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A modified hot processing strategy for beef: reduced electrical energy consumption in carcass chilling

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A beef processing strategy for improving energy and labour efficiencies, modified hot processing (MHP), was developed in a research abattoir. The work reported herein investigated carcass chilling rates and electrical energy usage in the chilling of carcasses that were processed using this approach. The MHP procedure removes the lower value cuts from the dressed carcass along with associated bone and fat. The remaining high value meat (posterior carcass quarter) is chilled in the usual manner, while the low value cuts are immediately processed (e.g. reduced into pre-blended, salted, chilled meat for emulsion-type products; rendered; directly processed as fresh, hot-boned meat, etc.). Carcasses prepared by the MHP method were dissected to quantify the amounts of lean meat, separable fat and bone removed in the procedure. These data were used with a simple model to predict the amount of chilling energy that could be saved by applying MHP prior to chilling. Electrical power to operate a blast chilling facility containing carcasses that had been processed either by conventional processing or by MHP methods was monitored and recorded, and the resulting data was used to confirm the model result. The MHP procedure reduced the refrigeration load for beef chilling by as much as 51% ($P < 0{\cdot}05$). The amount of chilling energy to be saved would depend upon the methods employed to further process the low value tissues, and was calculated to be no less than 7%. The time for the reduced MHP carcass quarters to chill to 10°C at the fat–muscle interface of the *longissimus dorsi* muscle (12/13 rib) was shorter for MHP carcasses than for conventional carcasses (5·77 h vs 7·08 h, respectively) ($P < 0{\cdot}05$). However, the times to chill the deep hip location of MHP hind quarters and conventional beef sides were not significantly different ($P > 0{\cdot}05$).

Keywords: Chilling, beef, meat, processing, refrigeration, energy, efficiency.

INTRODUCTION

In conventional abattoir practice, beef sides are chilled immediately after they have been dressed, usually for between 16 and 20 h. During that time the deep muscle temperature is ideally reduced from 40 to less than 7°C. Many abattoirs apply a nominal 36 or 48 h carcass chill at near-zero temperatures to ensure that adequate chilling has been achieved (James, 1987). Moreover, a 48 h commercial chill, with 24 h mean chiller temperatures as low as 1·5°C, was shown to be required to meet the EC requirement of a maximum beef carcass temperature of 7°C (James & Bailey, 1990). Williams (1978) reported that about 3·5 m^3 of chiller space is required for each beef carcass (two sides), whereas the amount of saleable meat from each carcass occupies only about 5% of this volume. Due to the large temperature reduction required during chilling and the large mass of the carcass, the chilling requirement is energy intensive. The refrigeration load of the chiller itself is further increased by numerous inefficiencies asso-

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ciated with the operation of the chiller, such as the frequent opening of chiller doors, the need to chill the surrounding air, and infiltration and heat losses through wall and ceiling surfaces. It is, therefore, not surprising that the initial carcass chilling process can account for about 30% of the total electrical energy used to run a typical modern abattoir (observed). The need to maintain the entire dressed carcass at less than 10°C after primary chilling during the boning and fabrication steps adds substantially to the total refrigeration cost. The meat packing industry ranks high amongst industries in overall energy consumption, with refrigeration and rendering being primal energy consuming processes (Ouellette *et al.*, 1980).

These observations have led to the development of hot-processing (HP), or hot-boning, a procedure in which meat cuts are removed from the carcass before it is chilled. Tissues destined for rendering are thus removed as a load from the refrigeration system, and meat destined for use in manufactured products can be quickly processed. About 30% of the beef carcass consists of inedible tissues, for which chilling serves little or no purpose (Williams, 1978). In a lean dressed bull carcass, approximately 17% is bone, 17% is fat and a smaller percentage is cartilage and connective tissues. These values suggest that about 34% of the energy associated with beef carcass chilling alone could be directly saved by employing a hot processing strategy. Moreover, the additional thermal energy needed in the rendering of these tissues to overcome the effects of the initial chilling process could also be saved, roughly doubling this particular energy saving.

