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The Chill Chain "from Carcass to Consumer"

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ABSTRACT

To provide safe meat and meat products of high organoleptic quality, attention must be paid to every aspect of the chill chain. The process commences with the initial chilling of the freshly slaughtered carcass and continues through to the storage of the chilled retail portion within the home. Within the chill chain are two different categories of refrigeration processes. In the first group are those such as primary and secondary chilling, where the aim is to change the average temperature of the meat. In the others, such as chilled storage, transport and retail display, maintaining the initial temperature of the meat or meat product is the prime aim. Failure to understand the needs of each process results in excessive weight loss, higher energy use, reduced shelf life or a deterioration in product quality. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Throughout the food industry food poisoning is a real and growing problem and meat one of its main sources. In addition to the effect of pathogens on meat, the growth of spoilage organisms leads to considerable waste and resulting financial loss. Refrigeration is the prime process controlling the growth of pathogenic and spoilage microorganisms. It is, therefore, very important to understand the refrigeration methodology that is required in each stage of the cold chain and the interaction between the stages. However, it should always be born in mind that there are novel alternatives to refrigeration. Abugroun *et al.* (1993) for example found that by using a combination of prerigor cooking and organic acid they produced a meat that was stable for 2 weeks at 22°C.

Removing the required amount of heat from a carcass is a difficult, time consuming operation but critical to the operation of the cold chain. Many of the subsequent processes are designed to maintain not reduce temperature. As a meat product moves along the cold chain it becomes increasingly difficult to control and maintain its temperature. Temperatures of bulk packs of chilled product in large store rooms are far less sensitive to small heat inputs than single consumer packs in transport, open display cases or in domestic refrigeration.

STAGES IN THE CHILL CHAIN

Primary chilling

The rate of heat removal and the resulting rate of temperature reduction at the surface and within the carcass has a substantial influence on the weight loss, storage life and eating quality of the meat produced. EU regulations require that all meat temperatures within the carcass must be reduced below 7°C before the carcass is further processed or moved from the chiller. Careful control is required to achieve conditions that will reduce the carcass temperature in the designed time cycle. This has to be carried out in the most economic manner taking into account weight loss and energy consumption. The design and operation must also consider the quality aspects. A summary of the conditions required for beef, lamb and pork are given in James and Bailey (1989), Swain and James (1988) and Brown and James (1992) respectively.

Using conventional single stage chilling regimes only relatively light, lean beef sides can be cooled to 7°C in the deep tissue during a 24 hour operating cycle, whilst evaporative losses are of the order of 2%. Pork is conventionally cooled overnight whilst lamb can be transported on the same day as slaughter. There is considerable interest in methods of shortening cooling times and reducing evaporative weight loss. All accelerated cooling systems are likely to be more expensive to install and operate than conventional plants. Therefore to be cost-effective they must offer substantial savings in terms of increased throughput and/or higher yields of saleable meat.

Most accelerated chilling systems rely on the maintenance of very low temperatures (–15 to –70°C) during the initial stages of the chilling process, by either powerful mechanical refrigeration plant or cryogenic liquids. Since any substantial freezing would produce increased drip loss on final cutting accelerated systems only maintain very low temperatures during the first few hours of the chilling process. One or more successive stages at progressively higher temperatures are employed with the final stage at or above 0°C to either remove the last of the heat or to allow for temperature equalisation.

Data from accelerated chilling systems for beef on cooling times, environmental conditions, weight losses or savings in weight loss where comparisons have been made with conventional carcass chilling systems are given in Table 1. All the accelerated chilling systems offer substantial increases in yield, 0.4 to 1.37% and the majority cool all but the heaviest sides to below 7°C in under 18 hours to achieve a 24 hour processing cycle.

Despite the considerable number of trials that have taken place and the cost advantages shown in feasibility studies, no commercial plants (with the possible exception of some systems in the USSR) are believed to have resulted from the work on accelerated beef chilling, possibly due to the risk of cold shortening.

Spray chilling

An alternative system in the USA that seems to be rapidly gaining commercial acceptance for beef, is spray chilling. Practical spray chilling systems have used a combination of air and sprays for the initial part of the chilling period and then air only for the rest of the chilling cycle. The sprays are not applied continuously but in short bursts, 90s at 15 minute intervals for the first 8 hours in one system (Allen *et al.*, 1987) and 30s at 30 minute intervals for the first 12 hours in another (Hamby *et al.*, 1987). Cooled water at 2 to 3°C is used in the sprays and in the latter 11 litres were delivered from 11 nozzles over the 30s period.

The main advantage claimed for the system is a reduced weight loss measured over 24 hours of 0.32% compared with 1.46% in conventional air chilling at 0°C. No data on cooling times were provided in the papers on spray chilling but the higher rates of heat transfer and the heat extracted to evaporate the added water should substantially reduce the chilling time. However, surface drying is an important factor in limiting microbial growth. If the surface remains wet there may be microbial problems that shorted shelf life and the addition of lactic or acetic acid has been found to reduce bacterial contamination (Hamby *et al.*, 1987).

