MODIFICATION AND TESTING OF A NITROGEN REFRIGERATED, CONTROLLED ATMOSPHERE CONTAINER FOR THE DISTRIBUTION OF FRESH RED MEAT

by

Melissa Nicole Nadya Habok

A thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
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ABSTRACT

An extension of the storage life of fresh red meat is required for the worldwide distribution of the product. Storage life of red meat is most successfully extended if the storage temperature is maintained at -1.5±0.5°C and modified atmosphere packaging techniques are employed. In addition, the implementation of a centralized packaging system, which may be embraced by larger retailers as an efficient and convenient method of distributing fresh meat, would also benefit if accompanied by an extension in product storage life.

An insulated container was modified with the objective of improving the variable nitrogen use of a system which was previously used in a similar study. It was attempted to distribute the nitrogen within the container without the use of fans, however this proved unsuccessful. A centrifugal fan, which had a motor residing outside the container, provided a uniform temperature within the container and lowered the variable nitrogen use of the system. The target temperature range for the system was changed to -1.0±0.5°C to eliminate any economical losses attributed to meat tissue freezing, however, as a result, the storage life was thought to have been shortened by 10 %.

A master pack was simulated by placing 6-kg pork butt roasts in an aluminum tray and over wrapped with an unsealed plastic bag, with the temperature of the meat within each tray being recorded. The container was tested at outside temperatures of 30, 15, 0, and -15°C. Chilling of the product from an initial temperature of 7.0°C to -1.0°C required on average 33.7, 31.7, 34.7, and 30.6 kg of nitrogen for 30, 15, 0, and -15°C outside temperatures, respectively.

Average variable nitrogen use for maintaining the required temperature was 4.8, 2.8, 1.2, and 0.1 kg/h for 30, 15, 0, and -15°C outside temperatures, respectively. These values for nitrogen use were an improvement over the previous system. The overall maximum temperature of the container during the trials was -0.3°C, while the overall minimum was -1.4°C.

A vacuum insulated transfer line decreased variable nitrogen use by 50.9 % in comparison to a steel braided transfer line. A simulated nitrogen failure of the system resulted in an average temperature increase of 0.5 °C/h within the container.

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1. INTRODUCTION

Faced with the challenge of providing food to the increasing world population, engineers and scientists need to adopt more effective methods to preserve and distribute the food that is produced. As many of these foods are perishable, these challenges become increasingly difficult. One such perishable food, which is susceptible to microbial contamination and spoilage, is fresh meat. Fresh red meat is more pleasing to consumers than frozen meat as the meat tissues do not suffer detrimental effects due to ice crystal formation (Taylor 1985). Production of red meat is increasing due to the growth of exports to countries in the Asia-Pacific and Mexico regions. These exports currently account for 10% of the total market (Anonymous 1995). Shay and Egan (1990) report that the preparation, sea transportation, and distribution of vacuum-packed meats to these distant markets can take up to 10 weeks. Retail display life of fresh meat in conventional over-wrapped trays is shortened by changes in colour and appearance that occurs after 2-3 days (Shay and Egan 1990). Thus, the shelf life attained using conventional packaging practices could not meet the export demands satisfactorily, thus signifying that an extension in storage life is needed. "A shortened and variable storage life restricts the marketing possibilities for the product, tightly constraining production and distribution schedules, and is a major cause of customer dissatisfaction or outright rejection of the product" (Gill and Phillips 1993a). Therefore, even shipment to local markets could possibly be adversely affected by inadequate storage life. To overcome the difficulties in distributing fresh red meat, scientists have established proven packaging techniques [modified atmosphere packaging (MAP) and strict temperature control (-1.5±0.5°C)] which could enable the worldwide distribution of this product (Gill and Phillips 1993a; Holley et al. 1993). Carbon dioxide is the most successful of the gases used in MAP since a shelf life of 18 wk can be attained utilizing CO_2-gas-packing techniques at -1.5°C (Jeremiah et al. 1992). There also exists a packaging technique (master packaging) which combines the bacteriostatic effect created by CO_2 yet eliminates the colour instability associated with MAP with CO_2.

Industry is becoming increasingly aware of the economic advantages of distributing packed portions of meat directly to retail outlets from centrally located cutting and packing plants (Taylor 1985). Centralized cutting and packing would diminish the labour and floor space at the retailers devoted to packaging the product for display, thus translating into economic savings. However, a reliable method of supplying retailers with fresh, microbiologically-safe, and acceptably coloured products must be devised to ensure the success of centralized packaging and further facilitate a supply to distant markets.

The objectives of this thesis were:

1. To modify a container designed by Bailey (1997) (a container which uses liquid nitrogen as the refrigerating medium) with the objective of improving the nitrogen use of the system.
2. To test the modified container's ability to chill and maintain meat temperatures over a range of operating conditions.

3. To compare the use of a steel braided transfer line with a vacuum insulated transfer line, as suggested by Bailey (1997).

2. REVIEW OF LITERATURE

2.1 Centralized Packaging

Regionally, the distribution of red meat is currently accomplished through a system of small packaging plants which supply retailers in close proximity to the plant. The animals are slaughtered and then subsequently cut into primal and sub-primal cuts (15-20 kg) which, upon arrival at the retail outlet, require further preparation to create retail-ready cuts (Bailey 1997).

Centralized packaging differs from the current distribution system in that fewer and larger packaging plants would supply retailers at greater distances from the plant. The centralized packaging plant would utilize vacuum packs or modified atmosphere packs to prepare retail-ready portions, thus lowering in-store labour costs (Creighton 1996). Taylor (1985) reports that the space and labour required at the retail outlet for preparation of the final retail packs are expensive. A reduction in the floor space required for meat cutting at the retail level would allow the space to be allocated to a more profitable use such as merchandising. Furthermore, only two-thirds of a beef carcass is usable meat, thus centralized packaging would eliminate the cost of transporting the trimmings and waste on a carcass (Taylor 1985).

If CO_2-gas-packing techniques are combined with the desired temperature for storage (-1.5°C), then centralized packaging is benefited by an extension of product shelf life of up to 6 to 10 wk.

2.2 Factors Affecting Storage Life of Meat

2.2.1 Microbiological Growth Bacterial growth is an important consideration with regard to the safety of the product. "Fresh meat is inevitably contaminated with a variety of bacteria" (Gill and Phillips 1993a). The initial contamination of the meat occurs at the packing plant, whereupon after dressing, the beef carcass may carry 10^2-10^4 bacteria/cm^2 (Taylor 1985). Suppression of any further growth of microorganisms is desirable as spoilage odours associated with their growth become apparent when bacterial numbers exceed 10^8 bacteria/cm^2 (Gill 1986, as cited by Gill and Phillips 1993b). The bacterial species which are able to multiply in the surrounding air and are the most dominant bacteria on chilled meat belong to the *Pseudomonas* genus (Taylor 1985). Pseudomonads are psychrotrophic Gram-negative organisms and are able to grow at temperatures as low as -3°C. Being chemoheterotrophs, they also require oxygen for metabolic activity and succeed in depreciating meat quality by degrading the product's lipids and proteins (Prescott et al. 1996), resulting in deterioration of product appearance. Microbiological growth is of particular concern when packaging fresh pork, as it tends to have a relatively high pH in comparison to beef. Shay and Egan (1986a) report that there is increased growth of psychrotrophic Gram-negative bacteria if the pH of the meat is high, i.e., pH>6.0 (Refer to Section 2.3.1).

2.2.2 Colour Product colour, a factor which influences the storage life of fresh meat, is important because it is a visual indicator of product quality. "Excluding cost and culinary considerations, colour is arguably the most important factor considered by consumers selecting raw red meat" (Penney and Bell 1993).

Red meat derives its colour from the muscle pigment myoglobin and its reactions with oxygen (Taylor 1985; Penney and Bell 1993; Shay and Egan 1986b). Meat which is in an environment having a complete absence of oxygen will retain the purple colour of myoglobin. If red meat is placed in an environment containing a high concentration of oxygen, the purple myoglobin will become oxygenated to produce oxymyoglobin. Oxymyoglobin is responsible for giving meat its red colour which consumers deem as acceptable. Yet, if raw meat is exposed to low concentrations of oxygen, the myoglobin oxidizes to form metmyoglobin, which gives the meat a brown colour which consumers associate with spoilage. Colour changes are more of a limiting factor when packaging beef rather than pork, since the myoglobin content of pork is 1/10 of that in beef (Lawrie 1974, as cited by Penney and Bell 1993).

2.2.3 Temperature The storage temperature of chilled meat plays a significant role in product storage life. Although pseudomonads are able to grow at sub-zero temperatures, their growth rate increases as the temperature is increased and they experience optimum growth at 20-30°C (Prescott et al. 1996). Thus, the maximum storage life for fresh meat is attained when the product is held at the lowest temperature which can be maintained indefinitely without muscle tissue freezing (Gill and Phillips 1993a). This temperature has been determined by Gill et al. (1988, as cited by Gill and Phillips 1993a) to be -1.5°C. There is a definite advantage in maintaining the storage temperature as close as possible to -1.5°C. Gill and Phillips (1993a) found that reducing the temperature from -1.0 to -1.5°C increases the storage life by approximately 10 %. Thus, product temperature is significant, especially for shipments to distant export markets, as the storage times required are greater than the storage life needed for shipment to local markets.

2.3 Packaging Techniques

2.3.1 MAP With Carbon Dioxide One of the techniques used to extend the storage life of fresh meat is modified atmosphere packaging (MAP). This entails the enclosure of food products in materials which provide a barrier to certain gases and also enclose a gaseous environment which has been altered to retard the microbiological respiration, microbiological growth, and reduce enzymatic spoilage (Young et al. 1988). MAP with carbon dioxide involves the reliance on CO_2 within the package to extend the storage life of the product. Carbon dioxide has the ability to produce a bacteriostatic effect (Young et al. 1988; Jeremiah et al. 1992; Shay and Egan 1986b), and therefore is commonly used in MAP technology. Shay and Egan (1986b) state that CO_2 reduces the growth rate of bacteria and delays the onset of active growth of those organisms which are not actively growing, thus it extends lag phases and increases generation times. The effectiveness of CO_2 as an inhibitor of microbial growth is further increased as its concentration increases (Finne 1982, as cited by Shay and Egan 1986b), and product temperature decreases (Shay and Egan 1986b).

There are currently two methods which utilize the bacteriostatic action of CO_2; (i) vacuum-packaging and (ii) gas packing with CO_2. The former of these involves a vacuum being drawn in the gas impermeable package containing the meat, thus eliminating the volume of air surrounding the product. The objective of each of these packaging techniques is to lower the O_2 concentration within the meat package. If the ratio of residual air to meat within the resultant package is low enough, the remaining oxygen is consumed by the respiring meat tissues and CO_2 is produced thus raising the CO_2 concentration inside the package. This occurrence has the following advantages; (i) suppression of pseudomonad growth, thus allowing the psychrotrophic lactic acid bacteria, which are non-putrefactive and non-pathogenic, to predominate (Shay and Egan 1986a), and (ii) metmyoglobin formation is minimized.

Gas packing with CO_2 involves initially removing the air from the meat package and then injecting CO_2 gas into the package. The recommended quantity of CO_2 is 1.5-2.0 L/kg meat, because approximately 1.0 L/kg of the gas is absorbed by the meat (Penney and Bell 1993). Jeremiah et al. (1992) compared the storage life obtained from vacuum packaged and CO_2-gas-packed chilled pork and reported that vacuum packs and CO_2-gas packs containing pork at -1.5°C give a storage life of 12 and 18 wk, respectively.

The disadvantages associated with MAP utilizing CO_2 pertain to unacceptable product colour. Since myoglobin is not oxidised nor oxygenated the meat retains the purple colour of myoglobin, which consumers deem unacceptable. Also, if the air removal process does not adequately rid the package of oxygen, the meat may experience some metmyoglobin formation. This problem, however, may be resolved if the quantity of residual oxygen within the package is minimal. According to Penney and Bell (1993), if the residual oxygen concentration in CO_2-gas packaging are less than 0.15% and 1.0% for beef and pork, respectively, colour changes due to metmyoglobin formation does not occur. Furthermore, research to ascertain consumer acceptance of CO_2-gas packaged meat found that exudate present in the packages resulted in consumer complaints (Gill et al. 1994). Gill et al.(1994) suggest that excess exudate could be soaked up by an absorbent of adequate capacity.

2.3.2 MAP With Oxygen Modified atmosphere packaging techniques using a high oxygen, O_2, concentration are most commonly used in combination with CO_2. According to Georgala and Davidson (1970, as cited by Shay and Egan 1986b), the most successful of the gas mixtures for fresh meat is 80% O_2 and 20% CO_2. This combination utilizes the high oxygen concentration to promote oxymyoglobin formation as well as creating the bacteriostatic effect resulting from the presence of CO_2. Shay and Egan (1986b) report that 80 % O_2 and 20 % CO_2 mixtures result in a storage life of 15 d at 4°C. In contrast, MAP using a high CO_2 concentration can achieve a storage life greater than 18 wk at -1.5°C (Jeremiah et al. 1992). Gill and McGinnis (1993, as cited by Gill et al. 1994) state that a storage life of 3 wk is required for beef to ensure safe shipment from the packing plant to the retail outlet. Hence, MAP using O_2 does not provide the storage life needed to facilitate centralized packaging.

2.3.3 MAP With Nitrogen The use of nitrogen, N_2, in gas packaging has also been examined as a packaging technique for fresh meat. According to Taylor (1985), nitrogen produces a similar effect to vacuum packaging however the residual oxygen concentration is more diluted with MAP using nitrogen and therefore metmyoglobin formation is less pronounced. Nitrogen does not possess the bacteriostatic properties of CO_2, hence it only extends storage life via its elimination of O_2 within the package. MAP using N_2 also has the disadvantage in that the product will retain a purple colour as myoglobin does not undergo any reaction and thus deters purchase by the consumer.

2.3.4 Master Packaging of Meat Master packaging is a technique which incorporates the advantage of MAP-enhanced storage life and eliminates the disadvantage of colour instability presented by the MAP packaging techniques. Master packaging involves the use of two packaging films; one of which being O_2-CO_2 impermeable and the other being O_2-CO_2 permeable (Fig. 1).

