DESIGN AND EVALUATION OF A PORTABLE, NITROGEN-REFRIGERATED, JACKETED CONTAINER FOR STORAGE AND DISTRIBUTION OF CHILLED MEAT

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Design and Evaluation of a Portable, Nitrogen-Refrigerated, Jacketed Container for Storage and Distribution of Chilled Meat

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

The current meat distribution system is inefficient because packaging is done at both meat packer and retail level. Greater economies would be realized if retail packaging was done at the meat packer. Master packaging is suitable for centralized packaging because it yields suitable storage life and maintains the desirable red colour of the meat during storage and retail display. Master packaging of fresh meat with strict temperature control at -1.5 °C during distribution and storage gives a storage life up to 6 weeks. Inconsistent temperature control of meat within a narrow range just above freezing is a weak link in the current meat distribution system in North America.

To improve the temperature control, a small-scale jacketed container was designed and evaluated for maintaining the temperature of pre-chilled meats. Tests were conducted with saline water bags, which thermally simulated the meat. Liquid nitrogen was injected in the jacket when the outside temperature was higher than -1.5 °C, and a heater was switched on when the outside temperature was lower than -1.5 °C.

Based on the preliminary study, a full-size container of 200-300 kg meat capacity was then designed and tested at outside temperatures of -15, 0, 15, and 30 °C. Tests were conducted with retail packs of pork and beef. The target temperature was set at -1.0±0.5 °C to prevent surface freezing of meat during extended storage periods, and an additional margin of -1.5 to -2.0 °C was allowed.

Except the meat on the first (shelf) level of the container, the temperatures were maintained within the designed limits at outside temperatures of 0, 15, and 30 °C. Nitrogen consumption was 0.9, 2.4, and 4.3 kg/h at outside temperatures of 0, 15, and

30°C, respectively. The maximum temperature of all 4 trials at -15°C outside temperature was -0.2°C.

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1. INTRODUCTION

Curing, smoking, drying, cooking, and fermentation are traditional methods of preserving food. Over the recent years, chemical preservatives have been added to prolong the storage life of food. However, health conscious consumers are concerned about the "side-effects" of these chemical preservatives (Russell and Gould 1991). Consequently, the trend is presently towards minimally-processed, fresh-like foods. During processing and preservation of foods, the texture, flavour, colour, and freshness taste are affected. Unlike most food preservation methods, food products preserved by chilling alone retain most of the qualities of the fresh foods (Rosset 1982). Chilling reduces the growth of microorganisms thereby extending the storage life of the food products, while freezing halts bacterial growth but there is an attendant product quality loss. Nonetheless, preservation of food by chilling is a safe and reliable means of providing fresh food products (Dade 1992). The demand for chilled foods with long storage life is growing (Farber 1991). A premium is paid for fresh foods, particularly for meat products.

Although premiums are paid for fresh chilled meat compared to frozen (especially in Japan), the short storage life of chilled meat limits its sale to distant markets. Shipping of fresh meats from Canada to distant overseas markets requires a product storage life of six weeks or longer. Meat must be red in colour during retail display to attract consumers. Therefore, the red colour of the meat has to be preserved for any extended storage periods.

The current meat distribution system is inefficient because packaging is done at both meat packer and retail level. Centralized packaging of retail cuts of meat yields a

better control over the product quality and eliminates the butchery preparation work required at the retail level. However the short storage life of retail meat cuts restricts the use of centralized packaging only to local markets. Master packaging is a new technique in which 4-6 retail-ready packaged meat cuts are placed in a larger bag, called a mother bag, which is flushed with desired modified atmosphere. Storage of meat cuts in a 100% CO_2 atmosphere gives maximum storage life (Spahl et al. 1981). Within 30 min of removal of the mother (outer) bag of the master pack at the retail store, the desired red colour of meat develops (Penny and Bell 1993). Thus, master packaging is suitable for centralized processing and packaging of meat and provides suitable storage life and desirable red color during retail display.

Storage temperature is the most important extrinsic factor affecting the storage life of fresh meats (Gill and Phillips 1993). Maximum storage life is achieved when meat is stored at the minimum temperature (-1.5°C) before freezing occurs. The concept of master packaging has been known to the food industry for over a decade. However, its use has been compromised by lack of temperature control during distribution. Therefore, a portable refrigerated container capable of consistently maintaining -1.5°C throughout the distribution chain would clearly benefit the meat industry.

Bailey (1997) designed and tested a N_2-refrigerated shipping container to maintain temperature of meat (simulated using saline water bags) at -1.5±0.5°C. Liquid N_2 was injected directly inside the container and the gas was circulated using 4 fans. His results demonstrated that a N_2 refrigeration system was capable of controlling the temperature of the meat within the required narrow range. However, the fans produced a considerable

amount of heat which increased N_2 consumption.

The objective of this thesis was to develop an alternate container design equipped with a liquid N_2 refrigeration system, by eliminating fans to reduce the N_2 consumption. The concept of a jacketed container design was first studied with a small-scale model jacketed container. Based on the results of the preliminary study, a full size jacketed container was designed, fabricated, and evaluated for maintenance of the temperature of pre-chilled beef and pork.

2. BACKGROUND AND CONCEPT DEVELOPMENT

2.1 Meat Colour

Consumers relate the red colour of meat to its freshness and attribute brown colour of the meat to bacterial spoilage or meat from mature animals. Colour deterioration is the major factor limiting the marketability of fresh red meats (Shay and Egan 1987). Discolouration of packaged fresh meat in the retail case is known as "loss of bloom" in the meat industry (Seideman et al. 1984). Retailers must trim away the discoloured areas from meat to overcome consumer reluctance to purchase discoloured meat. Otherwise discoloured meat must be sold at discounted prices which results in substantial economic losses at retail. Either alternative increases the overall cost of fresh meat. Understanding the underlying scientific concepts of meat biochemistry related to colour will help in finding a solution.

Hemoglobin is the primary pigment of blood. Its biological function is to distribute oxygen to various parts of the body. Myoglobin is a muscle pigment which receives O_2 at the cell wall from hemoglobin (Seideman et al. 1984), which is used for various metabolic activities in the cell. When the animal is killed and bled, most of the hemoglobin is removed (Varnam and Sutherland 1995).

Myoglobin consists of a centrally located iron atom with six bonds or coordination sites (Fig. 1). The iron atom is bound to four N_2 atoms and a globin (protein) moiety. The sixth bond is free and is available for chemical reactions (Cross et al. 1986). The type of molecule attached to the sixth bond and the oxidation state of the iron atom (ferrous or ferric) determine the colour of the meat (Fig. 1).

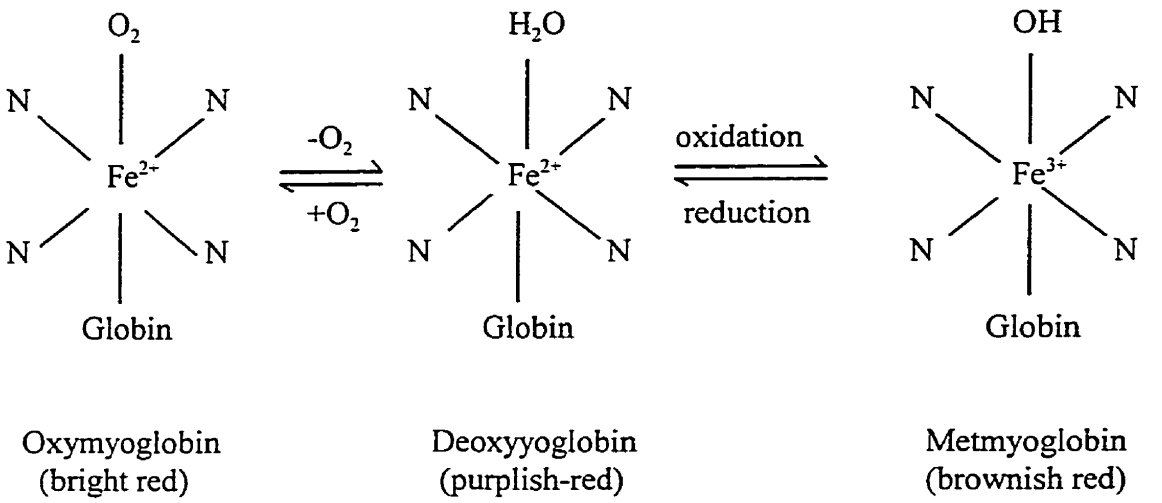

Fig. 1. Pigment changes in red meat. (Adapted from Cross et al. 1986).

Myoglobin is commonly found in three forms; namely oxymyoglobin, deoxymyoglobin, and metmyoglobin. The relative proportions of these three forms of myoglobin determines the colour of fresh meat. When the animal is alive, major proportion of myoglobin is in the oxygenated form, i.e., an O_2 molecule binds to the free binding site of myoglobin and the iron is in the ferrous state. Oxymyoglobin is bright red in colour and is desirable in fresh meats. When O_2 is not available, myoglobin is in the deoxygenated form, which is purple (Fig. 1). In this form, the iron is in the ferrous state and a water molecule is attached at the sixth bond (Varnam and Sutherland 1995). The oxygenation of purple deoxymyoglobin to red oxymyoglobin occurs rapidly, and is the "covalent binding" of an O_2 molecule from the atmosphere to the free binding site of myoglobin (Seideman et al. 1984). The conversion of oxymyoglobin to reduced-myoglobin is a reversible reaction.

Conditions like low O_2 tension especially in the range of 1 to 20 mm of Hg partial pressures, high temperature, ultra-violet rays, and exposure to atmospheric O_2 for long

periods of time cause the denaturation of the globin moiety of oxymyoglobin, resulting in loss of its functional properties (Seideman et al. 1984). Once the globin moiety is denatured, the iron atom is left unprotected. This leads to the spontaneous oxidation of the iron molecule from the ferrous to the ferric state (Seideman et al. 1984), resulting in the formation of brown metmyoglobin. In this form, a hydroxyl group is attached to the sixth binding site (Fig. 1). Metmyoglobin is the major pigment responsible for discolouration of meat.

Meat contains limited reducing substances such as reduced nicotinamide adenine dinucleotide (NADH) which are capable of reducing metmyoglobin to myoglobin (Varnam and Sutherland 1995). The enzyme methemoglobin reductase found in red blood cells is also responsible for reduction of metmyoglobin to myoglobin. These reactions are energy dependent and therefore cease with time *post mortem* (Penny and Bell 1993). The formation of metmyoglobin is a major concern to the fresh meat industry because consumers relate the brown colour of meat to absence of freshness due to excessive growth of bacteria and incipient spoilage or the meat from mature animals. Large numbers of aerobic bacteria (10^8 - $10^9/cm^2$) can reduce the O_2 tension on the meat surface which is favorable for metmyoglobin formation. Under aerobic conditions, before discolouration due to aerobic bacteria occurs, spoilage would be normally detected.

Under vacuum or modified atmospheres, the red colour of the meat is suppressed due to a lack of O_2, which has no correlation to bacterial growth and freshness (Shay and Egan 1987). Such meats are perfectly edible. However, until the consumers are educated

regarding the colour of meat in vacuum and modified or controlled atmosphere packages, these types of packaging can not be adopted for retail-ready sale of meats.

Hood (1980) reported that the degree of discolouration of *psoas major* muscle is about 8 times greater than that of *longissimus dorsi* muscle after 4 d of storage at 0°C. Therefore, inter-muscular variability is one of the major factors influencing the rate of metmyoglobin formation and accumulation. The same author reported that the degree of discolouration increases with an increase in temperature.

2.2 Storage Life

Storage life of meats is determined by off-odours or discolouration associated with microbial growth (Dainty 1989). Therefore, the onset of spoilage can be defined as when certain bacteria reach a maximum acceptable level or when the product develops an unacceptable off-odour, off-flavour, or appearance. The threshold level of bacteria at which spoilage can be detected is higher in vacuum or anoxic atmospheres than when meat is stored in O_2 permeable films (Borch et al. 1996).

It takes up to 3 weeks from slaughter for meat to reach the display in retail-ready cases because of unpredictable fluctuations in consumer demand (Jeremiah and Gibson, 1997). Increasing the storage life of fresh meat will broaden the scope of its market (Spahl et al. 1981). Modified atmosphere packaging (MAP) in combination with optimum temperature control and processing hygiene is the most effective means of extending the storage life of fresh chilled meat and maintaining product quality and safety (Greer et al. 1993). At the same time, it is necessary to ensure that meat has a red colour at the time of display. This can be achieved by three methods:

1. In the first method, primal and sub-primal cuts are packed with a modified gas mixture which is devoid of O_2, which keeps myoglobin in the reduced form and the colour of the meat is purple (Shay and Egan 1987). At the retail store, the meat is further fabricated and packaged in an O_2-permeable film. The O_2 in the atmosphere combines with deoxymyoglobin to form oxymyoglobin resulting in the blooming of the meat to a desirable red colour. This method is commonly practiced in the meat industry at the present time and is discussed in detail in the next section.

2. In the second method, the gas mixture includes O_2 to keep the myoglobin in the oxygenated form. Because metmyoglobin is formed at low O_2 tensions, O_2 concentration in the gas mixture is usually higher than that in air (Shay and Egan 1987). Therefore, the colour of the meat is bright red throughout the storage period. Aerobic bacteria tolerate high concentrations of O_2 and their growth rate can be reduced by including CO_2 in the gas mixture (Gill and Molin 1991). Work by Gill and Jones (1994) indicates that high-O_2 MAP systems extend the storage life of beef by 2 weeks while maintaining acceptable red colour at -1.5°C. High O_2 MAP reduces the discolouration of meat, but the extension in storage life is not enough for transporting meat to distant markets.

3. The last method is a relatively new technique, called master packaging involving anoxic atmospheres, which is discussed in section 2.5.

Various gas mixtures have been tried, but MAP with 100% CO_2 gives the maximum storage life. Fresh meat stored in air spoils rapidly due to the growth of

aerobic bacteria such as pseudomonads and facultative types such as the *Enterobacteriaceae* (Egan 1983). Storage of meats in CO_2-enriched atmospheres inhibits these fast-growing putrefactive aerobic bacteria and favours slow-growing lactic acid bacteria (LAB) whose metabolic byproducts are less offensive (McMullen and Stiles 1991). Spahl et al. (1981) reported that the most effective gas environment from the point of view of sensory acceptability is 100% CO_2. Blickstad and Molin (1983) reported that the storage of lean pork in 100% CO_2 at 0°C gives a storage life of about 3 months. The disadvantage of this type of packaging is that the red colour of the meat is suppressed due to anoxic conditions.

2.3 Current Meat Distribution System

The current meat distribution system involves the transportation of primal and sub-primal cuts in vacuum packages to retail stores and yields a storage life of about 42 d (pork) to 45 d (beef). The myoglobin is in the purple deoxymyoglobin form. It is generally believed that the flesh of healthy animals is sterile. However, when the animal is slaughtered and primal and sub-primal cuts are prepared, microorganisms are introduced on the surface of the meat cuts by cross-contamination. Bacteria normally grow only on the surface of the meat. Once the nutrients on the surface of the meat are depleted, incipient spoilage begins and proceeds towards the interior of the meat cut. Once the primal cuts reach the retail stores, they are trimmed to remove surface discoloured meat which can have a high microbial load. They are then cut into consumer size cuts, and packaged in disposable retail trays using O_2-permeable films. Oxygen from the atmosphere binds with the free binding site of myoglobin to form oxymyoglobin, which

produces bright red colour. This is commonly known as "blooming" in the meat industry (Seideman et al. 1984). This oxygenation reaction takes place in less than half an hour, as myoglobin has high affinity towards O_2 (Penny and Bell 1993).

If meat is prepared under good manufacturing practices (GMP), incipient spoilage occurs only after 5-6 d and off-odours are developed. However, a considerable amount of metmyoglobin is formed in about 3-4 d. Therefore, if this retail-ready meat is not sold within 3-4 days, the discoloured meat has to be sold at reduced prices. This causes substantial economic loss to the retailer. This leads to an overall increase in the selling price of fresh red meat to accommodate unpredictable market fluctuations and short storage life. Thus, colour deterioration of fresh red meats greatly restricts its marketing (Shay and Egan 1987).

The current meat distribution system is inefficient in the following respects:

1. Packaging is done at both packer and retail levels.
2. The control over product microbial quality at the retail level is not generally adequate.
3. Only two-thirds of the carcass is usable. Bones, fat trims, and other inedible parts are also refrigerated and transported from the packer to the retail store.
4. Byproducts and edible waste are under-utilized at the retail level.
5. Considerable floor space in retail stores is used for fabrication of retail cuts which could be used more effectively for merchandising products.
6. Specialized labour crews and machineries are not usually available at the retail stores which results in higher labour costs for fabrication of retail-ready cuts.

2.4 Centralized Packaging

Moving the packaging of retail-ready cuts from retail stores to the packer level or centralized packaging center eliminates the need for meat cutting and packaging at retail stores. A centralized packaging center can support specialized machinery like robotics which minimizes human handing, thereby greatly improving food safety and quality. Higher efficiency can be achieved at the centralized location, due to the greater mass of production (Scholtz et al. 1992).

Problem in implementing the centralized packaging of retail-ready meat is associated with short storage life of the meat products. Because the colour of meat must be red in the retail case to attract consumers, meat must be packaged in an O_2 permeable film. As already stated, the storage life of such conventional retail-ready meat exposed to atmospheric air is 5-6 d, and colour deterioration occurs in 3-4 d. Because no further manipulation of centralized packaged meat is done, the discolouration precedes bacterial spoilage and this dictates the storage life. This short storage life of the retail-ready meats has discouraged the widespread use of centralized packaging systems (Shay and Egan 1987). A considerable portion of storage life is lost by the time the retail-ready meat is placed into the display cabinet, which restricts the use of centralized packaging systems to local markets within short distances.

2.5 Master Packaging

In most packaging methods, either meat colour is compromised to get longer storage life or storage life is compromised to get an attractive red colour. This problem can be overcome by master packaging in anoxic atmospheres (Holley et al. 1993). In this

technique, 4-6 conventional retail packs (i.e.,over-wrapped in O_2-permeable films) are placed within a large pouch which is usually made of a metalized laminate with no measurable O_2-transmission, known as mother bag (Gill and Jones 1994). The laminate pouch is then evacuated to remove O_2 and back-flushed with a desired gas mixture. The most effective gas composition with respect to extending storage life and sensory characteristics is saturating (100%) CO_2 (Spahl et al. 1981). Provided the gas volume used is large enough, the package atmospheres will remain at 100% CO_2 and can be described as a form of controlled atmosphere packaging (CAP). Holes are burned in at least two locations on the O_2-permeable films of the retail packs so that retail packs comes in contact with CO_2 rapidly. The packaging cost is less than that of individual modified atmosphere packs (Shay and Egan 1987). In response to consumer demand, master packs are individually opened and the retail cuts are placed in the retail-display case. Within 30 min of exposure to atmospheric O_2, the meat blooms to desirable red colour (Penny and Bell 1993).

2.6 Transient Discolouration

Most commercial MAP machines are not capable of evacuating O_2 completely from the packages. The presence of a small amount of O_2 is conducive to the formation of metmyoglobin, which is a stable compound. Because the meat has only limited capacity to reduce the metmyoglobin to deoxymyoglobin, metmyoglobin formation in the retail-ready packs can prevent blooming of the meat to a red colour when the master pack is opened.

The Captech process is a promising packaging method developed at the New Zealand Meat Research Institute, Hamilton, New Zealand, which is capable of creating a CO_2 atmosphere in the package with less than 300 ppm of residual O_2 (Varnam and Sutherland 1995). The chamber and the pack are evacuated in phases, which prevents air entrapment and reduces the mechanical stress on the meat and pouch. In this process, the meat is packaged in a triple laminated pouch consisting of high-strength plastic film, aluminum foil, and a low strength plastic film (SecureFresh Pacific Ltd, Auckland, New Zealand). The aluminum foil is a good gas barrier and, together with a high strength plastic film on the outside, provides sufficient mechanical strength to avoid puncture during transport. The inner low-strength plastic film is helpful in heat sealing the package. Non-metalized film laminates with the same gas transmission properties are now commercially available (Winpak, Winnipeg, MB). As the packaging material used has no measurable O_2 transmission, the O_2 present in the package is sufficiently low enough for the meat to convert it to CO_2 through respiration.

Meat must be prepared under good manufacturing practices (GMP) and the meat must be fresh enough for the metmyoglobin-reducing activity to be present. Penny and Bell (1993) reported that there is no discolouration of meat after 1 d of storage of meat in master packages, if the O_2 concentration is less than 600 ppm. Gill and Jones (1994) state that a duration of 2 d is required for the metmyoglobin reducing activity of the muscle tissue to bring about sufficient reduction of metmyoglobin so that meat blooms, when exposed to air. Therefore, if the package is opened within 2 d of packaging for retail display, the meat might not bloom properly, but normally it takes more than 2 d to reach

the display unit from the processing plant. If the meat is going to be displayed within such a short time, then modified atmosphere packaging is not necessary and meat can be packed in conventional retail packs wrapped with O_2-permeable films. It is probable that retailers might be reluctant to use conventional packs, once the master-packaging of retail-ready cuts is well established in the distribution chain. In such cases, the master packs can be flushed with a gas mixture containing a high concentration of O_2. In master packs flushed with high O_2 mixtures, there is no problem of transient discolouration and a storage life of about 2 weeks in master packs followed by 2 d retail display life is attainable (Gill and Jones, 1994). This is sufficient to market retail-ready meat in local markets.

The problem of transient discolouration is minimal when the temperature of the meat is maintained below 0 °C, and the rate of transient discolouration increases as the temperature increases (Gill and McGinnis, 1995a).

To ensure that the meat blooms after few weeks of anaerobic storage in master packs, O_2 scavengers (chemicals that absorb O_2) can be either incorporated in the packaging material or put in a sachet inside a master pack to remove the residual O_2 from the package. This will ensure that metmyoglobin is not formed and that meat blooms, when the master pack is opened.

O'Keeffe and Hood (1980) examined an O_2 scavenging system which uses a palladium catalyst and the addition of small amounts of hydrogen to the gas mixture. The hydrogen combines with the residual O_2 to form water in the presence of the palladium catalyst. This system requires about one week to prevent metmyoglobin formation. They

reported that this system has removed the O_2 successfully for a period of 3 weeks at 0°C and prevented meat discolouration. They also used an O_2-scavenger film, Maraflex-7F, in which the palladium catalyst is incorporated in the film structure. In their study, the modified atmosphere mixture contained 92% N_2 and 8% H_2, which retained the red colour of the meat up to 4 weeks at 0 and 5°C (O'Keeffe and Hood 1980). They also reported that O_2-free atmosphere in the packages can be established with a CO_2 and hydrogen gas mixture.

Gill and McGinnis (1995b) used FreshPax™ 200R, a commercially available iron-based O_2 scavenger in a sachet to prevent transient discolouration. FreshPax™ 200R is composed of activated iron-oxide powder mixed with acids, salts, and humectants to promote oxidation of iron. Oxidation of iron compound removes O_2 from the package atmosphere and prevents transient discolouration. The same authors reported that O_2 concentration in the pack atmosphere must be reduced to below 10 ppm within 30 min at 2°C or within 2 h at -1.5°C for blooming of ground beef.