TABLE 1
Beef Side Weights, Time to Reach a Maximum Meat Temperature of 7°C, Total Cooling Time, Weight Loss and Savings Over Conventional Chilling Systems

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

The chilling system conditions are:
1:3 h at −30°C with liquid nitrogen injection then gradually rising to a constant 0°C over 4 h
2:3 h at −19°C, 1.2 m/s followed by 17 h at 0.6°C, 0.75 m/s
3:3 h at −19°C, 1.2 m/s than gradually rising to 0.7°C over 7 h with air at 0.75 m/s
4:2.5 h at −19.5°C, 1.2 m/s, 3 h at −9.5°C, 0.75 m/s then rising to 0°C.
5:4 h at −29°C with liquid air
6:4 to 8 h at −15 to −10°C, 1 to 2 m/s then 6 to 8 h at −1°C, 0.1 to 0.2 m/s
7:6 h at −15°C, 0.5 to 1.5 m/s, then air gradually rising to 4°C over 12 h
8:1 h at 15°C, 2 m/s; 3 h at −12°C, 2 m/s then 17 at 4°C
9:6 h at −15°C, 2.3 m/s, then 15 h at 0°C, 0.5 m/s
10:5 h at −70°C then 19°C for 4 h and then 1°C for 15 h.

Novel cooling systems

A wide range of "novel" cooling technologies have been investigated for the primary chilling of pork carcasses.

James *et al.* (1983) investigated the use of air at −30 to −35°C to completely remove the required amount of heat from carcasses or sides in a 3 to 4 hour continuous chilling process. At that time the carcass could be band sawn into primals and either stored or transported. However, the process produced a decrease in tenderness in sides which required the application of electrical stimulation to overcome (Gigiel & James, 1984).

A way of reducing weight loss in chilling, storage and display is to increase the humidity of the air surrounding the food. Ice bank refrigeration systems produce high humidity air at a steady temperature close to 0°C, have proven advantages in storage of fruit and vegetables and their use in pig chilling has been investigated by Gigiel and Badran (1988). Such systems use refrigeration coils or plates to cool tanks of water and then build up 'banks' of ice. The chilled water is then used to cool and humidify air, by direct contact, which is in turn used to cool the product. The ice bank is energy and cost effective because it uses smaller compressors operating at full power and hence high efficiency. It can also be run overnight on off-peak electricity to build up the bank of ice for use the next day. This bank can then be used to overcome the high heat loads that are initially produced when the hot products are loaded into a chill room.

TABLE 2
Effect of Different Chilling Systems on Weight Loss, Drip, Cooling Time and Texture of Pork

Treatment	*Weight loss (%)*	*Drip (%)*	*Cooling time to 7°C (h)*	*Texture (J)*
Ice Bank	1.96	0.81	16.2	0.20
Delay + spray	0.95	0.97	17.7	0.20
Rapid + Ice Bank	1.53	0.88	16.1	0.21
Conventional	2.17	1.55	17.7	0.21
Ultra rapid				
-side	1.13	2.3	>7.0	0.18
-whole carcass	1.10	0.9	>8.0	0.21
Immersion	0.32	1.5	—	0.30–0.23

Most frozen poultry is initially chilled by being immersed in chilled water or an ice water mixture. The procedure is very rapid and the birds actually gain weight during the process. In trials on pork meat it has been vacuum packed before immersion in iced water or brine (Brown *et al.*, 1988). The vacuum packaging prevents water pick up and overcomes any possibility of cross contamination, both of which are considered a problem in the poultry system.

James *et al.* (1988*a*) and Gigiel *et al.* (1989) have compared some of the advantages and disadvantages of some of the more novel chilling systems when chilling pork (Table 2). Ultra-rapid and immersion chilling provide substantial gains in reduced weight loss and increased operational efficiency but would require large capital investment in purpose built plant, and can produce slightly tougher pork. Ice bank and spray are easier to integrate with existing systems and can produce significant weight savings without textural problems but still require an overnight chilling time.

Chilled storage

After chilling carcass meat is often stored for a period, ranging from a few hours to two weeks, unwrapped in a chill storage room. Meat primals and consumer cuts are often placed, wrapped or unwrapped, in trays or on racks in similar rooms. Low temperatures, minimal air movements and high relative humidities should be maintained around unwrapped meat in order to maximise storage life and minimise weight loss. With wrapped and unwrapped meat low velocities are also desirable to minimise energy consumption. Many storage rooms are designed and constructed with little regard to air distribution and localised velocities over products. Horizontal throw refrigeration coils are often mounted in the free space above racks or rails of product and no attempt is made to minimise the air velocity over the surface of unwrapped meat. Using a false ceiling or other form of ducting to distribute the air throughout the storage room can substantially reduce variations in velocity and temperature. Maximum air velocities of 0.75 and 0.4 m/s were measured over products in two store rooms having 30 cm deep false ceilings with slits to distribute the air throughout the rooms. The maximum temperature distribution measured within the rooms was less than 2°C. Using air socks improved air distributions can be maintained with localised velocities not exceeding 0.2 m/s.

Currently many retailers are requiring meat that has been aged for at least 2 weeks in chilled storage. This is best achieved by vacuum packing the primals before storage and maintaining the stores at a temperature close to, but not below the initial freezing point of the meat. There has also been increased use of controlled atmosphere retails packs to extend display life of meat. Since the packs tend to be large and insulate the products,

TABLE 3
Examples of Commercial Ham Cooling in the UK (James, 1990*b*)

Cooling method	*Weight*	*Thickness (cm)*	*Cooling time*		*Final temperature (°C)*
			To 20°C (h)	*Total (h)*	
In metal mould in chill room 17 to 6 °C, 0.2 m/s	6.4	19	12	1.4	15
In bag in chill room -3 to -10°C 0.3 n,4/s	7.3	18	9.3	21	2
In bag water shower then chill room at −1 then 3 to 5°C	6.8	18	6.6	14	5
In bag in ambient 15 to 7°C	6.8	20	—	13.5	24

effective pre-cooling before packaging is especially important if product quality is to be maintained.