Individual retail cuts of meat are placed on retail trays and are over wrapped with O_2-CO_2 permeable film. Several retail trays are arranged on a master tray, which is enclosed in an O_2-CO_2 impermeable film. Prior to sealing the package in the O_2-CO_2 impermeable membrane, air is back flushed out of the master tray and CO_2 is injected into the space within the master tray at a capacity of 1.5-2.0 L/kg of meat. The permeable film over wrapping the retail trays allows CO_2 to enter the retail packages and hence inhibit microbiological growth on the product. Upon need at the retailers, the O_2-CO_2 impermeable film is removed from the master trays to facilitate oxygen penetration into

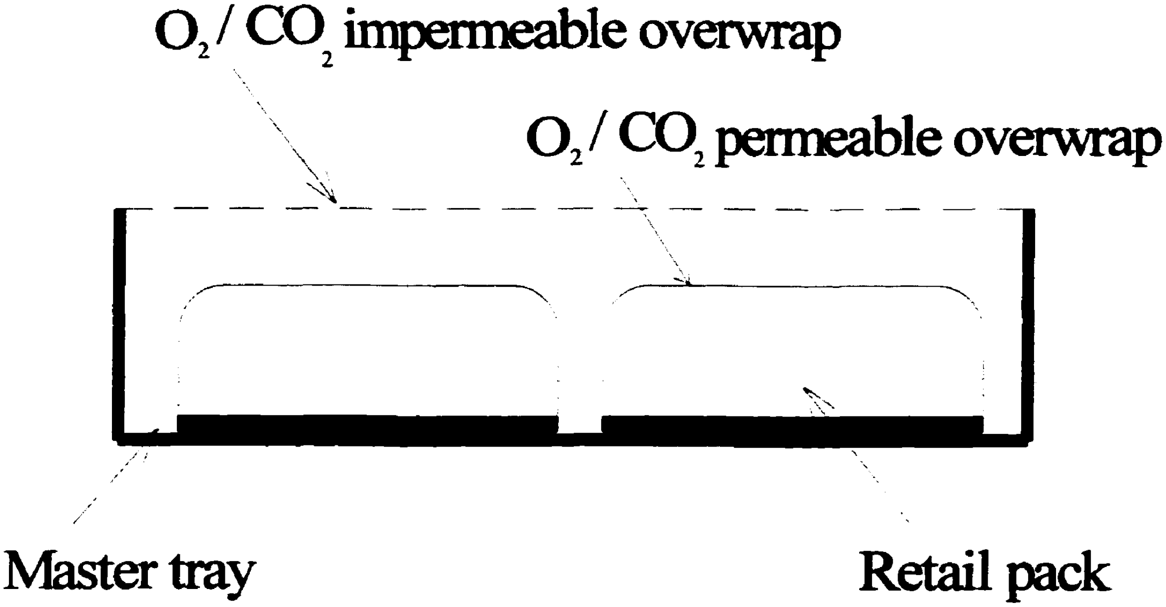


Figure 1. Schematic of a master pack (Adapted from Bailey 1997).

the retail packs through the O_2-CO_2 permeable film. Taylor (1985) reports that the subsequent oxygenation of myoglobin to produce a desirable red colour takes approximately 0.5 to 2.0 h. The storage life expectation of master packed retail ready products is approximately 6 to 10 wk since cut or uncut muscle surfaces act as the primary points of deterioration for chilled meat (Tewari et al. 1999). A study by Gill et al. (1994) assessed consumer acceptability of retail packs of beef stored using the master packaging technique and concluded that master packaging provides a solution to the disadvantages presented by the other techniques.

2.4 Use of Cryogenics in Fresh Meat Transport

To successfully accommodate centralized packaging and the distribution of fresh meat over long distances, a narrow temperature range of -1.5±0.5°C should be maintained. Mechanical refrigeration systems have proven inadequate in maintaining the narrow temperature range desired (Gill and Phillips 1993a, 1993b). Specifically, Gill and Phillips (1993b) state that in current railway wagons, the off-coil temperature may not be set with any great accuracy. Furthermore, according to Guilfoy and Mongelli (1971), the fixed costs associated with a nitrogen refrigeration system are less than that for the mechanical refrigeration systems. The report further states that shipping costs could be reduced with the use of a nitrogen refrigeration system because it's mass is almost half the mass of its mechanical counterpart.

Refrigeration using cycled injections of liquid nitrogen can provide cooling of the fresh meat product in the aforementioned range. Bailey (1997) experimented with a liquid nitrogen cooling unit and was able to maintain the storage temperature between -2.0 to -0.7°C. It was further noted that this could be improved upon if modifications to the experimental prototype were completed. The use of liquid nitrogen for refrigeration also has the advantage of reducing the oxygen concentration within the shipping unit and hence guarding against O_2 transmission through improperly sealed packages.

2.5 Summary

The economic advantages of centralized packaging enable it to become a feasible distribution system for red meat. However, the implementation of a centralized packaging system must be accompanied by an extension of storage life to gain customer acceptance and maintain product safety. MAP with CO_2 is successful at extending the product shelf life to 18 wk with primal and sub-primal cuts of meat and 6 to 10 wk for retail ready packages of meat at -1.5°C, thus meeting the requirements for shipment regionally and internationally.

Utilization of cryogenic refrigeration using liquid nitrogen presents an improvement in storage temperature accuracy over conventional mechanical refrigeration systems and also provides additional advantages in terms of reduced shipping costs and lower fixed costs in system implementation.

3. MATERIALS AND METHODS

3.1 Previous Prototype Used

A container, previously designed and tested by Bailey (1997), was used in this study. The container (Model: C-54, Les Contenants Xactics Ltée, Joliette, PQ) was equipped with a stainless-steel shelving-system, capable of holding 36 master trays at nine levels, with four master trays at each level (Figure 2) (Bailey 1997).

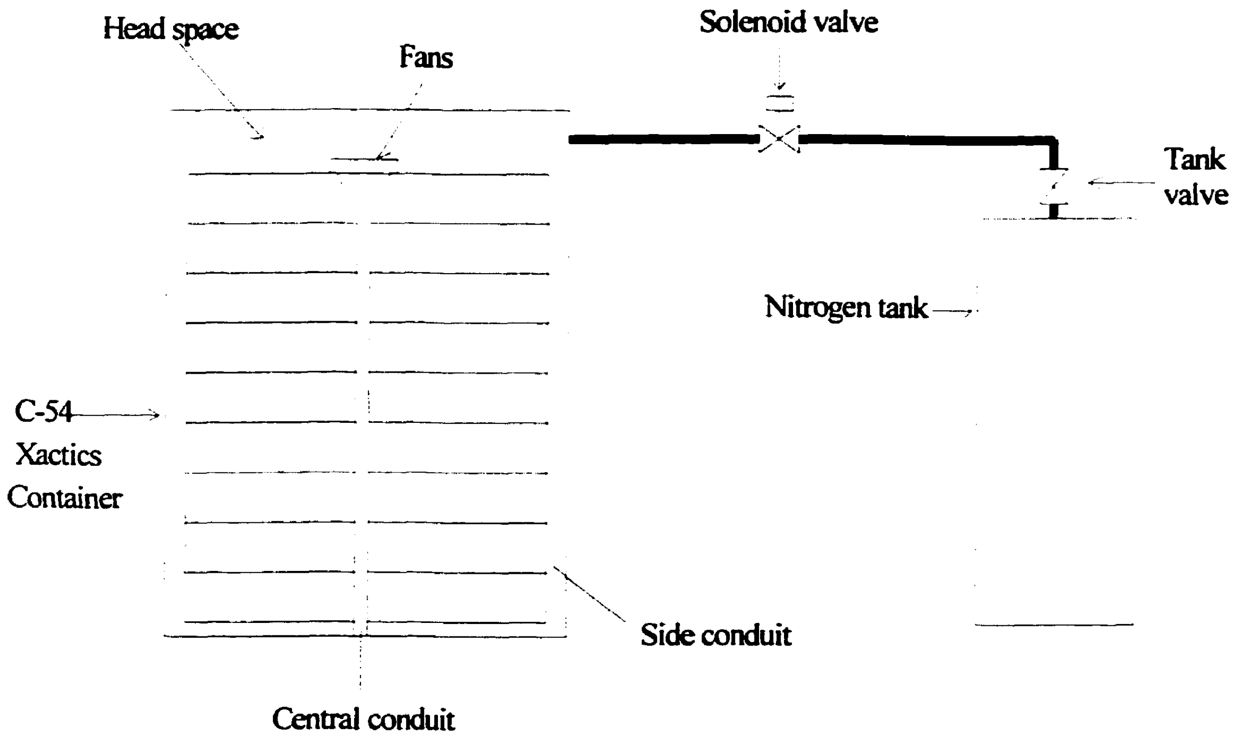


Figure 2. Schematic of the container used by Bailey (1997) and in this study (side view of container given in Appendix C).

The shelving unit is able to accommodate master trays, with dimensions 508×381×60 mm, used to package red meat. The refrigerating medium, liquid nitrogen, used to chill the container was supplied from a pressurized tank (capable of holding 115-120 kg of liquid nitrogen) (DURA SERIES, MVE, New Prague, MN) via a transfer line. Liquid nitrogen was dispersed in the head space with the use of copper piping and agricultural sprayer nozzles. The design by Bailey (1997) relied on the use of six fans located in the headspace at the top of the container to circulate the cooling medium throughout the container. Regulation and control of the nitrogen injections was accomplished through a computer control algorithm (Bailey 1997) which administered nitrogen to the container via a solenoid valve (Model: 8263G206 LT, ASCOlectric Ltd., Brantford, ON) located in the transfer line. The container was placed within an environmental chamber (Model: C1010, CONVIRON, Controlled Environments Ltd., Winnipeg, MB) to enable testing of the container over a range of outside temperatures.

3.2 Chronology of Design Changes to the Container

3.2.1 Circulation of Nitrogen Without the Use of Fans Bailey (1997) reported that the use of fans to circulate the liquid nitrogen created an excess of heat within the container that had to be subsequently removed through the injection of additional nitrogen. Because an increase in nitrogen use would increase the variable cost of the system, an investigation was conducted to distribute the nitrogen without the use of fans. Variables which directly influence the dispersion of nitrogen within the container were the type of injection nozzles used and the positioning of these nozzles. The following nozzle configurations within the container were designed and tested for their effectiveness in distributing the nitrogen:

(i) V-pattern nozzles (Model: 11006VS, Even-Spray and Chemicals Ltd., Winnipeg, MB) pointing downwards along the outside conduit of the frame [Figure 3(i)],

(ii) nozzles with a cone shaped spray pattern (Model: D8, Even-Spray and Chemicals Ltd., Winnipeg, MB) positioned at mid-height in the container and spraying perpendicularly against each side wall of the container [Figure 3(ii)],

(iii) V-pattern nozzles pointing upwards located at the level of the bottom shelf [Figure 3(iii)], and

(iv) V-pattern nozzles pointing upwards located at the second level from the bottom shelf [Figure 3(iv)].

For each of the above configurations, 9.5 mm diameter copper piping (insulated with standard foam pipe insulation) and brass compression fittings were used to accommodate the nozzle positions.

Briefly, the results from testing (using saline bags initially at a temperature of 7±1.5°C) each design change, respectively, are as follows;

(i) A temperature gradient was established within the container, with the top of the container being too warm (0.3°C) and the bottom of the container being too cold (-3.8°C).

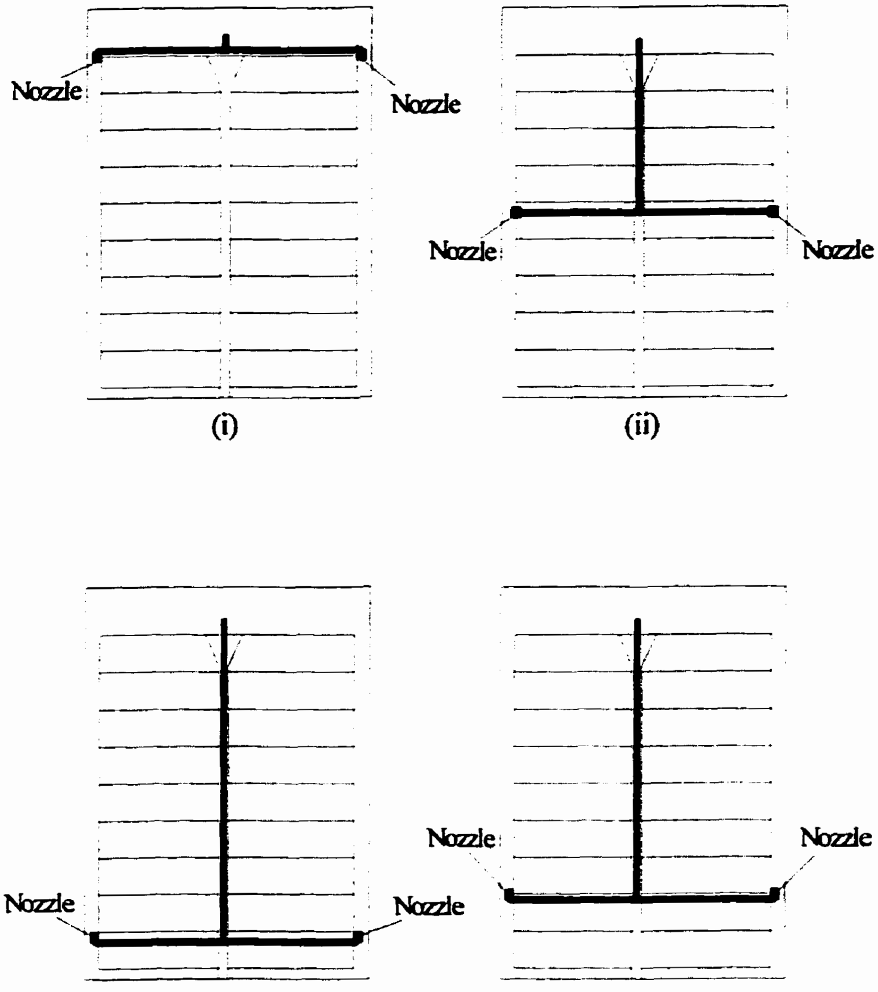
(ii) Top of the container was too warm (approximately 1.9°C) and the bottom of the container and areas adjacent to the injection nozzles were too cold (approximately -4.1°C) and the average container temperature was at -1.7°C.

(iii) Top of the container was too warm (0.8°C), bottom of the container was too cold (-5.8°C), however the average temperature (-1.3°C) was closer to the design temperature of -1.5°C.

(iv) The maximum (1.0°C) and minimum (-2.8°C) temperatures were outside of the desired range (-1 to -2°C) and the average temperature was -0.8°C.

The last design [Figure 3(iv)] was considered to be the most desirable as the minimum temperature was closer to the desired range, thus indicating that less meat would undergo the undesirable changes associated with freezing.

The design with the nozzles injecting liquid nitrogen vertically from the second-from-bottom shelf also proved to be an efficient design in terms of nitrogen consumption. The fixed and variable nitrogen use for this design were determined using a method similar to that used by Bailey (1997) (Refer to Section 4.1.1) and were 12.3 kg and 4.6 kg/h, respectively, while optimum values of fixed and variable nitrogen use with the former design using fans were 18.8 kg and 5.3 kg/h (Bailey 1997). Although the new nozzle design posed problems with temperature uniformity throughout the container relative to the design used by Bailey (1997), its nitrogen use and superior nitrogen distribution as compared to the other fan-free designs made it the most feasible nozzle design explored.



(i) (ii)

(iii) (iv)

Figure 3. Schematics of the tested nozzle configurations.

3.2.2. Changes Made to the Container and Shelving. Additional changes were made to the shelving unit and the container to enhance uniform nitrogen distribution within the container. These changes include;

(i) insertion of the central conduit which was previously removed simultaneously with fan removal,

(ii) replacement of the polyethylene panel (6 mm thickness) along the bottom three shelves with styrofoam insulation to shield the saline bags in those locations from direct chilling from the nozzle outlets or vaporized nitrogen which had settled in the lower portion of the container, or both,

(iii) randomly drilling four holes (diameter of 19.5mm) in the polyethylene panel on the top shelf to increase the amount of nitrogen reaching this area via the side conduits,

(iv) increasing the relative amount of nitrogen supplied to the front nozzles (Model: 11006VS, Even-Spray and Chemicals Ltd., Winnipeg, MB) by restricting the flow to the back nozzles (Model: 8002LP, Even-Spray) to account for the front-to-back temperature gradient due to the difference in container wall thickness (approximately 12 mm difference) from the front to the back, and

(v) placing the control sensors at the top and bottom of the container and averaging the reading from both to better reflect the average internal container temperature.

All of the aforementioned changes were expected to enhance the uniformity of nitrogen distribution at all levels within the container and to reduce the nitrogen consumption.

The following additional changes were made to the container to improve its functionality:

(i) replacing the transfer line of copper piping used by Bailey (1997) with a vacuum insulated transfer line (MediGas, Winnipeg, MB), as recommended by Bailey,

(ii) replacement of the mahogany shelves with plastic shelving to facilitate cleaning, and

(iii) avoiding use of the second-from-bottom level to eliminate freezing of muscle tissue in this location as the copper tubing lies directly above the shelf. For practical use, the container shelving could be reconstructed so that the spacing between levels is smaller and the capacity of the container is not reduced.