Possibly the most important advantage of hot processing is the ability to process an animal into meat cuts within one day, thereby avoiding the need for chilled storage. The potential reduction of shrink associated with carcass surface drying during chilling is another advantage, since meat cuts can be immediately sealed in hermetic packages or in bulk packs. Furthermore, because much of the moisture from shrink freezes onto the refrigeration 'coils' (i.e., refrigerant/air heat exchanger surfaces), thereby reducing the system refrigeration efficiency, avoidance of shrink by early, rapid processing can reduce electrical energy used for chilling.

Aside from the above advantages, the reduced size and increased relative surface area of the HP excised meat cuts facilitates more rapid chilling, thereby enabling faster product throughput with less opportunity for bacterial proliferation. Furthermore, Daudin and Culioli (1987) found that chilling of isolated muscles led to better control and improved homogeneity of the chilling process. However, excised prerigor muscle is more susceptible to rigor shortening due to the loss of muscle–bone attachments. Also, acceleration of the chilling process would enhance the possibility of cold shortening of the muscle tissues (Bendall, 1972; Locker, 1985). Thus the removal of skeletal restraint and increased susceptibility to cold shortening effects can result in serious decreases in meat tenderness (Reagan, 1983). It is therefore not surprising that HP production methods have not been widely adopted by the prime beef industry.

To overcome the problems of applying HP to prime beef processing, an alternative processing approach was considered, referred to herein as modified hot processing (MHP: Aalhus *et al.*, 1994; Gariépy *et al.*, 1994). In this strategy the lower value cuts would be removed from the carcass before chilling, leaving the high value carcass portion to be conventionally chilled. The low value portion (i.e. quarter), comprising prerigor manufacturing-quality meat as well as fat and bone, would be immediately reduced into smaller portions. The warm prerigor muscle portion could be immediately processed, or temporarily chilled and stored as preblended meat, with possible applications in a variety of manufactured meat products (Gariépy *et al.*, 1994). This procedure would eliminate cooling of bone and fat destined for rendering. Immediate chilling of the low value excised meat fragments might also be avoided when that meat is used in processes involving non-refrigerated manufacturing conditions.

The objectives of the research reported in this paper were to: (1) assess the refrigeration energy saving potential associated with the adoption of MHP; and (2) determine chilling rate differences between sides processed by MHP and by conventional means.

MATERIALS AND METHODS

Direct comparisons were made to determine the effects on carcass chilling of using either a conventional processing (CP) or MHP strategy. One set of experiments was conducted to establish the electrical energies required for chilling MHP and CP carcasses in a blast chill facility. Beef carcass compositional data were also obtained to enable the theoretical chilling energy saving to be estimated. The Lacombe Research Station blast chill facility used can accommodate about 20 beef sides. It is a stainless-steel lined room that is 9·45 m in length, 4·88 m in overall height and 2·87 m in overall width. Carcasses in the blast hill system are supported by an overhead rail system that forms a complete flattened-oval circuit by means of two 1·42 m diameter bull-wheels located at either end of the room. Air flow is accomplished by six, 2-HP electric overhead propeller fans that direct air vertically downwards around and over the carcasses suspended along one side of the rail system. This air is directed below a central partition wall, assisted by a concave floor system, from which point it flows vertically upward past the carcasses suspended along the opposite side, to return to the evaporator coils and fans located above the rail system, thereby completing the airflow circuit. Carcass sides in such a system receive virtually identical treatment over the chilling period by means of the rail system which moves the carcasses at a speed of 3·66 m/min. The overhead fans accomplish a vertical airspeed of about 1·5 m/s at the carcass mid-point, and 2·3 m/s above the carcass (model 228-MS vane anemometer, Solomat Manufacturing Ltd, Bristol, UK). The compressor for the refrigeration system [model TSMC 108L (1988), Sabroe, Aarhus, Denmark] has a rated refrigeration capacity of 69 kW, uses R-502 refrigerant, and is powered by a 75 HP, 230 V, three phase electric motor.

