (1971) (Tefimupot, Solid State Equipment, P.O. Box 30–089 Lower Hutt, New Zealand). In this device the sensor (a thermistor) is attached by a flexible cable to the circuitry and display unit. The OR curve has been incorporated into the circuitry which converts impulses received from the sensor, sums the temperature history and displays the integrated information as equivalent days at 0 °C.

Although the relative rates of spoilage of various substrates are similar, the actual time to reach a specified level will also depend on the nature of the substrate and the initial number of contaminants (Daud *et al.* 1978). A continuing plant quality assurance program is required to maintain initial contamination levels at those expected by adherence to good manufacturing practice.

The first step in predicting shelf life is therefore to estimate the expected keeping quality of the product. This can be done by incubation trials under specified storage conditions or calculated, as shown below, from a knowledge of the microbial ecology of the product.

Generation times (g.t) of psychrotrophs reported in the literature are very variable, e.g. Barnes and Impey (1968) reported the following generation times in brain-heart infusion both at pH 7.0: *Pseudomonas* group I 9 h; *Pseudomonas* group II 8.6 h; *Alteromonas putrefaciens* 7.8 h. On minced breast muscle the latter had a generation time of 12 h.

Mean generation time for the spoilage flora on broiler skin calculated from the data of Kotula and Kinner (1967) was 19.2 h at 1 °C (10.4 h at 5 °C) and from the data of Daud *et al.* (1979) it was 16 h at 2 °C (10.2 h at 5 °C). In the calculations shown in Table 7 this has been reduced to 8 h to build in a safety factor.

The initial bacterial load has been estimated from that attained in good commercial practice and may be varied according to the conditions pertaining in a particular plant. The plant in which these trials have been carried out consistently produces carcasses with counts of <5000 cm^{-2} which indicates a maximum psychrotrophic load of $\simeq 500$ cm^{-2} (Table 1).

To reach a spoilage level of $\simeq 10^8$ cells cm^{-2} 18 generations are required. Therefore if the carcass is stored at 5 °C (g.t.8 h), the minimum predicted shelf life will be: 18 x 8 = 144 h (6 days). The effect of initial bacterial numbers is illustrated in Table 7, e.g. if this is 10 000 psychrotrophs cm^{-2}, only 10 generations are required to reach 10^8 m^{-2}, i.e. 80 h (3.3 days) or a loss of 3.7 days shelf life at 5 °C.

It will be obvious from the above that even under excellent conditions of plant hygiene, storage at 5 °C is insufficient to guarantee an acceptable shelf life. Many retail chains specify a minimum keeping time of 7 days after arrival at their premises, to which must be added time elapsed during processing, storage at the plant and transport. Therefore it is necessary to produce a bird with a shelf life of 9–10 days and this can only be achieved by storage in the range 0–2 °C (Table 7).

Table 7. Minimum predicted shelf life (days) of aerobically stored carcasses (Assumes mean generation time of psychrotrophs of 8 h at 5 °C.)

Storage temp. (°C)	Relative spoilage rate	Total count of psychrotrophs		
		5000 cm^{-2} 500 cm^{-2}	10 000 cm^{-2} 1000 cm^{-2}	100 000 cm^{-2} 10 000 cm^{-2}
0	1.00	13.2	12.5	7.3
1.0	1.20	11.0	10.4	6.1
2.0	1.40	9.4	8.9	5.2
3.0	1.65	8.0	7.6	4.4
4.0	1.90	6.9	6.6	3.8
5.0	2.20	6.0	5.7	3.3
6.0	2.50	5.3	5.0	2.9
7.0	2.80	4.7	4.4	2.6
8.0	3.20	4.1	3.9	2.3
9.0	3.60	3.7	3.5	2.0
10.0	4.00	3.3	3.1	1.8
15.0	6.45	2.1	1.9	1.1

Table 8. Effect of decreasing storage temperature on the shelf life of poultry carcasses