Furthermore, 24 thermistors were added throughout the container, in addition to the 24 thermistors used by Bailey (1997), to better monitor the temperatures at all locations (Figure 4).

3.2.3 Decision to Include a Fan in the Design It was determined that the nozzle design depicted in Figure 3(iv) was the most effective in terms of nitrogen use and temperature uniformity in comparison to the other designs without a fan. However, since the maximum and minimum temperatures, 1.0 and -2.8°C, respectively, were outside the desired range (-1.5±0.5°C) and because the other changes which were made to the container to enhance nitrogen distribution did not improve it sufficiently, then it was determined that the addition of a fan to the design was necessary.

3.2.4 Addition of a Fan to the Proposed Nozzle Design. A fan was added to the best nozzle configuration to enhance uniformity of the temperatures within the container and

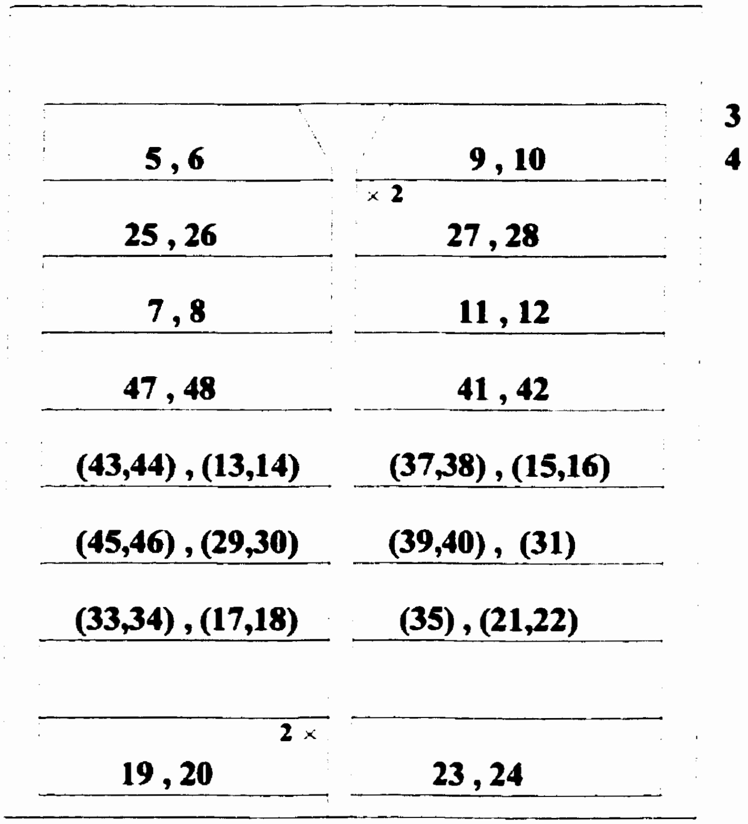


Figure 4. Positions of the original (#2 to 24)(Bailey 1997) and additional thermistors (#25 to 48). (Thermistor numbers on the left of each side were at the front of the container, while those numbers on the right were at the back).

to improve the accuracy of the temperatures in relation to the target temperature of -1.5 ± 0.5°C. Bailey (1997) determined that variable nitrogen use increased as the number of fans increased, due to heat generated by the fan motors situated inside the container Therefore, it was decided that the addition of a fan would only prove beneficial if the additional heat generated by its motor did not enter the container. This was achieved by placing the fan motor on the outside back wall of the container and then connecting it via a flexible drive shaft (Model: 3410201, Wolfcraft, Princess Auto, Winnipeg, MB) to a centrifugal fan. This design proved to be an improvement as the maximum, average, and minimum temperatures within the container were 0.1, -0.8 and -2.3°C, respectively, while the fixed and variable nitrogen use (Defined in Section 4.1.1) were 9.1 kg and 6.9 kg/h, respectively. While the temperature data indicated that the addition of the fan proved beneficial, the nitrogen use data indicated that this design was inefficient; Bailey (1997) reported fixed and variable nitrogen uses of 20.1 kg and 5.7 kg/h, respectively, with four fans operating within the container. A possible source of heat with the current design consisting of the fan powered via a flexible shaft was the heat created from the friction of the flexible shaft against its outer rubber sheath. To alleviate this problem, the position of the motor was aligned to facilitate the replacement of the flexible shaft with a straight shaft, a 1/4" diameter steel rod, with rubber tubing serving as the couplings. Fixed and variable nitrogen use from trials conducted with the straight shaft were 13.2 kg and 5.2 kg/h, respectively, while the maximum, average, and minimum container temperatures were -1.0°C, -1.6°C, and -2.8°C, respectively. Although the design featuring the straight shaft proved feasible in terms of nitrogen consumption and temperature uniformity, the age of the fan caused it to fail and a new fan arrangement was again required.

The resultant fan design was the final fan design for the present system. It consists of a centrifugal fan encased within a metal enclosure, drawing nitrogen in from an open bottom. The metal enclosure discharges nitrogen from the fan into a plenum, consisting of a wooden box, which, in turn, discharges vaporized nitrogen into two circular (each with a diameter of 4") metal conduits extending vertically downwards from the plenum. The circular conduits empty into the central conduit within the shelving structure of the container. Testing of the container with the new fan gave maximum, average, and minimum temperatures of -1.2°C, -1.8°C, and -2.7°C, respectively, while the fixed and variable nitrogen use were 4.6 kg and 4.3 kg/h, respectively.

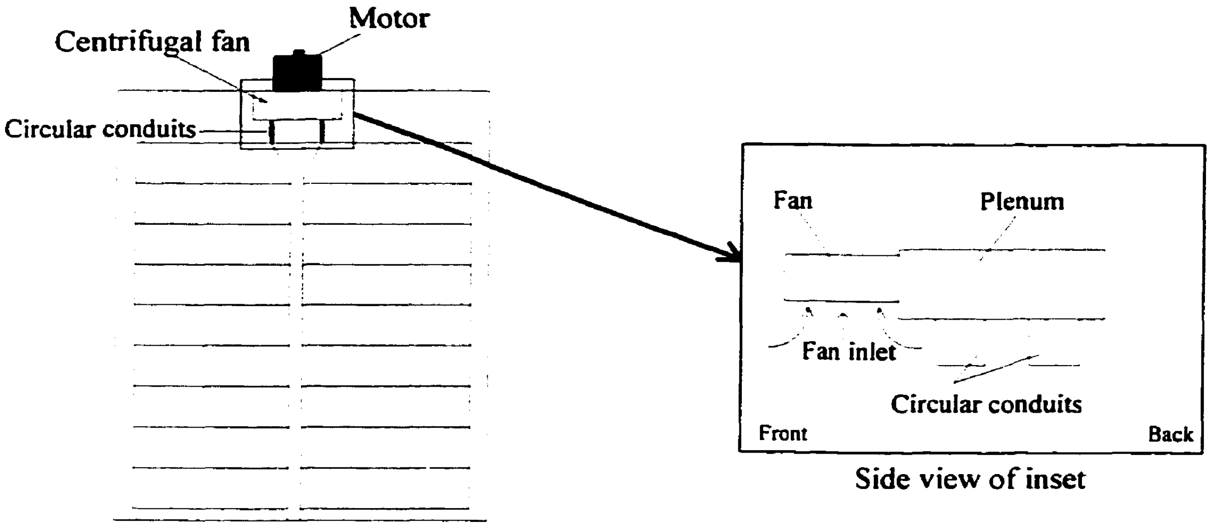


Figure 5. Schematic of the final fan design used in this study.

3.3 Instrumentation

Instrumentation was needed to monitor the temperatures and nitrogen use of the container. All data were written to the hard drive of a 486 PC by a Quick BASIC program. To measure nitrogen use, the nitrogen tank was placed on a floor scale (Model:2136, Mettler-Toledo Inc., Burlington, ON) and its mass was taken every minute by the QuickBASIC control algorithm. A RS 232 connection was used to transfer the mass data to the hard disk.

Forty-four thermistors (Model: 44034, OMEGA Engineering Inc., Stamford, CT) were used to assess the meat temperatures throughout the container and 2 thermistors (#3, 4) were used to measure the temperature of the CONVIRON chamber (Figure 4). Two thermistors (#2) were used as control sensors for the control algorithm (Figure 4). Each thermistor had an accuracy of ± 0.1°C. A data acquisition and control unit (Model: 3852A, Hewlett-Packard Co., Loveland, CO) was used to measure the resistance of the thermistors and in turn, relayed the information to the computer through a serial port. Activation of the solenoid valve was controlled by the control algorithm.

3.4 Temperature Control Algorithm

3.4.1 Previous Temperature Control Algorithm The objective of the temperature control algorithm used by Bailey (1997) was to chill the product from 10°C to -1.5°C and also to maintain the product within ±0.5°C. The control algorithm used by Bailey (1997) relies on the belief that the temperature of the product will converge to the cyclic mean temperature of the internal container temperature. However, there also exists the requirement for the product to be chilled to ≤4°C within approximately the first two hours of storage to ensure the microbiological safety of the meat (Holley, R.A., personal communication, 1998). Preliminary testing of the container following the design changes in this study, using pork roasts and simulated master trays, showed that it took approximately 20 h to reach the target temperature from an initial temperature of 7±1.5°C. Therefore, changes to the control algorithm were required to properly chill the meat in less than 2 h.

3.4.2 Modifications to the Temperature Control Algorithm As the control algorithm used by Bailey (1997) utilized the mean cyclic internal temperature within the container to control the activation of the solenoid valve, the algorithm would prematurely shut off the solenoid prior to the meat attaining the correct temperature. Therefore, the temperature control algorithm needed to be modified to use the meat temperatures to control the activation of the solenoid in the chilling portion of the storage period to bring the meat to the correct temperature in the shortest amount of time. In addition, the target temperature for the meat also needed to be changed to -1.0 ± 0.5°C , as suggested by C.O. Gill, L.E. Jeremiah, (both Research Scientists, Agriculture Canada, Lacombe, AB), D.S. Jayas, and R.A. Holley (personal communication, March 6, 1999), to ensure that none of the meat would undergo the detrimental process of freezing. It was thought that as meat is a variable, biological material, that some cuts would freeze above the theoretical freezing point of -2.0°C. Therefore, a safety factor should be built into the target temperature of the control algorithm to ensure that none of the meat cuts within the container will freeze. As this is an expensive technology for chilling, quality of the final product should not be jeopardized in any way to ensure that a premium price could be obtained to warrant feasibility of the process.

The control algorithm used by Bailey (1997) was designed so that nitrogen would only be injected throughout the last 40 s of the 60 s time cycle to allow for an equilisation of temperatures within the container and to allow the instrumentation system to take temperature measurements in the first 20 s of the cycle. However, the data acquisition unit used in the present study (Model: 3852A, Hewlett Packard, Avondale, PA) does not require the additional time to take readings; therefore temperature readings can be taken simultaneously with nitrogen injections. Furthermore, if the activation of the solenoid relies solely upon the meat temperature, then an equilisation period is not needed. To ensure that none of the meat freezes during the chilling segment, the minimum meat temperature was not allowed to drop below -1.75°C, to account for the biological variability of samples. In addition, the constraint preventing the internal container temperature to fall below -20.0°C ensured that the meat would not freeze due to thermal conduction from the vaporized nitrogen to the meat. This value for the minimum internal temperature was largely decided upon through trial and error observations.

The complete schematic of the changes to the chilling segment of the temperature control algorithm is provided in Appendix B. The basic details of the program are as follows: meat temperatures were read and the maximum, average, and minimum values were calculated. If the average meat temperature was greater than 0°C, then the solenoid was activated continuously until one of two, or both, scenarios occur; (i) the internal temperature within the container drops below -20.0°C, (ii) the minimum meat temperature drops below -1.75°C. If the former were true, then the solenoid valve is simply inactivated until the internal temperature rises above -20.0°C, after which it is turned on again. If the latter holds true, then the program switches over to the temperature control algorithm used by Bailey (1997), however the target temperature for the internal environment was set at -1.25°C. If the average meat temperature again exceeded 0°C, then the program would revert back to the process of continuously adding liquid nitrogen until one of the aforementioned scenarios proved true again.

3.5 Simulation of Master Packages of Meat

3.5.1 Preliminary Testing With Saline Bags To minimize cost, preliminary design changes were evaluated with the use of saline bags as opposed to testing with actual meat cuts. A mixture of 10% salt by mass and water in bags was used to simulate the heat storage characteristics of the quantity of meat which would be contained within one master tray. According to R.A. Holley, (personal communication, August 1998), as this is an expensive technology, primarily premium cuts of meat would be transported in such a manner, therefore it was assumed that loin roasts would often occupy the master trays. According to the area of the tray and the average height of a loin roast, it was determined that each saline bag should have the heat storage characteristics similar to 6.0 kg of meat.

To further model an actual master tray and hence, create a situation inside the container similar to if it were filled with master trays, each saline bag was placed inside an aluminum roasting tray (47.3×36.5×6.7 cm) similar in size to an actual master tray.

3.5.2 Simulated Master Trays After preliminary testing of the container was completed and a final container design was determined, testing of the container was conducted with meat samples (3, 2-kg roasts per tray) contained within simulated master trays. The idea of using a simulated master tray is important as it should be representative of the size of an actual master tray so that the flow patterns of nitrogen within the container and the heat transfer within the trays will be patterned as close as possible to the actual situation.

The design of the simulated master tray (Figure 6) consists of an aluminum roasting pan (47.3×36.5×6.7 cm), with an overlying wire frame (steel), bent to create a head space above the meat (6-kg per tray). The tray and frame were surrounded by a plastic bag (56×87 cm) that is open at one end to allow the insertion of a thermistor used to measure the meat temperature. The head space between the meat and the plastic bag is necessary to simulate the dead space created within a master package from the modified atmosphere. This dead space will affect the heat transfer to the tray and hence, models the actual use of a master tray. The thermistor used to measure the meat temperature was attached to the meat surface, without penetrating the meat surface, under the plastic wrap of the meat and held in place with duct tape. The surface temperature of the meat must be measured as muscle tissue freezing would first occur at the surface.

3.6 Experimental Method

3.6.1 Temperature and Nitrogen Use Tests The CONVIRON chamber was used to chill the container and either the saline bags or meat samples to 7 ± 1.5°C because this was considered an average temperature of meat entering the chilling process at a processing facility (Gill and Phillips 1993a). After this temperature had been attained, the container door was closed and the CONVIRON chamber was then set to the desired outside temperature for the test to be conducted. After which, the valve to the nitrogen tank was opened and the temperature control algorithm was started. The preliminary tests of the container were conducted for an 8-h duration, in accordance with the testing completed by Bailey (1997), however, tests conducted with the final design of the container lasted for approximately 2 days to ensure that a stable temperature had been reached in the system. Three replicates were completed for the outside temperatures of 30, 15, 0, and -15°C.

3.6.2 Comparison of Vacuum Insulated and Steel Braided Transfer Lines Two replicates at a chamber temperature of 15°C were conducted to compare the effect of using a vacuum insulated transfer line on nitrogen use to an uninsulated steel braided transfer line. Each of these replicates was conducted for approximately 1 day.