Secondary chilling

Any handling operation, such as, cutting, wrapping, mincing, dicing, etc. will add heat to the previously chilled meat. It is important that a secondary chilling operation is carried out to remove this added heat before the product is bulk packed.

The aim of any precooking process for chilled foods is to ensure the destruction of vegetative stages of any pathogenic micro-organisms. However, there is always the possibility that some micro-organisms which produce spores will not be killed by the cooking process or that the food can become recontaminated. Therefore the temperature of the food should be rapidly reduced to below 7°C to prevent multiplication. In addition to the microbiological factors rapid reduction in product temperature aids retention of nutrients which is vital in systems such as cook-chill which are often used for the preparation of meals for the old, infirm and young people.

The majority of plants rely on air blast cooling systems for the chilling of precooked products or ready meals. In batch systems the products, packs or trays of cooked material are placed directly on racks in the chiller or on trolleys that can be wheeled into the chiller when fully loaded. Continuous systems range from trolleys pulled through tunnels to conveyerised spiral or tunnel air blast chillers.

Some meals and products are chilled using cryogenic tunnels however care must be taken to avoid surface freezing. Sous-vide and other imperviously packed products are often chilled by immersion in cooled water or other suitable liquid. With some cooked products such as large hams in moulds and sausages chlorinated water sprays can be used in the initial stages of cooling. Increasingly pie and ready meal fillings are pressure cooked and vacuum cooled. With many products an initial cooling stage using ambient air can often substantially reduce the refrigeration load in the cooling system.

Cooked meat

In many industrial cooking operations whole hams and large meat joints are often cooked and cooled in an intact form and then supplied to restaurants or retail shops where they are sliced before sale. James (1990*a*) has reported that in commercial operations methods are variable and processes cooling times can be long, up to 21 hours, and final temperatures high, 15 to 20°C (Table 3). Laboratory studies by Burfoot *et al.* (1990) showed that, for large (6.8 to 7.3 kg) hams, immersion cooling to be almost twice as fast as air cooling (Table 4). Vacuum cooling was an order of magnitude faster than immersion cooling however weight losses were substantially (over twice) higher.

TABLE 4
Cooling Times of Hams in Forced Air, Water Immersion and Vacuum Systems (James, 1990*b*)

Time (h) from	*Air, at 0°C, 1.2 m/s*	*Water, at 0°C*	*Vacuum, 5 mbar*
70 to 10°C	10.4	5.9	0.5
50 to 10°C	8.9	4.8	0.5

Pastry products

Although it should be a far simpler and quicker operation to reduce the temperature of small individual items, such as meat pies, many manufacturers allow an inadequate length of time for the cooling operation and the products are packaged at temperatures substantially above the storage value. Typically pie manufacturers allow 1 h for their single stage cooling operations and the core temperature of pies before packing can range from 17 to 37°C (Table 5).

The importance of achieving a minimum required air velocity around small products was clearly demonstrated by data obtained from cooling pork pies (Fig. 1). To guarantee that all the crust remained above −2°C on the unwrapped 400 g (70 mm high, 95 mm diameter) pies an air temperature of -1.5 ± 0.5°C was used. At this temperature a small increase in air velocity from 0.5 to 1.0 m/s reduced the cooling time by 85 m (almost 30%). Even at very high velocities (> 6.0 m/s) appreciable reductions in cooling time were still being achieved. In a high throughput baking line (> 1000 items per h) the 7% increase in throughput, which would be achieved by raising the air velocity from 6 to 10 m/s and consequently reducing the cooling time by 10 minutes, could justify the higher capital and running costs of larger fans.

Ready meals

In simple single-stage batch chilling systems the risk of surface freezing limits the lowest air temperature that can be used. The problem is complicated in two-compartment ready meal consumer packs which typically contain rice or pasta in one compartment, and a meat or fish based product in the second, because the thermal properties of the two items are often very different, and may be filled to different depths.

TABLE 5
Examples of Commercial Single Stage Cooling of Pastry Products in the UK (James, 1990*a*)

Product	*Type of chiller*	*Air*		*Cooling time (h)*	*Temperature*	
		Temp. (°C)	*Velocity (m/s)*		*Initial (°C)*	*Final (°C)*
Steak & Kidney pie (185 g)	Spiral	−11 to −17	0.5	1.0	90 to 95	17 to 20
	Spiral	−3	3 to 5	1.0	90 to 95	17 to 20
	Cold store	−30	< 0.2	1.0	90 to 95	30
	Ambient	20	0.3	1.0	90 to 95	37
	Ambient	20	3.5	1.0	90 to 95	32
Sausage rolls	Spiral	−11 to −17	0.5	0.8	93 to 96	10
Pork pie (4.5 kg)	Ambient	16 to 23	< 0.2	8.0	68	25