2.7 Importance of Temperature Control

Spoilage of chilled meat is caused by psychrotrophic bacteria. The minimum temperature of growth for the most important psychrotrophic bacteria is about -3°C, while muscle tissue in packaged meat begins to freeze at -1.5°C (Gill and Phillips 1993). Therefore meat spoilage can not be prevented as long as the meat remains unfrozen. The maximum potential storage life of fresh meat can be achieved when the product is held at the lowest possible temperature without freezing (-1.5°C).

Gill and Phillips (1993) reported that at temperatures of 0, 2, 5, and 10°C, the

storage life of meat is approximately 70, 50, 30, and 15%, respectively, of the storage life attainable at -1.5°C. Obviously, a very small rise from the optimum storage temperature (-1.5°C) causes a large loss in meat storage life. Extension of storage life is very important, when chilled meat is transported by surface for distribution in distant markets. Product temperature must be controlled very near to the optimum storage temperature and within a narrow range to achieve maximum and consistent storage life, respectively. Holley et al. (1994) reported that storage life of fresh pork under modified atmospheres containing 100% CO_2 can reach 9 weeks at the optimum temperature of -1.5°C.

Temperature is an important extrinsic factor affecting the discolouration of meat. The degree of discolouration after 4 d of storage at 10°C is from 2 to 5 times higher than that at 0°C, depending on the type of muscle (Hood 1980). Metmyoglobin reducing systems also remain active for many weeks at 1°C or lower (Varnam and Sutherland 1995). Consequently storage of meat at sub-zero temperatures will reduce the discolouration of meat in addition to optimizing the extension of storage life.

2.8 Refrigeration Systems

A need exists for a refrigeration system which consistently maintains the temperature at -1.5 ± 0.5°C throughout the distribution system. In addition to high initial cost and greater space and weight, many mechanical refrigeration systems still use chlorinated flurocarbons (CFCs) and hydrochloroflurocarbons (HCFCs) which cause global warming. In addition, the former has ozone depletion potential. Commercial mechanical refrigeration system have largely proven inadequate for maintaining product temperatures within this narrow range (Gill and Phillips 1993). Fans are usually used to force cold air

over product stored in mechanical refrigeration systems. When a container is loaded with meat to its full capacity, products near the fan are much cooler than products in other areas of the container. This can give a larger distribution of temperature throughout the container.

Bailey et al. (1997) reported that a liquid N_2 refrigeration is a successful and reliable means of refrigeration of meat in portable containers. Their results showed that the temperature can be maintained within the narrow range throughout the container. Nitrogen is environmentally friendly. However, the operating costs of a liquid N_2 refrigeration system is approximately double that of a mechanical refrigeration system. Stringent future control over mechanical refrigeration for environmental reasons will make liquid N_2 refrigeration systems more competitive. In addition, there are other advantages of N_2 refrigeration systems such as lower fixed costs, lower weight, and better temperature control. The cost of N_2 is the major operating cost, which depends on cost of production and distribution as well as demand. The cost of distribution is the major factor influencing the price (Clough 1969). If this refrigeration system is accepted by the food industry, the cost of liquid N_2 will be reduced drastically.

2.9 Microbiology of Chilled Meat Stored under 100% CO_2

Most modified atmosphere packaging studies have been conducted with primal and sub-primal wholesale meat cuts. From wholesale meats, following storage for extended periods, retail cuts are prepared after trimming and fresh surfaces are created from the primal cuts. Because spoilage occurs primarily on exposed surfaces, the creation of new surfaces after extended storage sets the "spoilage clock" back to near zero. With

modified atmosphere packaged retail-ready cuts, there is no subsequent trimming or new surface creation. Therefore, the storage life of master packaged retail-ready meat is considerably less than that of primal cuts under similar modified atmosphere conditions. Factors influencing delay of growth by spoilage microorganisms must be carefully considered in order to optimize preservation of retail-ready product as no additional trimming is possible following initial packaging.

2.9.1 Pathogens Potential pathogens in meat stored under anaerobic conditions and at low temperatures capable of growth are *Yersinia enterocolitica, Listeria monocytogenes,* and *Aeromonas hydrophila*. At low temperatures, competitive spoilage bacteria are inhibited and these pathogens grow slowly. As modified atmosphere packaging extends the storage life extensively, these pathogens have time to grow to dangerous levels and cause food poisoning, without warnings of incipient spoilage (putrefactive odours). Enfors et al. (1979) reported that *Yersinia* and *Aeromonas* spp. are found on vacuum-, N_2 atmosphere-, and low CO_2 atmosphere-packaged meat. When 100% CO_2 and a storage temperature of -1.5°C are simultaneously applied (hurdle concept), none of the above pathogens are able to grow and compete with the dominating LAB (Farber 1991; Enfors et al. 1979). Buchanan and Klawitter (1992) reported that *Carnobacterium piscicola* suppress and outgrow *Listeria monocytogenes* in various refrigerated foods. Therefore, health hazard would not be expected as long as 100% CO_2 and -1.5°C are stringently maintained and controlled.

When the CO_2 is introduced, meat absorbs CO_2 diluting the atmosphere volume. Therefore, a sufficient amount of CO_2 must be applied to maintain a 100% concentration

throughout the storage period. The optimum level of CO_2 has been reported to be 1 to 2 L/kg meat (Penny and Bell 1993; Shay and Egan, 1987; Jeremiah et al. 1996).

Another safety consideration for storage of pork at lower temperatures is the formation of biogenic amines (hystamine and tyramine). These are potentially toxic compounds formed by decarboxylation of amino acids during the growth of LAB. Preliminary results showed that some of these compounds may be formed in substantial amounts due to extended storage, and may cause illness in sensitive individuals (Nadon 1998). Further investigations are required to confirm these results.

2.9.2 Spoilage microorganisms Storage of meat in CO_2 atmospheres at low temperatures inhibits the aerobic, putrefactive bacteria and extends storage life considerably. This selects for the growth of psychrotrophic LAB (*Lactobacillus* and *Leuconostoc*), *Carnobacterium*, and *Brochothrix thermosphacta*. *B.thermosphacta* produces organoleptically offensive byproducts and can cause early spoilage of meat under anoxic conditions (Gill and Harrison 1989). If an anoxic 100% CO_2 atmosphere is maintained without any trace of O_2, LAB dominate *B. thermosphacta* (McMullen and Stiles 1991). Gill and Harrison (1989) reported that *B. thermosphacta* was the dominant bacteria in the storage on surface of retail-ready pork stored under CO_2 atmospheres at 3°C. But at -1.5°C, *B. thermosphacta* is totally inhibited by CO_2 and the dominant organisms are LAB. As *B. thermosphacta* is sensitive to undissociated lactic acid and low pH under anaerobic conditions, LAB dominate over *B. thermosphacta* in meat at low temperatures (Grau 1980).

Some lactobacilli were re-classified and moved to a new genus, *Carnobacterium*

(Collins et al. 1987). They are similar to LAB, producing predominantly lactic acid from glucose, and are found in vacuum-packaged meat and related products at low temperatures. Their rate of growth is higher than LAB at low temperatures and therefore they initially dominate in fresh meat packaged under anoxic atmospheres. They differ from LAB in that they can not grow on acetate agar or broth and can not tolerate low pH (Collins et al. 1987). Following the initial dominant growth of carnobacteria for 4-6 weeks, they are suppressed by production of lactic acid and a slight drop in pH of meat, and LAB become the dominant microflora. Lactic acid bacteria reach maximum numbers after 6 to 9 weeks of storage and the products become unacceptable organoleptically (Jeremiah and Gibson 1997). Thus, the microflora of chilled meat under anoxic atmospheres is dominated first by carnobacteria and then by LAB throughout the storage period. This reduces threat from pathogens and promotes food safety.

When pork chops are transferred from CO_2 to air, LAB initially dominate the aerobic microflora, but pseudomonads emerge as the second most dominant group (Greer et al. 1993). A sufficient amount of CO_2 binds to proteins such as hemoglobin which accounts for the residual effect. The binding of CO_2 to free amino groups is reversible but the process is relatively slow at low temperatures (Jones, 1989).

Holley et al. (1994) studied the effect of different gas pressures (1.0 and 1.2 atm) of 100% CO_2 on the storage life of meat and reported that the gas pressure does not have any significant impact on storage life. They also reported that the storage life of 100% CO_2-packaged retail ready pork at -1 °C is more than 21 d.

Blickstad et al. (1981) studied the effect of hyperbaric CO_2 pressure on the

microbial flora of pork stored at 4 and 14°C. They reported that the time needed at 4°C to reach a total aerobic count of 5 x 10^6 was about three times longer in 5 atm CO_2 than in 1 atm CO_2. They also reported that there was no effect of hyperbaric pressure at 14°C.

Gill and Harrison (1989) studied the storage life of retail-ready pork, individually packed in CO_2 atmospheres and reported that all the samples were acceptable for 10 weeks. At 12 weeks, one sample showed the onset of spoilage. At 18 weeks, 10 samples were acceptable, and the other 5 samples were unacceptable either due to odour or flavour. After 26 weeks, all samples were spoiled. Based on this study, the storage life of retail-ready pork under 100% CO_2 atmospheres at -1.5°C can be taken as 10 weeks.

2.10 Storage life of Master Packaged Meat

Scholtz et al. (1992) studied the influence of different centralized packaging systems (PVC over-wrap, modified atmosphere packaging of individual retail packs, vacuum skin packaging, and the mother bag concept or master packaging) on the storage life of fresh pork at 0°C. Master packaging system is the most promising with regard to storage life (21 d master pack storage with a subsequent retail case life of 4 d) followed in order by individual modified atmosphere packaging (14 d), vacuum skin packaging (7 d), and PVC over-wrap (4 d). Thus, master packaging of meat under 100% CO_2 at 0°C gives a storage life of just under a month. But, storage life of the wholesale primal pork loins stored in 100% CO_2 atmospheres at 0°C is 3 months (Blickstad and Molin 1983). The reason for the reduction in storage life of pre-packaged retail cuts compared to wholesale cuts is due to the larger surface area of the former, which is susceptible to surface discolouration and bacterial proliferation. In addition, the final cut surface of master

packaged retail-ready products eventually presented to the consumer is much older than that of retail-ready products prepared from primal and sub-primal cuts at retail level. Bacteria reach spoilage levels primarily by their growth at the meat surface. Storage of primal and sub-primal in modified atmospheres is followed by trimming and retail products are fabricated and displayed. Newly prepared surfaces have few bacteria present and appear fresh. Thus, successful distribution of retail-ready meats demands high level of control over sanitation and temperature to restrict bacterial growth on surfaces which will not be trimmed further before display.

Holley et al. (1993) studied the storage life of master packaged pork. Pork under 100% CO_2 atmospheres at 4°C has a storage life of 2 weeks under modified atmospheres with a subsequent 6 d aerobic storage life.

Jeremiah and Gibson (1997) studied the effect of 100% CO_2 atmospheres on the flavour and texture profiles of master packaged pork cuts at -1.5°C. Flavour became inappropriate, unbalanced, and unblended after 12 days of storage. Consequently, off-flavour development constitutes the limiting factor for extending the chilled storage life of display-ready pork in controlled atmosphere master packs. They also postulated that the off-flavours are probably produced by the LAB after about 6 weeks of storage of chilled meat under anoxic atmospheres. The lower storage life obtained in this study probably was due to the poor initial microbiological quality of the meat. Therefore they indicated that the storage life of the master-packed pork can be extended by use of products with very low initial numbers of bacteria. More recent evidence indicates that early off-flavour development coincides with a shift in the dominant microflora from

non-aciduric to aciduric LAB (Nattress et al. 1998).

Gill and Jones (1994) studied the storage life of master packaged beef steaks under various atmospheres at -1.5 °C. Steaks stored under 100% CO_2 or 100% N_2 for less than 4 d are only slightly desirable because of the formation of metmyoglobin on the surface due to the presence of small amounts of residual O_2 in packages. Within 4 d of storage, metmyoglobin is converted to myoglobin by muscle tissue enzymes (reductases) and the meat has a desirable appearance. Master packaging under a CO_2+O_2 (1:2 v/v) atmosphere gives an acceptable appearance initially but the colour begins to deteriorate after 12 d of storage. Therefore, they concluded that a CO_2+O_2 atmosphere is appropriate for storing meats that are intended for markets having a distribution time less than 4 d. Master packaging in 100% N_2 gives a storage life of 4 weeks and 2 d of subsequent retail display, while master packaging in 100% CO_2 gives about 7 weeks of storage life in the master pack and 2 d of subsequent retail display. After 7 weeks of storage in 100% CO_2, LAB produces slight acid odours. Meat also loses its colour stability beyond 7 weeks. They clearly warned that this storage life can be obtained only with products of high microbiological quality. This study also showed that 100% CO_2 modified atmospheres gives the maximum storage life of fresh meats.

2.11 Portable Refrigerated Container

There has not been much work done in the area of temperature control during transportation and storage of meat. There is only one reported study (Bailey et al. 1997) on a liquid N_2-refrigerated shipping container for distribution of fresh red meats, which is discussed in detail below.

Bailey et al. (1997) used an insulated container (Model C-54, Xactics, QC) of cross section 1000 x 875 mm and 1600 mm high. The container was equipped with stainless steel shelving system suitable for holding 36 master trays of size 508 x 381 x 60 mm in 9 levels. Refrigeration was accomplished by injecting liquid N_2 from a pressurized tank into the container using two agricultural spray nozzles (Model: 11006, Spraying Systems, Chicago, IL). Six fans mixed the injected N_2 with circulated air to achieve a uniform temperature. The fans were operated in combinations of 2, 4, or 6 during testing. Injection of liquid N_2 was computer controlled by means of cycling an electrically actuated solenoid valve. Bags containing saline solution (10% by mass) were used to simulate meat.

Each trial was run for an 8 h. Initial temperature of the saline bags was at 10°C to examine the cooling capability of the system. In all tests, the bags were cooled to -1.5°C in approximately 5.5 h. A 4 fan combination resulted in the best overall temperature control with a temperature range from -2.0 to -0.7°C. It is interesting to note that neither the 2 nor 6 fan combination was able to maintain the design temperature (-1.5±0.5°C). A larger temperature differential was noted from the front to back of the container. Variable N_2 usage represents the N_2 required to maintain the temperature, after bringing the temperature of the saline bags down to the desired temperature. Actual variable N_2 use was 5.5, 4.0, 2.6, and 0.93 kg/h at outside temperatures of 30, 15, 0, -15°C, respectively, when a 4 fan combination was used. The corresponding theoretical variable N_2 use was 3.6, 2.5, 1.4, and 0.1 kg/h, respectively. Bailey et al. (1997) speculated that this difference in variable N_2 use arose either from calculations of heat flow to the transfer

line connecting the liquid N_2 tank and the container or an unknown variable existed.

In summary, work done by Bailey (1997) demonstrated that liquid N_2 refrigeration is successful in maintaining the temperature of meat in a portable container. However, additional work is required before commercializing this technology. The circulation fans produced significant amounts of heat, which increased variable N_2 usage. It was found that 1.3 kg/h of N_2 consumption was required to remove the heat produced by 4 fans. Therefore, further investigations are required to determine the ways to eliminate the circulation fans without affecting temperature uniformity. Also, 5.5 h was required to bring down the temperature of saline bags to the design temperature. When master packaged meat would be placed in the container, it should take more than 5.5 h to bring down the temperature, because the modified gas atmosphere surrounding the meat would act as an insulator. Of an 8 h duration trial, 5.5 h was used to cool the product, therefore only 2.5 h interval of maintained temperatures were used to examine the efficiency of N_2 refrigeration system in maintaining the temperature within the narrow range. As the objective of the study was to design a container for extended storage of fresh meat, the tests should be conducted for longer intervals to examine the capability of the system in maintaining desired temperature. Further tests must be conducted with meat to verify the results that were obtained using saline bags. The mass of the steel shelving can be reduced by replacing it with food grade plastics. Also, the number of trays could be increased to increase the capacity of the container.

2.12 Concept

To eliminate the fans for reducing the variable N_2 use (Bailey 1997), a jacketed container

design was proposed. As envisioned, the master packages of meat will be pre-cooled to -1.5 °C at the centralized packaging center. Because the meat is stored under modified atmosphere conditions, the heat of respiration of the meat tissue is negligible. The only source of heat is the heat conducted through the walls of the container. A jacketed container can be designed with liquid N_2 injected in the jacket to maintain the temperature at -1.5 °C. This should ensure that meat will be indefinitely maintained at the temperature of -1.5 °C.

Different compartments of the container would be filled with different products (steaks, roasts, chops, ground meat, etc.) to satisfy customer requirements. Once filled, the container would be refrigerated and held until the transportation carrier arrived. The container would then be disconnected from the packer's liquid N_2 source, moved on board the carrier (truck, railcar), and reconnected to the carrier's liquid N_2 source (use of the container eliminates the need for insulated and refrigerated transport carriers). The containers would then be transported to the customer (retail outlet), and then disconnected from the carrier's liquid N_2 source, moved into the retail outlet storage area, and reconnected to the retailer's liquid N_2 source (use of the container eliminates the need for refrigerated storage coolers for bulk inventory at the retail outlet). Because the container will be always connected to the N_2 source during distribution and storage, the temperature of the meat will be consistently maintained. Based on the demand, the master packs will be periodically removed from the container. The outer impermeable wrap will be removed and retail packs will be placed in the retail display case. In less than half an hour, the myoglobin will get oxygenated and the meat will bloom to a bright

red colour (Penny and Bell 1993). Once the container is empty, the container will be disconnected from the liquid N_2 source at the retail outlet to await transport back to the packer for refilling, when a carrier arrives with more product.

2.13 Benefits of the Proposed System

Centralized meat distribution is an innovative concept and has the potential to revolutionize the meat distribution system in Canada as well as in other countries. Integration of the master packaging technique with a liquid N_2 refrigeration system for stringent temperature control for centralized preparation of retail-ready meats has the following advantages:

1. Carcasses are broken down into display-ready retail cuts at the packer level. Consequently, inedible components (e.g., bone, fat trim, etc.) need not be refrigerated and shipped to retail stores. Moreover, these components need not be refrigerated in retail outlets during storage prior to retail cut preparation (Taylor 1985).
2. Efficiencies from economies of scale at the packer level through the use of specialized equipment and labor will substantially reduce both labour and operating costs, making Canadian products more cost competitive in both domestic and export markets.
3. Centralized processing and packing permits retail outlets to use space, presently being utilized to fabricate and package retail cuts for merchandising products. As retail space is usually very expensive this is an important consideration.
4. By using this technology, meat packers can deliver a good assortment of

convenient display-ready retail cuts of meat in the quantities exactly required by the retailers. This will help the meat packers to quickly respond to ever-changing consumer needs, thereby improving the working relationships in the supply chain (Burn 1999).

5. Liquid N_2 refrigeration will permit stringent control of product temperatures during both distribution and storage, which is not presently attainable with conventional refrigeration (Bailey et al. 1997). This will facilitate distribution of display-ready retail cuts over longer distances and allow Canada to supply display-ready retail cuts to both domestic and export markets anywhere in the North American continent using surface transport, thereby adding considerably to the value of Canadian agricultural production.

6. The additional storage life acquired with stringent temperature control during distribution and storage will permit more effective and efficient inventory control. This will virtually eliminate spoilage losses and substantially reduce the hazard of food borne illness.

7. Use of liquid N_2 refrigerated containers will eliminate the need for and use of cardboard cartons, which will reduce costs and the requirement for packaging materials which must be either ultimately recycled or disposed of in landfills, since the container is both returnable and reusable. Consequently, there are both beneficial economic and environmental impacts.

8. The requirement for refrigerated storage (inventory) coolers at the retailer level is eliminated, as the proposed container is self-refrigerated.

9. Refrigerant is only being used when the container contains product.

10. This system eliminates the need for refrigerated trucks. This is an important consideration, as only limited number of refrigerated carriers are available in Canada and the demand is very high in summer time. As many refrigerated carriers deal only with large food packers who can promise year-round volumes, small meat packers and retailers who have a difficulty in securing refrigerated carriers will benefit from the N_2-refrigerated container (Young 1999).

11. Many small convenience retail outlets and food service outlets presently are unable to merchandize chilled meat products due to short and fluctuating storage life. The proposed system will provide the additional storage life required for these outlets to effectively merchandize chilled meat products without incurring spoilage losses. This advantage is particularly relevant in northern Canada, where chilled meat is not presently available.

12. Canada has the distinct advantage of producing speciality meats from bison, white-tailed deer, and elk with export potential to Europe and Japan, as these species are not grown there. Because of the short storage life of these speciality cuts, packers face difficulty in capitalizing on this highly profitable business (Eagle 1999). The proposed system can be very well applied to any type of meat product and can be used to transport speciality cuts to overseas markets.

13. Consumers will benefit from safer, fresher products consistently provided at lower cost, potentially expanding the demand for Canadian agricultural products and contributing to the sustainability of rural Canadian animal husbandry.

3. MATERIALS AND METHODS

The concept of spraying liquid N_2 in the jacket for maintaining the temperature of meat placed inside the container, was initially studied in a model jacketed container. Based on the results of the preliminary study with the model jacketed container, a full size container was designed, fabricated, and tested. This section includes the materials and methods and results of the preliminary study with the model jacketed container and materials and methods for the full-size container study.

3.1 Model Jacketed Container

The food industry uses an insulated container (Model C-54, Xactics, Joliette, QC) of cross section (1000 x 875 mm) and 1600 mm high for distributing frozen foods to local markets. Bailey (1997) implemented a liquid N_2 refrigeration system in this container. It was expected that the temperature distribution would vary along the height of the container and it was important to verify the efficiency of the N_2-refrigeration system in maintaining the uniform distribution of temperature along the height of the container. Therefore, the height of the model jacketed container was designed to be the same as the height of the full size container (the C-54 container). The cross-section of the model jacketed container was approximately one-fourth of the full size container. Each level in the model jacketed container was able to hold one tray of meat.

The internal dimensions of the model jacketed container were 425 x 425 x 1500 mm (Fig. A.1). All sides of the jacket were formed by placing two 1-mm mild steel sheets at a gap of 25 mm on all six sides. A 50 mm thick Styrofoam* SM (Dow Chemical Canada Inc., Richmond, BC) of R value 10 was used to insulate the jacket. The outer

cover was made using 12.5 mm thick plywood over the styrofoam on all sides. The container jacket was connected to the door jacket through a 25 mm diameter flexible rubber hose at the bottom (Fig. A.2). Nine shelves were fitted inside the container with 150 mm spacing between them. The first, fifth, and ninth (shelf) level from the top were designated as top, middle, and bottom level, respectively.