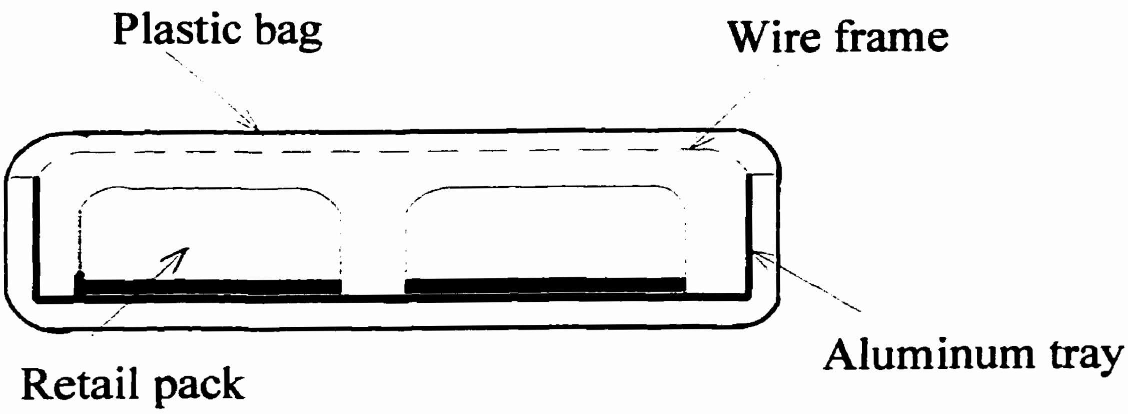


Figure 6. Schematic of a simulated master tray.

3.6.3 Failure Testing Failure testing was conducted to simulate the situation of a nitrogen failure and to determine the resulting effect on the container temperature. The container and meat samples were equilibrated to -1.0 ± 1.5°C using the CONVIRON chamber. After this temperature had been attained, the container door was closed and the CONVIRON chamber was then set to 30°C. Temperatures throughout the container were then recorded for an 8-h duration and three replicates of such testing were conducted.

3.6.4 Method of Data Analysis Temperature and nitrogen use data from all tests conducted were initially stored on the hard drive of the PC unit and were subsequently imported into Quattro Pro (Corel Corporation, Ottawa, ON, 1997) spreadsheets for further analysis. The temperature control algorithm had written the mass of the liquid nitrogen tank and the temperatures every 60 s to the PC's hard drive. In Quattro Pro, the imported data were used to calculate the cumulative nitrogen use and maximum, average, and minimum temperatures for each trial every 60 s. From this, temperature history versus time were graphed and nitrogen use in terms of its fixed and variable components were determined. These parameters were graphed and are included in Appendix A (Figures A.1. to A.31.).

4. RESULTS AND DISCUSSION

4.1 Temperature and Nitrogen Use Data

4.1.1 Initial Data Analysis The means of maximum, average, and minimum temperatures (Table 1) of meat samples were determined from time = 5.5 h until the trial was completed, to coincide with the method used by Bailey (1997) and also because the meat samples had reached a temperature equilibrium at that point (Appendix A).

Nitrogen consumption throughout a test was split into two types of use; fixed and variable. The former refers to the quantity of nitrogen required to chill the contents of the container from 7±1.5°C to -1.0±0.5°C, while the latter relates to the amount of nitrogen needed to remove the heat conducted through the walls and transfer line, and heat produced by the fan. To ensure that results from this study could be fairly compared to those produced in a past study (Bailey 1997), the variable nitrogen use was calculated using a procedure similar to Bailey (1997). This involved performing a linear regression on the nitrogen use data over time from 5.5 h until test completion. After 5.5 h, the nitrogen use by the container had reached a constant value (Appendix A), (Bailey 1997). The slope of the line between nitrogen use versus time represented the variable nitrogen use. The fixed nitrogen use was determined as the amount of nitrogen consumed up to the beginning of the horizontal section of the curve for nitrogen use versus time (Depicted in Appendix A). Table 2 shows the experimental values for fixed and variable nitrogen use.

4.1.2 Temperature in Relation to Location Temperature data indicate that there were no temperature gradients, i.e., temperature was uniform within the container. The minimum readings were generally found at thermistor location 30 (Figure 4), while the maximum readings varied with location from test to test.

4.1.3 Effect of Outside Temperature The temperature range, i.e., the spread between maximum and minimum temperatures, measured in the container was similar for each outside temperature tested. However, there was a slight rise in the temperature range as the outside temperature decreased, i.e., the maximum values shifted approximately 0.1 to 0.2°C higher at 0 and -15 °C than at the higher outside temperatures.

The present design has the additional advantage of being able to operate at sub zero outside temperatures and avoid freezing of the meat samples due to the heat generated by the fan.

4.1.4 Nitrogen Use Data - Fixed Use Tables 2 and 3 show the fixed nitrogen use values for each test. Fixed nitrogen use was similar for all temperatures tested (Scheffé's mean comparison test $\alpha = 0.05$).

Bailey (1997) observed an average fixed nitrogen use of 18.1 kg, while the data from this study yielded an average fixed nitrogen use of 32.7 kg. The increased fixed nitrogen use observed with the present design is most likely attributed to the fact that Bailey (1997) conducted trials using saline bags which only represented 3.6 kg of meat

Table 1. The maximum, average, and minimum temperatures of meat samples within the container, from time = 5.5 to 48 h.

Outside temperature (°C)	Trial number	Temperature		
		Max (°C)	Avg (°C)	Min (°C)
30	1	-0.6	-0.9	-1.4
	2	-0.7	-0.9	-1.1
	3	-0.5	-0.9	-1.1
15	1	-0.7	-1.0	-1.2
	2	-0.5	-0.9	-1.1
	3	-0.4	-0.9	-1.1
0	1	-0.4	-0.9	-1.0
	2	-0.4	-0.8	-1.0
	3	-0.3	-0.8	-1.1
-15[b]	1	-0.5	-0.9	-1.3
	2	-0.3	-0.9	-1.2
	3	-0.4	-0.9	-1.2
		Steel braided transfer line used[a]		
15	1	-0.3	-0.8	-1.0
	2	-0.2	-0.8	-1.1

[a] Steel braided transfer line as opposed to a vacuum insulated transfer line used in all other tests.

[b] Trials conducted for 24 h with the same meat used for the 3 replicates.

Table 2. Experimental values of fixed and variable nitrogen use.

Outside temperature (°C)	Trial number	Fixed nitrogen use (kg)	Variable nitrogen use (kg/h)
30	1	33.0	4.5
	2	30.6	5.0
	3	37.4	5.0
	Mean	33.7	4.8
15	1	25.2	2.8
	2	31.6	2.7
	3	38.2	2.8
	Mean	31.7	2.8
0	1	38.6	1.2
	2	31.2	1.2
	3	34.2	1.2
	Mean	34.7	1.2
-15	1	33.2	0.0
	2	29.6	0.1
	3	29.0	0.1
	Mean	30.6	0.1

A vacuum insulated transfer line used in all tests.

Table 3. Experimental values of fixed and variable nitrogen use for the steel braided transfer line.

Outside temperature	Trial number	Fixed nitrogen use (kg)	Variable nitrogen use (kg/h)
15°C	1	41.0	5.5
	2	38.4	5.5
	Mean	39.7	5.5

per master tray, while in this study, simulated master trays contained approximately 6 kg of meat. The increased amount of meat within the container for the present study would increase the fixed amount of nitrogen required to initially chill the contents of the container.

4.1.5 Nitrogen Use Data - Variable Use Variable nitrogen use is also shown in Tables 2 and 3. As expected, data from this study indicate that variable nitrogen use increased as the outside temperature increased. This is due to the higher rate of heat conduction occurring through the transfer line and container walls at the higher outside temperatures. In fact, each subsequent increase in outside temperature, for instance, increasing the outside temperature from 15 to 30°C, resulted in the variable nitrogen use almost doubling in magnitude.

Bailey (1997) reported achieving average variable nitrogen use values of 5.5, 4.0, 2.6, and 0.9 kg/h for 30, 15, 0, and -15°C outside temperatures, respectively, using the four fan design. In this study, values of 4.8, 2.8, 1.2, and 0.1 kg/h (nitrogen was used at

-15°C since the fan was producing enough heat to require nitrogen injection) for 30, 15, 0, and -15°C outside temperatures, respectively, were determined for variable nitrogen use. Therefore, it can be concluded that the present design is improvement in the efficiency of variable nitrogen use in comparison to the former design by Bailey (1997), considering the above data and the fact that the storage capacity was almost doubled.

4.1.6 Temperature Data As the target temperature range for this study (-1.0±0.5°C) and the previous study by Bailey (1997), (-1.5±0.5°C), are not the same, a direct comparison in terms of temperature uniformity between the two designs cannot be made. However, Table 4 provides an analysis of the temperature range in the container and yields the finding that the present design is an improvement over the design by Bailey (1997) in that the temperature range is smaller and does not appear to be affected to the same extent as Bailey's system by a change in outside temperature.

Table 4. A comparison of the average temperature ranges for different outside temperatures between this study and the study by Bailey (1997).

Outside temperature (°C)	Average temperature range (°C)	
	Present study	Study by Bailey (1997)
30	0.6	1.2
15	0.6	1.0
0	0.7	0.6
-15	0.8	0.4

4.2 Comparison of Vacuum Insulated and Steel Braided Transfer Lines

A comparison was made between the steel braided transfer line and the vacuum insulated line at the outside temperature of 15°C (Tables 1, 2, and 3). Average fixed nitrogen use was similar for both types of transfer lines and had the values of 31.7 and 39.7 kg for tests with vacuum insulated and steel braided transfer lines, respectively (Tables 2 and 3) (LSD mean comparison test $\alpha = 0.05$). Variable nitrogen use, however, was affected by the type of transfer line used. Average values were 2.8 and 5.5 kg/h, respectively, for the vacuum insulated and steel braided transfer lines. This result was expected because the vacuum insulated transfer line guards against heat conduction through the transfer line and thus, lowers the variable nitrogen use. In the final design of the system, a vacuum insulated line should be used.

A comparison of the temperature data of the two types of transfer lines showed that although the minimum and average temperatures were similar, the tests with the steel braided transfer line had a maximum temperature which was approximately 0.3°C higher than the maximum temperature of the tests using the vacuum insulated transfer line. It is possible that heat conduction through the steel braided was sufficient enough to have affected the cooling potential of the injected nitrogen and hence, had a noticeable effect on the maximum meat temperature

4.3 Nitrogen Failure Data

A linear regression was performed on the average temperatures of the meat samples during a test to determine the rate of temperature increase following a nitrogen failure (Table 5). The present system had an average rate of temperature increase following a nitrogen failure at approximately 1/4 of the values determined by Bailey (1997).

Table 5. Average rate of meat temperature increase after a nitrogen failure at an outside temperature of 30°C.

Trial number	Average rate of temperature increase (°C/h)	
	Present study	Study by Bailey (1997)[a]
1	0.4	1.9
2	0.5	2.0
3	0.5	2.0

[a] Data were adapted from Bailey (1997).

5. CONCLUSIONS

The following conclusions can be drawn from this study:

1. Removal of fans from the container did not create the temperature uniformity required (-1.0±0.5°C) within the container and resulted in the formation of temperature gradients from the top to the bottom of the container.
2. The addition of a single fan, with a motor residing outside the container, and nozzles injecting nitrogen upwards along the side conduits at a level near the second-from-bottom shelf served as the best design in terms of nitrogen use and temperature uniformity.
3. The container operated inside the temperature range (-1.0±0.5°C) for the average and minimum container temperatures, however, slightly outside the range as far as the maximum temperature is concerned. Maximum and minimum temperature readings for the container were -0.3 and -1.4°C, respectively.
4. Use of a vacuum insulated transfer line was beneficial with regard to the variable nitrogen use. Use of a vacuum insulated transfer line cut variable nitrogen use almost in half compared to the use of a steel braided transfer line.
5. Chilling the product from 7±1.5°C to the desired temperature range (-1.0±0.5°C) was best accomplished by utilizing meat temperatures in determining whether or not the solenoid valve is subsequently turned on or off.

6. The present design improves the variable nitrogen use over the former design by Bailey (1997) and would hence, serve as a more economically feasible method for fresh meat transport.

6. RECOMMENDATIONS FOR FUTURE WORK

The central goal for this study was to improve on the former design in terms of nitrogen use. Having accomplished this, there still remains other facets of this project which need to be explored, namely:

1. An economic feasibility study to assess the overall cost of instituting the cryogenic transport of fresh meat into the present meat distribution system should be conducted. The study should also be extended to determine how cryogenic chilling would fit into the distribution system, i.e., would it be used to chill and maintain, or just to maintain the temperature of pre-chilled meat.
2. The temperature control algorithm should be modified so that it does not rely on temperature readings from the meat, as inserting thermistors into cuts of meat in a practical setting would prove cumbersome. Therefore, a statistical analysis should be done on the output data for the solenoid valve which indicates when and how long it was turned on to maintain the correct temperature. The statistical inferences made from these data could then be used to modify the control algorithm to not utilize meat temperature data and make decisions based on the historical information.

7. REFERENCES

Anonymous. 1995. Industry profile-fresh red meat. Report commissioned to Kline & Co. Inc. New York, NY by AlliedSignal Inc., Morristown, NJ. [Online]. Available HTTP: http://www.asresin.com/plastic/trailer.map

Bailey, C. G. 1997. Design, fabrication, and testing of a returnable, insulated, nitrogen-refrigerated, controlled-atmosphere, shipping container for distribution of fresh red meat. Unpublished M.Sc. Thesis, Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB. 61 p.

Creighton, J. 1996. Modern butcher:centralized cutting lowers costs. *Winnipeg Free Press.* Winnipeg, MB., February 28:Sect.D:1.

Finne, G. 1982. Modified- and controlled-atmosphere storage of muscle foods. *Food Technology* 36(2):128-133., cited by Shay and Egan 1986b.

Georgala, D.L. and C.M. Davidson. 1970. British patent 1, 199, 998., cited by Shay and Egan 1986b.

Gill, C.O. 1986. The control of microbial spoilage in fresh meats. In *Advances in Meat Research, Vol.2,* ed. A.M. Pearson & T.R. Dutson, 49-88. Westport, CT:AVI Publishing Co., cited by Gill and Phillips 1993b.

Gill, C.O. and C. McGinnis. 1993. Changes in the microflora on commercial beef trimmings during their collection, distribution and preparation for retail sale as ground beef. *International Journal of Food Microbiology* 18:321-332.

Gill, C.O., C. McGinnis, and A.K.W. Tong. 1994. Consumer acceptance of display packs of beef stored under N_2 or CO_2 in master packs. *Meat Science* 38:397-406.

Gill, C.O. and D.M. Phillips. 1993a. Assessment of the preservative capabilities of storage and distribution processes. Technical Bulletin 1993-9E. Research Branch, Agriculture Canada, Canada. 22p.

Gill, C.O. and D.M. Phillips. 1993b. The efficiency of storage during distant continental transportation of beef sides and quarters. *Food Research International* 26:239-245.

Gill, C.O., D.M. Phillips, and J.C.L. Harrison. 1988. Product temperature criteria for shipment of chilled meats to distant markets. In *Refrigeration for Food and People*, International Institute of Refrigeration, 40-47. Paris, France, cited by Gill and Phillips 1993a.

Guilfoy, R.F., Jr. and R.C. Mongelli. 1971. Comparative operational tests of two different refrigeration systems for local delivery vehicles. In *Proceedings XIII International Congress of Refrigeration-Progress in Refrigeration Science and Technology* 4: 427-433. Washington, DC.

Holley, R.A., P. Delaquis, J. Gagnon, G. Doyon, and C. Gariépy. 1993. Modified atmosphere packaging of fresh pork. Food Research and Development Centre. Agriculture and Agri-Food Canada, St. Hyacinthe, PQ. Alimentech 6(3): 16-17.

Jeremiah, L.E., N. Penney, and C.O. Gill. 1992. The effects of prolonged storage under vacuum or CO_2 on the flavor and texture profiles of chilled pork. *Food Research International* 25:9-19.

Lawrie, R.A. 1974. *Meat Science*, 2nd ed. New York, NY:Pergamon Press., cited by Penney and Bell 1993.