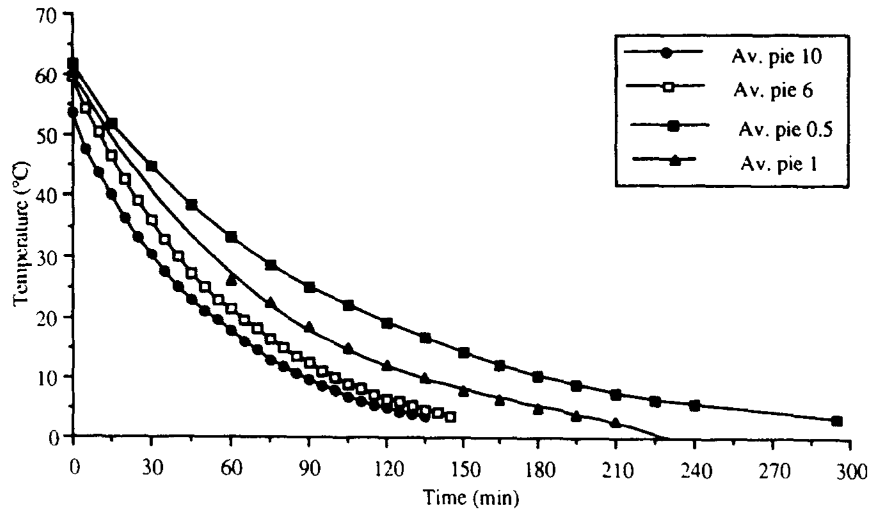

Fig. 1. Temperature at slowest cooling point in 400 g pork pies in air at −1.5°C and 10, 6, 1 and 0.5 m/s.

Using air at −10°C and a high velocity of 5m/s resulted in a cooling time of 34 minutes but substantial quantities of the product in both compartments were frozen (Table 6). Reducing the air velocity below 0.5 m/s more than doubled the cooling time and produced a situation where only a small area of the rice was frozen. With higher air temperatures the extent of freezing was reduced. At −5°C only a small amount of freezing occurred at 5.0 m/s and a cooling time of approximately 0.75 h was achieved.

Transportation

Effective temperature control during transportation is becoming increasingly important as shelf life of products is extended and legislation increased. Ship board transportation of chilled vacuum packed primals to distant markets is now common practice. However, to achieve the required shelf life, meat temperatures have to be maintained at −1 ± 0.5°C to avoid bacteria growth or freezing.

Most International Standard Organisation (ISO) containers for food transport are either 6 or 12 m long, hold up to 26 tonnes of product and can be 'insulated' or 'refrigerated'. The refrigerated containers incorporate insulation and have refrigeration units built into their structure. The units operate electrically, either from an external

TABLE 6
Effect of Air Temperature and Velocity on Cooling Time from 80 to 4°C in 30-mm Thick Two-Compartment Ready Meals (James, 1990*b*)

Air		*Time to 4°C (min)*	*Minimum temperature*	
Temperature (°C)	*Velocity (m/s)*		*Meat (°C)*	*Rice (°C)*
−10	5.0	34	−4.2	−3.8
−10	1.0	58	−1.4	−4.8
−10	0.5	78	−0.2	−2.2
−5	5.0	42	−2.2	−3.0

power supply on board the ship or dock or from a generator on a road vehicle. Insulated containers either utilise plug type refrigeration units or may be connected directly to an air-handling system in a ship's hold or at the docks. Close temperature control is most easily achieved in containers that are placed in insulated holds and connected to the ship's refrigeration system. However, suitable refrigeration facilities must be available for any overland sections of the journey. When the containers are fully loaded and the cooled air is forced uniformly through the spaces between cartons, the maximum difference between delivery and return air can be less than 0.8°C. All the product in a container can be maintained to within ± 1.0°C of the set point.

Refrigerated containers are easier to transport overland than the insulated types, but have to be carried on deck when shipped because of problems in operating the refrigeration units within closed holds. On board ship they are therefore subjected to much higher ambient temperatures and consequently larger heat gains which make it far more difficult to control product temperatures.

Overland transportation systems range from 12 m refrigerated containers for long distance road or rail movement of bulk chilled product to small uninsulated vans supplying food to local retail outlets or even directly to the consumer. Irrespective of the type of refrigeration equipment used the product will not be maintained at its desired temperature during transportation unless it is surrounded by air or surfaces at or below that temperature. This is usually achieved by a system that circulates moving air, either forced or by gravity, around the load. Inadequate air distribution is probably the principle cause of product deterioration and loss of shelf life during transport. Conventional forced air units usually discharge air over the stacked or suspended products either directly from the evaporator or through ducts towards the rear cargo doors. Because air takes the path of least resistance it circulates through the channels which have the largest cross sectional area. These tend to be around rather than through the product. If products have been cooled to the correct temperature before loading and do not generate heat then they only have to be isolated from external heat ingress. Surrounding them with a blanket of cooled air achieves this purpose. Care has to be taken during loading to avoid any product contact with the inner surfaces of the vehicle because this would allow heat ingress during transport. Many trucks are now being constructed with an inner skin that forms a return air duct along the side walls and floor, with the refrigerated air being supplied via a ceiling duct.

Control during local delivery is important if meat temperatures are to be maintained when the meat is transferred to a retail display. If carcass meat is fully chilled before transportation than thermal inertia helps in maintaining the desired temperature during transportation. Studies have revealed the difficulty of maintaining the temperature of consumer packs of chilled meat products in local delivery vehicles (James *et al.*, 1994). These vehicles have a limited refrigeration capacity and can be subjected to up to 70 door openings during an 8 hour delivery round in high ambient temperatures.