3.1.1 Nitrogen refrigeration system Liquid nitrogen was injected at the top of the jacket. There was no specific nozzle available for the cryogenic fluid. Bailey et al. (1997) used flat spray agricultural nozzles for spraying liquid N_2 and reported that they performed well. Flat surface nozzles are suitable because the liquid N_2 can be sprayed evenly in a thin sheet in the cavity of the jacket. The flat spray pattern is formed by using either an elliptical orifice or a round orifice tangential to a deflector surface (Anonymous 1996). In the elliptical orifice design, the axis of spray pattern is a continuation of the axis of an inlet tubing connection (Fig. 2).

Fig. 2. Elliptical orifice, flat spray nozzle.

Initially an elliptical orifice was tested. Because the nozzle was placed at the center of

the top surface of the container jacket, the liquid N_2 impinged on the mild steel plate at the top surface. This resulted in colder temperatures at the top and warmer temperatures at the bottom of the container. In the deflector design, the deflection surface diverts the spray pattern away from the axis of the inlet tubing connection (Fig. 3).

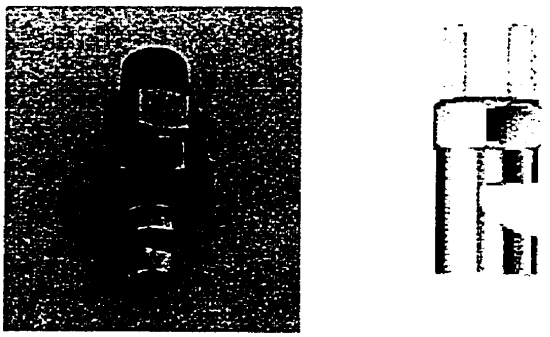

Fig. 3. Deflector orifice, flat spray nozzle.

By rotating the deflector nozzle on the vertical axis, the angle of spray on the horizontal plane can be changed, by which the temperature distribution in the jacket can be changed. The deflector forced the liquid N_2 with a great force and propelled the N_2 gas towards the bottom of the cabinet which resulted in uniform temperature distribution throughout the height of the container. A deflector orifice, flat spray nozzle (Model: TK3, Spraying Systems Co., Wheaton, IL) was used for all tests.

Liquid N_2 was withdrawn at 152 kPa gage pressure from a liquid N_2 tank (Dura-series cryogenic containers, Minnesota Valley Engineering, New Prague, MN). Nitrogen from the tank was transferred through a vacuum-insulated, flexible steel transfer hose (Lab-Dewar-Tech Series, Minnesota Valley Engineering, New Prague, MN) to the

container. The flow control of liquid N_2 was accomplished by an on-off cycling of a solenoid-actuated valve (Model: 25M41, Magnatrol Valve Corp., Hawthorne, NJ). This valve is designed for cryogenic operations. It is normally closed and opens when the power is supplied. Therefore, the valve remains closed in the event of power failure preventing the uncontrolled release of liquid N_2. Once the liquid N_2 was injected at the top of the container, it flashed into vapour. The gas was then transferred to the door-jacket through the hose (connecting the container jacket to the door jacket) at the bottom (Fig. A.2). The gas was then released to the atmosphere through two pressure release valves, located at the top of the door-jacket (Fig. A.1). The pressure release valves was set at pressures 0, 2.3, or 6.89 kPa gage by changing the spring in the valve. A safety valve was also placed at the bottom of the door with pressure set at 6.89 kPa (Fig. A.2).

3.1.2 Simulation of meat For initial testing, experiments were conducted with saline bags, because direct testing with meat would have been expensive during evaluation of the container in the design phase. The 10% (by mass) NaCl (Model: S-7653, Sigma Chemical Co., St. Louis, MO) brine has a specific heat of 3.715 kJ/(kg.K) and crystallization starts at -6.6 °C (ASHRAE Fundamentals Handbook 1993). The brine solution was packed in barrier bags (Model: Deli # 1, Winpak, Winnipeg, MB). The barrier bag was composed of nylon, EVOH, and polyethylene having an O_2 transmission rate of 2.3 mL/(m^2.d) at 23 °C. The moisture vapour transmission rate was 7.8 g/(m^2.d) at 37.8 °C and 90% R.H. The size of each bag was 240 x 300 mm. Based on the average ratio of mass of meat to surface area of the master trays, it was determined that 2.4 kg of meat could be packed in each barrier bag. The bag was filled with 1.8 kg of saline water

to achieve the same heat storage capacity (product of specific heat and the total mass of the product) as meat, using specific heat of meat as 2.8kJ/(kg K) (ASHRAE Fundamentals Handbook 1993). Each level of the container supported one saline bag.

3.1.3 Instrumentation The container was placed in a controlled environment chamber (Model: CONVIRON CMP 3244, Controlled Environments Ltd., Winnipeg, MB), capable of controlling air temperature in the chamber to within ±0.5 °C in the temperature range of -50 to 60 °C. It should be noted that only the air temperature measured by a sensor at a point in the environmental chamber is controlled within ±0.5 °C. When the saline bags were initially conditioned to -1.5 °C, the bags near the fans were colder and bags farther from the fans were warmer and it usually took more than a day to equilibrate to the temperature -1.5 ±0.5 °C.

Nitrogen use was measured by placing the N_2 tank on a floor scale (Model: 2136, Mettler-Toledo Inc., Burlington, ON). This scale measures up to 500 kg with 0.2 kg resolution.

The vacuum insulated, flexible steel transfer hose of 12.5 mm inside diameter was used to transfer the liquid N_2 from the N_2 tank to the container (Fig. A.9). The solenoid valve is normally closed and opens when the power is supplied. At the end of the experiment, the liquid release valve of the N_2 tank would be closed. Because the power was off at the end of experiment, the solenoid valve would also be closed. This would trap the liquid N_2 already present in the hose, which could reach the pressures of 100 MPa (ASHRAE Fundamentals Handbook 1993). Therefore, a safety release valve was placed before the solenoid valve which opens at a pressure of 345 kPa. As an additional

precaution, the selected solenoid valve opens when the differential pressure reaches 1 MPa and vents the excess pressure.

As the temperatures were to be controlled in a narrow range, thermistors were used. The higher sensitivity of the thermistor at lower temperatures makes it suitable for this application. Thermistors (Model: 44007, OMEGA Engineering Inc., Stamford, CT) with an accuracy ±0.2°C were used to measure the temperature of saline bags and the jacket. A multimeter (Model: HP 34401A, Hewlett-Packard Co., Loveland, CO) was used to measure the resistance of the thermistors. Three thermistors were used to measure the temperatures of saline bags at the top, middle, and bottom levels. One thermistor was used to measure the temperature of air inside the container. Eight thermistors (each on the centre of 3 sides, top, and bottom of the jacket, and 3 on the door jacket) were used to measure the temperature of the N_2 gas in the jacket at different locations. Each of the eight thermistors was inserted in a 6.25 mm diameter plastic tube of approximately 90 mm length such that only the measuring tip projected outside of the tube. The annular space between the tube and the thermistor was sealed with silicone. A 6.25 mm hole was drilled in the container at various points (as mentioned above) through which the tubes with thermistors were inserted giving a good seal. One thermistor was used to measure the temperature of outside air. The Steinhart and Hart equation was used to calibrate the thermistors (OMEGA 1992).

$$\frac{1}{T} = a + b\ln(R) + c\{\ln(R)\}^3 \qquad (1)$$

where:

T = Temperature (K),

R = Measured resistance of the thermistor (Ω), and

a,b,c are calibration constants.

The calibration constants a, b, c were found by selecting three data points on the published data curve and solving the three simultaneous equations (OMEGA 1992). When the data points are chosen to span no more than 100°C within the nominal center of the thermistor's temperature range, this equation approaches a rather remarkable ±.02°C curve fit (OMEGA 1992).

The calibration constants were determined by substituting the resistances at -5, 20, 45°C in Eq.1. The constants were: a = 0.00128375101868, b = 0.000236385479572, and c = 9.21168159471 x 10^{-8}. The resistance of the thermistors was measured by the multimeter and was converted to temperature using Eq. 1 and the above constants using a QuickBASIC program.

The multimeter was capable of measuring only one resistance at a time. For this reason, Bailey (1997) built a 24 channel multiplexer and connected it to the multimeter. The same multiplexer with minor modifications was used for this study. Channel one and two of the multiplexer were used to control the solenoid valve and heater, respectively. Channel activation was computer-controlled by a UNISYS 300 (an 80286 PC) by the QuickBASIC program.

If the outside temperature is less than -1.5°C, heat will be conducted from the meat. This will cause freezing of the product. Therefore, a heater was installed in the jacket and was turned on if the control sensor temperature dropped below -2.75°C. A

500 W rod heater (8 mm diameter and 1500 mm long, Red Devil Heater Manufacturing Co., Winnipeg, MB) was placed at the back of the container jacket. During initial trials, when the container was exposed to -20°C, the saline bags at the bottom of the container were colder than those at the top of the container. This is because the hot gas rises and cold gas settles due to density differences. Therefore, another 400 W heater was placed at the bottom of the jacket in addition to the rod heater at the back side of the jacket.

3.1.4 Temperature control algorithm Bailey et al. (1997) used a temperature control algorithm, which calculates the shut off temperature based on the previous temperature histories and reported that the algorithm worked well.

If the master packaged meat were placed inside the container at -1.5°C, and if the jacket were maintained at -1.5°C, the meat would also be maintained at the same temperature indefinitely. However, the temperature of the gas in the jacket changes dynamically following the injection of liquid N_2. Although the gas temperature in the jacket was not constant, the temperature of the saline bags was constant over short periods of time because of its large specific heat and large mass.

The sensor placed at the center of the back side of the container jacket was selected as a control sensor. The objective of the control algorithm was "to produce constant cyclic mean temperature (this refers to the time-weighted average gas temperature over the intervals between N_2 injections) of the control sensor with controlled injections of N_2" (Bailey et al. 1997). By trial and error, it was determined that a cyclic mean temperature of -2°C at the control sensor maintained the temperature of the product within the desired range. Therefore, this value was used for all tests. The heaters

were turned on if the control sensor temperature dropped below -2.75°C and turned off when the temperature reached -2.60°C.

A 60 s time cycle between N_2 injections was used. For the first 20 s of the cycle, liquid N_2 was not injected, because it would cause drastic fluctuations in the gas temperature. The time constant for the thermistors is 10 s in still air and 20 s is required to measure the temperature of gas and saline bags with up to 86% accuracy of the change in temperature (OMEGA 1992). On the remaining 40 s of the cycle, the N_2 was injected until the control sensor reached the shut-off temperature (shut-off temperature was calculated by the program based on the previous six temperature histories). Even if the shut-off temperature was not reached, the N_2 injection was stopped by the end of each cycle to take the temperature readings for the next cycle. All temperature readings and the mass of the N_2 tank were measured and recorded every 60 s. The temperature of the control sensor was measured every 5 s and was compared with the newly calculated shut-off temperature.

3.1.5 Testing conditions The temperatures of the jacket and saline bags were monitored when the container was exposed to outside temperatures (temperature of the conviron chamber) of -20, 15, and 30°C. The N_2 gas was held in the jacket at 0, 2.3, or 6.89 kPa gage pressures. At the beginning of each experiment, the container and saline bags were cooled to -1.5°C in the conviron chamber. Then the chamber temperature was set to -20, 15, or 30°C and the program was started.

3.1.6 Preliminary results All the pressures at which the N_2 gas was held in the jacket controlled the temperature within the required range. The jacket pressure had no

significant effect on N_2 consumption. Each pressure, however, required a different shut-off temperature to maintain the temperature in the desired range.

The temperature of the saline bags during a 24 h trial, when the container was exposed to 30°C, is shown in Fig. 4. The temperature of saline bags were maintained well within the range. The N_2 consumption for the above trial is shown in Fig. 5. Nitrogen consumption was linear with average N_2 consumption rates of 2.4 and 1.3 kg/h, when the container was exposed to outside temperatures of 30 and 15°C, respectively.

The temperature of saline bags, when the container was exposed to -20°C, is shown in Fig. 6. The temperature of the saline bag at the top level had a maximum temperature of -0.7°C, while the other two saline bags were maintained within the desired range. When the temperatures in different portions of the jacket were analyzed, the bottom portion was colder than the top portion, due to density differences that arise from the fact that hot gas rises and cold gas settles. Increasing the power of the heater at the bottom of the jacket may heat up the cold gas which settles at the bottom, and may alleviate this problem.

3.2.7 Summary of the preliminary study The preliminary results showed that the N_2-refrigerated, jacketed container is capable of maintaining the temperatures of saline bags in the narrow range for extended storage periods. The pressure at which N_2 gas is held in the jacket had no effect on temperature distribution or N_2 consumption. Therefore, the full size container was designed to operate only at atmospheric pressure which would reduce the cost of production and maintenance.

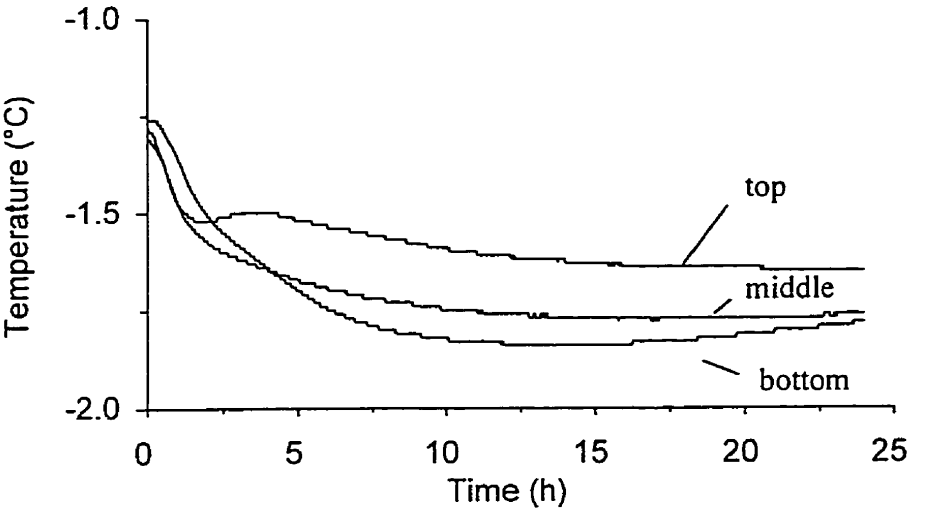

Fig. 4. Temperature of saline bags at top, middle, and bottom levels in the model jacketed container, when the container was exposed to an outside temperature of 30°C.

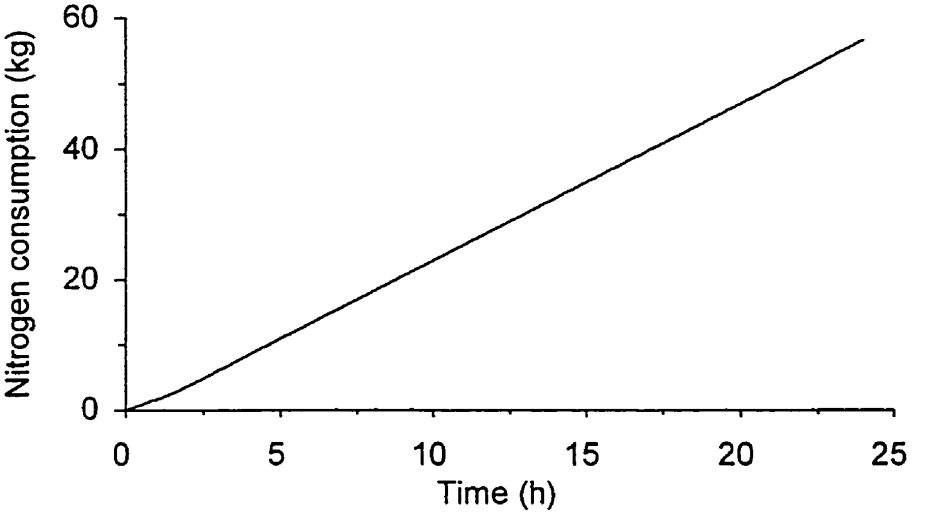

Fig. 5. Nitrogen consumption for the above trial (Fig. 4), when the model jacketed container was exposed to an outside temperature of 30°C.

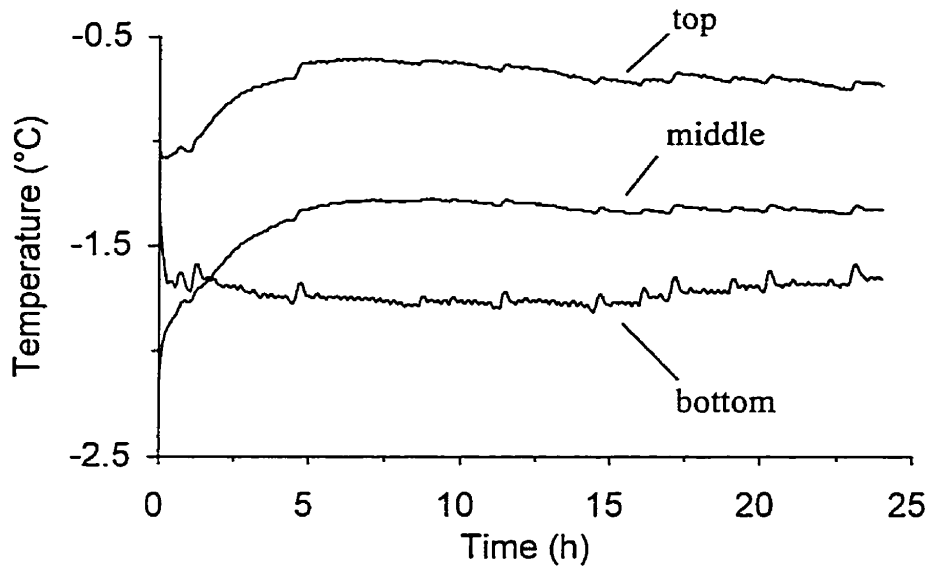

Fig. 6. Temperature of saline bags at top, middle, and bottom levels, when the model jacketed container was exposed to an outside temperature of -20 °C.

3.2 Full-size Container

Xactics (a division of Plasti-drain Ltd.), Joliette, QC, manufactures insulated containers used by the food industry. A container (Model: C-54) was provided by the company. Pictures of the container and the experimental set-up are included in Appendix A (Figs. A.3 to A.16). The size of the container was 1000 x 875 mm cross-section and 1600 mm high. Instead of building a jacket on the container walls, a plastic box was built and fitted inside the container such that a uniform space was formed between the container and the box, which would act as a jacket (Figs. A.7 and A.12). This construction would facilitate in making modifications during the design phase. Acrylic material was used for fabricating the box, as it is a food-grade plastic and has enough strength to hold a full load of meat. The box had to be sealed on all six sides so that circulation of N_2 gas takes

place uniformly throughout all sides of the jacket. Therefore, the acrylic box was equipped with a door on the front side. Closing and opening of the door of the acrylic box was accomplished by using magnetic strips on the acrylic container and a steel strip on the acrylic door (Fig. A.11). This configuration allowed the door to be "snapped" on or off and gave a tight seal. Twelve shelves were constructed (Fig. A.5) such that each shelf could support 4 meat trays (approximately 6 kg of meat per tray), giving a total capacity of 288 kg of meat. A back-pressure release valve (ball valve) was placed at the bottom of the front door of the container to release N_2 gas into the atmosphere (Fig. A.8).

3.2.1 Nozzles The placement of nozzles, discharge capacity of the nozzle, and angle at which liquid N_2 is sprayed are the important parameters involved in temperature control. These parameters were established by trial and error. The inlet pipe for liquid N_2 entered at the top of the container. From the inlet pipe, the distribution pipes (copper tubings) carried the liquid N_2 to the sides of the jacket where the liquid N_2 was sprayed down by the nozzles (Figs. A.15 and A.16). As liquid N_2 has to be sprayed on the axis of plane parallel to the vertical sides of the jacket, elliptical orifice nozzles (Model: XR8003, Spraying Systems Co., Wheaton, IL) were selected (Fig. 2). Initially, only three nozzles on three sides (other than front side) were tested. This configuration of nozzles gave an adequate temperature control when outside temperatures were 0 and 15°C. But as the outside temperature was increased, the temperature difference between the front and back sides of the container increased resulting in a larger range of temperature distribution. Then, 4 nozzles were used to inject liquid N_2 on all 4 vertical sides of the jacket which resulted in better temperature distribution, when the outside temperature was 30°C. This

configuration also minimized the temperature differences between the front and back sides of the container.

3.2.2 Instrumentation All tests were conducted within a controlled environmental chamber (Model: CONVIRON C1010, Controlled Environments Ltd., Winnipeg, MB), which is capable of controlling the temperature of air to within ±0.5°C in the temperature range from -20 to 50°C (Fig A.3). The environmental chamber, CMP 3244, which was used in preliminary study of the model jacketed container, was not used because its door opening was not big enough to allow the passage of the full-size container. Higher accuracy thermistors (±0.1°C accuracy, Model:44034, OMEGA Engineering Inc., Stamford, CT) were purchased. If the thermistors were calibrated individually against a standard temperature, the accuracy can be further improved. But the calibration thermometers available in the Instrumentation Lab had a least count of 0.1°C. At the ice point (0°C, water and ice mixture), the calibration thermometer gave a reading of 0.15°C, while all the thermistors gave the reading in the range of 0.08 to -0.03°C with an average reading of 0.036°C. It was concluded that the thermistors were more accurate than the calibration thermometer available. Therefore, published data provided by the manufacturer were used for finding the calibration constants for Eq. 1. The constants were found to be: a = 0.001285888187899, b = 0.0002359891353935, and c = 9.410840098881E-08.

Two thermistors each were placed diagonally on the top (locations are marked as 8O and 8B in Fig. A.16) and bottom of the container to measure the jacket temperature. Six thermistors were placed on each side of the container to measure the temperature of

the vertical component of the jacket (some thermistors are seen in Fig. A.14). Thus, 28 thermistors were used to measure the temperature of N_2 gas at various points in the jacket. Initially, these thermistors were placed inside a plastic tube and inserted through the container wall in the same manner described in the section 3.1.3. The two sensors at the centre of the back side of the container jacket were selected as control sensors. It was found that the control sensor had to be maintained at a temperature above -1.5 °C (0.5 and 1.5 °C when the outside temperatures were 15 and 30 °C, respectively) to maintain the temperature of meat within the desired range. There could have been a heat leak through the holes drilled into the container which caused the temperature around the thermistors to be higher than the surrounding temperature. When the thermistors with the tubes were moved into the jacket (as seen in Fig. A. 14) and placed away from the holes which were sealed silicone, the control sensor needed to be maintained between -1.5 and -3.0, depending on the outside temperature.

At each level, four master packs could be placed. Temperatures of the meat cuts were measured for all trays at 6 levels (1, 3, 5, 7, 10, and 12th level, counted from the top of the container). Thus, 24 thermistors were placed inside the acrylic box to measure the temperature of meat. Two thermistors were used to measure the temperature of the gas surrounding the meat. All the thermistor cables were connected through a connector to make it easy to move the container away from the data acquisition system.