Penney, N. and R.G. Bell. 1993. Effect of residual oxygen on the colour, odour and taste of carbon dioxide-packaged beef, lamb and pork during short term storage at chill temperatures. *Meat Science* 33:245-252.

Prescott, L.M., J.P. Harley, and D.A. Klein. 1996. Microbiology. 3rd. ed. Dubuque, IA.:Wm. C. Brown Publishers, 422-423.

Shay, B.J. and A.F. Egan. 1986a. Studies of possible techniques for extending the storage life of chilled pork. *Food Technology in Australia* 38(4):144-146.

Shay, B.J. and A.F. Egan. 1986b. The packaging of chilled red meats. *Food Technology in Australia* 39(6):283-285.

Shay, B.J. and A.F. Egan. 1990. Extending retail storage life of beef and lamb by modified atmosphere packaging. *Food Australia* 42(8):399-400, 404.

Taylor, A.A. 1985. Packaging fresh meat. In *Developments in Meat Science-3*, ed. R. Lawrie, 89-113. New York, NY:Elsevier Applied Science Publishers.

Tewari, G., D.S. Jayas, and R.A. Holley. 1999. Centralized packaging of retail meat cuts : a review. *Journal of Food Protection* 62(4):418-425.

Young, L.L., R.D. Reviere, and A.B. Cole. 1988. Fresh red meats:A place to apply modified atmospheres. *Food Technology* 42(7-12):65-67, 68-69.

APPENDIX A - TEMPERATURE AND N_2 USE DATA

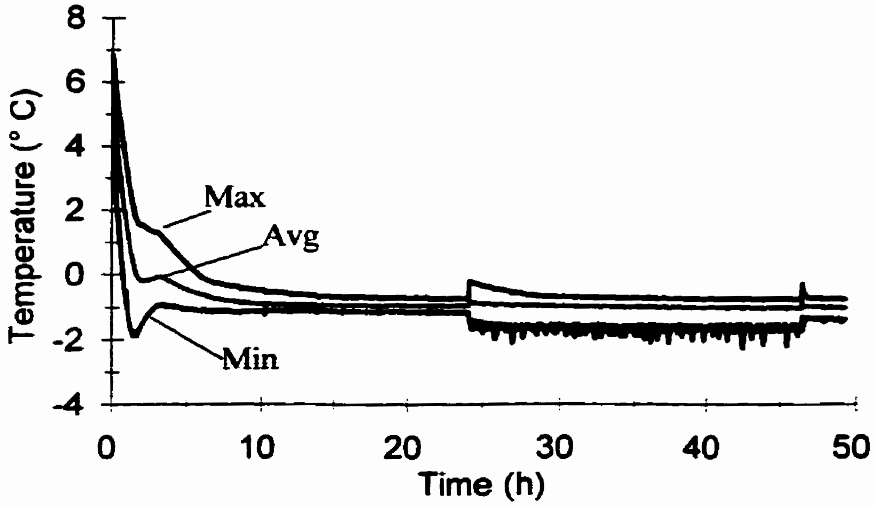


Figure A.1. Maximum, average, and minimum temperatures (Trial 1) of meat samples when the container was exposed to an outside temperature of 30°C.

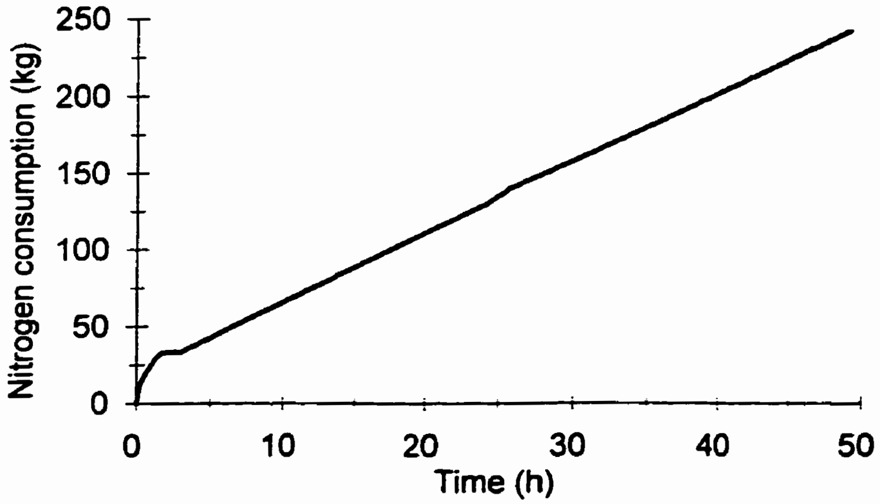


Figure A.2. Nitrogen consumption during Trial 1 (Figure A.1.).

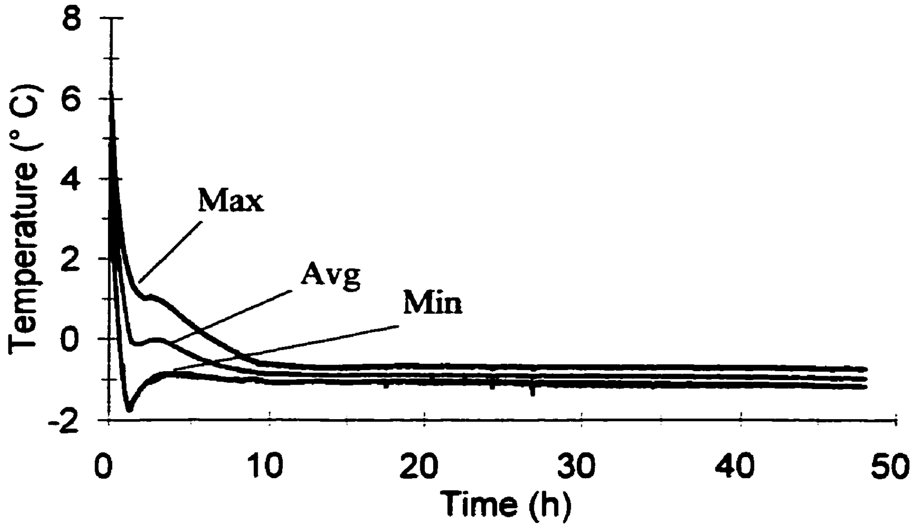


Figure A.3. Maximum, average, and minimum temperatures (Trial 2) of meat samples when the container was exposed to an outside temperature of 30°C.

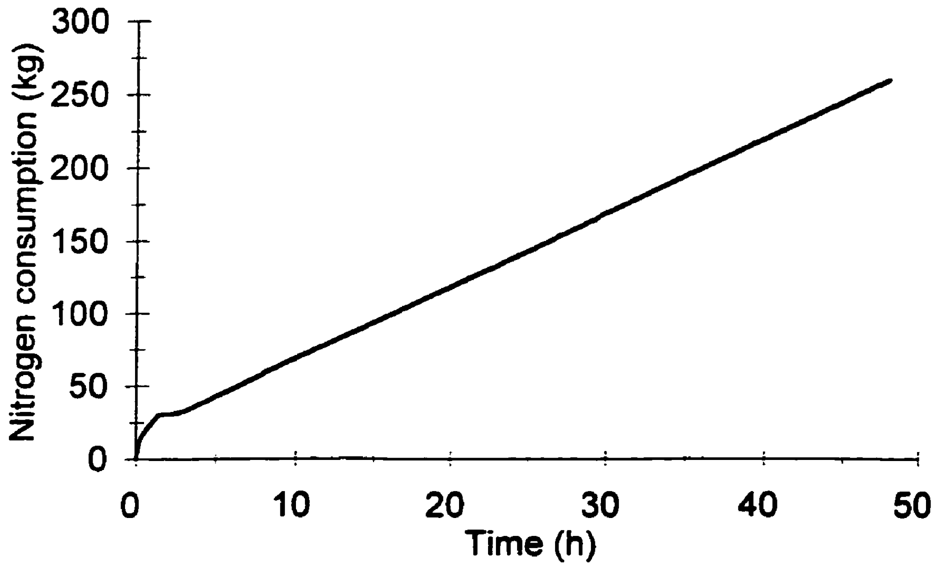


Figure A.4. Nitrogen consumption during Trial 2 (Figure A.3.).

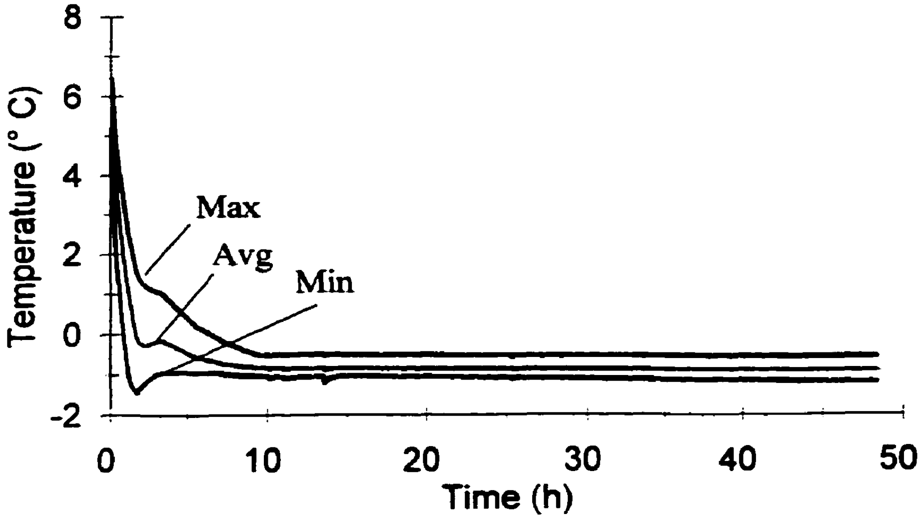


Figure A.5. Maximum, average, and minimum temperatures (Trial 3) of meat samples when the container was exposed to an outside temperature of 30°C.

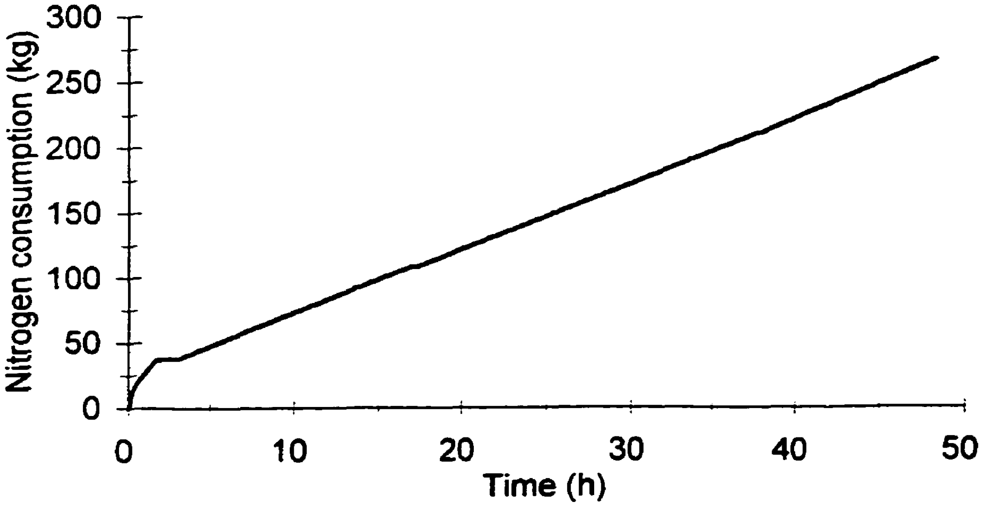


Figure A.6. Nitrogen consumption during Trial 3 (Figure A.5.).

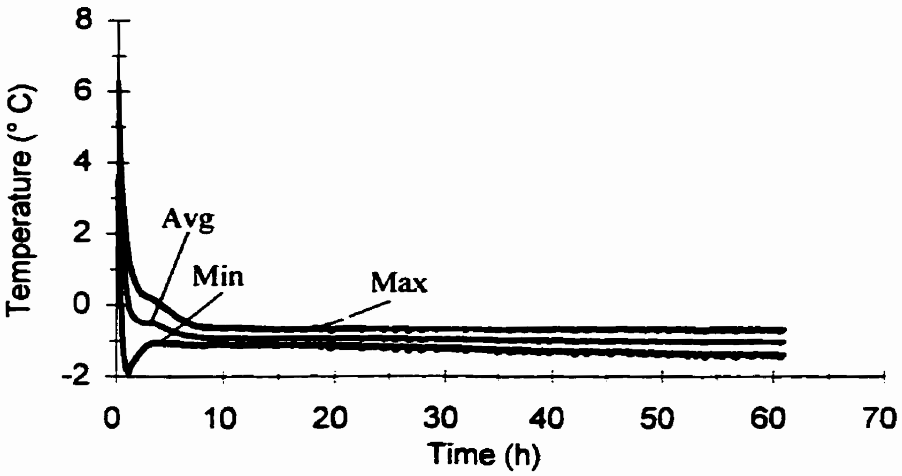


Figure A.7. Maximum, average, and minimum temperatures (Trial 1) of meat samples when the container was exposed to an outside temperature of 15°C.

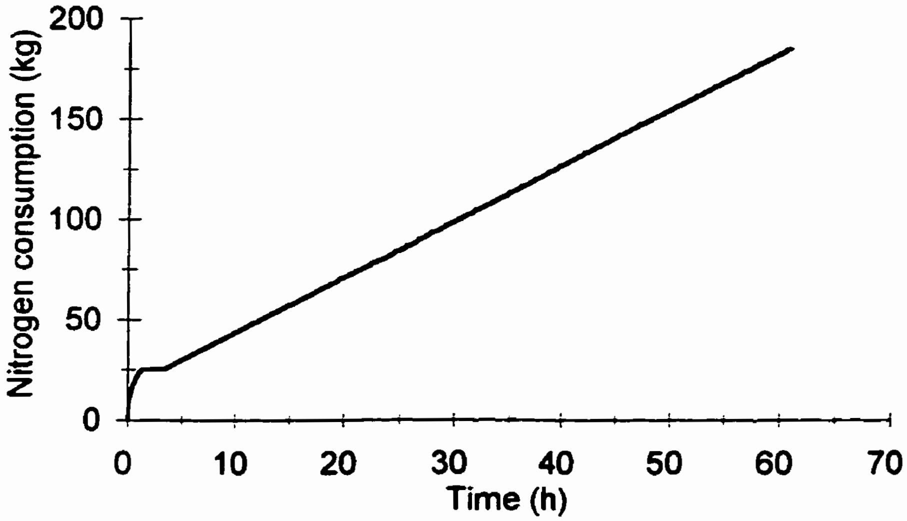


Figure A.8. Nitrogen consumption during Trial 1 (Figure A.7.).

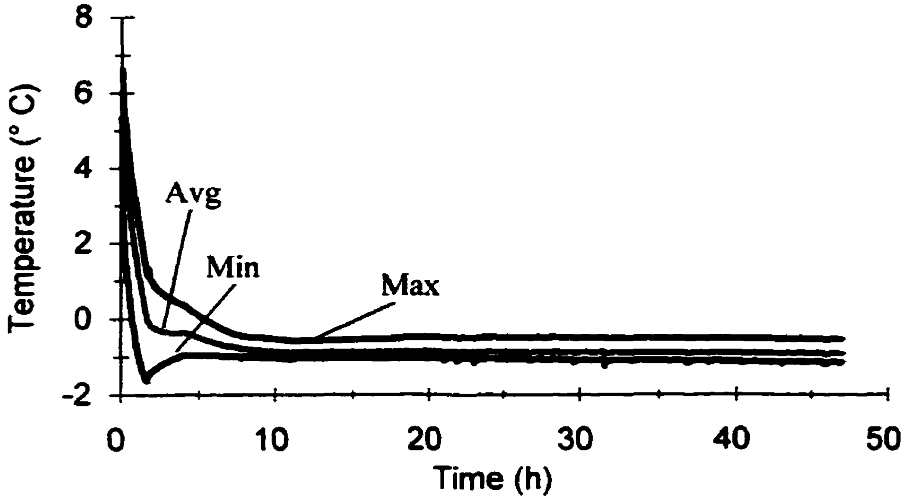


Figure A.9. Maximum, average, and minimum temperatures (Trial 2) of meat samples when the container was exposed to an outside temperature of 15°C.