A second experiment investigated differences in chilling rate characteristics under conventional chilling conditions of about 0°C in a batch air chiller with overhead fans. The fans in this chiller accomplish a vertical, downward airspeed of about 1 m/s at the carcass mid-point between adjacent carcasses. This chiller was partially loaded with paired MHP/CP carcass halves, and differences in rates of temperature decline and total chilling times between the treatments were determined from muscle temperature history data.

The following provides further details on the experimental procedures.

Carcass preparation and dressing procedures

In all experimental runs, carcasses were split, electrically stimulated and rinsed prior to chilling. High voltage electrical stimulation (ES: 470 V, 1 min, 60 Hz, 20 pulses/min) was applied after dressing to offset the cold shortening effects of the –20°C blast-air chilling process that was used. MHP carcass quarters were prepared following ES by removing the chuck, brisket (anterior to the 6th rib), the short plate and the flank (Fig. 1).

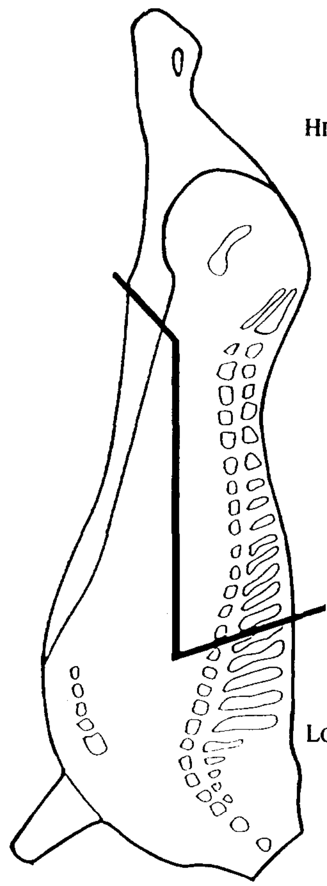

Fig. 1. Initial modified hot processing cut in which the beef side is segmented into anterior (low value) and posterior (high value) quarters.

Calculation of energy required in carcass chilling

The refrigeration heat load imposed by comparable sets of either MHP or CP carcasses was calculated on the basis of their known tissue compositions and temperature histories during chilling. Bull carcasses (N = 36) were dissected so that an average percentage breakdown of the separable fat (i.e. visible non-intramuscular fat), lean meat and bone tissue compositions of each of the carcass portions produced by MHP could be assessed. For comparison purposes, the refrigeration heat loads were arbitrarily calculated as the maximum energy to be removed by refrigeration from the side or MHP hind quarter of an average carcass in order for its temperature to be reduced from 40°C to a uniform internal temperature of 5°C, a temperature that is generally agreed to be suitable for shipping purposes. The additional heat loads arising from carcass evaporative losses (i.e. freezing and temperature reduction of moisture on the chiller coils) were also calculated and added to the total load. Chilling loads associated with physicochemical changes in fat and muscle were neglected. Since carcasses were electrically stimulated, heat production in the chiller due to glycolysis was assumed to be negligible (Pearson & Dutson, 1985). In general, therefore, the heat loads imposed byeither the MHP or CP chilled carcasses were calculated according to:

$$Q_t = (M_f \cdot C_{pf} + M_l \cdot C_{pl} + M_b \cdot C_{pb})\,\Delta T + (\lambda + C_{pw} \cdot \Delta T_w) \cdot M_w \quad (1)$$

where: Q_t = total heat load (kJ)
M_f, M_l, M_b = mass of tissue constituent (fat, lean, bone) (kg)
M_W = mass of carcass moisture evaporative loss (kg)
C_p = mean specific heat over the temperature range, ΔT (kJ/ kg K)
ΔT = change in carcass temperature (K)
ΔT_w = change in frozen water temperature on refrigeration coils (K)
λ = latent heat of fusion of water (kJ/kg).

The specific heat values for each of the tissue components were obtained from the available literature, and averages of the values reported in Table 1 were used for calculation purposes.