The solenoid valve (Model: 25M41, Magnatrol valve corp., Hawthorne, NJ) used in the model jacketed container perfromed well, but was bulky. Bailey (1997) used a solenoid valve (Model: 8263G206LT, ASCOlectric Ltd., Brantford, ON) and reported

that solenoid valve performed well. The same model was purchased and used in the full-size container. This valve is also normally closed and opens only when the power is supplied.

An improved data acquisition and control system (Model: HP3852A, Hewlett Packard, Alto, CA) was used for collecting data (Fig A.3). This system had the capability to measure resistance of the thermistors and eliminated the need for multimeter. The temperature control algorithm developed by Bailey (1997) was modified to work for the new data acquisition system and to control heater in addition to the solenoid valve (See Appendix B). The 60 s cycle was reduced to 30 s cycle, because the data acquisition system was capable of measuring the temperatures of all 56 thermistors in less than 10 s. The 30 s cycle should yield a better temperature control than the 60 s cycle, because more injections of N_2 over short periods of time would reduce the temperature fluctuation. Even though the time constant of the thermistor was 10 s, the change in temperature over a 30 s period was very small and gave better accuracy. The program converted the resistance of the thermistor into temperature by using the Steinhart-Hart equation (Eq. 1). Based on the temperature of the control sensors, the program sent a signal to the data acquisition and control system, which then switched on and off either the solenoid valve or the heater to establish the control of temperature.

3.2.3 Heater A heater was provided to prevent freezing of meat, when the outside temperature dropped below -1.5°C. The rod heater (used in the model jacketed container) was initially tested, but the plastic of the C-54 container near the heater melted. Then, flexible silicone rubber fibreglass insulated heater (Model: SRFG-1024/*-P,

OMEGA Engineering Inc., Stamford, CT) was tested at the bottom of the jacket. As there was no fan in the design, the convection current was not adequate which resulted in concentrated heat near the bottom leading to distortion of the acrylic plastic at the bottom. Then a roof de-icing cable of 300 W capacity and 18 m length (Model: ADKS-0300, Easyheat Ltd., Waterloo, ON) was tested and it performed well. As the surface temperature of the roof de-icing cable reaches a maximum of only about 5-10°C, the heater was clamped to the surface of the C-54 container (Figs. A.13 and A.14). The configuration of the heater wire could be easily changed to get uniform heat distribution. The heater wire was concentrated at the bottom to heat the settling cold gas and near the door to heat any cold air that might leak through the door seal (Figs. A.13 and A.14).

3.2.4 Meat Retail packs of fresh pork and beef were obtained from Millers Super Valu Meats, Winnipeg, MB. In each test, 144 butt roasts of pork of approximately 1.5 kg each packed in O_2- permeable films on styrofoam trays measuring 210 x 135 mm and 48 blade cuts of beef of the same size and weight were used.

3.2.5 Testing conditions The container was evaluated when exposed to outside temperatures of 30, 15, 0, and -15°C for 2 d period. Three trials were conducted at each outside temperature. Tests were also conducted to evaluate the performance of the container, if the N_2 tank became empty or the power was off. The duration of these trials was 8 h. Liquid N_2 release valve was closed for the first 4 h of the trial and was opened for the remaining 4 h to determine how far the temperature would rise during a N_2 shut-off period and how quickly the temperatures would be brought to the desired range after the valve was opened. Three replicates were used. Testing was done only at an outside

temperature of 30°C. The container was also evaluated for the effect of door opening intervals. The time required to remove 1, 2, and 3 trays from the container was approximately 15, 25, and 35 s, respectively. The container door and acrylic box door were opened for the specified period of time and were then closed. Tests were conducted, when the outside temperatures were 15 and 30°C. Three replicates were used for each test condition and the duration of each test was approximately 30 min.

3.2.6 Data analysis Temperature of the gas in the jacket and temperature of meat cuts were measured every 30 s. The temperature of the gas in the jacket fluctuated considerably after the injection of liquid N_2 and these data were used for control the solenoid valve. The temperature of meat was relatively constant over short periods of time due to its large mass and large specific heat capacity, and therefore the temperatures were recorded in the output files every 5 min during each 2 d trial. Data files were imported into Quattro Pro and graphs were plotted to show the variation of temperature of gas in the jacket at 28 locations and temperature of meat at 24 locations plus the temperature of gas surrounding the meat inside the acrylic box at 2 locations over the duration of trial. The distribution of temperature in the jacket gave an idea of gas flow in the jacket and these data were used for perfecting the nozzle location and capacity.

The first (shelf) level was the top level and the twelfth level was the bottom level. Four sensors were placed at each level where temperatures were monitored. Sensors 1 and 4 were near the door and sensors 2 and 3 were located behind 1 and 4, respectively (Fig. 7). Sensor 5(2) refers to sensor 2 at the fifth level from the top. This designation is used throughout the discussion for consistency.

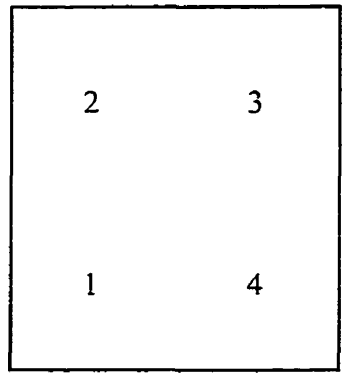

Fig. 7. Locations of the sensors (1-4) at a particular level (top view) in the container.

4. RESULTS AND DISCUSSION

4.1 Some Observations During Testing

Before discussing the results, some of the observations noted during testing are described in this section. Figure 8 shows the temperatures of meat at locations 1(2) and 1(3) during initial testing of the container at 30°C outside temperature. These data were

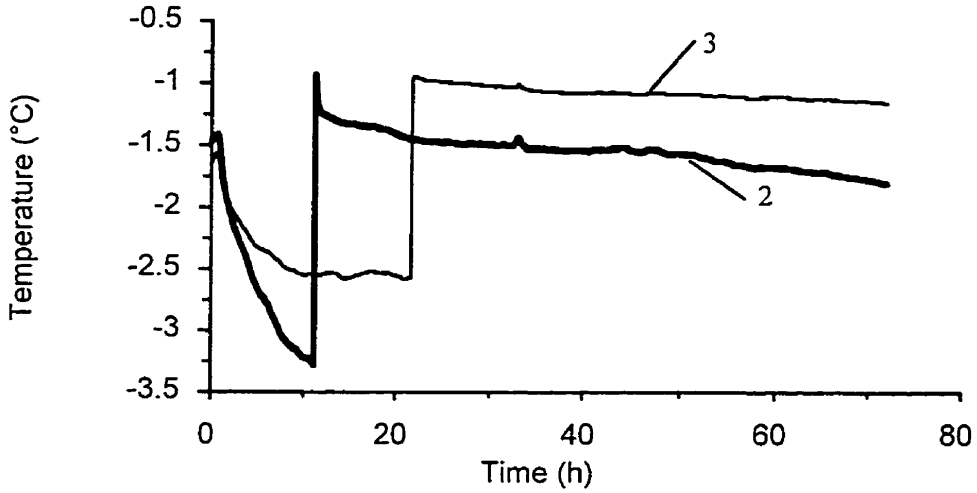

Fig. 8. Temperature of meat at locations 2 and 3 in the first level during one of the initial trials at 30°C outside temperature. (For locations, refer to Fig. 7).

collected during the initial phase of testing and were not included in the analysis. When the temperature of meat dropped below a certain temperature (-2.5 to -3.5°C), the temperature jumped suddenly by 1.5 to 2°C and then stayed relatively constant for the remaining testing period. It is interesting to note that this temperature change occurred within 30 s. In the freezing curve of any liquid or food, initial sub-zero cooling takes place to initiate nuclei formation. Once the nuclei are formed and crystallization starts, the latent heat of fusion is released, raising the temperature of meat to the initial freezing

point (Sahagian and Golf 1996). This rise in temperature occurs in less than a minute during freezing of beef (Desrosier and Desrosier 1977). Once the meat starts freezing, the temperature change occurs very slowly due to removal of latent heat of freezing. If the meat had started freezing during the initial chilling of meat in the environmental chamber before the start of the experiment, the temperature of meat would stay relatively constant around -1 to -1.5°C. The jacket temperature was maintained around -1.5 to -2°C, and therefore the temperature gradient between the meat and the jacket was low. The temperature change of the meat would be very slow, because the apparent specific heat of freezing meat is large due to release of latent heat of fusion. For instance, Fleming (1969) reported that the specific heat of fresh and frozen lamb is 4.6 (at 10°C) and 2.1 kJ/(kg°C) (at -10°C), respectively, while the apparent specific heat at the commencement of freezing rose up to 83.7 kJ/(kg°C). Therefore, care was taken to ensure that all meat used was fresh and not frozen before the start of each experiment. Also, at the end of each experiment, the meat cuts were randomly checked for freezing.

Initially, all the thermistors were placed at the center of meat cuts. A thermistor consists of a metal-oxide compound whose resistance varies with surrounding temperature. Resistance is measured and is related to the temperature (OMEGA 1992). If the seal of the thermistor around the metal-oxide compound was damaged, fluid in the meat cut could make a contact between the two lead wires from the thermistor and act as a parallel resistance to the resistance of the metal-oxide. The resistance of the meat was measured and found to be approximately 150-250 kΩ. The temperature of meat at location 1(3) increased from -3.25 to -1.00°C (Fig. 8), the corresponding resistances

being 19.25 kΩ and 17.18 kΩ, respectively. This resistance change will occur, if a resistance of 159.76 kΩ is added in parallel to 19.25 kΩ. Similarly if a resistance of 240.78 kΩ is added in parallel with the resistance of the thermistor at the location 1(2), a temperature change from -2.5 to -1.0°C will occur. Therefore, it is possible that an improper seal in the thermistor could also have caused the temperature change. The cause for the temperature change could not be reasoned out definitely, but it is more likely that freezing of meat was responsible for the temperature change.

To avoid this problem, the thermistor was placed on the surface of the meat (over the O_2-permeable film). Because the thermistor was not in direct contact with the meat, the meat fluid did not contaminate the thermistor and interfere with measurements. As freezing of meat is an important concern with respect to the objectives of the project, the surface of the meat was the coldest point. Also as the container is designed for extended storage of meat, the center temperature of meat will equilibrate with the surface temperature over time. After this change in thermistor attachment was made, during trial 3 at an outside temperature of 15°C, the temperature of the meat cut at location 1(3) increased from -2.65 to -1.29°C. At the end of the experiment, this particular meat cut was found to be frozen.

Initially, the target temperature was set at -1.5±0.5°C. As this temperature set point is the borderline for freezing of the meat, surface freezing was observed on some of the meat cuts (usually on the first level). Therefore, the target temperature was moved to -1.0±0.5°C and an additional margin of 0.5°C beyond -1.5°C was allowed.

4.2 Temperature Data in Relation to Outside Temperatures

The maximum, average, and minimum temperatures of meat for each trial were calculated and are presented in Table I. At outside temperatures of 0, 15, and 30°C, the coldest locations were usually at the first level. This is because the liquid N_2 was injected at the top of the jacket. Increasing the insulation at the top of the acrylic box would reduce the temperature of the first level and improve the overall temperature uniformity. The front sides of the first and twelfth levels were warmer by approximately 0.5°C than the mean of all temperatures. When the C-54 container was received from Xactics, the door was warped with a gap of about 5 mm at the top and bottom and a tight seal at the centre. Latches were attached at the top and bottom to improve the seal. But still, there was some heat leak at the top and bottom of the door. Therefore, as the outside temperature increased from 0 to 30°C, the front sides of the first and the twelfth levels became warmer. For the same reason, when the container was exposed to -15°C, the heat transfer occurred in the reverse direction, resulting in colder temperatures at front sides of the first and twelfth levels. The twelfth level showed a more pronounced effect of colder temperature, as the cold gas settles and hot gas rises due to density differences. If the container were equipped with a tight fitting door, the problem of warmer temperature at the front side of the first and twelfth levels could be eliminated. The colder temperature at the first level (when ambient temperature was higher and liquid N_2 was injected) could be eliminated by increasing the insulation near the first level. This can be accomplished by fitting an acrylic plastic sheet at the top of acrylic box with an air gap to provide more insulation. Such a cavity can also be used to hide the liquid nitrogen distribution pipes to

Table I. Maximum, average, and minimum temperatures of meat, and the warmest and coldest sensor locations that were outside the range.

Trial	Temperature (°C)			Sensor locations outside the range[a]		CS[b] (°C)
No.	Max	Avg	Min	Warmest	Coldest	
				Temperature outside the container = 0 °C		
1	-0.9	-1.4	-2.5	-	1(2)[c]	-1.60
2	-1.3	-1.5	-2.1	-	1(2)	-1.60
3	-1.1	-1.4	-2.3	-	1(2)	-1.60
				Temperature outside the container = 15 °C		
1	-0.3	-1.0	-2.3	12(2),10(2)	1(3)	-2.25
2	-0.9	-1.2	-2.5	-	1(2),3(2)	-2.50
3	-0.8	-1.4	-2.9	-	1(3),1(2),3(2)	-2.60
				Temperature outside the container = 30 °C		
1	-0.5	-1.0	-1.8	-	-	-3.00
2	-0.3	-1.3	-2.6	1(4)	1(2)	-3.00
3	-0.1	-0.7	-2.0	10(1),10(4),12(1), 12(2),12(3)	1(2)	-3.00
				Temperature outside the container = -15 °C		
1	-0.2	-1.1	-2.4	7(3),7(2)	12(1),1(3),1(4)	2.50
2	-0.2	-1.2	-2.6	7(3),7(2),5(2)	12(4),12(1),1(4)	2.50
3	-0.2	-1.3	-2.8	7(3),7(2)	12(4),12(1),1(4)	2.50
4	-0.2	-0.8	-2.0	7(3),7(2),5(2),7(4), 10(3),10(2)	12(1)	3.00

[a] Only the sensor locations outside the range (-0.5 to -2.0) are given

[b] CS : Control sensor temperature set point.

[c] 1(2) refers to sensor location 2 on level 1 (first level) (For locations, see Fig. 7).

improve the insulation and aesthetic appearance. As the acrylic box was already built and there was a space constraint at the top of the jacket, this modification could not be made. Table II summarizes the results when data from the first level were not included in the analysis.

Table II. Maximum, average, and minimum temperatures of meat, and the warmest and coldest sensor locations that were outside the range, when the data at the first level were not included in the analysis.

Trial	Temperature (°C)			Sensor locations outside the range[a]		CS[b] (°C)
No.	Max	Avg	Min	Warmest	Coldest	
				Temperature outside the container = 0 °C		
1	-0.9	-1.3	-1.9	-	-	-1.60
2	-1.3	-1.4	-1.6	-	-	-1.60
3	-1.1	-1.3	-1.7	-	-	-1.60
				Temperature outside the container = 15 °C		
1	-0.3	-0.9	-1.4	12(2)[c],10(2)	-	-2.25
2	-0.9	-1.2	-1.8	-	-	-2.50
3	-0.8	-1.4	-2.1	-	3(2)	-2.60
				Temperature outside the container = 30 °C		
1	-0.5	-1.0	-1.8	-	-	-3.00
2	-0.8	-1.3	-1.9	-	-	-3.00
3	-0.1	-0.7	-1.4	10(1),10(4),12(1), 12(2),12(3)	-	-3.00

[a] Only the sensor locations outside the range (-0.5 to -2.0) are given
[b] CS : Control sensor temperature set point.
[c] 12(2) refers to sensor location 2 on level 12 (See Fig. 7).

4.2.1 Outside temperature 0°C Figure 9 shows the temperature profiles of meat at different container locations for trial 1. The temperature at the sensor location 1(2) was outside the desired range. Although the temperatures of the meat at the third level were dropping slowly, they were expected to stay constant at around -2°C, as the temperature of gas around the third level varied between -1.5 and -2°C. Increasing the insulation above the first level would reduce the heat transfer rate near the top of the jacket and provide more cooling potential from the gas for removing heat near the bottom of the jacket. This potentially could increase the uniformity of the temperature in the container. Maximum, average, and minimum temperatures and N_2 consumption for 3 replicates are shown in Figs. C.1 to C.6. By trial and error, the control sensor temperature was set at -1.6°C, which provided adequate temperature control at 0°C. The N_2 consumption was linear. Linear regression analysis was performed and the slope of the curve was determined. The slope of the curve gives the N_2 consumption per hour or simply, the N_2 consumption rate. Table III gives the N_2 consumption rate for different trials at different outside temperatures with associated R^2 and standard errors of estimates.

In the second trial (Fig. C.3), one meat cut was warmer (0.25°C) than desired at the beginning of the trial. Although the container was not designed to chill meat products, the temperature of the meat was slowly brought to the desired range within 24 h. If the container is at room temperature and if the chilled meat at -1°C is placed on the container, the temperature of meat would be expected to rise. Because it takes more than a day to chill the product for couple of degrees, some storage life of the meat will

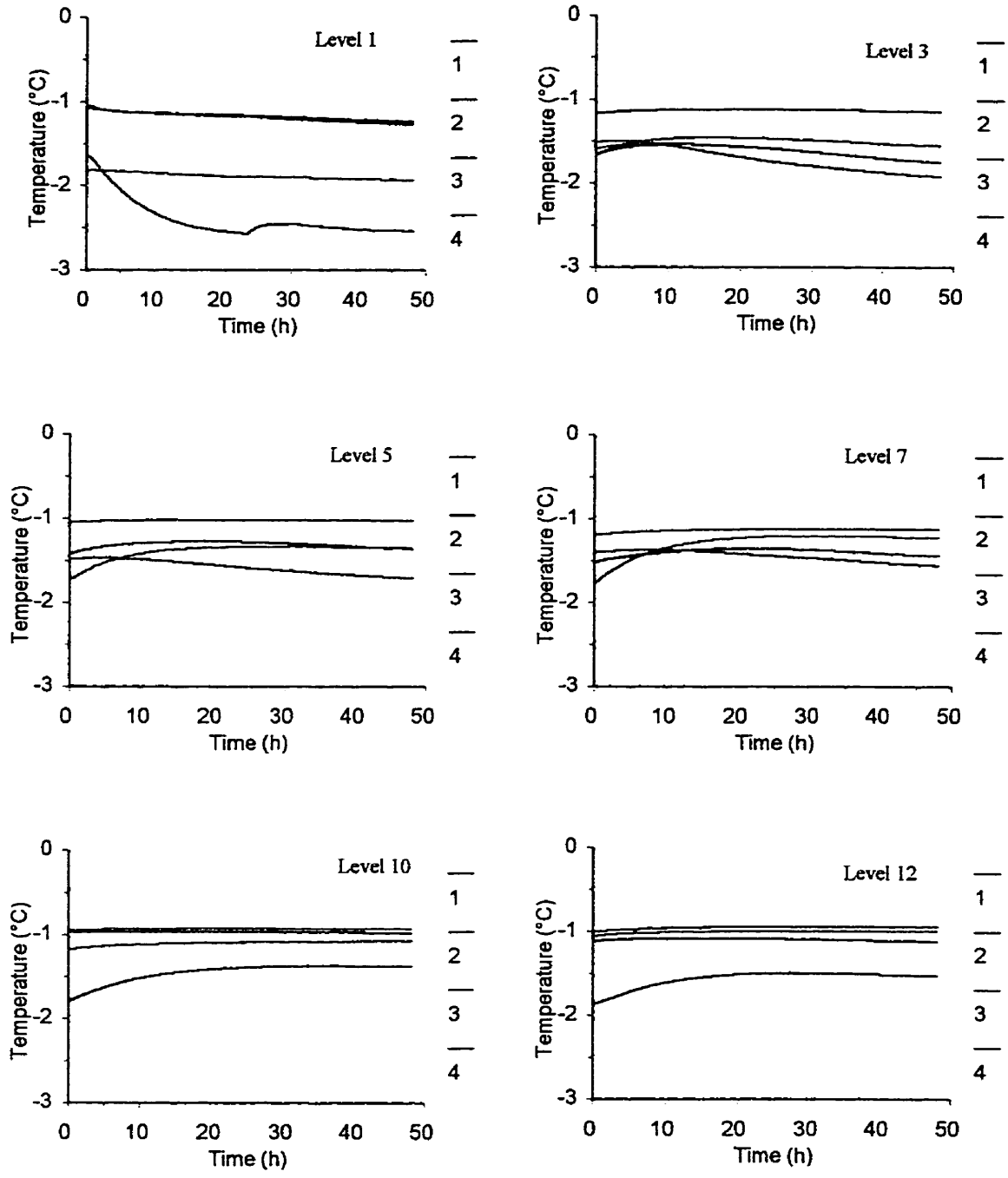

Fig. 9 Temperature profiles of meats, when the container was exposed to an outside temperature of 0 °C, trial 1. Numbers in legend refer to sensor locations at a particular level (Refer to Fig. 7).

Table III. Nitrogen consumption rate for different outside temperatures.

Trial No.	Nitrogen consumption rate (kg/h)	R^2	Std. Error of Co-efficient
Temperature outside the container = 0 °C			
1	0.9	0.994	0.002
2	0.9	0.993	0.003
3	0.6	0.949	0.003
Temperature outside the container = 15 °C			
1	2.3	0.999	0.001
2	2.4	0.997	0.003
3	2.5	0.997	0.003
Temperature outside the container = 30 °C			
1	4.2	0.999	0.003
2	4.3	1	0.001
3	4.3	0.999	0.001

be lost. It is also difficult to chill all meat cuts uniformly to -1 °C using a mechanical refrigerator, before placing them in the container. This practical difficulty will be encountered in the commercial meat distribution chain. A manual override control can be introduced into the program. If the initial temperature of meat is higher than the desired range, the door of the acrylic box can be removed and the manual control can be initiated. This will cause continuous injection of liquid N_2 without any interruption. As the acrylic box door is open, the N_2 gas will be circulated inside the acrylic box which will bring down the temperature of meat quickly. Once the desired temperature range is near, the automatic control can be initiated and the door to the acrylic box can be closed. However, the uniformity of temperature achieved by this approach will not be adequate,

as the acrylic box is open only on the front side. Also the initial N_2 consumption will be high, because the circulation of gas will not be efficient. A more effective solution would be to place nozzles inside the acrylic box so that initial chilling can be accomplished by injecting the liquid N_2 inside the box. Once the initial chilling is done, N_2 can be injected in the jacket to maintain the temperature. Hence another design of the N_2-refrigerated jacketed container including nozzles inside the acrylic box should be studied.

In the third trial (Fig. C.5), the initial temperatures were at the lower end of the desired range at the start of the experiment. Therefore, N_2 was not injected for the first few hours (Fig. C.6) and the temperatures of the meat rose to the desired limit and were then maintained. This resulted in lower N_2 consumption rate for the third trial (0.6 kg/h) compared to the other trials (0.9 kg/h), (Table III). It should be noted that the resolution of the weighing scale used to measure the mass of liquid nitrogen tank was 0.2 kg.