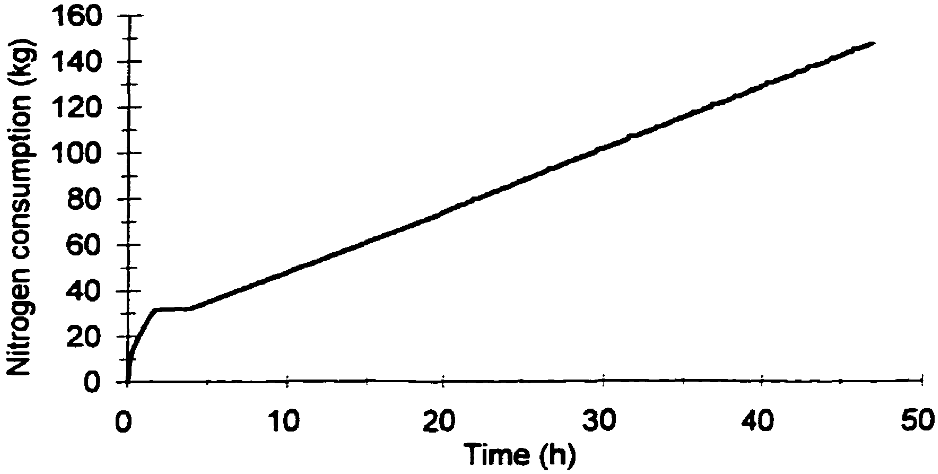


Figure A.10. Nitrogen consumption during Trial 2 (Figure A.9.).

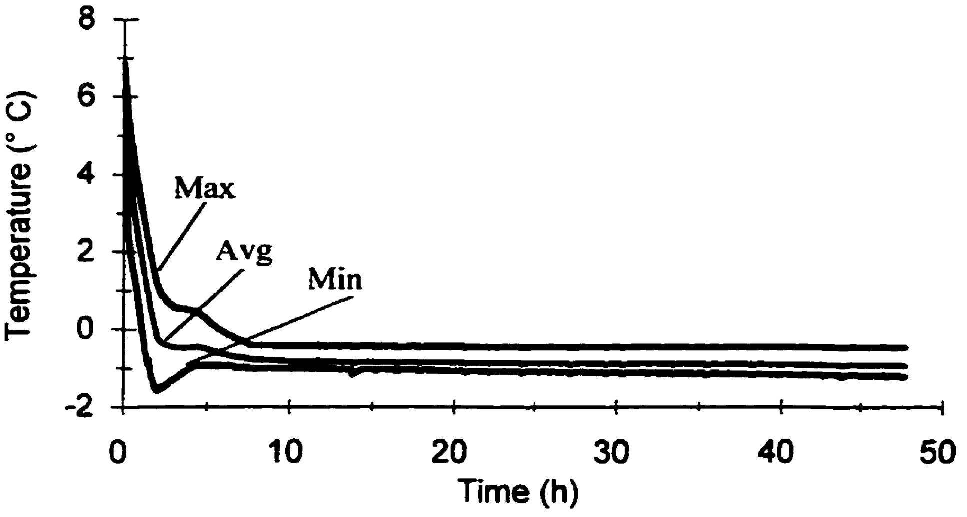


Figure A.11. Maximum, average, and minimum temperatures (Trial 3) of meat samples when the container was exposed to an outside temperature of 15°C.

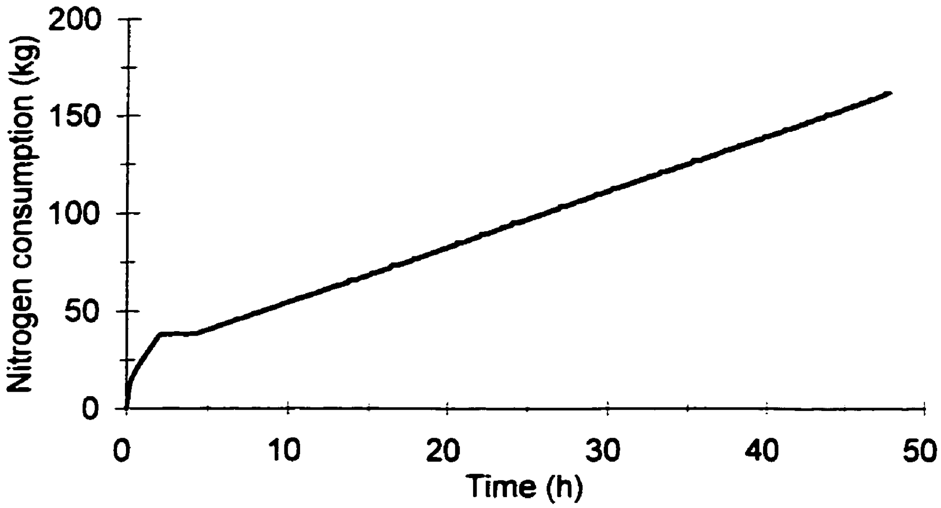


Figure A.12. Nitrogen consumption during Trial 3 (Figure A.11.).

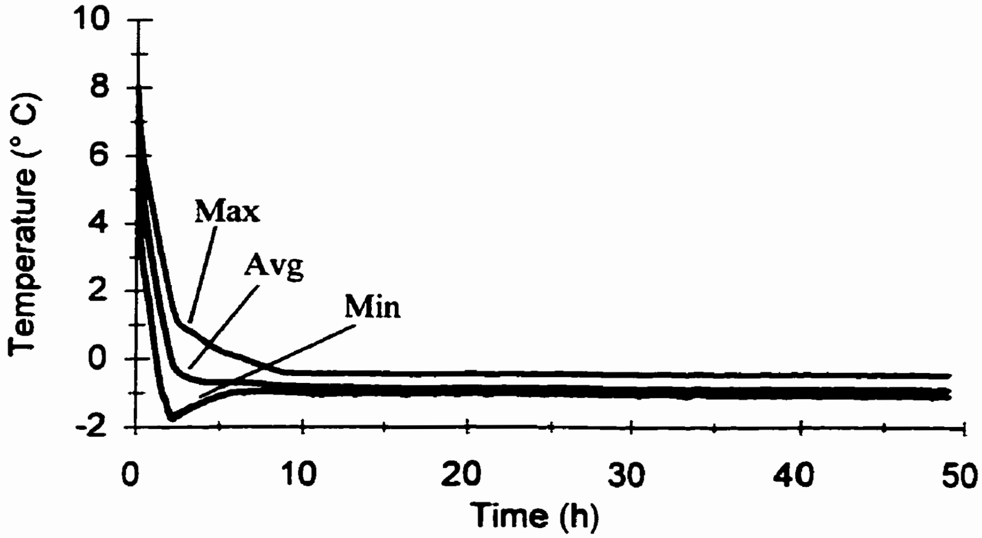


Figure A.13. Maximum, average, and minimum temperatures (Trial 1) of meat samples when the container was exposed to an outside temperature of 0°C.

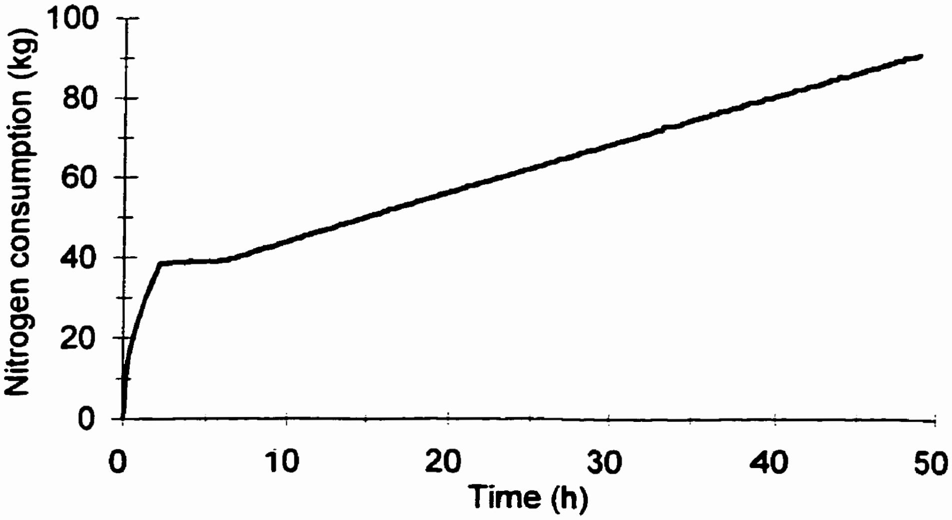


Figure A.14. Nitrogen consumption during Trial 1 (Figure A.13.).

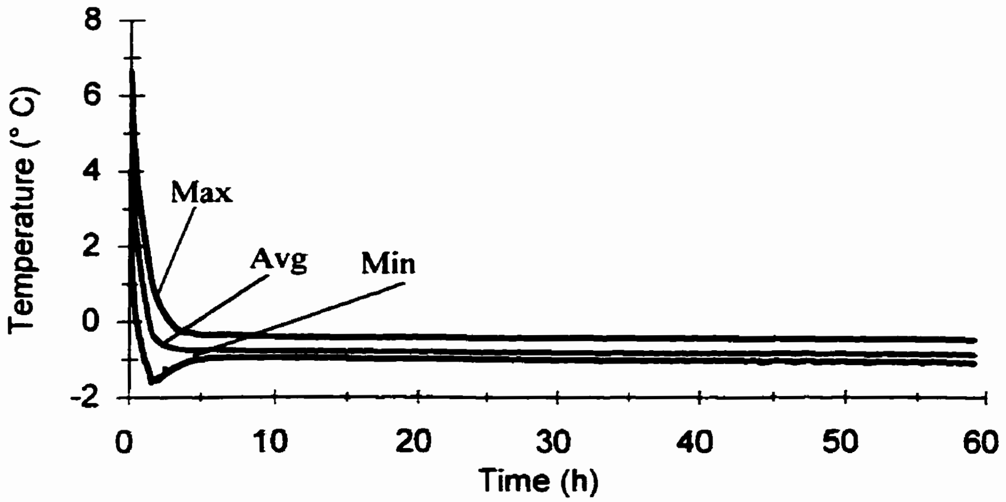


Figure A.15. Maximum, average, and minimum temperatures (Trial 2) of meat samples when the container was exposed to an outside temperature of 0°C.

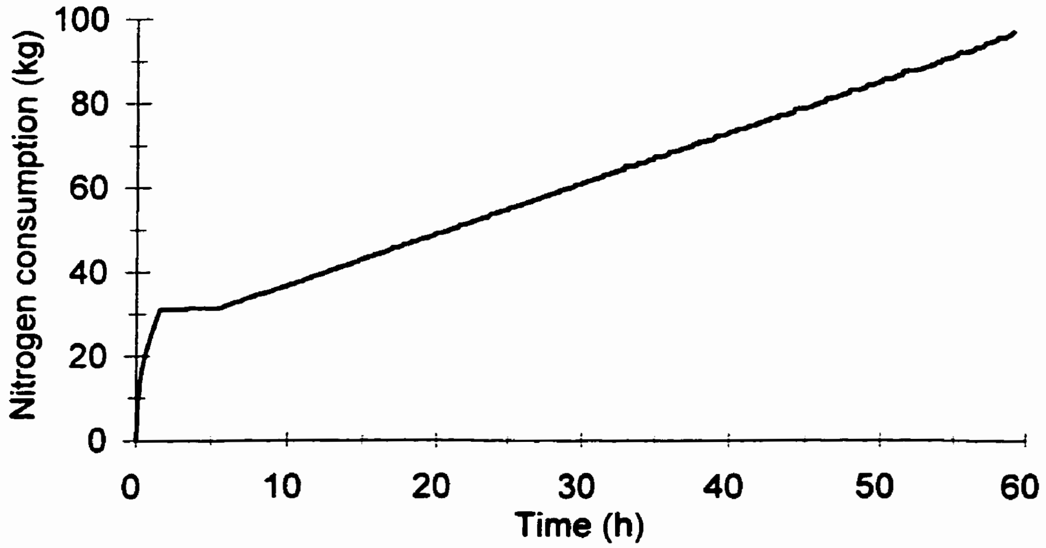


Figure A.16. Nitrogen consumption during Trial 2 (Figure A.15.).

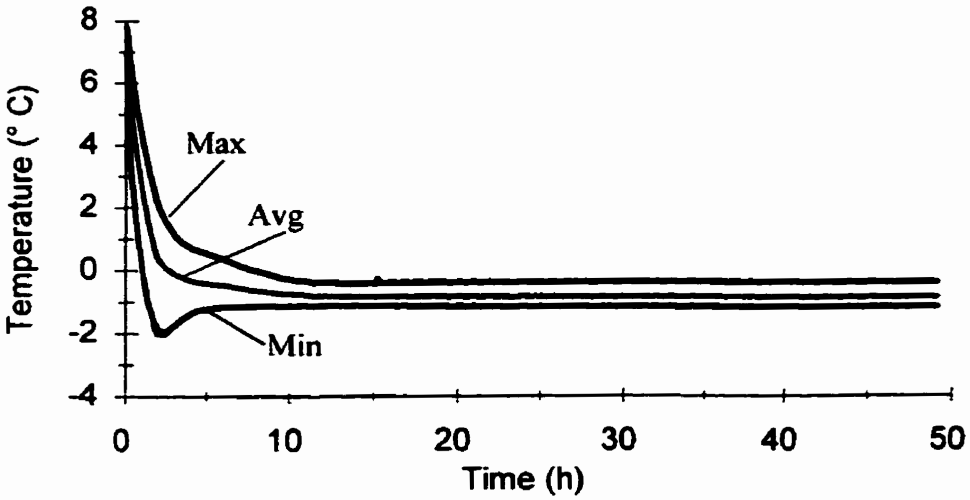


Figure A.17. Maximum, average, and minimum temperatures (Trial 3) of meat samples when the container was exposed to an outside temperature of 0°C.

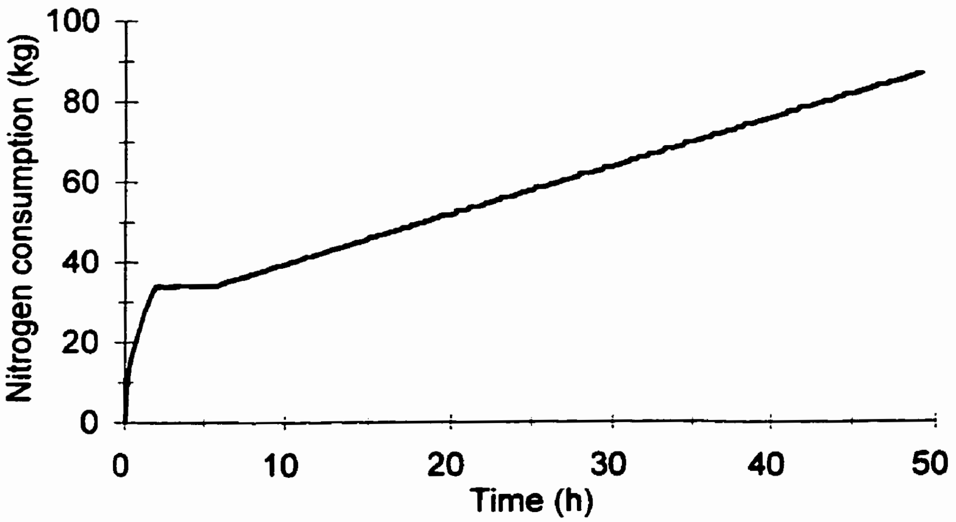


Figure A.18. Nitrogen consumption during Trial 3 (Figure A.17.).