Measurements of energy used for blast chilling

The electrical power consumption of the blast chilling facility, with the chiller containing identical numbers of either MHP or CP carcasses, was monitored using a programmable recording power meter (Model 808, Dranetz Technologies Inc., Edison, NJ, USA). A total of eight (8) runs with six of these involving six (6) bull carcasses and two involving eight (8) carcasses completed the experiment. All dressed carcasses were assembled as they arrived from the kill floor, prior to blast chilling, in an adjoining room that ordinarily serves as a drip cooler (i.e., spray chiller). This room was maintained at a temperature of 15°C to minimize carcass pre-cooling prior to blast chilling. The maximum carcass residence time in the holding room was about 2 h. During this period, the blast chiller was operated in the empty condition under near steady-state conditions and the power consumption of the chiller was monitored in order to calculate the base electric load imposed by the combination of fan motors, drive motors and thermal heat gains from the ambient environment. As the last carcass arrived in the holding room, carcasses were quickly moved into the blast chiller, which was then immediately sealed. At this time, logging of total chiller power consumption (input power) recommenced and the batch of carcasses was chilled for a minimum of 2·5 h. The recording power meter was set to record the real power, power factor and time at intervals of 5 min. Input power was measured from the leads (three phase) of the electrical breaker panel of the entire chilling system. Power supplied to the fans was separately measured to determine their contribution to the total load.

Table 1. Specific heat values for beef lean meat, bone and fat used in energy analysis

Beef component	Specific heat (kJ/kg K)	Reference
Whole beef	3·14	ASHRAE (1986)
Fat	3·89	Morley (1972)
	2·89	Ordinanz (1946)
Lean	3·517	Potter (1978)
	3·513	Charm (1971)
	3·58	Heldman (1977)
	3·56	Morley (1972)
	3·43	Ordinanz (1946)
Bone	2·51	Morley (1972)
	2·09	Ordinanz (1946)

The coefficient of system performance (COSP), defined by Gigiel (1983–84, 1989), was calculated for each set of chilling experiments to determine the relative performance of the system operating under the two load conditions (i.e. MHP quarters, CP sides). The COSP was calculated as follows:

$$\text{COSP} = \frac{\text{useful refrigeration effect}}{\text{total energy supplied to the system}} \quad (2)$$

The useful refrigeration effect was taken to equal the difference between the total energy required to run the system under load (doors closed) and that required to run the system with no internal carcass load.

Whereas the blast chiller is normally loaded one hot carcass at a time, the experimental load was introduced as a single batch of six or eight hot carcasses to eliminate the added thermal load associated with periodically opening the door. Furthermore, because of the need to load the chiller with carcasses before they had appreciably cooled outside of the blast chilling room, the blast chiller was not loaded to its full carcass capacity (i.e. maximum 20 sides and/or quarters). It was nevertheless estimated that the peak thermal load imposed by the experimental carcass lot would be approximately the same as that produced by the usual serial addition of carcasses.

The mean electrical power consumption for each run was calculated from the input power history data, and the total energy for blast chilling over each 2·5 h run was calculated by numerical integration using a 5 min time interval for the time step (the logger that was used produces the true average power reading for the specified time interval). The net average power or net energy was defined as that portion of the total power or energy consumed for carcass chilling only. These 'net' values were calculated by subtracting the mean power or energy used by the chiller when operated in the empty condition under approximately steady-state conditions from the total power or energy values. This 'non-productive' or base-line power was separately measured for each run during the hour preceding each run. The calculated differences between the 2·5 h experimental MHP and CP chilling runs in terms of the mean input power and the mean input energy were tested for significance by analysis of variance (GLM procedure, 1989, SAS Institute Inc., Cary, NC, USA).