4.2.2 Outside temperature 15°C Maximum, average, and minimum temperatures of meat and N_2 consumption for three trials are shown in the Figs. C.7 to C.12. The N_2 consumption rate was 2.4 kg/h (Table III). The control sensor temperature had to be maintained below -1.5°C to maintain the temperature of meat in the desired range. The control sensor temperature was set at -2.25°C for the first trial and the average temperature achieved was -0.89°C. The control sensor temperature was reduced to -2.5°C in the 2nd trial, which gave good temperature control (Table II). As the desired target temperature was initially set at -1.5°C, the control sensor temperature was further reduced to -2.6°C in the 3rd trial, which slightly reduced all the temperatures of meat, but the back sides of the 1st and 3rd levels were outside of the lower limit. In the 3rd trial, the

temperature of sensor 1(3) increased suddenly from -2.65 to -1.29°C and the meat was frozen. Therefore, a control sensor temperature of -2.5°C gave the best control, when the container was exposed to an outside temperature of 15°C.

The temperature profiles of meat at all locations for trial 2 are shown in Fig. 10. The temperatures of meat cuts were dynamically changing throughout the experiment. The N_2 tank was changed after 45.6 h of the trial. The small temperature rise between 35 and 45.6 h was due to low pressure of the tank as the liquid capacity of the tank was reduced. Once the tank was replaced, the temperature started to drop again. Although the concept was to prevent heat from reaching the pre-chilled meat, the dynamic heat transfer between meat and jacket and between the meats at different locations occurred continuously during the testing period and most of temperatures of the meat at various locations (except 1(2)) were maintained within the desired range.

4.2.3 Outside temperature 30°C Figure 11 shows the temperature profiles of meat at different locations for trial 1, when the container was exposed to an outside temperature of 30°C. All the temperatures were within the desired range during the 2 d trial. Maximum, average, and minimum temperatures plus N_2 consumption for 3 trials are shown in Figs. C.13 to C.18. Trial 3 resulted in comparatively higher maximum, average, and minimum temperatures than the other 2 trials. The control sensor temperature (-3°C) was the same for all 3 trials. This aberration could be due to biological variability and variation in N_2 tank pressure. The biological variability of the meat could have caused changes in heat transfer characteristics. Although, the temperature of any type of pre-chilled product stored in the container should reach the same final temperature after few

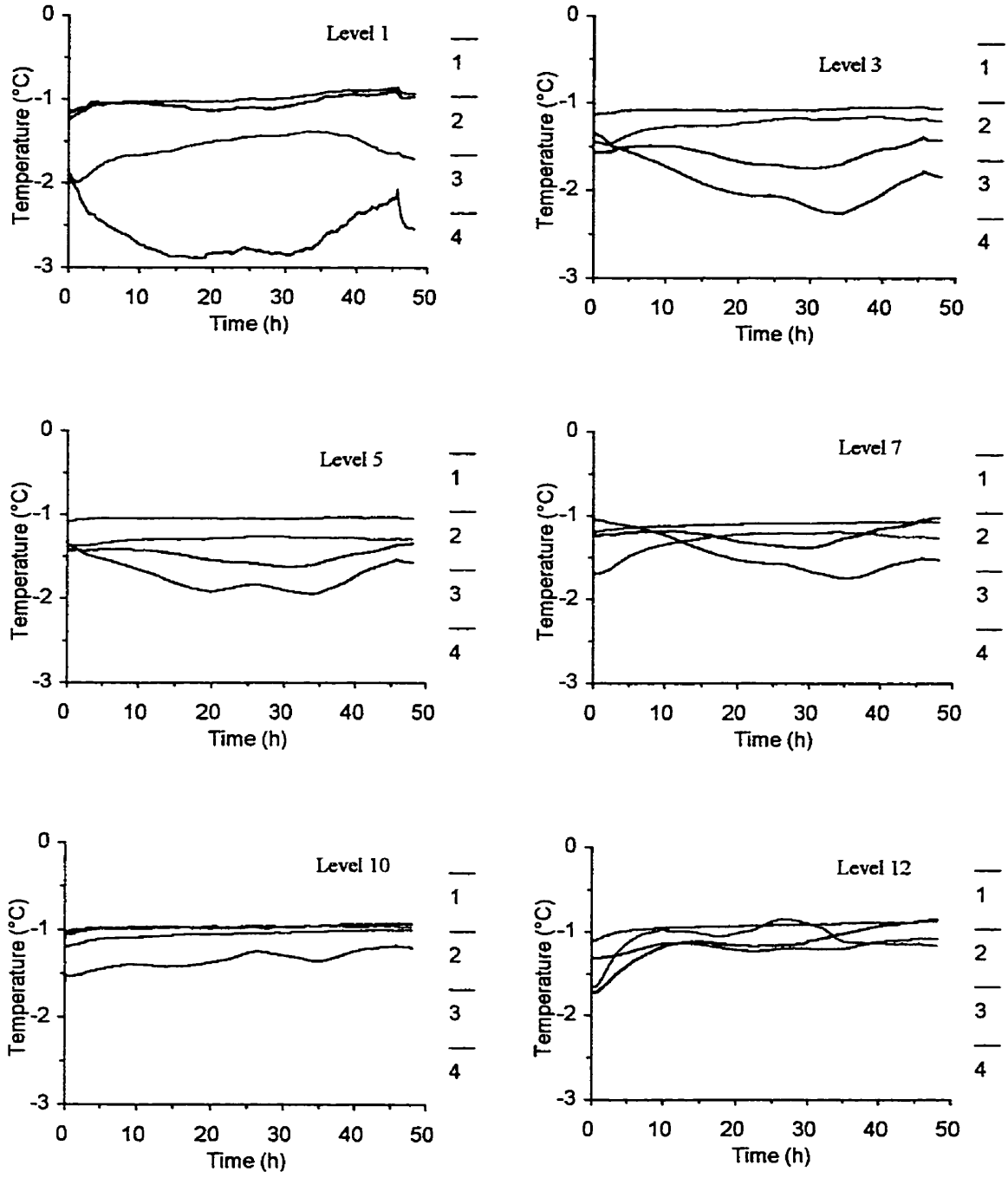

Fig. 10 Temperature profiles of meats, when the container was exposed to an outside temperature of 15°C, trial 2. Numbers in legend refer to sensor locations at a particular level (Refer to Fig. 7).

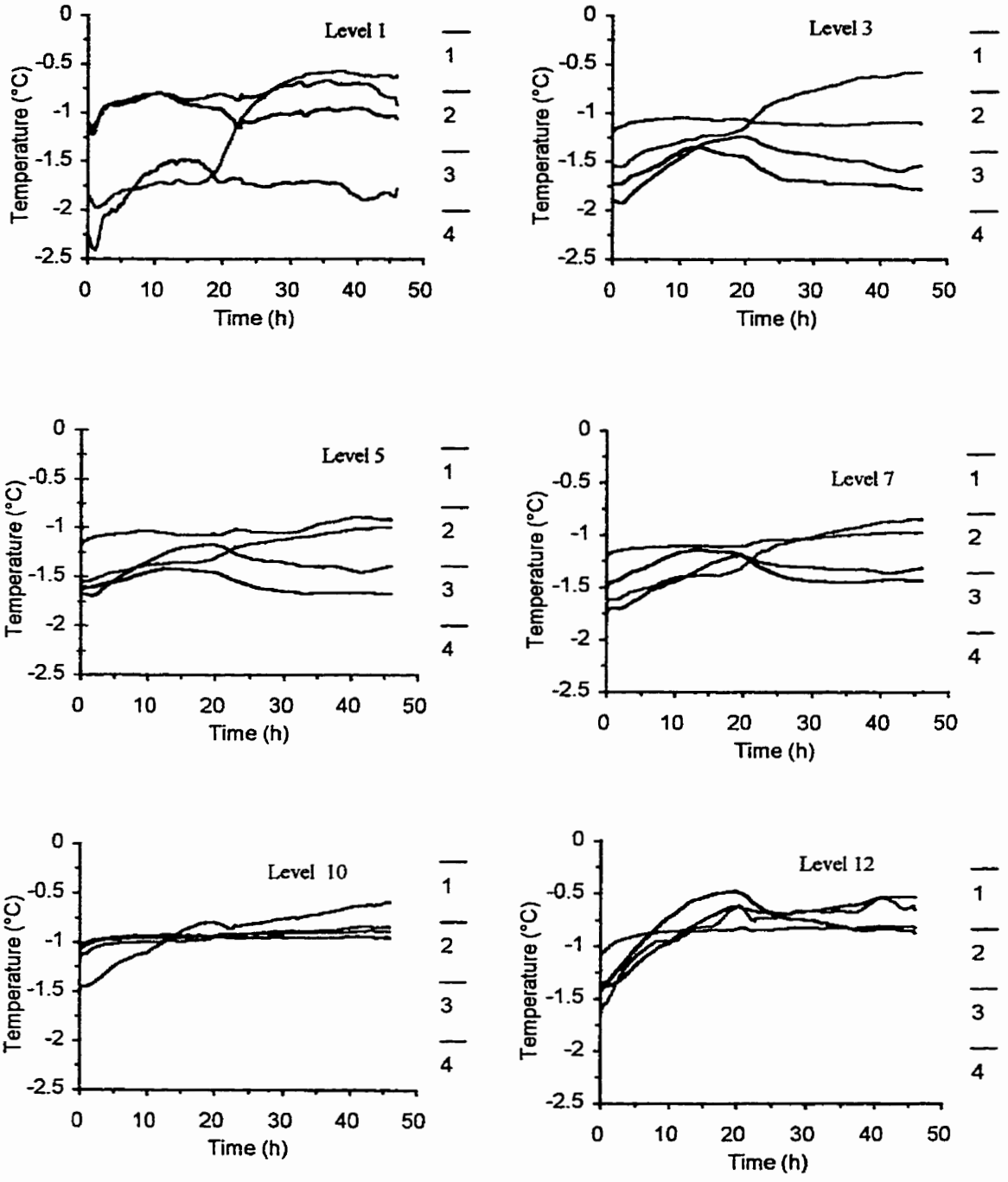

Fig. 11 Temperature profiles of meats, when the container was exposed to an outside temperature of 30°C, trial 1. Numbers in legend refer to sensor locations at a particular level (Refer to Fig. 7).

days of storage period, the type of product affects the rate of change in temperature of product due to variation in heat transfer characteristics. Because the change in temperature takes place slowly, the 2 d length of testing does not eliminate biological variability. The variation in N_2 tank pressure will have an influence on the temperature distribution along the height of the container. When the liquid N_2 is injected from the nozzles towards the bottom of the container, the liquid N_2 evaporates absorbing the heat from the surroundings. The pressure of the liquid N_2 tank affects the rate at which the liquid N_2 is shot downwards. If the pressure is lower, most of the evaporation takes places near the top of the jacket and less heat is absorbed near the bottom of the jacket resulting in warmer temperatures at the bottom of the container. This effect of N_2 tank pressure was obviously noticed in trial 2, when the outside temperature was 15°C, but was not noticed in any other trial. Liquid N_2 tanks were fitted with a 251 kPa pressure control valve and the vapourization of liquid inside the tank gave the impetus for release of the liquid at a constant pressure of 251 kPa. Occasionally a few tanks do not deliver at a constant pressure if they are not filled using proper procedures (Personal communication, Mr. Jim Madden, Territory Manager, Praxair Products Inc., Winnipeg, MB). Figure C.17 shows that the maximum temperature of meat during trial 3 had a slightly positive slope. The warmest location was at the bottom of the container (Table II). The jacket temperatures at the bottom of the container varied between -1.5 and 0.5°C. Therefore the temperatures at the bottom of the container must stabilize around 0°C after few hours.

4.2.4 Outside temperature -15°C The temperature profiles of meat at different levels are shown in Fig. 12. Temperatures at the sensor locations 12(1),1(3), and 1(4) were below the desired range. As mentioned earlier, the door seal was not tight at the top and bottom. As the cold gas settles and warm gas rises due to density differences, the twelfth level was colder than the first level. All other temperatures of meat at other locations were maintained within the range. The control sensor temperature was maintained at a temperature higher than -1.5°C. The first 3 trials were conducted with a control sensor temperature set at 2.5°C. More heater length was placed at the bottom section and near the door to heat the settling cold gas and leaking cold air, respectively. The heater was not installed at the top half of the container jacket except near the door. A higher temperature at the center of the container (control sensor temperature) gave lower temperatures at the bottom and top of the container. Therefore, meat at the back side of the seventh level, where the control sensor was located behind the acrylic box in the jacket, was warmer (-0.2°C). Trial 2 and 3 gave similar results. Trial 4 was conducted to determine the effect of increasing the control sensor temperatures to 3°C (Table I). This resulted in an increase of temperature at the twelfth level to -2.04°C, but also increased the temperature of back sides of the 5^{th}, 7^{th}, and 10^{th} levels just above the range (-0.23°C). As freezing is more detrimental, a control sensor temperature of 3°C is more suitable for this heater configuration. Increasing the length of heater at the bottom of the jacket would be expected to improve the uniformity of temperature.

It should be noted that the container would not normally be exposed to -15°C for

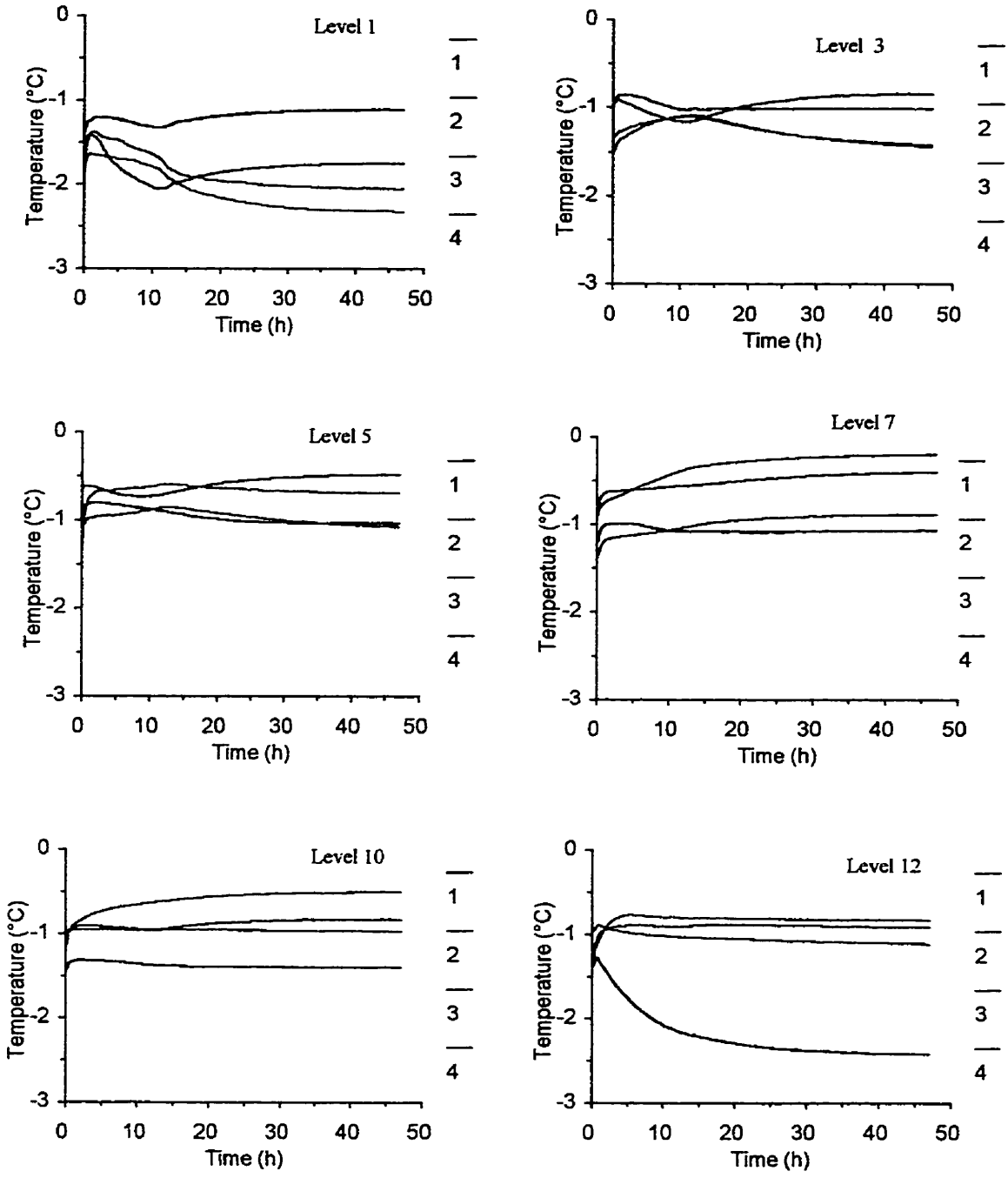

Fig. 12 Temperature profiles of meats, when the container was exposed to an outside temperature of -15°C, trial 1. Numbers in legend refer to sensor locations at a particular level (Refer to Fig. 7).

periods approaching 2 d. One potential situation might be that the transport truck could leave the containers outside the retail store during early morning hours and the containers would be moved into the store on opening. Therefore, the container will be probably exposed to low temperatures during the winter for 4 - 6 h. For these short periods, this heater configuration is sufficient to prevent freezing of meat provided that a driver can connect the system to an electrical outlet or the container is designed to have a battery.

4.2.5 Control sensor temperature Based upon trial results, the control sensor temperature should be set at -1.6, -2.5, and -3.0°C when the outside temperature was 0, 15, and 30°C, respectively. A quadratic equation for control sensor temperature set point as a function of outside temperature was fitted and was used in the program, when the outside temperature was above 0°C (See. Appendix B). The control sensor temperature should be set at 3°C and -1.6°C when the outside temperature was -15 and 0°C, respectively. Therefore a linear equation for control sensor temperature was fitted and was used, when the ambient temperature was below 0°C. The control sensor set point versus outside temperature is shown in the Fig. 13.

4.3 Nitrogen Failure Tests

If the N_2 tank is empty or if there is a power failure, N_2 will not be injected. Failure tests were conducted only at 30°C. The liquid N_2 release valve in the tank was closed at the start of the experiment and the valve was opened after 4 h from the start of the experiment to simulate power failure and resumption of power or to simulate the delivery of containers to retail store in early morning and re-connection to tanks sometime later at store opening. The duration of each trial was 8 h. The maximum, average, and minimum

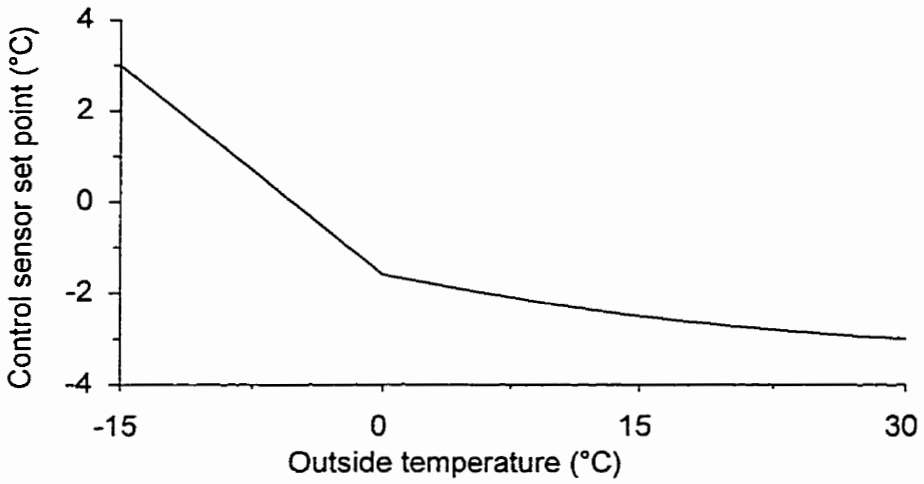

Fig. 13. Control sensor set point calculated by the temperature control algorithm based on outside temperature.

temperatures of meat and N_2 consumption for the three trials at an outside temperature of 30°C are shown in Figs. C.23 to C.28. During the first trial, the average temperature rose from -1.39°C to -0.28°C in the first 4 h, and was then brought down to -0.93°C in the next 4 h. Even though the container was not designed to chill the products, the temperature of the meat was slowly brought down into the desired range. Providing some nozzles inside the acrylic box as explained earlier would bring down the temperature to the desired range quickly.

In the 2nd trial, the temperature of the meat cut at the location 1(2) dropped to -2.33°C and then suddenly increased to -1.77°C in 5 min and then stayed relatively constant for the remaining period (Fig. C.25). Therefore, the meat cut at location 1(2) must be frozen (See section 4.1). Note that the frequency of recording of each measurement was 5 min.

4.4 Door Opening Tests

Door opening tests were conducted both at 15 and 30°C, because the usual temperature of the room where the container will be placed in the retail store would be expected to be in the range of 15 and 30°C. The door was opened for 15, 25, and 35 s and the maximum, average, and minimum temperatures of the meat were calculated for each trial and are given in Figs. C.29 to C.34. The temperatures of meat were recorded every 30 s. The temperature at the surface of the meat rose drastically immediately after opening the doors. This was due to method of measurement of temperature. As the thermistors were attached to the surface of meats, they sensed the temperature of air surrounding the meat. Once the door was closed, the temperatures dropped quickly. Temperatures were brought to the desired range within 5 min in all tests, but the average temperature of all meat cuts showed a residual temperature rise of 0.1 to 0.2°C after 15 min of closing the door. This temperature would be restored to the original temperature after few hours, as the container was not designed to chill products.

If the door is opened frequently, the temperature may rise beyond the range and it might take a long time to bring the temperatures under control. If the container is opened for removal of meat frequently, it probably means that the meat will be sold in a short period of time and any loss of storage life due to small temperature increases will not be a problem in practice. A more effective solution would be to place one or two nozzles inside the acrylic box which can be used to inject liquid N_2 directly inside the box when the temperatures of meat are outside the range. Once the temperatures had been brought under control, liquid N_2 could be injected in the jacket to maintain the temperature.

4.5 Liquid Nitrogen Distribution

Liquid N_2 is required at all times to refrigerate the container. Even if the liquid N_2 is not used, it will be lost by evaporation. Heat-leak into the liquid N_2 tank boils off about 2% of tank capacity per day. Cost of distribution of liquid N_2 is the major operating cost. For instance, when transferring liquid N_2 from a bulk tank to a small distribution tank, about 20 - 40% of the liquid N_2 can be lost by flash-off. Cost of liquid N_2 can be reduced by buying in a bulk tank, but handling a bulk tank will be a problem. Also it is not reasonable to expect retailers or packers to have a weigh scale for each tank to check when the N_2 tank is empty. Even though the liquid level gauge and the pressure gauge in the liquid N_2 tank can give an idea of amount of liquid N_2 remaining in the tank, this accuracy is only 30 - 40%. Also, if the liquid N_2 is exhausted from the tank in the middle of the night, the temperature will not be maintained properly. Even during the day, if the retailer did not have enough N_2 tanks in stock or if some of the N_2 tanks were empty, then the temperature control will be greatly affected. This is a serious limitation of liquid N_2 refrigeration, which can be circumvented.