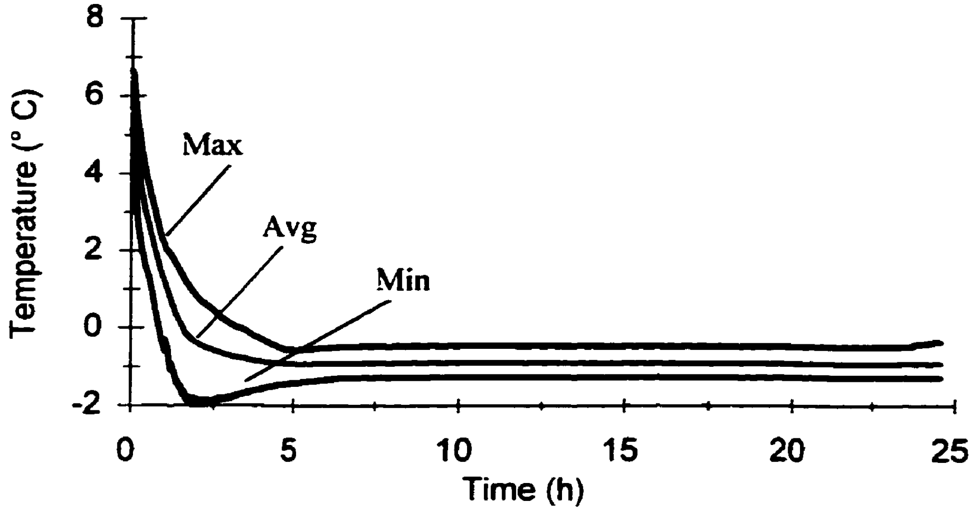


Figure A.19. Maximum, average, and minimum temperatures (Trial 1) of meat samples when the container was exposed to an outside temperature of -15°C.

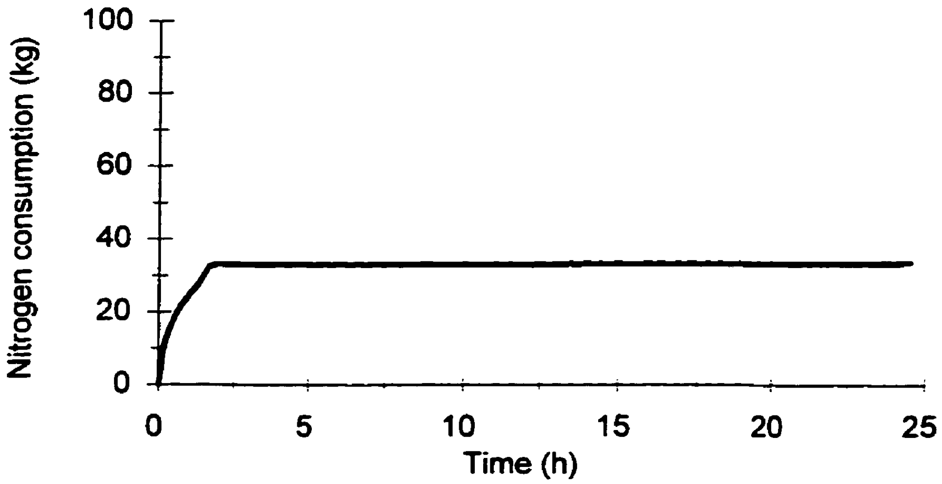


Figure A.20. Nitrogen consumption during Trial 1 (Figure A.19.).

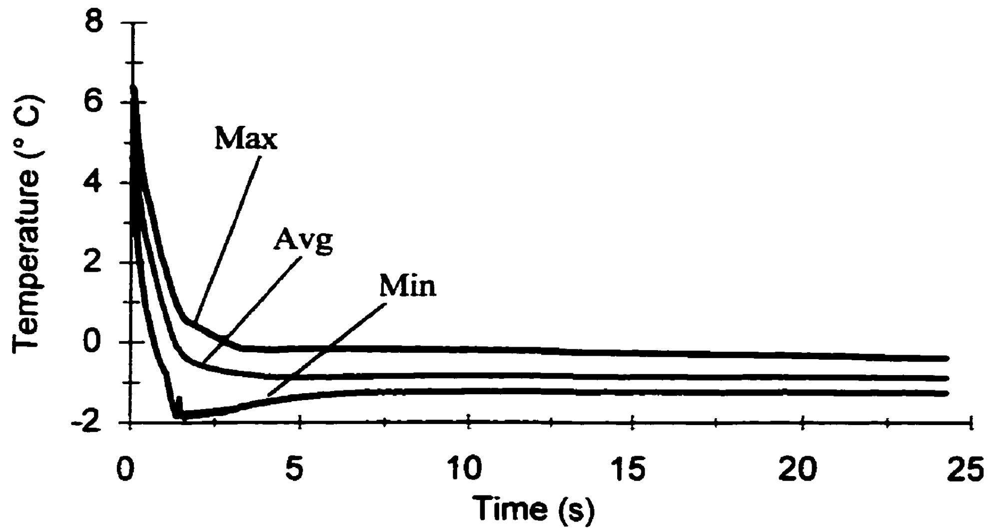


Figure A.21. Maximum, average, and minimum temperatures (Trial 2) of meat samples when the container was exposed to an outside temperature of -15°C.

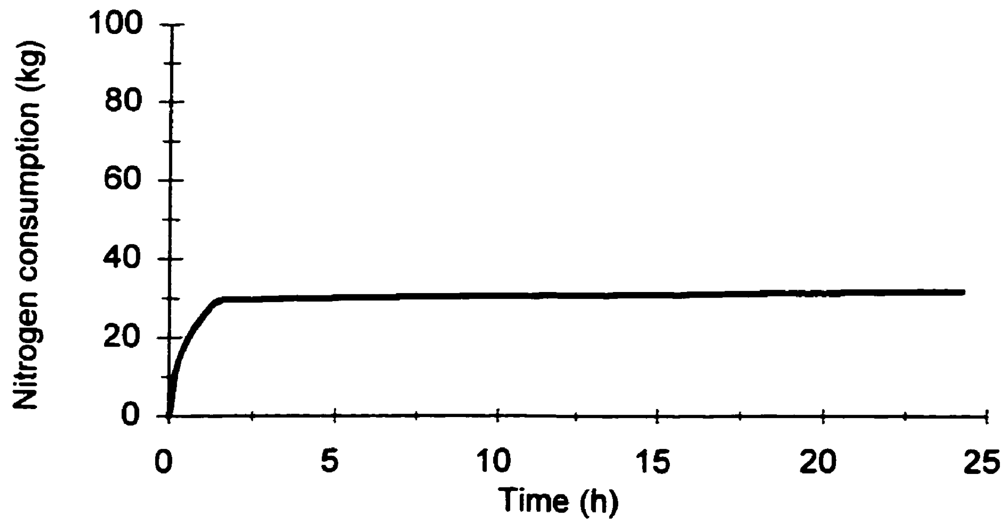


Figure A.22. Nitrogen consumption during Trial 2 (Figure A.21.).

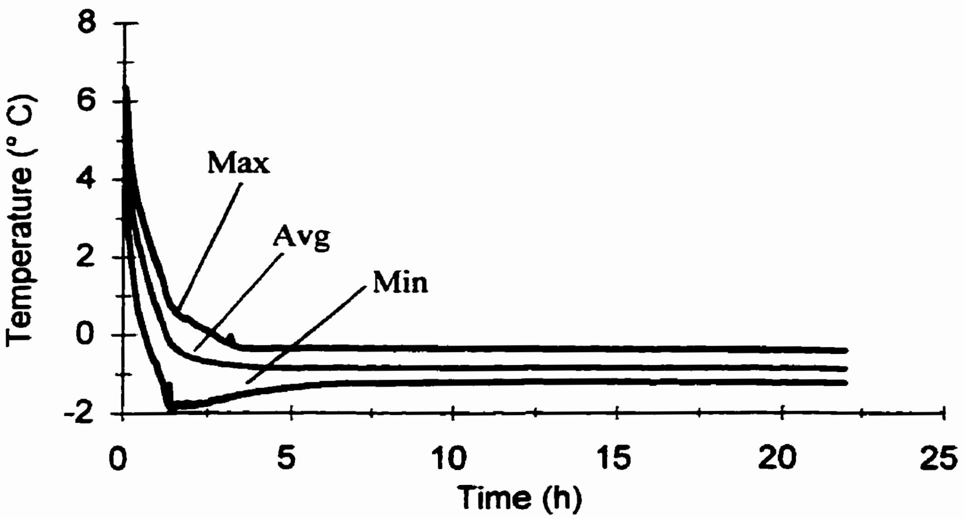


Figure A.23. Maximum, average, and minimum temperatures (Trial 3) of meat samples when the container was exposed to an outside temperature of -15°C.

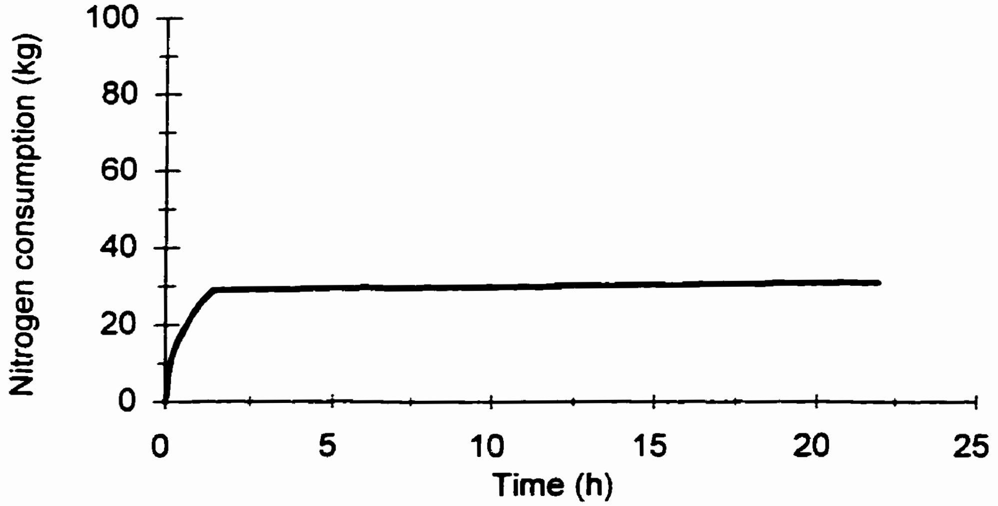


Figure A.24. Nitrogen consumption during Trial 3 (Figure A.23.).

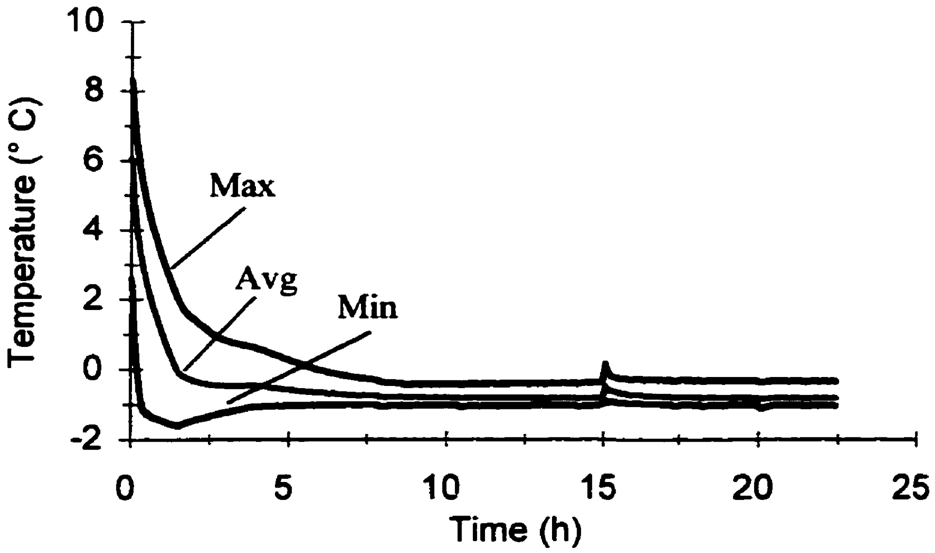


Figure A.25. Maximum, average, and minimum temperatures (Trial 1) of meat samples when a steel braided transfer line was used and the container was exposed to an outside temperature of 15°C.

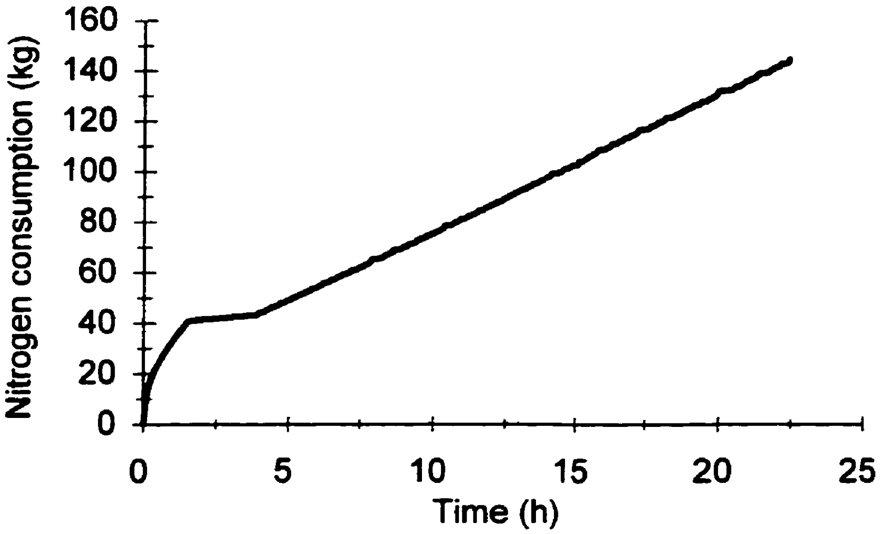


Figure A.26. Nitrogen consumption during Trial 1 (Figure A.25.).

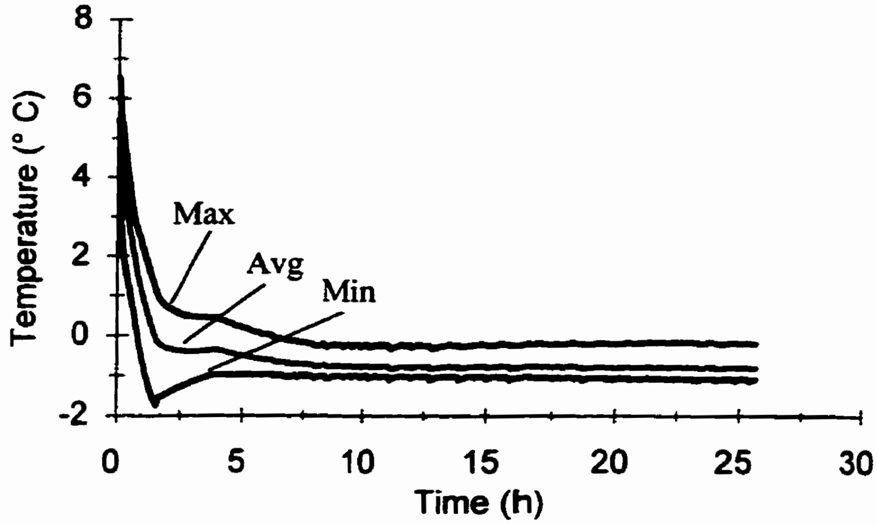


Figure A.27. Maximum, average, and minimum temperatures (Trial 2) of meat samples when a steel braided transfer line was used and the container was exposed to an outside temperature of 15°C.