Storage temp. (°C)	Relative spoilage rate	Shelf life (days)	Increase in shelf life (days) per 2°C drop in storage temp.
0	1.00	13.2	3.8
2	1.40	9.4	2.5
4	1.90	6.9	1.6
6	2.50	5.3	0.7
8	3.20	3.7	0.4
10	4.00	3.3	

The effect of reductions in storage temperature on shelf life can be calculated from Table 8. A noticeable feature is that close to 0°C, equivalent reductions in temperature have an increasing effect on shelf life. This would be predicted from theoretical considerations, e.g. the deviation from linearity of Arrhenius' plots of the growth rates of psychrotrophs close to 0°C (Harder and Veldkanp 1971) and the markedly increased activation energies reported by Olley and Ratkowsky (1973a).

Temperature function integrators offer the possibility of monitoring the complete temperature history of aerobically stored poultry through the entire processing, transport, and retailing sequence. They can be used to estimate the remaining shelf life of a product or identify weak links in the cold chain. It is important to note that relative spoilage rate information is available only for aerobically stored flesh foods at high a_w values, which spoil as a result of the activities of a predominantly gram negative microflora, particularly pseudomonads. The application of other environmental constraints such as high carbon dioxide levels (Ogilvy and Ayres 1951) or reduced a_w value (Scott 1937) which have a greater effect on the rate of microbial development near 0°C, and increase the relative rate of spoilage and invalidate the OR curve. Further work is required to determine the relative spoilage rates of vacuum-packaged products at different temperatures.

The instrument described is one of several now available and for further information on temperature function integrators and other devices the reader is referred to Olley (1978). Other devices include chemical indicators and permeation indicators. The most recent of these has been patented by Allied Chemical Corporation and is intended primarily for use with vaccines. It is based on a diacetylenic compound which reacts in the solid state as a function of accumulated time-temperature history to provide a sharp colour change. The reaction kinetics obey the Arrhenius equation and activation energies of different diacetylenes lie between 19 and 27 kcal mole which suggests that these may be useful GO-NO-GO indicators for foods. True temperature function integrators will also benefit from recent advances in the design and development of electronic information storage and retrieval devices. These will lead to the production of smaller and less costly units and their increased use in the food industry.

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Refrigerated foods in the supermarket

Can shelf life be measured?

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Sensory properties play a critical role in determining food acceptance. No matter how sound or beneficial a food might be nutritionally, it will not be eaten if its flavour is disliked. With a few exceptions, e.g. wine and some cheeses, the appearance, flavour and texture of food deteriorate with storage, and this deterioration usually renders food unacceptable before there is any significant physical or chemical breakdown. It is therefore vital that these sensory properties be maintained in peak condition until the food reaches the consumer. Shelf life has been defined as 'the period between manufacture and retail purchase of a food product during which the product is of satisfactory quality' (IFT 1974). But can this period be specified?

I aim to demonstrate that there is not, and never will be, a definitive solution to this time-honoured problem. The precise specification of shelf life based on sensory methods is an unrealistic aspiration because it overlooks inherent limitations of the human sensory system. This fact has escaped many food scientists and legislators. Nevertheless, a sensory method for determining shelf life will be proposed which, although still arbitrary, has greater practical potential than those traditionally employed.

Failure of the traditional approach

The traditional sensory approach to the measurement of shelf life, especially of frozen foods, involves the concept of the 'just noticeable difference' (JND; see Van Arsdel *et al.* 1969, p. 3) where trained observers are required to detect a difference between a control sample and a test sample. In the case of frozen food, the control sample is a product stored under conditions, e.g. $-30\,^{\circ}C$ or colder, which permit negligible change over the time period concerned. The test sample is identical to the control in all respects but for the temperature at which it is stored. By using a sensory difference test, it is possible to establish quantitatively whether a given storage regime has changed the test sample sufficiently for it to be reliably detected as being different from the control, i.e. whether the JND has been reached.