In restaurants, liquid CO_2 tanks are currently used for carbonation of beverages. From the liquid CO_2 tank, a vapourizer converts the liquid into gas and the gas is used for carbonation. A typical restaurant uses a small amount of liquid CO_2 (about 5-10 L/d), and the cryogenic industry is equipped to supply liquid CO_2 directly to customers. A 165 L tank is installed in a restaurant and its liquid filling port is extended through the wall to facilitate filling of the tank from outside. The liquid CO_2 supplier fills the tank at regular intervals from outside of the restaurant, without disturbing the customers. So the

restaurants need not worry about changing liquid CO_2 tanks.

Nitrogen tanks can also be designed to be filled from outside a building similar to liquid CO_2 tanks that are currently used in the restaurants. If N_2 refrigeration is accepted by the meat industry, retail stores and meat packing plants would be using a large quantities of liquid N_2. Liquid N_2 storage tanks are available in 116, 165, 196, 230, 290, 620, 1400, and 1612 L capacity (Minnesota Valley Engineering, Inc., New Prague, MN). Based on consumption, a retail store or a meat packer can have a bulk tank, set to be filled from outside. Based on room temperature and number of containers refrigerated, it is possible to determine approximately the numbers of hours each bulk tank would last. Based on this calculated interval, a liquid N_2 supplier can regularly fill the bulk tank from outside. Accurate liquid level detectors using microwave technology are available in the market, but their cost prevents their common use. From the bulk tank, a vacuum insulated liquid N_2 circulation line can be built on the roof of the room where the containers will be stored. At appropriate intervals on the vacuum insulated line, valves can be fixed so that the containers can be attached to the liquid N_2 line by a quick-fit connection. The initial installation cost will be expensive, but this system will reduce the liquid N_2 boil-off and reduce the operating cost considerably.

A 165 L tank lasts for approximately one and half days to refrigerate full load of meat in a container, when it was exposed to a room temperature of 20°C. Therefore for meat distribution to local markets, any non-refrigerated truck can be used for transportation. If master packaging technology is accepted by the meat industry, a large number of N_2-refrigerated containers will be used. For efficient surface transportation to

distant markets, custom-made transportation trucks can be built. A large liquid N_2 tank can be placed at the nose of the trailer and a vacuum insulated line on its roof can be built to deliver liquid N_2 to many containers. The bulk tank can be elliptical in cross-section, so that the space occupied by the tank is greatly reduced. The tank can also be designed to be filled from outside. Almost all the major cities in North America have a liquid N_2 supplier outlet, and the liquid N_2 tank in the truck can be filled in transit, during a long haul. The tank size can be designed such that the full tank can refrigerate all the containers in the truck for 2-3 days. When this technology is commercially successful, there will be lots of custom made trucks to carry liquid N_2-refrigerated containers and many refueling sites can have a bulk liquid N_2 tank. The truck can be filled with liquid N_2 conveniently en route, in much the same manner as propane and gasoline are filled in the tanks of automobiles and other vehicles. The truck has to be fitted with safety valves to vent the excess pressure of N_2 gas to the atmosphere continuously.

When the requirement for liquid CO_2 by restaurants was identified by cryogenic liquid suppliers, it took about 10 years to develop a system which met the need of restaurants. Similarly, it might take a few years for the cryogenic liquid suppliers to respond to the needs of the meat industry. Once an initial N_2-refrigeration system has been established, it would be competitive to mechanical refrigeration systems. This will also avoid environmental problems associated with the mechanical refrigeration system.

5. CONCLUSIONS

The following conclusions were drawn from this study:

1. Liquid N_2-refrigerated jacketed container was successful in maintaining the temperature of the meat within the desired narrow range (-1.0±0.5 °C).
2. The design was economical in terms of N_2 consumption compared to the previous design of Bailey (1997). The N_2 consumption rates were 0.9, 2.4, and 4.3 kg/h, when the container was exposed to outside temperatures of 0, 15, and 30 °C, respectively. The current design reduced the N_2 consumption by 65, 40, and 22%, respectively, over the previous design (Bailey 1997).
3. In most of the trials, both the minimum and maximum of measured temperatures of meat at 24 locations were found at the first level of the container. At other levels, most of the temperatures of meat were within the desired range.
4. The container was equipped with a heater to permit operation during severe winters. When the outside temperature was -15 °C, the container operated slightly above the range. The maximum temperature of all 4 trials was -0.20 °C.

6. RECOMMENDATIONS FOR FUTURE WORK

1. The insulation (R-value) of the C-54 container can be increased further to reduce N_2 consumption. Even though the initial cost of the container will be high, the lower operating cost should reduce the pay-back period. Designing a door with a tight seal will improve temperature uniformity within the container.

2. The present design is to maintain the temperature of meat but is not capable of chilling meat to desired range quickly. Two nozzles can be placed inside the acrylic box and can be operated for initial chilling, when the meat temperatures are outside the desired range (-1.0±0.5 °C). Once the temperatures of meat are brought within the range, the nozzles in the jacket can be operated to maintain the temperature. This design direction could be explored.

3. A more efficient way of distributing liquid N_2 to the meat packers and retail stores has to be explored. Unless the distribution cost is substantially reduced, the cost of liquid N_2 would be prohibitive for use in the meat industry.

4. An "in-field" study to evaluate the economic feasibility and suitability of the container in the commercial meat distribution chain has to be conducted. The study should involve a meat packer, a transport truck company, a liquid N_2 supplier, and a retail store. Master packaged meat should be tested in the container for longer durations (3-6 weeks). Consumer acceptance of the master packaged fresh meat should also be studied.

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APPENDIX A

PICTURES OF THE EXPERIMENTAL SET-UP

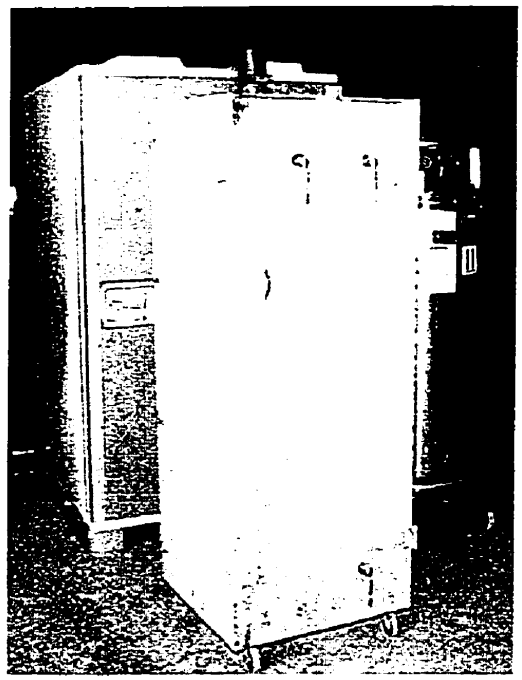

Fig. A.1. Full view of the model jacketed container with door closed. The full size container and N_2 tank are shown behind the model jacketed container.

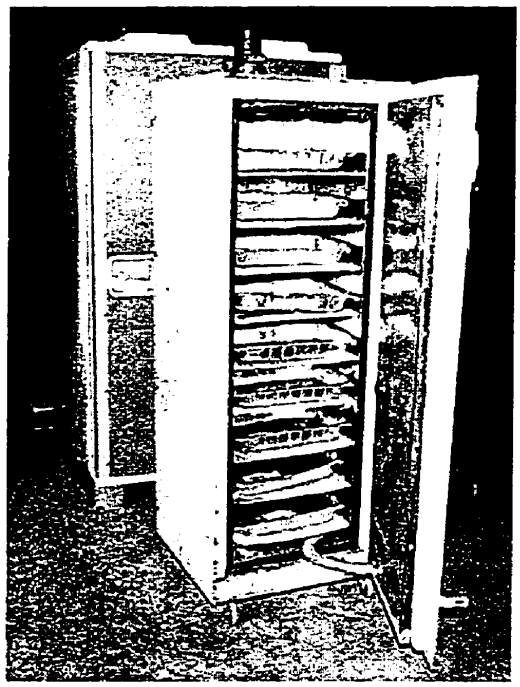

Fig. A.2. Full view of the model jacketed container with door opened. The full size container is shown behind the model jacketed container.

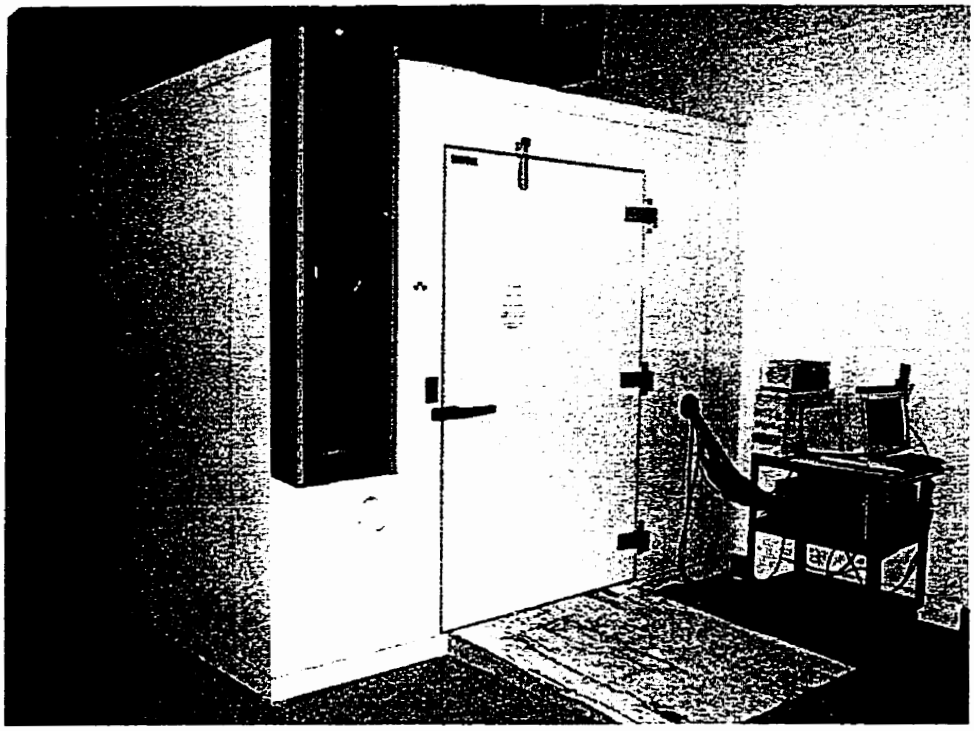

Fig. A.3. Environmental chamber with data acquisition system setup.

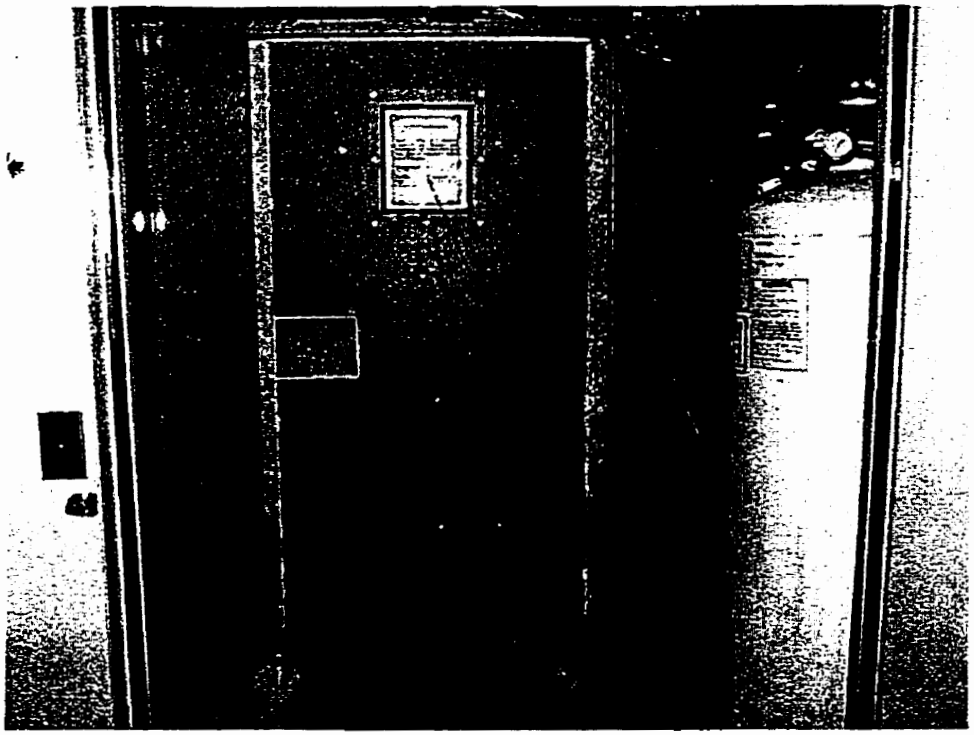

Fig. A.4. Full-size container connected to a liquid N_2 tank by a vacuum insulated transfer hose.

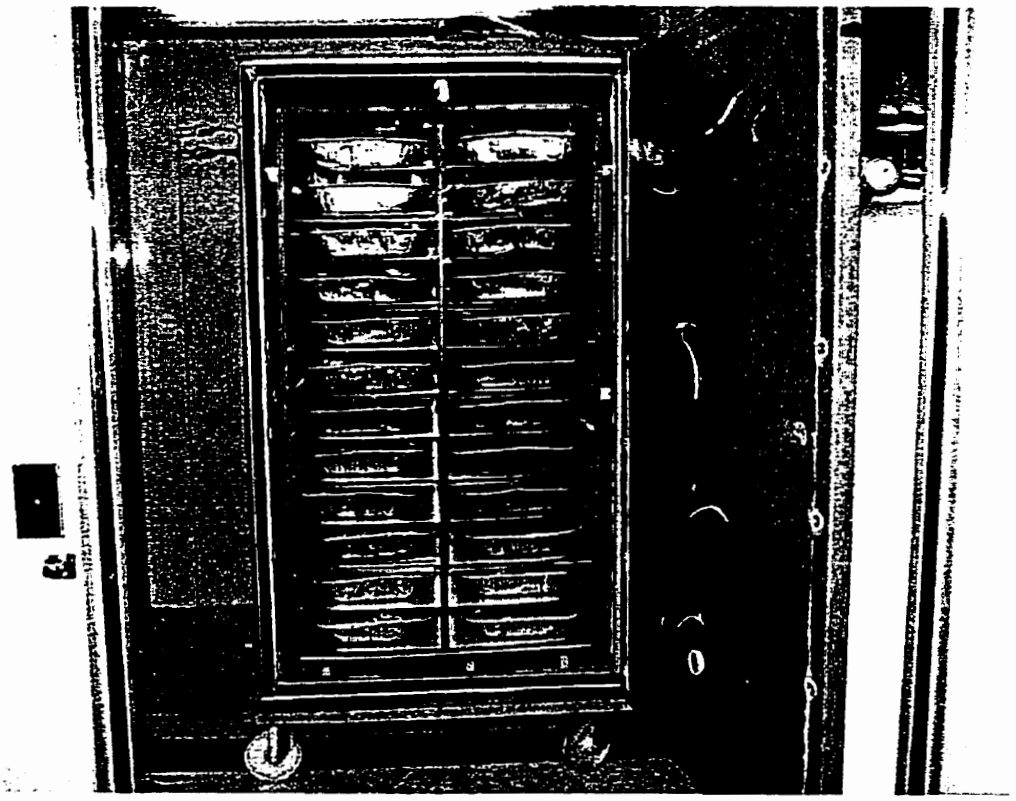

Fig. A.5. Full-size container with the door opened.

Fig. A.6. Retail packs of meat placed in the container.

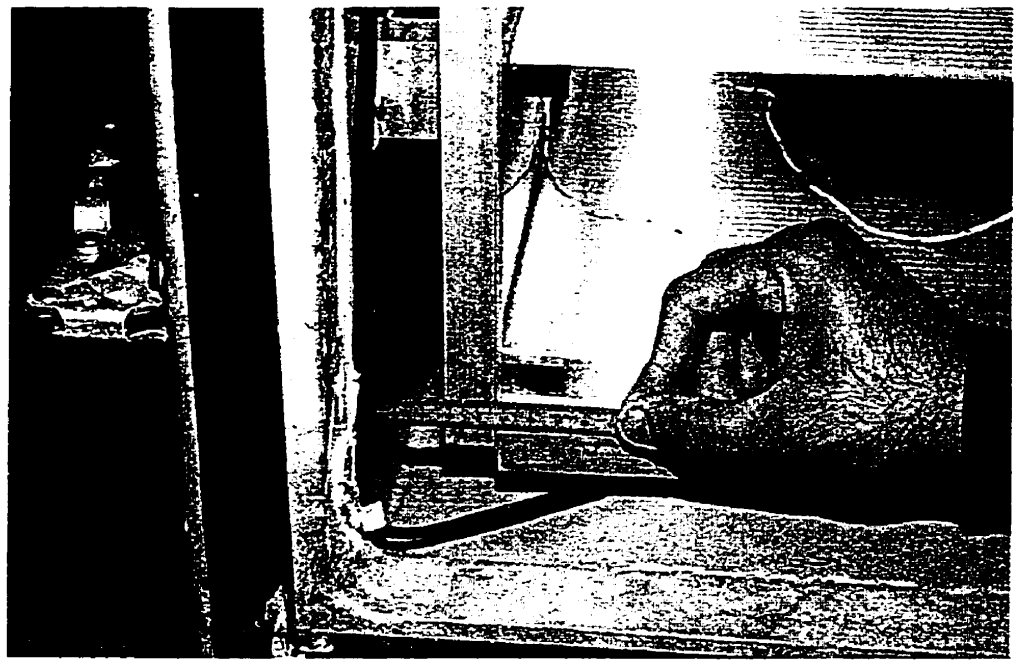

Fig. A.7. A jacket space (approximately 30 mm) on all six sides.

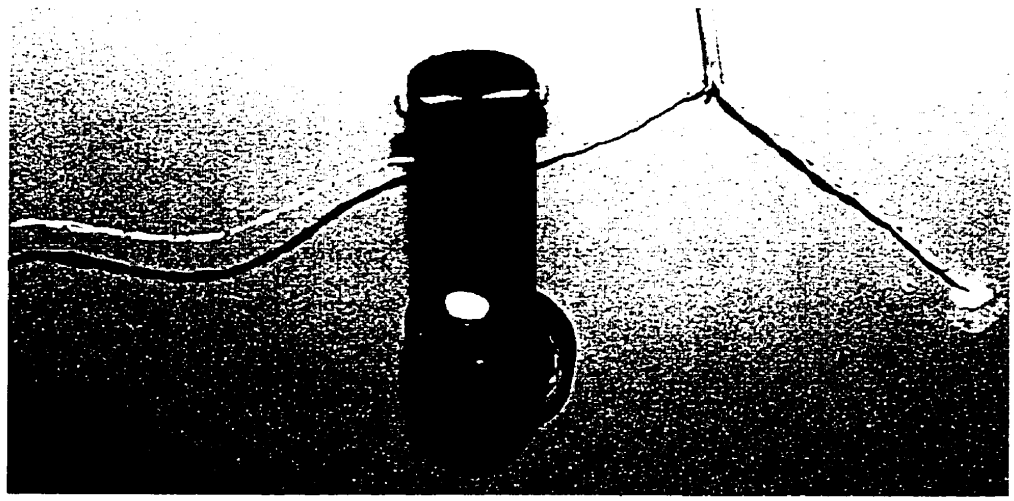

Fig. A.8. Back-pressure release valve (ball valve) for N_2 gas escape on the bottom of the door of the C-54 container.

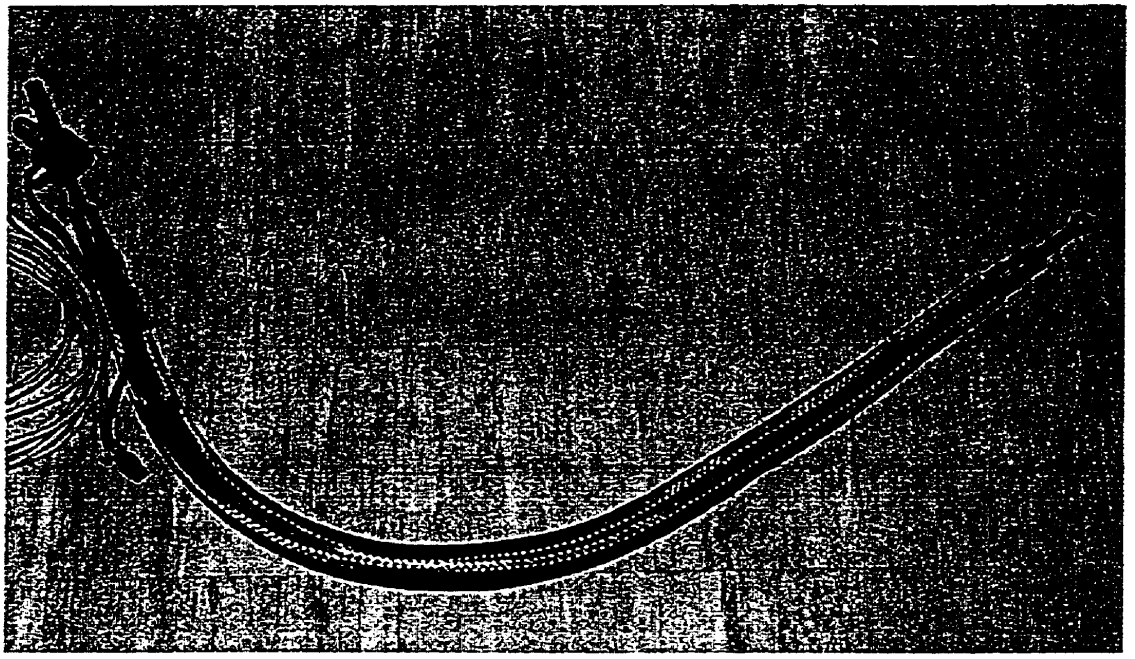

Fig. A.9. Vacuum insulated, flexible steel transfer hose for transferring liquid N_2 from the liquid N_2 tank to the container. The solenoid valve is connected at the end of the transfer hose.