Retail display

The retail display of chilled food has been shown to be the weakest link in the cold chain. Lyons and Drew (1985) found that average temperatures in chill displays varied considerably from cabinet to cabinet, with inlet and outlet values ranging from –6.7 to +6.0°C, and –0.3 to +7.8°C. Malton (1972) found that air temperatures at a given point also fluctuate widely, from 5 to 20°C was not uncommon, with resulting large cycles in product temperature from 6 to 12°C.

The required retail display life and consequent environmental conditions for wrapped chilled products differ from those for unwrapped products. The desired chilled display life

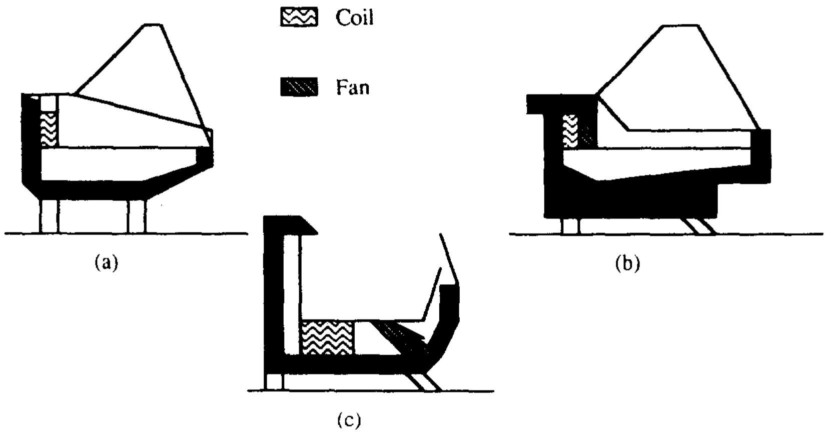

Fig. 2. Three types of retail display cabinet for unwrapped products.

for wrapped meat and meat products ranges from a few days to many weeks and is primarily limited by microbiological considerations. Retailers of unwrapped fish, meat and delicatessen products, e.g. sliced meats, pate normally require a display life of one working day.

Unwrapped products

Display cabinets for delicatessen products are available with gravity or forced convection coils and the glass fronts may be nearly vertical or angled up to 20°. Sections through three of the commonest types of delicatessen cabinet are shown in Fig. 2. In the gravity cabinet (Fig. 2a) cooled air from the raised rear mounted evaporator coil descends into the display well by natural convection and the warm air rises back to the evaporator. In the forced circulation cabinets (Fig. 2b and Fig. 2c) air is drawn through an evaporator coil by a fan and then ducted into the rear of the display, returning to the coil after passing directly over the products (Fig. 2b), or forming an air curtain (Fig. 2c), via a slot in the front of the cabinet and a duct under the display shelf.

Changes in appearance are normally the criteria which limit display of unwrapped foods with the consumer selecting newly loaded product in preference to that displayed for some time. Deterioration in appearance has been related to degree of dehydration in red meat (Table 7) and are likely to similarly occur in other foods. Apart from any relationship to appearance, weight loss is of considerable importance in its own right. The direct cost of evaporative loss from unwrapped foods in chilled display cabinets in the UK is in excess of 6.25 m ecu per annum.

James and Swain (1986) found that changes in relative humidity (RH) had a substantial effect with a reduction from 95 to 40% increasing weight loss over a six hour display period by a factor of between 14 and 18. The effect of air velocity on weight loss was confounded by that of relative humidity. Raising the air velocity from 0.1 to 0.5 m/s had little effect on weight loss at 95% RH but increased the loss by a factor of between 2 and 2.4 at 60% RH. Temperature changes from 2 to 6°C had a far smaller effect on weight loss than the changes in either relative humidity or velocity used in the investigations. Fulton *et al.* (1987) and James *et al.* (1988*b*) showed that fluctuations in temperature or relative humidity had little effect on weight loss and any apparent effect is caused by changes in the mean conditions.

TABLE 7
The Relationship Between Evaporative Weight Loss and the Appearance of Sliced Beef Topside After 6 h Display

Evaporative loss (g/cm^2)	*Change in appearance*
Up to 0.01	Red, attractive and still wet; May lose some brightness
0.015-0.025	Surface becoming drier; still attractive but darker
0.025-0.035	Distinct obvious darkening; becoming dry and leathery
0.05	Dry, blackening
0.05-0.10	Black

Wrapped products

To achieve the display life of days to weeks required for wrapped chilled foods the product should be maintained at a temperature as close to its initial freezing point as possible i.e. in the range –1 to 0°C.

Air movement and relative humidity have little affect on the display life of a wrapped product, but the degree of temperature control can be important especially with transparent, controlled atmosphere packs. During any control cycle, the cabinet temperature rises, heat enters the pack, the atmosphere inside the pack warms with consequent reduction in RH and increase in the surface temperature of the product. As the surface temperature rises so does its saturation vapour pressure (a factor controlling evaporation) and more water evaporates into the sealed atmosphere of the pack. If the cabinet temperature stabilised then evaporation would continue until the atmosphere became saturated. However, in practice the cabinet air temperature cycles and as it is reduced the wrapping film is cooled. If it reaches a temperature below the dew point of the atmosphere inside the pack then water vapour will condense on the inner surface of the pack. This film of water can obscure the product and consequently reduce consumer appeal. As the cycling process continues the appearance of the product deteriorates.