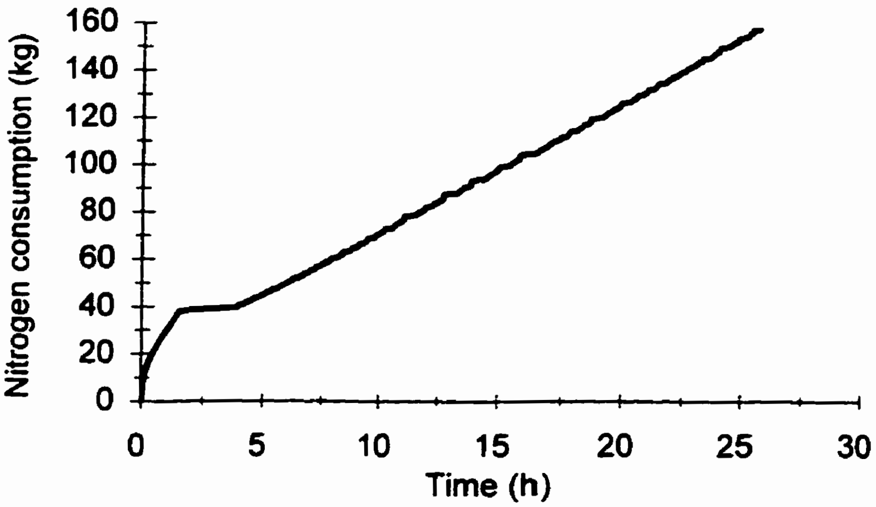


Figure A.28. Nitrogen consumption during Trial 2 (Figure A.27.).

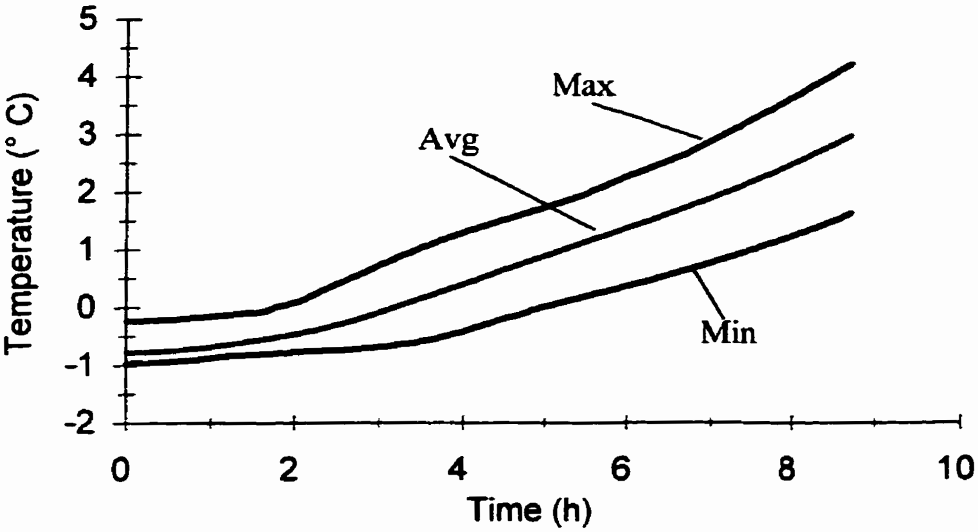


Figure A.29. Maximum, average, and minimum temperatures (Trial 1) of meat samples when the container was exposed to an outside temperature of 30°C and experiences a nitrogen failure at time = 0 h.

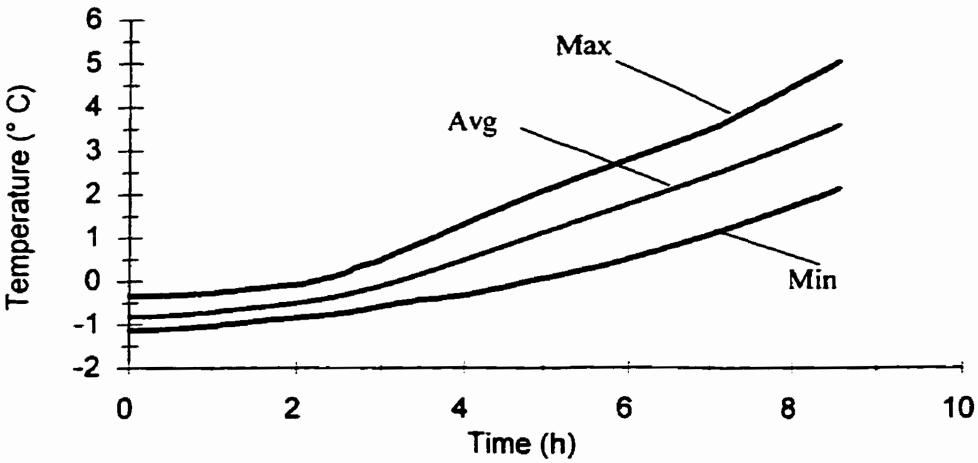


Figure A.30. Maximum, average, and minimum temperatures (Trial 2) of meat samples when the container was exposed to an outside temperature of 30°C and experiences a nitrogen failure at time = 0 h.

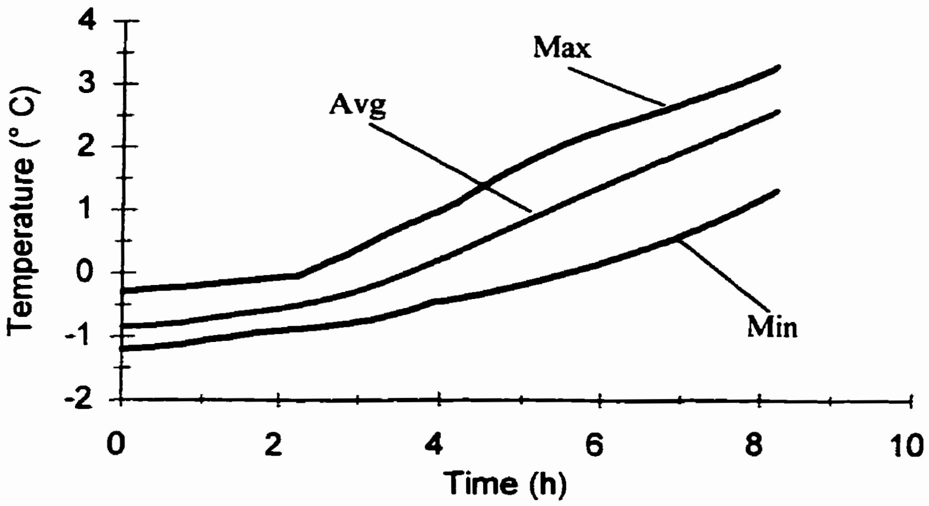


Figure A.31. **Maximum, average, and minimum temperatures (Trial 3) of meat samples when the container was exposed to an outside temperature of 30°C and experiences a nitrogen failure at time = 0 h.**

APPENDIX B - FLOW CHART OF CHANGES TO THE TEMPERATURE CONTROL ALGORITHM

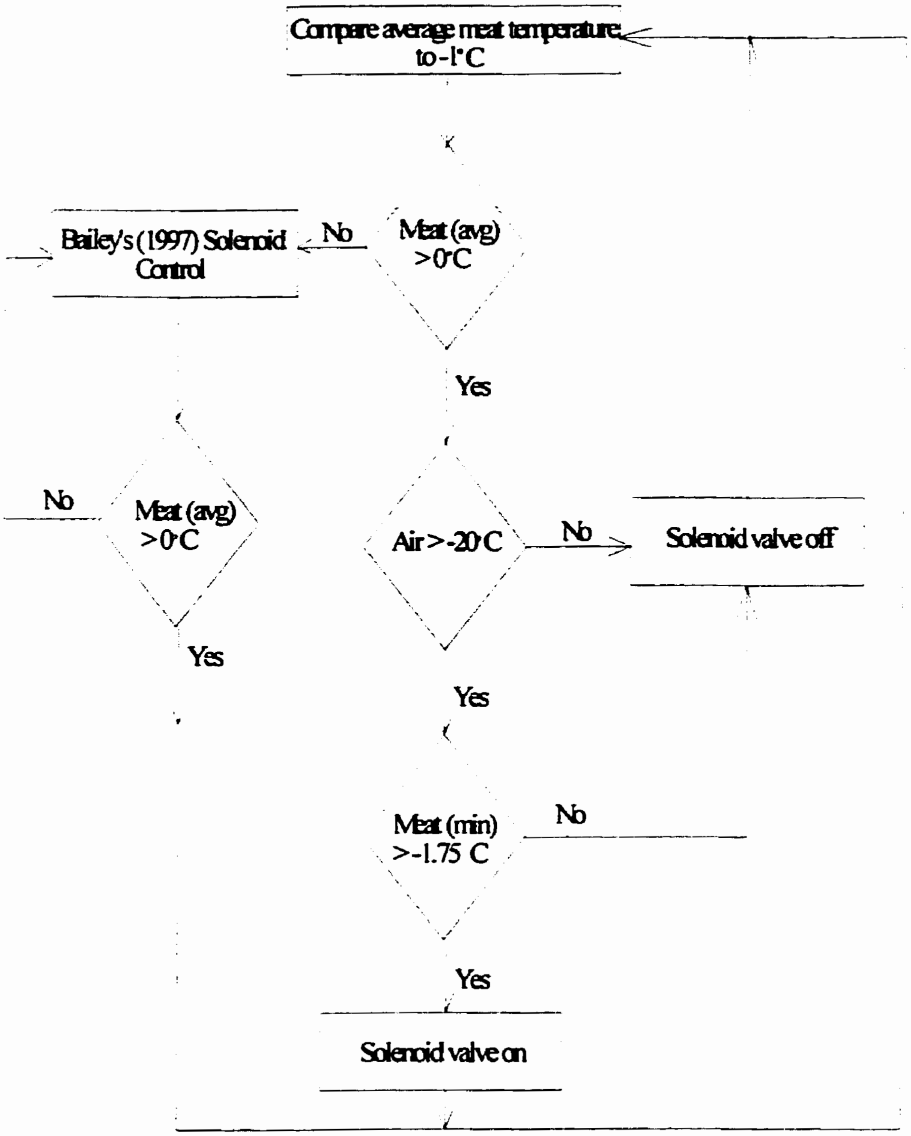


Figure B.1. Flow chart of the changes to the chilling portion of the temperature control algorithm.

APPENDIX C - SCHEMATICS OF THE CONTAINER

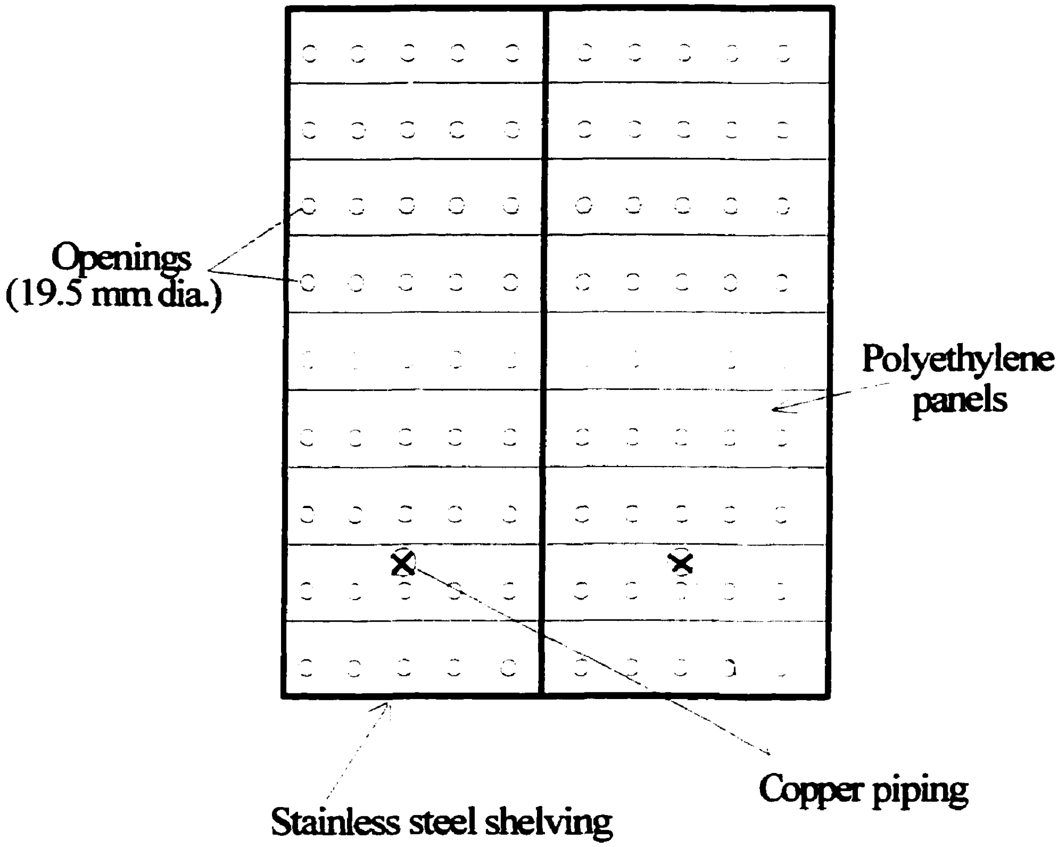


Figure C.1. Schematic of the side view of the central conduit of the container.

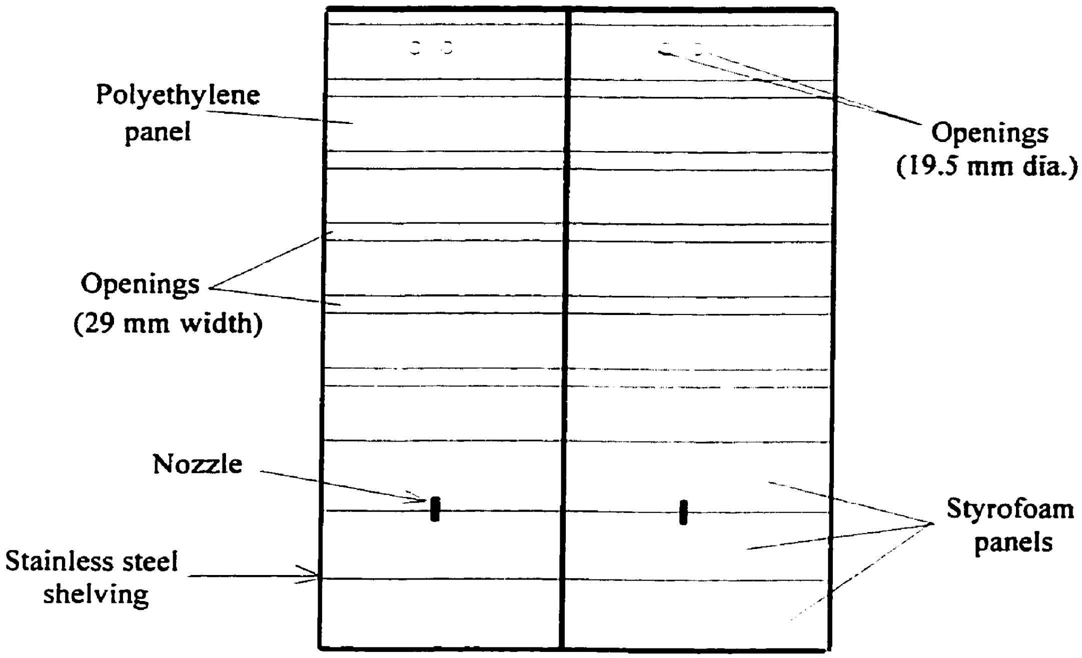


Figure C.2. Schematic of the side view of the side conduit of the container.