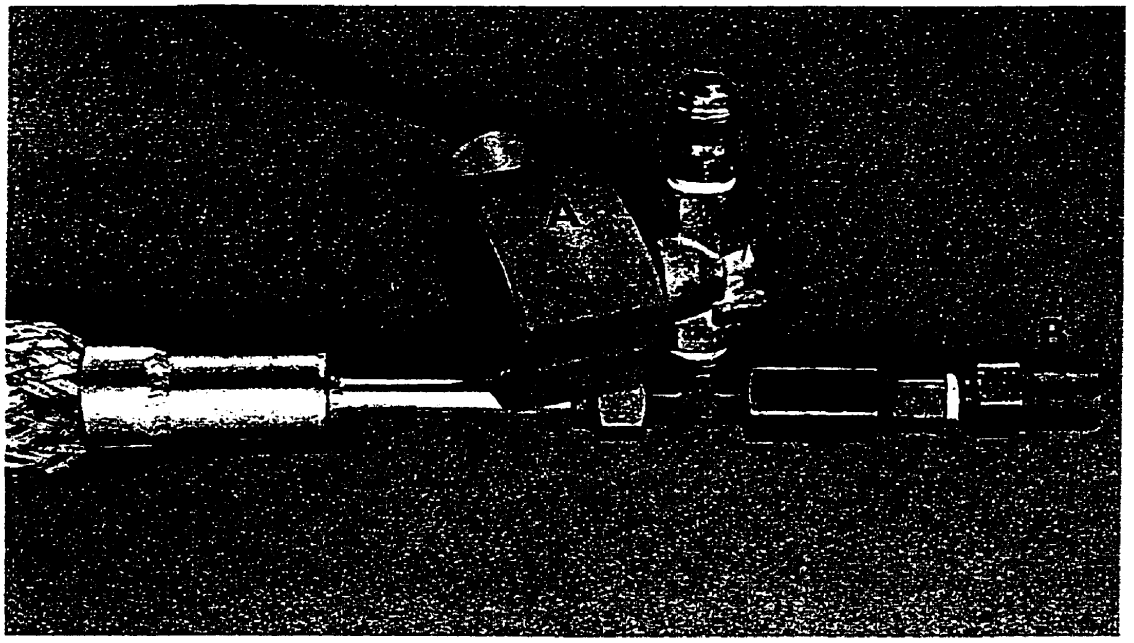

Fig. A.10. Solenoid valve (A) and pressure release valve (B) connected to one end of the transfer hose.

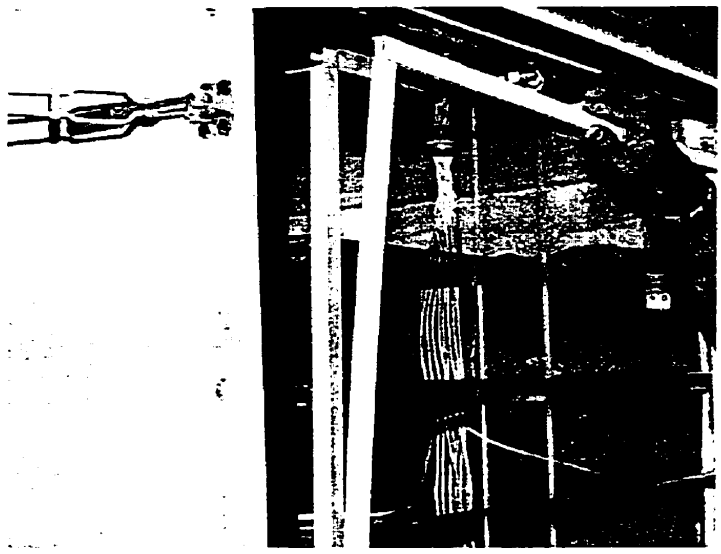

Fig. A.11. Removing the acrylic door which is fitted to the acrylic box by magnetic seal.

Fig. A.12. Modified C-54 container and acrylic box.

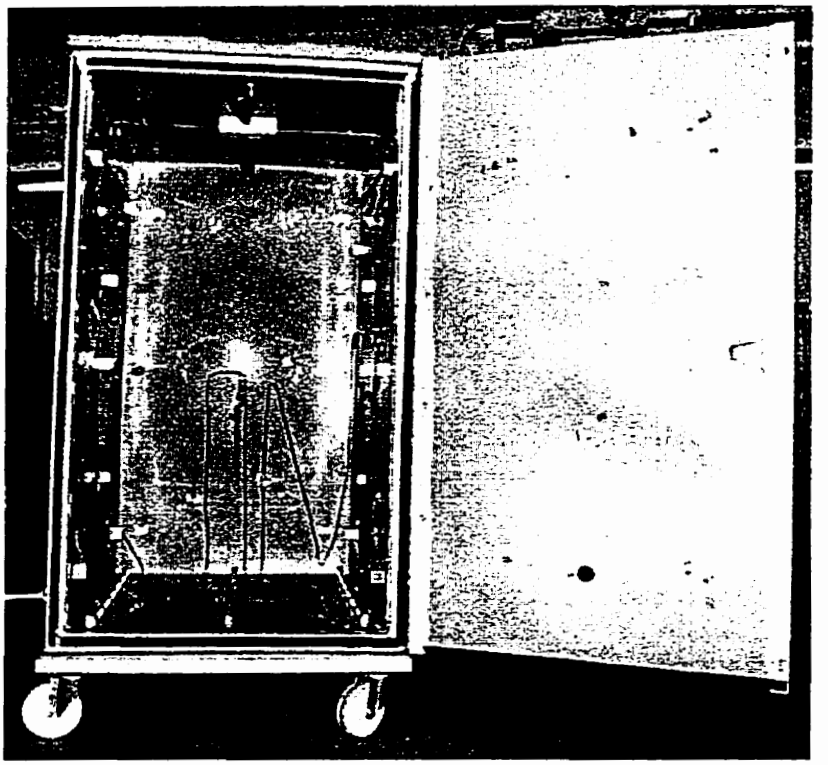

Fig. A.13. The C-54 container with acrylic box removed.

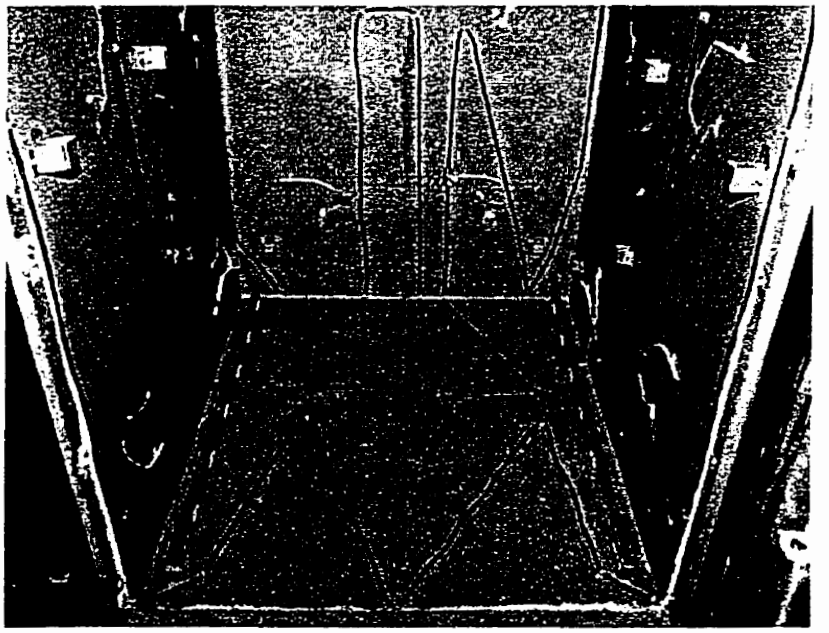

Fig. A.14. Configuration of heater wire on the inner wall of the C-54 container.

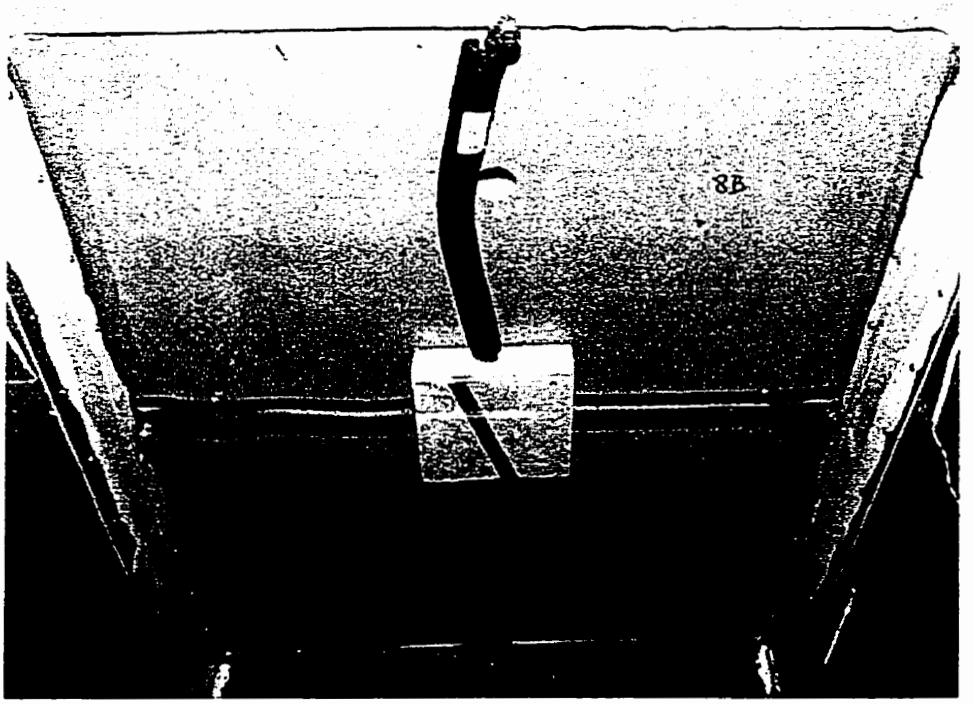

Fig. A.15. Liquid N_2 distribution lines (with insulation) and nozzles on the jacket (top inner surface of C-54 container).

Fig. A.16. Liquid N_2 distribution lines (without insulation) and nozzles on the jacket (top inner surface of C-54 container).

APPENDIX B

TEMPERATURE CONTROL PROGRAM

```
DECLARE SUB ParallelPortOut ()
DECLARE SUB ControlTemp ()
DECLARE SUB Temperatures ()
DECLARE SUB PrintTime ()
DECLARE SUB FileDating ()
DECLARE SUB TakeReadings ()
DECLARE SUB PrintGraph ()
DECLARE SUB SoleControl ()
DECLARE SUB Initialize ()
DECLARE SUB Reinitialize ()

'**********************Variable Description*******************************
' IniData%      Reads value of the data bus (address &H378) at beginning of program and
'               restores it at the end of the program.
' IniStatus%    Reads value of the status bus (address &H379) at beginning of program
'               and restores it at the end of the program.
' IniControl%   Reads value of the control bus (address &H37A) at beginning
'               of program and restores it at the end of the program.
' FileName1$    Retains the name used for the data file containing
'               temperature and mass data.
' FileName2$    Retains the name used for the data file containing the
'               solenoid control information.
' Channel%      Stores the number of the active channel.
' Solenoid%     If = 1 then solenoid is energized.  If 0 then solenoid is closed.
' Heat%         If = 1 then heater is switched on. If 0, then heater is switched off.
' Quit$         If Quit$ = "quit" then program will shut down.
' TempOff       Stores temperature at which solenoid is turned off.
' Max()         An array with the 10 previous maximum temperatures.
' Avg()         An array with the 10 previous average temperatures.
' Min()         An array with the 10 previous minimum temperatures.
' T()           An array that stores the current temperatures (sensors 0 to 55)
' AveCoolerTemp     Stores the cyclic average of temperature sensor 0.
' Weight        Stores the mass of the LGS
' Tare          Stores the tare mass of the LGS - stamped in side of LGS.
' BeginTime     Stores the start time of test.
' PrevTime      Stores the last time that the PrintTime subroutine was called.
' Time          Stores the total number of seconds ellapsed since test begun.
' RollTime      Stores the number of times the timer has rolled past midnight.
' LoopTime      Counts the number of seconds into each 60 s loop.
' Ratio()       Stores the ratios of average cycle temperatures to TempOff.
' BeginWeight   Stores the mass of the LGS at beginning of test.
' CT            Control temperature set point
' AT            Ambient or outside temperature
```

```
DIM R(55), T(55), Max(10), Min(10), Avg(10), Ratio(6)

COMMON SHARED IniData%, IniStatus%, IniControl%, Dev&
COMMON SHARED FileName1$, FileName2$, FileName3$, BeginWeight
COMMON SHARED channel%, Solenoid%, Heat%, Quit$, TempOff, Optionn, Ratio()
COMMON SHARED Max(), Avg(), Min(), T(), R(), SumCoolerTemp, Weight, Tare, CT
COMMON SHARED BeginTime, PrevTime, time, RollTime, looptime, number

REM $INCLUDE: 'QBSETUP'
Dev& = 709

SCREEN 9
CALL Initialize: CALL FileDating
BeginTime = TIMER

Strt:

DO:
CALL PrintTime
IF looptime = 0 THEN CALL TakeReadings: CALL PrintGraph
IF time <= 286400 THEN
IF looptime = 10 THEN CALL SoleControl
END IF

CALL Reinitialize

END    '************************************************************

SUB ControlTemp

 A = .001285888188#: B = .000235989135#: C = .000000094108401#

' Two thermistors are connected in series to the channel 0 and are used as control sensors

 Cmnd$ = "CONFMEAS OHM,100,USE 000"      'read all thermistors
 CALL IOOUTPUTS(Dev&, Cmnd$, LEN(Cmnd$))
 CALL IOENTER(Dev&, R)
 R = R / 2                    'average of 2 series thermistors

' If the temperature is beyond the range of -20 and 66°C, a default value of -20 is shown

 IF R < 1000 OR R > 50000 THEN R = 48560
 LOGV = LOG(R) / LOG(2.71828)    'calculates log to base e
```

```
T(0) = CINT((1 / (A + B * LOGV + C * (LOGV ^ 3)) - 273.15) * 100) / 100

END SUB


SUB FileDating

COLOR 12, 0: CLS
LOCATE 3, 1: PRINT "Please correct the current date and time or"
LOCATE 4, 1: PRINT "press <ENTER> to accept the default values."
LOCATE 5, 1: PRINT "Note:  Data files are labelled according to"
LOCATE 6, 1: PRINT "the  starting  date and time  of the  test.": PRINT

'Change date and time through the DOS shell and create a filename from date.
SHELL "Date": PRINT : SHELL "Time"
name1$ = LEFT$(DATE$, 2) + MID$(DATE$, 4, 2)
name2$ = LEFT$(TIME$, 2) + MID$(TIME$, 4, 2)
name3$ = LEFT$(TIME$, 2) + MID$(TIME$, 4, 2)
FileName1$ = name1$ + name2$ + ".txt"
FileName2$ = FileName1$: MID$(FileName2$, 8) = "s"
FileName3$ = FileName1$: MID$(FileName3$, 8) = "h"
LOCATE 14, 1: PRINT "Based on the time and date given, the name"
LOCATE 15, 1: PRINT "of the temperature and solenoid data file are:"
COLOR 7, 0: LOCATE 17, 1: PRINT "C:\JEYAM\"; FileName1$
LOCATE 18, 1: PRINT "C:\JEYAM\"; FileName2$
LOCATE 19, 1: PRINT "C:\JEYAM\"; FileName3$
OPEN "C:\JEYAM\" + FileName1$ FOR OUTPUT AS #1: CLOSE #1
OPEN "C:\JEYAM\" + FileName2$ FOR OUTPUT AS #2: CLOSE #2
OPEN "C:\JEYAM\" + FileName3$ FOR OUTPUT AS #3: CLOSE #3

END SUB

SUB Initialize

'Store initial values of data, control and status registers.
IniData% = INP(&H378): IniStatus% = INP(&H379): IniControl% = INP(&H37A)

OPEN "COM1:9600,E,7,2,RS,DS" FOR RANDOM AS #4          'COM 2 for scale

OUT &H378, &H3                    'set data port so bits 1&2 are high

'Initialize variables
FOR I = 1 TO 6: Ratio(I) = 1: NEXT I: TempOff = -2!
```

```
FOR I = 1 TO 10: Max(I) = -10: Min(I) = 99: Avg(I) = 99: NEXT I

'Display a description of the program.
LOCATE 2, 1: COLOR 12, 0
PRINT "                JEYAM's Program"
COLOR 7, 0: PRINT
PRINT "                              Written by Chris Bailey."
PRINT "                              Modified by Jeyam with the help of Matt "

DO: LOOP UNTIL INKEY$ <> ""

'Read the initial mass of the container and ask for tare mass.
CLS
LOCATE 12, 10: INPUT "Please enter the tare weight of the LGS (kg)"; Tare
PRINT #4, "P": INPUT #4, Weight$
BeginWeight = VAL(MID$(Weight$, 4, 5))

END SUB

SUB ParallelPortOut

IF Solenoid% = 0 THEN
  IF Heat% = 0 THEN
    OUT &H378, &HFF     'Put clear signal on databus.
    OUT &H37A, &HB      'Enable latch 1.
    OUT &H37A, &H1      'Disable latches.
  ELSE
    OUT &H378, &HFD     'the heat control relay and channel and put on databus.
    OUT &H37A, &HB      'Enable latch 1.
    OUT &H37A, &H1      'Disable latches.
  END IF
ELSE
  OUT &H378, &HFE       'the solenoid control relay and channel and put on databus.
  OUT &H37A, &HB        'Enable latch 1.
  OUT &H37A, &H1        'Disable latches.
END IF

END SUB

SUB PrintGraph

'Define graphing window.
CLS 1: CLS 2: VIEW (55, 7)-(500, 298), , 9: COLOR 12, 0
```

```
 LOCATE 1, 65: PRINT "TIME"
 LOCATE 5, 65: PRINT "TEMPERATURES"
 LOCATE 6, 65: PRINT USING "Max:  ###.## °C"; Max(1)
 LOCATE 7, 65: PRINT USING "Avg:  ###.## °C"; Avg(1)
 LOCATE 8, 65: PRINT USING "Min:  ###.## °C"; Min(1)
 LOCATE 9, 65: PRINT USING "Rng:  ###.## °C"; Max(1) - Min(1)
 LOCATE 10, 65: PRINT USING "Out:  ###.## °C"; T(1) / 2 + T(2) / 2

 LOCATE 16, 65: PRINT "LGS STATUS"
 LOCATE 17, 65: PRINT USING "Rmd:  ####.# kg"; Weight - Tare
 LOCATE 18, 65: PRINT USING "Usd:  ####.# kg"; BeginWeight - Weight

 LOCATE 20, 65: PRINT "SOLENOID STATUS"
 IF Solenoid% = 0 THEN
  LOCATE 21, 65: PRINT "OFF           "
 ELSE
  LOCATE 21, 65: PRINT USING "ON:   ###.## °C"; TempOff
 END IF

 LOCATE 22, 65: PRINT " HEAT STATUS"
 IF Heat% = 0 THEN
   LOCATE 23, 65: PRINT "OFF"
 ELSE
   LOCATE 23, 65: PRINT USING "ON:   ###.## °C"; TempOff
 END IF

 'Finds limits of graph.
 MaxL = -10000: MinL = 10000
 FOR I = 1 TO 10
  IF Max(I) > MaxL THEN MaxL = Max(I)
  IF Min(I) < MinL THEN MinL = Min(I)
 NEXT I

 'Label temperature axis.
 n = 0
 FOR I = 22 TO 1 STEP -3
  value = (MaxL - MinL + 2) / 7 * n + MinL - 1
  n = n + 1
  LOCATE I, 1: COLOR 7, 0: PRINT USING "###.##"; value
 NEXT I

 'Assign coordinates to graph window and draw lines at -1 and -2°C.
 WINDOW (1, MinL - 1)-(11, MaxL + 1): COLOR 7, 0
```

```
LINE (1, -1)-(11, -1): LINE (1, -2)-(11, -2)
LINE (1, -1.5)-(11, -1.5), , , &H8080

'Plot MAX, AVG, and Min temperature in graph window.
n = 11
FOR I = 1 TO 10
 n = n - 1
 PSET (I, Max(n)), 14: PSET (I, Avg(n)), 14: PSET (I, Min(n)), 14
NEXT I

END SUB

SUB PrintTime

'Timer resets to zero every 86400 s (24 h) at midnight.
PrevTime = time
Tm:
time = INT(TIMER + RollTime * 86400 - BeginTime)
IF time = PrevTime THEN GOTO Tm
IF time < PrevTime THEN RollTime = RollTime + 1

looptime = time MOD 30
LOCATE 2, 65: COLOR 12, 0: PRINT USING "Elps: ######  s"; time
LOCATE 3, 65: PRINT USING "Loop: ######  s"; looptime

IF looptime MOD 5 = 0 THEN
 CALL ControlTemp
 SumCoolerTemp = SumCoolerTemp + T(0): number = number + 1
 LOCATE 12, 65: COLOR 12, 0: PRINT "CONTROL SENSORS"
 LOCATE 13, 65: PRINT USING "Now:  ###.## °C"; T(0)
 LOCATE 14, 65: PRINT USING "Avg:  ###.## °C"; SumCoolerTemp / number
END IF

END SUB

SUB Reinitialize

'Return registers to their initial value.
OUT &H378, IniData%: OUT &H379, IniStatus%: OUT &H37A, IniControl%

END SUB

SUB SoleControl
```

```
'Calculates the control sensor temperature set point based on ambient temperature.
AT =  (T(1)+T(2))/2
IF AT>0 THEN
        CT = -1.6-0.0733*AT+0.0008889*AT*AT
ELSE
        CT = -1.6-0.30667*AT
ENDIF

'Calculates the latest temperature ratio - that is the average air temperature
'during a 30 s cycle divided by the temperature of the control sensor at the moment
'the solenoid is de-energized.  Note:  Algorithm is based on Kelvin.
FOR I = 1 TO 5: Ratio(I) = Ratio(I + 1): NEXT I
AveCoolerTemp = SumCoolerTemp / number
Ratio(6) = (TempOff + 273.15) / (AveCoolerTemp + 273.15)

CALL ControlTemp

SumCoolerTemp = 0: number = 0

'Calculates the air temperature at which the solenoid should be turned off so as to
'maintain the constant cyclic mean temperature of control sensor.
FOR I = 1 TO 6: Sum = Sum + Ratio(I): NEXT I
TempOff = ((273.15 - CT) / 6) * Sum - 273.15

'Decides if solenoid needs to be turned on and acts accordingly.
IF AT>  0 THEN
  IF T(0) > TempOff THEN
        Solenoid% = 1: CALL ParallelPortOut
        LOCATE 21, 65: PRINT USING "ON:   ###.## °C"; TempOff
        OPEN "C:\JEYAM\" + FileName2$ FOR APPEND AS #2
        WRITE #2, time, Ratio(6), AveCoolerTemp, T(0), TempOff, Solenoid%: CLOSE
        #2

        DO
        CALL PrintTime: CALL ControlTemp
        LOCATE 13, 65: PRINT USING "Now:  ###.## °C"; T(0)
        LOOP UNTIL T(0) - TempOff < .01 OR looptime >= 29 OR Quit$ = "quit"

  END IF


  IF Solenoid% = 1 THEN
        Solenoid% = 0: CALL ParallelPortOut
```

```
        OPEN "C:\JEYAM\" + FileName2$ FOR APPEND AS #2
        WRITE #2, time, Ratio(6), AveCoolerTemp, T(0), TempOff, Solenoid%: CLOSE
        #2
         LOCATE 21, 65: PRINT "OFF          "
        TempOff = T(0)
        END IF
ELSE
 Heat% = 1: CALL ParallelPortOut
 LOCATE 23, 65: PRINT USING "ON:  ###.## °C"; T(0)
 OPEN "C:\JEYAM\" + FileName3$ FOR APPEND AS #3
 WRITE #3, time, Ratio(6), AveCoolerTemp, T(0), Heat%: CLOSE #3

 DO
       CALL PrintTime: CALL ControlTemp
       LOCATE 13, 65: PRINT USING "Now:  ###.## °C"; T(0)
 LOOP UNTIL T(0) - TempOff < .01 OR looptime >= 29 OR Quit$ = "quit"
END IF

IF Heat% = 1 THEN
 Heat% = 0: CALL ParallelPortOut
 OPEN "C:\JEYAM\" + FileName3$ FOR APPEND AS #3
 WRITE #3, time, Ratio(6), AveCoolerTemp, T(0), Heat%: CLOSE #3
 LOCATE 23, 65: PRINT "OFF          "
TempOff = T(0)
END IF

END SUB

SUB TakeReadings

'Stores ten previous max, min, and avg temperatures in arrays.
FOR I = 10 TO 2 STEP -1
Max(I) = Max(I - 1): Avg(I) = Avg(I - 1): Min(I) = Min(I - 1)
NEXT I

'Initializing some variables
FileTime = time

CALL Temperatures
'CALL PrintTime

Max(1) = -10000: Min(1) = 10000: Avg(1) = 0
```

```
 FOR channel% = 29 TO 52
   IF T(channel%) > Max(1) THEN Max(1) = T(channel%)
   IF T(channel%) < Min(1) THEN Min(1) = T(channel%)
   Avg(1) = Avg(1) + T(channel%) / 24
 NEXT channel%

 'Reads mass of nitrogen cylinder.
 PRINT #4, "P": INPUT #4, Weight$
 Weight = VAL(MID$(Weight$, 4, 5))

 IF time MOD 300 = 0 THEN
 'Write temperature and mass readings to a file every 5 min.
 OPEN "C:\JEYAM\" + FileName1$ FOR APPEND AS #1
 WRITE #1, FileTime, Weight, T(0), T(1), T(2), T(3), T(4), T(5), T(6), T(7), T(8), T(9),
 T(10), T(11), T(12), T(13), T(14), T(15), T(16), T(17), T(18), T(19), T(20), T(21), T(22),
 T(23), T(24), T(25), T(26), T(27), T(28), T(29), T(30), T(31), T(32), _
 T(33), T(34), T(35), T(36), T(37), T(38), T(39), T(40), T(41), T(42), T(43), T(44), T(45),
 T(46), T(47), T(48), T(49), T(50), T(51), T(52), T(53), T(54)
 CLOSE #1
 END IF

 END SUB

 SUB Temperatures

 D = .00128375101868#: E = .000236385479572#: F = 9.21168159471D-08

 MAXE% = 55
 ACTE% = 0
 Cmnd$ = "CONFMEAS OHM,100-208,300-405,USE 000"      'read all thermistors
 CALL IOOUTPUTS(Dev&, Cmnd$, LEN(Cmnd$))
 CALL IOENTERA(Dev&, SEG R(0), MAXE%, ACTE%)
 FOR channel% = 1 TO 2
   IF R(channel%) < 1000 OR R(channel%) > 50000 THEN R(channel%) = 48560
   LOGV = LOG(R(channel%)) / LOG(2.71828)    'calculates log to base e
   T(channel%) = CINT((1 / (D + E * LOGV + F * (LOGV ^ 3)) - 273.15) * 100) / 100
 NEXT channel%

A = .001285888188#: B = .000235989135#: C = .000000094108401#

 R(0) = R(0) / 2                    'average of 2 series thermistors
 IF R(0) < 1000 OR R(0) > 50000 THEN R(0) = 48560
 LOGV = LOG(R(0)) / LOG(2.71828)    'calculates log to base e
```

```
 T(0) = CINT((1 / (A + B * LOGV + C * (LOGV ^ 3)) - 273.15) * 100) / 100

FOR channel% = 3 TO 54
  IF R(channel%) < 1000 OR R(channel%) > 50000 THEN R(channel%) = 48560
  LOGV = LOG(R(channel%)) / LOG(2.71828)    'calculates log to base e
  T(channel%) = CINT((1 / (A + B * LOGV + C * (LOGV ^ 3)) - 273.15) * 100) / 100
NEXT channel%
END SUB
```