Although cabinets of the type described for delicatessen products can be used for wrapped foods most are sold from multi-deck cabinets with single or twin air curtain systems (Fig. 3). Twin air curtains tend to provide more constant product temperatures but are more expensive. It is important that the front edges of the cabinet shelves do not project through the air curtain since the refrigerated air will then be diverted out of the cabinet. On the other hand if narrow shelves are used the curtain may collapse and ambient air can be drawn into the display well.

To maintain product temperatures close to 0°C the air off the coil must typically be –4°C and any ingress of humid air from within the store will quickly cause the coil to ice up. Frequent defrosts are often required and even in a well maintained unit the cabinet temperature will then rise to 10 to 12°C and the product by at least 3°C. External factors such as the store ambient temperature, the sitting of the cabinet and poor pre-treatment and placement of products substantially affect cabinet performance. Warm and humid ambient air and loading with insufficiently cooled products can also overload the refrigeration system. Even if the food is at its correct temperature, uneven loading or too much product can disturb the air flow patterns and destroy the insulating layer of cooled air surrounding the product.

Transport from retail store to domestic storage

After meat or a meat product is removed from the retail display cabinet or butchers cold store it is subjected to a period outside the control of a refrigeration system whilst it is transported to the home. A survey (Evans *et al.*, 1991) has shown that consumers take

TABLE 8
Maximum Temperatures and Increase in Bacterial Numbers (Generations) During 1 h in a Car Followed by 5 h in a Domestic Refrigerator

Product	*Conditions*	*Maximum temperature*	*Pseudomonas*	*Clostridium*
Pate:	Ambient Car	25	1.5	0.4
	Cool Box Car	13	< 0.4	0
Raw Chicken:	Ambient Car	24	1.6	0.2
	Cool Box Car	4	0	0
Cooked Chicken	Ambient Car	28	1.8	0.7
	Cool Box Car	12	0	0
Sausage roll	Ambient Car	28	—	—
	Cool Box Car	12	—	—
Smoked ham	Ambient Car	30	—	—
	Cool Box Car	14	—	—

between 2 and 510 minutes to transport chilled foods from retail shops to their homes and up to a further 90 minutes to empty their cars and/or shopping bags and place the products in refrigerators. Typically chilled products would be placed in the refrigerator within 30 minutes of leaving the retail outlet with approximately 15% of the transfers taking 60 minutes or over. To investigate the affect of this period on temperature control, chilled products were purchased from a large retail store and placed in a pre-cooled insulated box containing eutectic ice packs or left loose in the boot of a car (Evans, 1994). Some product temperatures on samples placed in the boot rose to approaching 40°C (Table 8) during a one hour car journey. Most of the samples placed in the insulated box cooled during the car journey, except for a few at the top of the box which remained at their initial temperature. After being placed in a domestic refrigerator it required approximately 5 hours before the temperature was reduced below 7°C.

Predictions made using a mathematical model that calculated bacterial growth from temperature/time relationships indicated that increases of up to 1.8 generations in bacterial numbers (Table 8) can occur during this transport and domestic cooling phase. The model assumes that bacteria require a time to acclimatise to a change in temperature (the lag phase) and that no acclimatisation had occurred during display. If this rather optimistic assumption is not made then up to 4.2 doublings of Pseudomonas and growth of both Salmonella and Listeria were predicted. Very small increases in bacterial numbers (< 0.4 generations Table 8) were predicted when the insulted box was used due to the lower product temperatures.

In their survey Evans *et al.* (1991) found that a very small proportion of users used any form of insulated container when brining chilled foods home after purchase. Their work identified a clear need for consumer education in this area.

Domestic refrigeration

After purchase chilled meat and meat products food can spend a period between a few hours and many weeks in a domestic refrigerator. The refrigerator is probably the commonest domestic appliance with approximately 20 million United Kingdom households possessing at least one. Data can be found on energy consumption (Dlugoszewski & Minczewski, 1984) evaporator coil design (Karpinski, 1984) and the shelf life advantages to be gained with product stored in a special refrigerator containing a 0°C chamber with fan air circulation (Olsson, 1988). However, there appears to be little published data on temperature control within domestic refrigeration apart from that carried out in the United Kingdom (Evans *et al.*, 1991, Flynn *et al.*, 1992, James & Evans, 1992*a*).

TABLE 9
Time Taken (h) to Cool One Litre Packs of Orange Juice and Simulated Chicken Portions and Drumsticks from 20 to 7°C in Domestic Refrigerator and Fridge-Freezer at Different Control Settings

Setting	*Box plate refrigerator*			*Fridge-freezer*		
	1	*3*	*6*	*1*	*3*	*6*
Orange in door	> 18	11.6	7.52	> 18	15.92	3.95
Orange top shelf	11.6	5.71	5.0	18	9.02	2.43
Surface drumstick	4.73	2.22	1.63	18	5.3 to 8.6	1.75
Deep drumstick	5.33	2.52	1.93	> 18	5.4 to 8.6	1.86
Surface portion	5.22	2.22	1.93	18	5.1 to 7.5	1.83
Deep portion	7.73	3.42	2.23	> 18	5.9 to 8.0	1.98

James & Evans (1992*b*) used an array of 22 copper-constantan temperature sensors to continuously measure temperature distributions within examples of three of the most common refrigerator configurations, at different control settings and when subjected to different operations i.e. door openings and loading with 'warm' food.