Determination of chilling rate characteristics

Carcasses were split into halves, with one half prepared according to the MHP method, and the other by the CP method. Differences in chilling behaviours between MHP and CP carcasses were investigated by monitoring muscle temperatures in opposing sides of each carcass. The experiment involved three (3) bull carcasses per run and three replicate runs. All carcasses were statically suspended and subjected to chilling under typical commercial chilling conditions of 0°C and 1 m/s velocity, vertical, downward air movement in the cooler. Moisture was not added to the cooler and relative humidity in the cooler was not monitored. After all of the carcasses were assembled in the cooler, its doors remained closed. The time–temperature data for this experiment were obtained using a multi-channel data logger (MPM-4000/4013, Solomat Manufacturing Ltd, Bristol, UK) equipped with 24 type 'K' thermocouples encased within stainless steel bayonet-type probes. The time of each carcass entry into the cooler was recorded, and probes were inserted into the carcasses and connected to the data logger. In addition to air temperature, three temperature measurements were made of each side or quarter in the *longissimus dorsi* (LD) muscle at the grading site (12/13th rib). These measurements were made at the interface between the outer fat layer and muscle, the interface between the rib and muscle, and at (or near) the geometric centre of the muscle cross section on a plane lying perpendicular to the rib. The LD muscle centre and fat–muscle interface depths were determined by cross-sectional depth measurements using an ultrasonic echo-imaging instrument (AEC, Aloka Co. Ltd, Tokyo, Japan) with a model UST-5021, 3·5 MHz probe head. In addition to these measurements, the deep hip temperature, adjacent to the hip bone, was monitored in four of every six sides or quarters.

As a basis for comparison between MHP and CP carcasses, the chilling times required for each muscle location to reach a value of 10°C were determined from their respective chilling temperature histories. These profiles were analysed by non-linear regression analysis (NLIN procedure, 1989, SAS Institute Inc., Cary, NC, USA) using the following model:

$$T = T_i - (T_i - T_f) \cdot e^{(-(\alpha + \beta \cdot \theta)/\theta^2)} \quad (3)$$

where: T = muscle temperature (°C)
T_f = final or equilibrium temperature (at time = infinity; °C)
T_i = initial temperature on entrance to chiller (at time = 0; °C)
α = experimental parameter (s^2)
β = experimental parameter (s)
θ = time (s).

This model was selected for general applicability and goodness of fit to all of the experimental temperature versus time profiles. For each of the temperature histories the time at which temperature was reduced to 10°C (θ_{10}) was determined by solving Equation (3) for time with temperature set at 10°C. Differences in θ_{10} between the MHP and CP processing treatments were tested for significance by analysis of variance (GLM procedure, 1989, SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Theoretical reduction in chilling energy by MHP

The tissue compositions of the modified front and hind quarters did not differ greatly from those of the whole sides (Table 2). The lean meat, separable fat and bone percentage points of the anterior and posterior quarters differed by 0·5, 1·2 and 0·7%, respectively. Furthermore, the average portion (front quarter) of the total carcass side re-

Table 2. Gross tissue compositions of dressed experimental bull carcasses and excised portions produced by modified hot processing[a]

Carcass component	Hot sides	Hind quarters	Front quarters	Hinds sides	Front sides
Lean meat: mean lean meat percent, dressed & chilled carcass[b] (%)	65·2 (3·0)	65·5 (2·9)	65·0 (3·4)	1·005	0·997
Separable fat: mean separable fat percent, dressed & chilled carcass[b] (%)	17·5 (3·8)	16·9 (3·7)	18·1 (3·9)	0·966	1·034
Bone: mean bone percent, dressed & chilled carcass[b] (%)	17·3 (1·1)	17·6 (1·2)	16·9 (1·2)	1·017	0·977
Total: mean weight of total hot dressed carcass portions[c] (kg)	336·4 (54·0)	162·3 (23·7)	174·1 (30·9)	0·483	0·517
Lean meat: mean weight of excised lean from sides or quarters[d] (kg)	219·4	106·3	113·2	0·485	0·515
Separable fat: mean weight of excised fat from sides or quarters[d] (kg)	58·9	27·4	31·5	0·465	0·535
Bone: mean weight of excised bone from sides or quarters[d] (kg)	58·2	28·6	29·4	0·505	0·495