Unfortunately, the JND approach is mainly of academic interest and of little practical value to the food industry. The JND determination is artificially sensitive; a food may continue to be acceptable to consumers long after the JND has been reached (Gutschmidt 1974). But there is an even more fundamental objection to the use of the JND method. In the determination of shelf life, the small changes in sensory properties upon which the JND method is focused are not necessarily of *practical* relevance. For example, the JND approach reveals that green beans stored for 32 days at −8 °C are detected as significantly different from beans stored for the same period at −30 °C (McBride and Richardson 1979). But this finding is of no relevance whatsoever unless the *acceptability* of the beans stored at −8 °C has also been adversely affected. (It is conceivable, that some people may even prefer the sample stored at −8 °C over that stored at −30 °C).

It is the acceptability response, i.e. the degree to which a food is liked or disliked, which is pertinent in the assessment shelf life, not the discriminative response elicited by the JND approach. Pfaffmann (1978) reports that these two types of response are not only different conceptually, but that as sensory processes they are also independent neurophysiologically. Many food scientists fail to appreciate this distinction.

The measurement of acceptability

The acceptability response can be measured, but certainly not with the degree of precision and absoluteness desired by legislators. The method most commonly used is that of hedonic scaling (Peryam and Pilgrim 1957). This utilizes a 9-point category scale, where the extreme categories labelled 'Like extremely' (9) and 'Dislike extremely' (1) are symmetrical about the mid point, 'Neither like nor dislike' (5). Consumers readily relate to this scale without special training; they are asked simply to select the category on the scale which best describes their impression of a food. From these ratings a mean response score can be derived which then serves as an estimate of acceptability.

However, estimates so derived should not necessarily be taken at face value. For instance, in order to calibrate the acceptability scale, it is sometimes suggested that the mid point (5) on the hedonic scale could serve as a cut-off criterion, i.e. any product receiving a mean rating below 5 is no longer acceptable. But this notion is unrealistic. In a comprehensive survey of food preferences using the 9-point hedonic scale, Peryam *et al.* (1960) showed that there is substantial variation between products in intrinsic acceptability. Icecream, for example, received an overall mean rating of 8.3, while leafy green vegetables were scored as 5.0. Clearly, it would not be legitimate to propose the mid point as a general acceptability cut-off. If an icecream product were scored as low as 5.0, then it might well be reaching the lower limit of acceptability, whereas a green vegetable given the same rating would be in prime condition. Besides these differences between products, there are also differences between consumer groups: those who assess food on a regular basis in the laboratory are apt to be more critical and give lower ratings.

These considerations lead to the realization that *there are no absolutes in the measurement of acceptability*. Acceptability ratings are notoriously unstable. They depend upon past experience, conditioning and context, as well as the psychological and physiological state of the respondent. Therefore failure to measure acceptability in any 'absolute' sense is not due to shortcomings in methodology, but rather to the inherent, chronic variability in the human sensory system.

Recognition of this lack of absoluteness in sensory scaling has led to tests which measure only *relative* differences in acceptability. In this format, two or more products are presented side by side and the acceptability of each is rated on a hedonic scale. For instance, in a shelf-life study a control sample (say a product stored for 30 days at −30 °C) might be presented alongside a test sample, e.g. a product stored for the same period at −12 °C. Of course the products are not labelled 'control' and 'test', but the comparison is implicit if not explicit. Statistical analysis is applied to check whether the mean acceptability score accorded the test sample is significantly different from the control.

This side-by-side evaluation is commonly used in the food laboratory and is often recommended (e.g. Peryam 1964; Dethmers 1979). Its reliance upon acceptability ratings, not discriminations, makes it a considerable advance over the JND approach, but regrettably it still shares a major defect with the JND method – it, too, is artificially sensitive. Consumers do not, as a matter of practice, compare two variants of the same product side by side. The consumer evaluates foods at meal-times where the only comparison possible is against a remembered level of quality. Also, the quality assessment is usually incidental rather than intentional. So the side-by-side evaluation, like the JND technique, is liable to give an overly conservative estimate of shelf life. This is the dilemma of shelf-life assessment: it is not possible to measure acceptability in absolute terms, yet when measured purely in relative terms the estimates are over sensitive. Is there a compromise?