To study domestic cooling 2 joints and 2 drumsticks of simulated chicken (Tylose) and 2 one litre cartons of orange juice that had all been equilibrated at 20°C were placed in the refrigerators and their temperatures monitored. Since areas of the fridge-freezer were close to or even above 7°C when it was operating at setting 1, many of the items monitored failed to reach 7°C during the 18 hour measurement period (Table 9). At setting 3 over 2 hours was required, in the box plate refrigerator, to reduce the surface temperature of the drumsticks and portions to 7°C compared with over 5 hours in the fridge-freezer (Table 9). A minimum cooling time of approximately 2 hours was required in either appliance even when operating at the lowest temperature setting of 6. With multiple door openings the average temperatures tended to progressively increase with each subsequent opening and the degree of temperature recovery reduced (Fig. 4).

In the studies carried out by Evans et. al. (1991) a miniature data logger, with three air and two product sensors, was placed into refrigerators in 276 households to record mean temperatures approximately every 5 minutes for a period exceeding seven days. The temperatures recorded in each individual refrigerator were analysed and an overall mean air temperature calculated for the whole refrigerator. The highest recorded mean temperature was 11.4°C, the lowest –0.9°C and the overall mean 6.04°C (Fig. 5). In 69.9% of refrigerators the warmest place was in the top and in 45.1% the coolest place was in the middle. In most refrigerators (86.9%) the range in temperatures between the highest and lowest mean was less than 5°C, with the greatest range being 12°C.

Frequency distribution of the percentage time spent between certain temperatures during the survey was calculated for all refrigerators. The greatest proportion of time (80.3%) was spent between 3 and 8.9°C. Only small amounts of time were spent above 9°C. Only 4 refrigerators (1.6%) in the whole survey operated below 5°C during all the monitoring period and 33.3% of refrigerators spent all their time above 5°C.

Manufacturers, distributors and retailers of chilled meat and meat products need to be aware off and take into account the time that their products will be in the hands of the consumer before consumption. The likely time-temperature history of the product during that time is a critical factor to be allowed for in any "best before" eating recommendations.

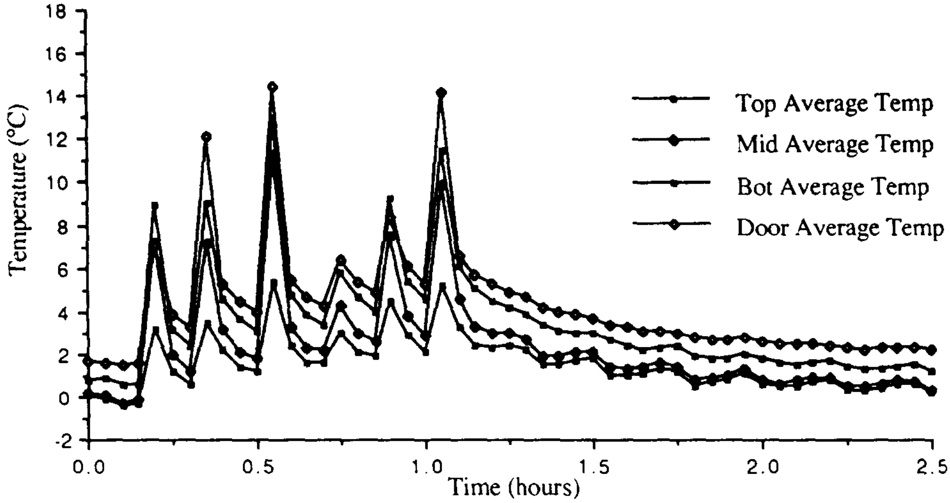

Fig. 4. Response of air temperatures in a domestic refrigerator to six 1-min door openings at 10 min intervals.

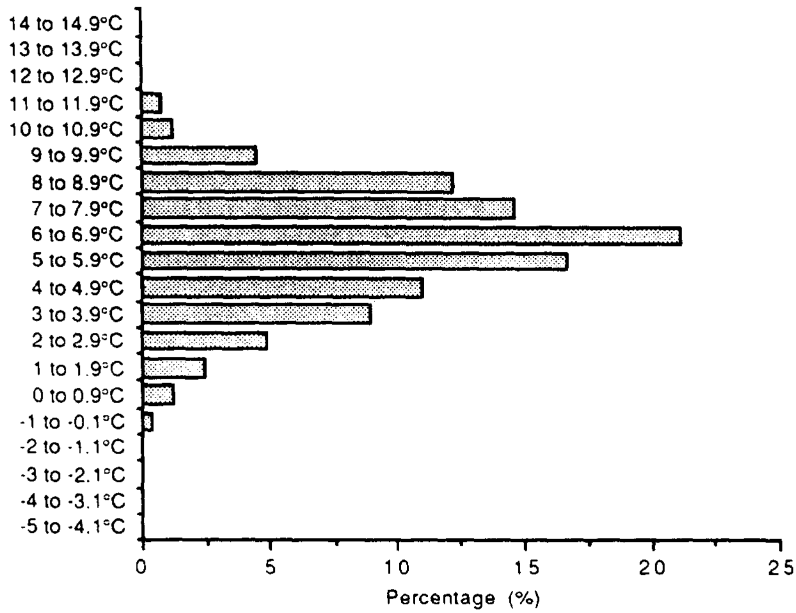

Fig. 5. Percentage of refrigerators in different overall mean temperature ranges.