[a] Values shown in brackets are one standard deviation of the measured result.
[b] Sample size, $N = 36$.
[c] Sample size, $N = 26$.
[d] Calculated mean weights based upon above mean percentages.

moved by MHP was found to be 51·7%. Thus, the theoretical maximum energy saving associated with the chilling of MHP carcasses using Equation (1) was 51·8%, which would be the case if the subsequent processing treatment of the anterior quarter could be accomplished without the need for immediate chilling. While this would currently apply for only a limited number of products, certain advantages might be realized by directly processing the hot-boned meat in a non-refrigerated condition. For example, hot cures may be used to accelerate the entire processing operation by allowing all or part of the heating or cooking step to be essentially carried out at the same time as curing (Kramlich *et al.*, 1982).

In the more likely scenario, all or part of the low-value hot-boned tissues, including fat, would be chilled, and possibly chopped and blended with other ingredients before being further processed into an emulsion-type product. In this case the maximum theoretical energy saving would depend upon the quantity of bone excised from the front quarter. Assuming that the bone, comprising 16·9% of the anterior portion of the carcass, is fully removed, the theoretical energy saving using Equation (1) would be 7·1%. With all of the separable fat trimmed from the low value meat for immediate rendering, the chilling energy saving could be as high as 17·7%. As all lean meat and edible fat must eventually be chilled, the achievement of chill energy savings in excess of 17·7% implies that re-chilling of the lower value meats is avoided by their being heat-processed prior to chilling.

Measured electrical energy used for chilling

Composite (mean) time profiles of the net input power per unit mass of full carcass side (W/kg) for blast chilling MHP quarters and CP sides are presented in Figure 2. The cyclic patterns of the composite input power profiles in Figure 2 reflect

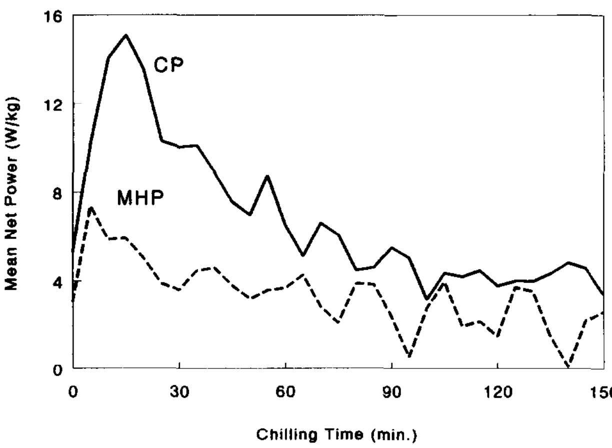

Fig. 2. Mean power consumption histories of the blast chiller over 2·5 h during chilling of beef carcasses prepared by modified hot processing (MHP ················) and conventional processing (CP ———), shown on the basis of instantaneous power devoted to useful chilling per unit weight of dressed carcass.

Table 3. Comparison between CP and MHP experimental processing characteristics and associated energy requirements for carcass chilling over 2·5 h[a] (N_{mhp} = 26; N_{cp} = 26)

Experimental carcass or process characteristic	Least square means CP	MHP	CP–MHP difference	Quotients MHP/CP	CP–MHP/CP
Processed Carcass Weights					
Total weights:					
Hot dressed weight (kg)	8816·7	8747·4	69·3	0·992	0·008
Chilled carcass weight (kg)	8816·7	4220·8	4595·9	0·479	0·521
Hot process carcass weight (kg)	0·0	4526·6	NA	NA	NA
Mean weights & percentages:					
Mean dressed weights (left + right whole sides; kg)	339·10 [48·53]	336·44 [53·99]	NA	NA	NA
Mean chilled carcass weight[b] (left + right sides or hind quarters; kg)	339·10 [48·53]	162·34 [23·69]	174·10 [30·88]	0·483	0·517
Electrical Energy Consumed					
Per kilogram of chilled carcass mass:[c]					
Mean total average power (W/kg)	14·52 (2·95)	25·03 (2·95)	−10·51*	1·724	−0·724
Mean net average power (W/kg)	6·79 (1·52)	6·81 (1·52)	−0·03 NS		
Mean net energy (kJ/kg)	61·07 (13·65)	61·32 (13·65)	−0·25 NS		
Per kilogram of dressed whole carcass:[c]					
Mean total average power (W/kg)	14·52 (1·89)	12·18 (1·89)	2·34 NS		
Mean net average power (W/kg)	6·79 (0·99)	3·34 (0·99)	3·44*	0·492	0·508
Mean net energy (kJ/kg)	61·07 (8·88)	30·07 (8·88)	30·99*	0·492	0·508