Toward a more valid measure of shelf life

Recent work at this laboratory has shown that there may be a satisfactory compromise. Instead of requiring respondents to make side-by-side assessments of acceptability, each respondent is restricted to the evaluation of a single sample. This design more closely simulates everyday consumer assessment. It does require more respondents; if there are three storage treatments to assess, then three separate matched groups of respondents are needed. However, this disadvantage is compensated for by the increased practical validity of the estimates obtained. If one of the storage treatments is a control (e.g. −30 °C), application of a one-way analysis of variance will establish whether there is a significant difference between the control and the other storage treatments. Statistically, this is a less sensitive approach than the side-by-side design, but then this is desirable. Here it is more likely that statistically significant differences, if obtained, are also of practical significance.

An empirical example

At this laboratory a study is under way into the shelf life of two quality grades of sultanas (graded first and second quality on the basis of size and colour). Before storage trials commenced, the initial acceptability of each grade was assessed using the hedonic scale. The two designs described previously were compared: single evaluation and side-by-side evaluation.

In the single evaluation, the acceptability of the two grades of sultanas was evaluated by two separate groups of 21 respondents, only *one* grade per group. Mean scores are given in Table 1. Although the score for first grade (7.33) is slightly higher than the score for second grade (7.00), an unpaired 't' test shows this difference is not statistically significant (t = 0.96, df = 40).

In the side-by-side evaluation a few days later, the same two grades of sultanas were assessed by the same 42 respondents who had taken part in the single evaluations. The mean scores are given in Table 1, but in this case the difference between grades *is* statistically significant (unpaired 't' test, t = 2.23, df = 82, $P < 0.05$). The products, the respondents, and the statistical analyses are identical in the single and side-by-side evaluations, so how has this curious discrepancy arisen?

When samples are presented side by side, respondents can discern very slight differences in acceptability. No matter how insignificant these differences might be, some respondents feel compelled to record their discriminatory ability. Thus in the comparison of the first and second grade sultanas, if first grade is rated as 7, then the next lowest score available for second grade is 6, a whole point lower. If the real difference in acceptability is small (as the single evaluation suggests) then side-by-side presentation accentuates the difference. This phenomenon is an example of a *range effect* (Poulton 1975, 1977). Range effects are prevalent whenever quantitative subjective assessments are used.

Table 1. Mean hedonic scores for two grades of sultanas assessed either separately or side by side

Grade	Single evaluation	Side-by-side evaluation
First	7.33	7.12
Second	7.00NS	6.55A

NS, No significant difference.
A, Statistically significant ($P < 0.05$).

Implications

To draw a hypothetical analogy with the shelf-life assessment of frozen food, suppose that first grade in the above example corresponds to a product stored at −30 °C for a given period (the control sample), while second grade corresponds to the same product maintained at −12 °C for the same period (the test sample). The side-by-side evaluation would have it that the limit of shelf life has been reached, because the mean acceptability scores are significantly different. However, this difference would certainly not be significant in practice. It is spurious because it is not replicated in the single evaluation approach, the approach which more closely simulates ordinary consumer assessment. Thus in this analogy, if a consumer were to purchase a product unwittingly that had been stored at −12 °C instead of −30 °C, it is highly improbable that any difference would be noticed. Only when a statistically significant difference is obtained in the single evaluation does it become likely that the consumer will notice a decrement in quality and perhaps be dissuaded from buying the same brand again.

In caution, it should be noted that if a food is prone to rapid deterioration during storage, then it is advisable to play safe and accept the more conservative estimate of shelf life obtained from the side-by-side evaluation. However, most processed foods, including frozen foods, deteriorate slowly during storage and for these the single evaluation technique provides a more valid measure of that elusive concept, practical shelf life.

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