CONCLUSIONS

Data are now available that can be used to optimise many parts of the total chill chain for beef, lamb and pork meat and many meat products. In some areas i.e. beef, pork and lamb chilling, these data provide much related information on temperatures, weight losses and quality affects. More limited studies have looked at both heat and mass transfer during retail display and meat temperatures in domestic refrigeration.

There are very few studies that follow the whole refrigeration chain through from primary chilling to domestic refrigeration. Nortje *et al.* (1990) followed meat from slaughter to retailing in South Africa with microbial condition being of most interest. No similar studies have been located from other parts of the world. Although weight loss is of considerable economic importance to the meat industry, the simultaneous modelling of mass and heat transfer within and from meat is still in its infancy. Relatively little data are available on the chilling of meat products, retail display and domestic refrigeration.

The most important thing that needs to be done is to transfer the scientific data that is already available into the meat industry. It is a very conservative industry with a low profitability fighting to maintain its share of the food market. Existing scientific knowledge has to be transferred into practical refrigeration processes that can be shown to produce an economic return to the industry.

REFERENCES

Abugroun, H. A., Cousin, M. A. & Judge, M. D. (1993). *Meat Sci.*, **33**, 207.
Allen, D. M., Hunt, M. C., Luchiari Filho, A., Danler, R. J. & Goll, S. J. (1987). *J. Anim Sci.*, **64**, 165.
Brown, T., Gigiel, A. J., Swain, M. V. L. & Higgins, J. A. (1988). *Meat Sci.*, **22**, 173.
Brown, T. & James, S. J. (1992). *Int. J. Refrig.* **15**, 5, 281.
Burfoot, D., Self, K. P., Wilkins, T. J. & James, S. J. (1990). *Int. J. Food Sci. and Technol.*, **25**, 657.
Dlugoszewski, B. & Minczewski, R. (1984). *Chlodnictwo*, **6**, 25.
Evans, J. A., Stanton, J. I., Russell, S. L. & James, S. J. (1991). *MAFF Publications*, London SE99 7TP.
Evans, J. A. (1994). The Cool Option. *XIV International Home Economics and Consumer Studies Research Conference, Sheffield.*
Flynn, O. M. J., Blair, I. & McDowell, D. (1992). *Int. J. Refrig.* **15**, 5, 307.
Fulton, G. S. Burfoot, D., Bailey, C., & James, S. J. (1987). *XVIIth Int. Cong. Refrig., Vienna*, C2-8.
Gigiel, A. J. & James, S. J. (1984). *Meat Sci.*, **11**, 1.
Gigiel, A. J. & Badran, R. (1988). *Int J. Refrig.*, **11**, 2, 100.
Gigiel, A. J., Butler, F. & Hudson, W. R. (1989). *Meat Sci.*, **26**, 67.
Hamby, P. L., Savell, J., Acuff, G. R., Vanderzant, C. & Cross, H. R. (1987). *Meat Sci.*, **21**, 1.
James, S. J., Gigiel, A. J. & Hudson, W. R. (1983). *Meat Sci.*, **8**, 63.
James, S. J. & Swain, M. V. L. (1986). Proc. *Inst. Refrig.*, **83**, 3.1.
James, S. J., Fulton, G., Swain, M. V. L. & Burfoot, D. (1988*a*). *Int. Inst. Refrig.* Refrigeration for Food and People. (1988-3). Brisbane, 111.
James, S. J., Gigiel, A. J. & Bailey, C. (1988*b*). *Int. Inst. Refrig.* Refrigeration for Food and People. (1988-3). Brisbane.
James, S. J. & Bailey, C. (1989). *Int. J. Refrig.*, **12**, 42.
James, S. J. (1990*a*). *Int. Inst. Refrig.*, Dresden, 30.
James, S. J. (1990*b*). In *Process Engineering in the Food Industry: 2 Convenience Foods and Quality Assurance*, ed. R. W. Field & J. A. Howell. Elsevier Science Publishers, 88.
James, S. J. & Evans, J. A. (1992). *Int. J. Refrig.*, **5**, 313.
James, S. J. & Evans, J. A. (1992). *Int. J. Refrig.*, **5**, 299.
James, S. J., Gigiel, A. J. & Parry-Jones, S. E. (1994). *Dev. Food Sci.*, **36**. Elsevier 199.
Karpinski, W. (1984). *Chlodnictwo*, **6**, 7.
Lyons, H. & Drew, K. (1985). *Food*, December, 15.
Malton, R. (1972). Proc. *Meat Res. Inst. Symp.* no 1, 29.1.
Nortje, G. L., Nel, L., Jordaan, E., Badenhorst, K., Goedhart, G., Holzapfel, W. H. & Grimbeek, R. J. (1990). *J. Food. Protect.*, **53**, 5, 411.
Olsson, P. (1988). *Int Inst. of Refrig. Conf.*. Refrigeration for Food and People, Brisbane, 90.
Swain, M. V. L. & James, S. J. (1988). *AFRC Inst. Food Res.* Bristol Subject Day, Meat Chilling.