* Differences are significant at a level of $P \geq 0{\cdot}95$; NS denotes 'not significant'.
[a] Numbers in square brackets are one *standard deviation* of the measurement.or result.
Numbers in curved brackets are the *standard error* of the measurement or result.
[b] In this row, 'CP' in cols. 3, 4 & 5 refers to mean MHP carcass side weight prior to MHP initial cut (i.e. 336·44 kg).
[c] 'Total' denotes electrical demand (power or energy) to run entire blast chill facility.
'Net' power denotes electrical demand (power or energy) for carcass chilling only.

similar patterns observed in each run. These patterns are the result of the excess capacity of the refrigeration system relative to the size of the thermal loads imposed by each batch of carcasses. The lower net power consumption of the MHP chilling runs was found to be almost totally due to the reduced MHP carcass load. Mean profiles for the MHP and CP runs over the 2·5 h period of the net input power per unit mass of carcass tissue chilled were very similar (not shown).

A comparison between the average power and net energy inputs for chilling MHP and CP carcasses is presented in Table 3. The mean net input energies per unit mass of carcass tissue chilled over the 2·5 h period for the MHP and CP chilling runs were found to be not significantly different (61·3 kJ/kg and 61·1 kJ/kg respectively; $P \leq 0{\cdot}01$). If MHP quarters had chilled at a faster rate during this period, the net unit energy required to chill these quarters would have been greater. Thus, overall differences between MHP and CP in chilling rate over 2·5 h for the blast chilling conditions of this study were too small to be detected by the measured differences in electrical energy consumption. Since MHP carcass quarters experienced only a slightly faster overall rate of temperature decline than the CP sides under conventional chilling conditions (see below), a similar result could be expected for chilling under conventional conditions.

With reference to the values reported in Table 3 for net energy consumption per kilogram of whole dressed carcass, the net unit energy for chilling MHP prepared carcass quarters was calculated to be 49·2% ($P \leq 0{\cdot}05$) of that for chilling CP carcass sides, based on carcasses of equal weight. This

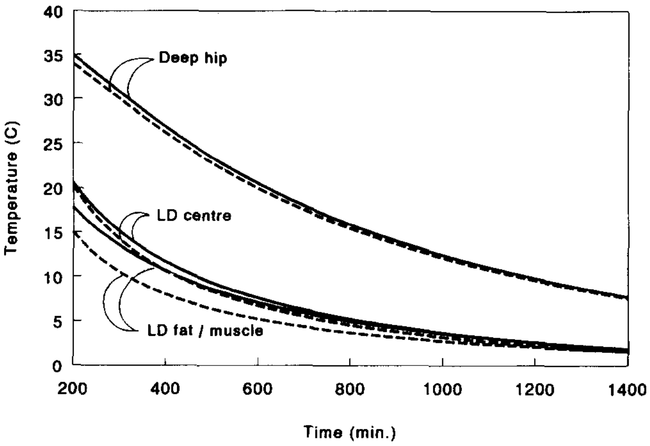

Fig. 3. Mean temperature decline histories of muscles during chilling from carcasses prepared by modified hot processing (MHP ··········) and conventional processing (CP ———).

result, indicating a maximum 50·8% energy saving in the carcass chilling operation, is in good agreement with the theoretical result of 51·8%, given above.

The total energy required to chill MHP carcasses per unit weight of carcass mass chilled exceeded that for chilling CP carcasses (Table 3). This reflects a decline in total refrigeration system efficiency for the MHP chilling runs which can be attributed to the reduced refrigeration load. The COSP values were 0·27 and 0·47 for chilling MHP and CP carcasses, respectively.

Chilling time for MHP versus CP carcasses

Figure 3 shows the composite (mean) temperature histories of LD muscles from carcasses prepared by MHP and CP during conventional chilling in the drip cooler. Comparisons of the average calculated [Eq. (3)] chilling times required for the different muscle locations to reach 10°C are presented in Table 4. The average chilling time was lower by 1·3 h for MHP carcasses compared to CP carcass sides at the LD fat–muscle interface location ($P \leq 0{\cdot}05$). The difference in the calculated average chilling time for the centre of the LD muscle between the MHP quarters and the CP sides (0·55 h) was not found to be significant ($P > 0{\cdot}05$). Likewise, the differences in chilling times between MHP and CP for the bone–muscle interface location of the LD muscle and for the deep hip location were also not significant ($P > 0{\cdot}05$). That chilling rate is not appreciably affected by the MHP carcass reduction is consistent with the finding that the quality of meat from the posterior carcass quarter is not significantly ($P > 0{\cdot}05$) affected by the interaction of MHP treatment and blast chilling when ES is applied (Aalhus *et al.*, 1994).

CONCLUSIONS

Useful data was obtained in this study, indicating that very substantial savings in electrical energy for carcass chilling are possible by adopting a modified hot processing strategy. However, it must be understood that the experimental chiller system employed in this study was not modified in order to match the reduced thermal load of the modified carcasses, as reflected by a change in the overall energy efficiency of the chiller. It would, therefore, be incumbent upon the producer to ensure that the refrigeration system is suitably designed or modified by matching the refrigeration system capacity to the expected thermal load.

Nevertheless, by adopting a modified hot processing strategy an abattoir could conceivably double its throughput of animals with roughly the same chilling cost. The resulting overall chill energy saving amount would strictly depend upon the type of manufacturing that is applied to the

Table 4. Time for muscle temperature to reach 10°C (θ_{10}) following the introduction of the hot carcass into the drip cooler with air temperature held at 0°C[a]

Muscle location	Conventional (N_{cp} = 9) Depth (cm)[b]	θ_{10}(h)	Modified (N_{mhp} = 9) Depth (cm)[b]	θ_{10}(h)
Fat–muscle interface	0·6 (0·03)	7·08 (0·42)*	0·5 (0·03)	5·77 (0·42)*
Centre of muscle	4·6 (0·15)	7·37 (0·58)	4·8 (0·13)	6·82 (0·58)
Bone–muscle interface	8·4 (0·17)	7·30 (0·43)	8·6 (0·15)	7·42 (0·43)
Deep hip	23·1 (0·85)	19·64 (1·57)	24·2 (0·85)	19·15 (1·57)

* CP–MHP–θ_{10} difference is significant at a probability level > 95%.
[a]Except for deep hip, locations are on a plane passing between the 12 & 13 rib of the LD muscle. Numbers in brackets are the standard error.
[b]Depths are measured from the dressed carcass exterior surface.

lower value tissues removed from the MHP anterior quarter, this amount being in the minimum range of 7–51% of the energy currently used to chill beef sides. Where specific manufacturing practices are contemplated, Equation (1) can be applied to predict the potential overall energy saving benefit associated with the chilling of MHP beef.

Finally, the times required to chill the MHP posterior carcass quarter at interior muscle locations under conventional chilling conditions (i.e 0°C, 1 m/s air) are not significantly ($P > 0{\cdot}05$) different from those required to chill such locations in full sides of beef. This appears to be also true for the rapid blast-chilling case, based upon the analysis of energy used for chilling. Therefore, it could not be demonstrated in this study that the MHP treatment is capable of reducing the chilling time that would normally be required before shipping. Also, for this reason, the reduction of sides into MHP quarters will not have a substantial impact on the peak chiller input power requirement, or energy demand profile, where the carcass mass load inside the chiller and other factors remain unchanged.

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