APPENDIX C

TEMPERATURE AND N_2 USE DATA

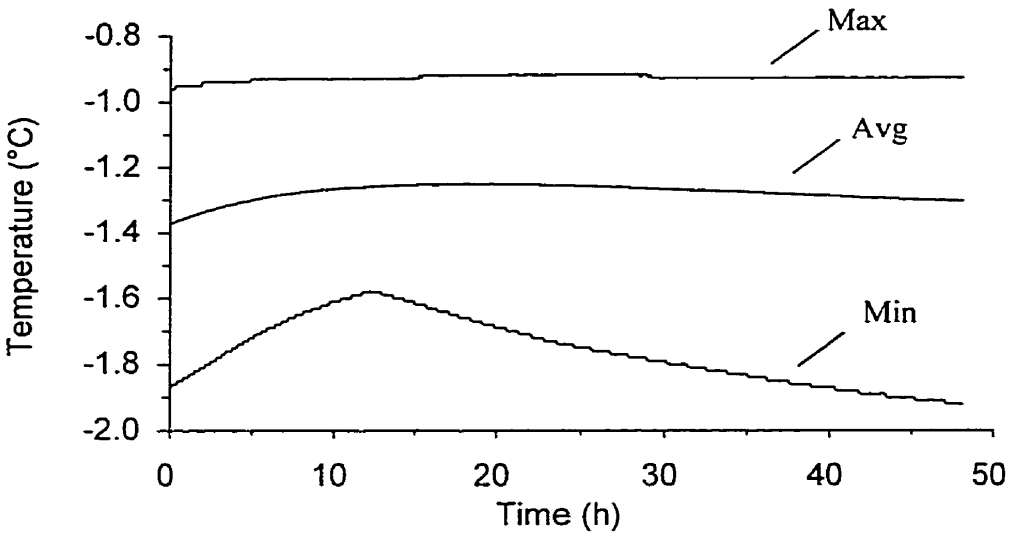

Fig. C.1. Maximum, average, and minimum temperatures (Trial 1) of meat (except 1st level) , when the container was exposed to an outside temperature of 0°C.

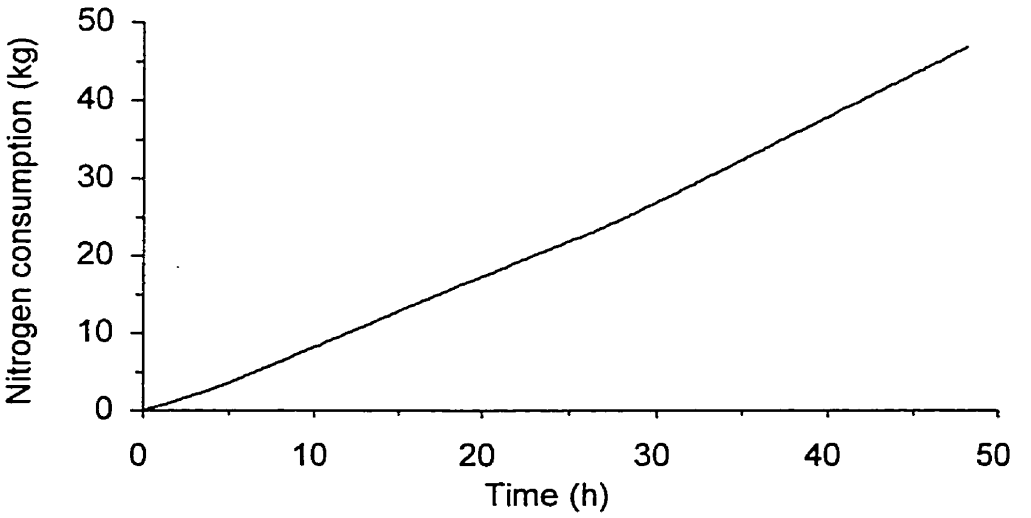

Fig. C.2. Nitrogen consumption during trial 1 (Fig. C.1).

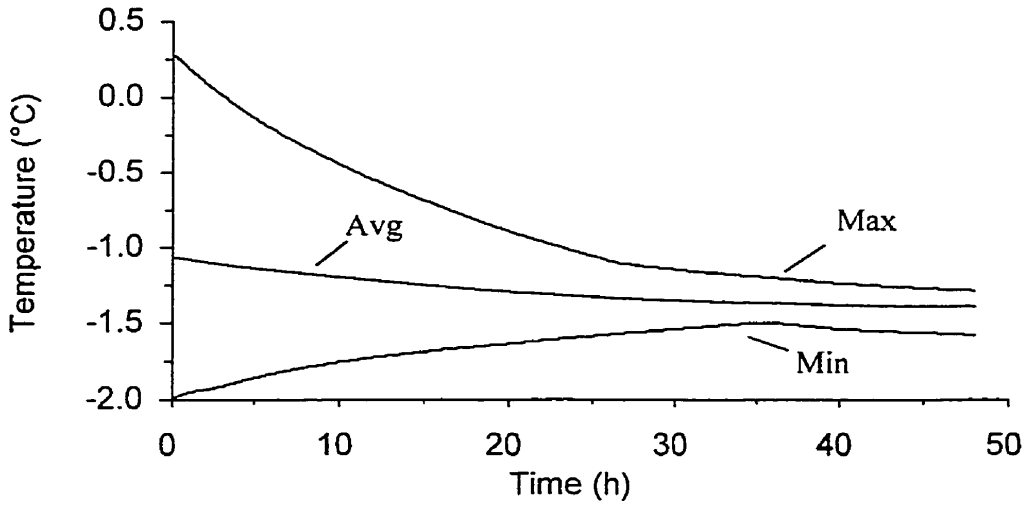

Fig. C.3. Maximum, average, and minimum temperatures (Trial 2) of meat (except 1st level) , when the container was exposed to an outside temperature of 0°C.

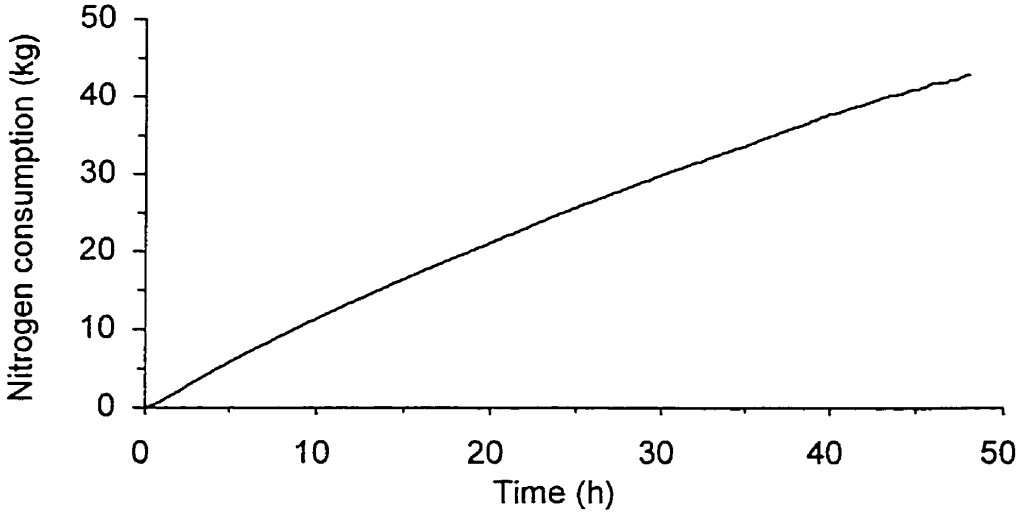

Fig. C.4. Nitrogen consumption during trial 2 (Fig. C.3).

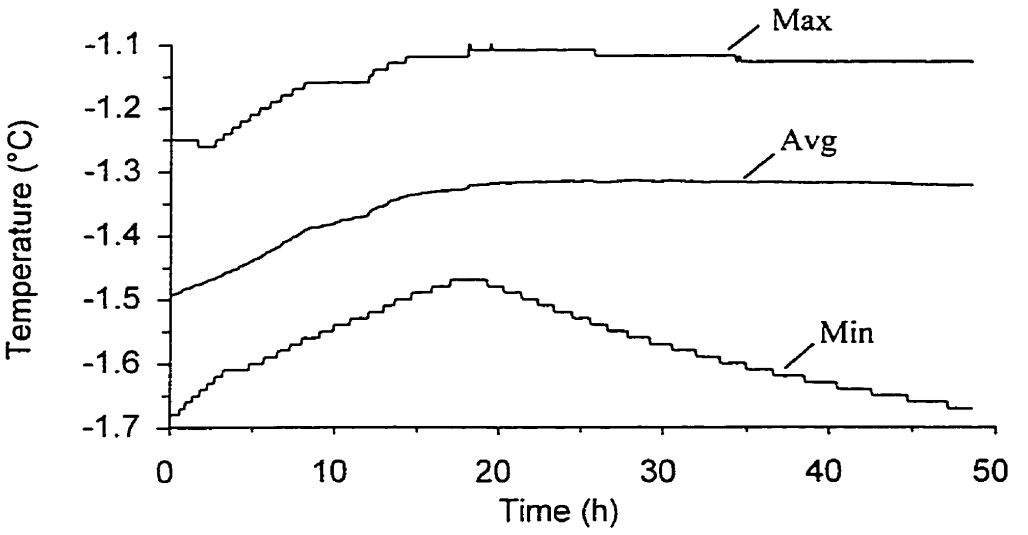

Fig. C.5. Maximum, average, and minimum temperatures (Trial 3) of meat (except 1st level) , when the container was exposed to an outside temperature of 0°C.

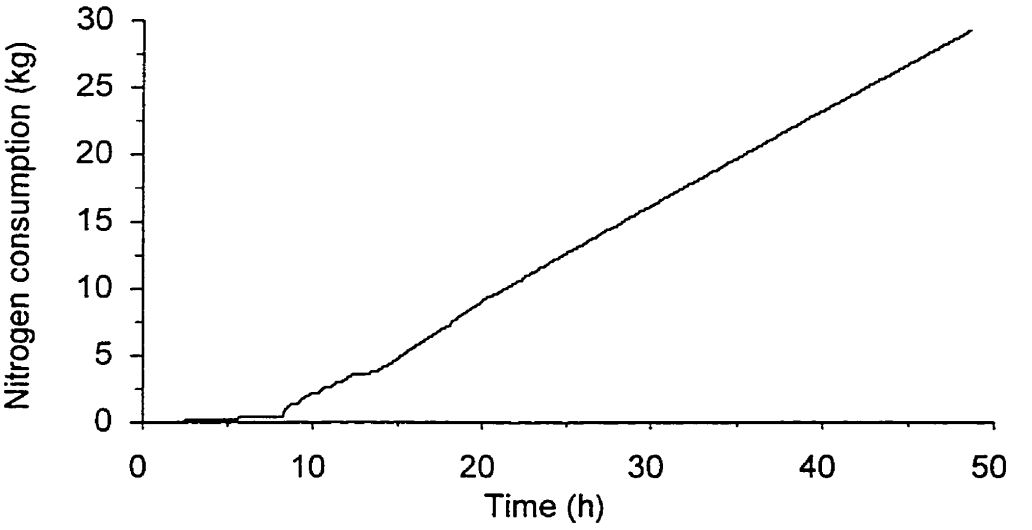

Fig. C.6. Nitrogen consumption during trial 3 (Fig. C.5).

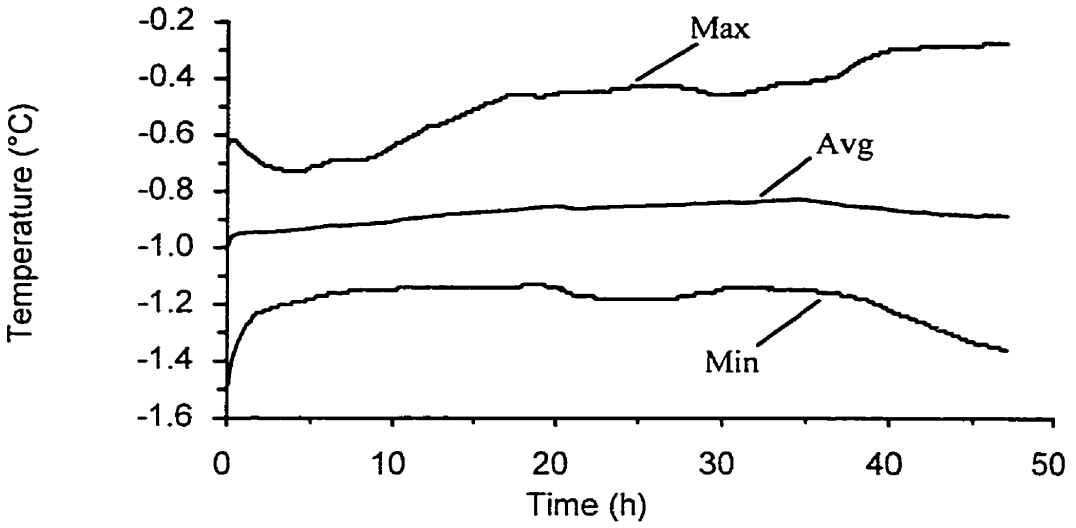

Fig. C.7. Maximum, average, and minimum temperatures (Trial 1) of meat (except 1st level) , when the container was exposed to an outside temperature of 15°C. (Control sensor temperature set at -2.25°C).

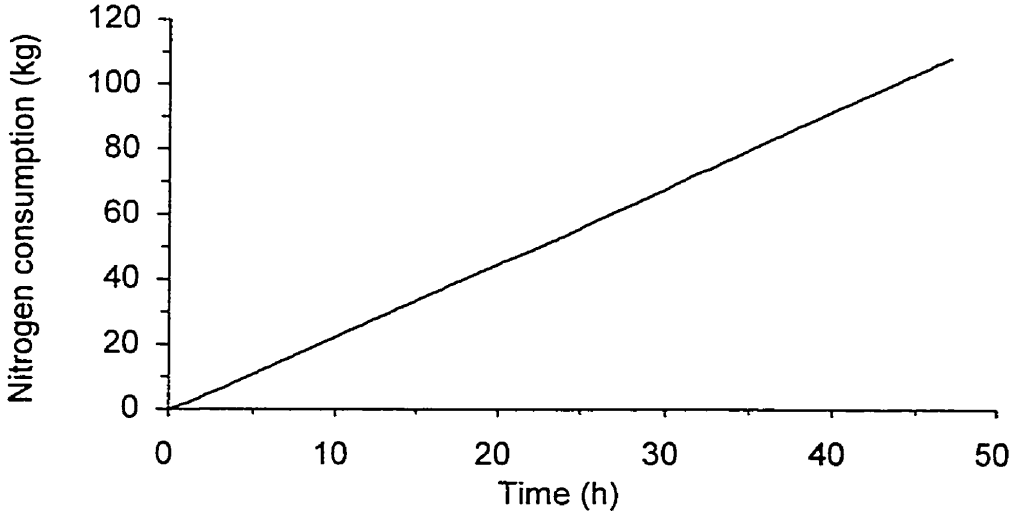

Fig. C.8. Nitrogen consumption during trial 1 (Fig. C.7).

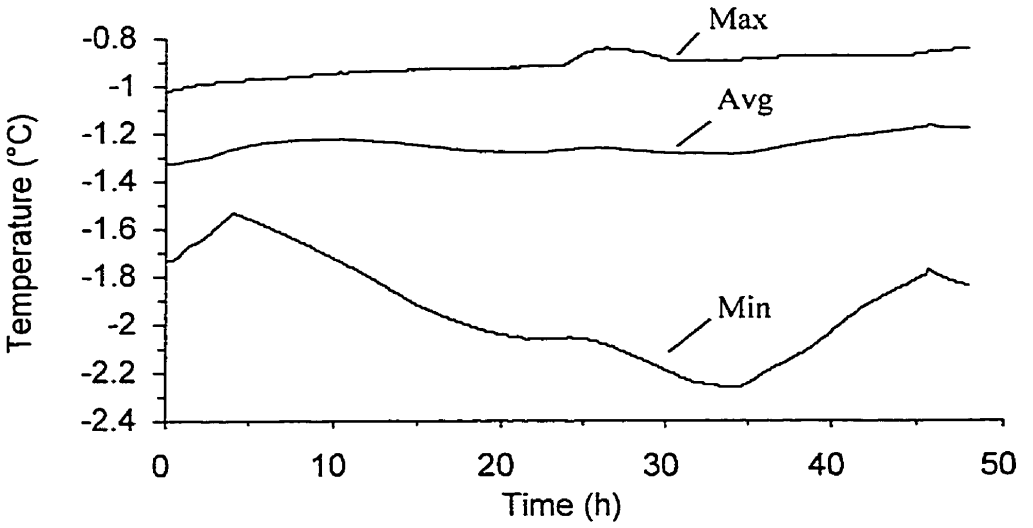

Fig. C.9. Maximum, average, and minimum temperatures (Trial 2) of meat (except 1st level) , when the container was exposed to an outside temperature of 15°C. (Control sensor temperature set at -2.50°C).

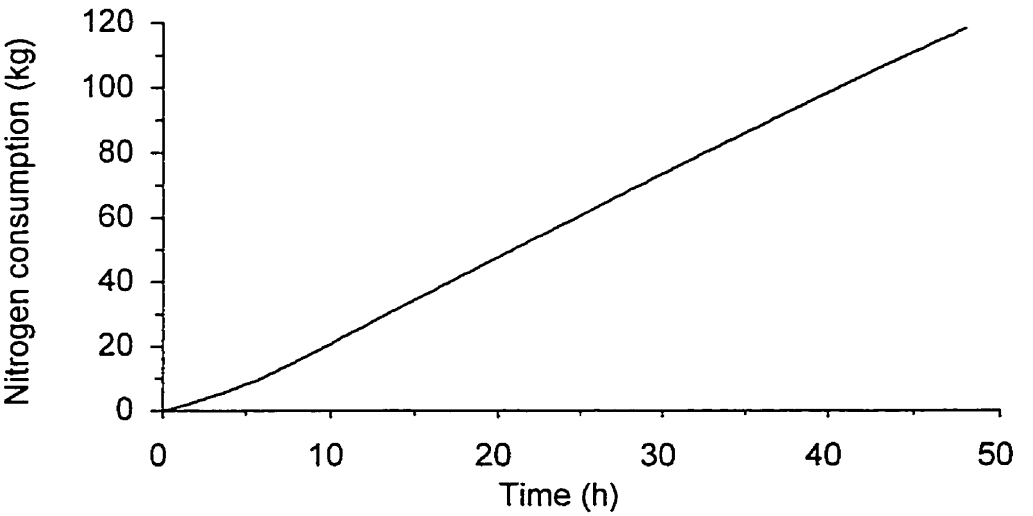

Fig. C.10. Nitrogen consumption during trial 2 (Fig. C.9).

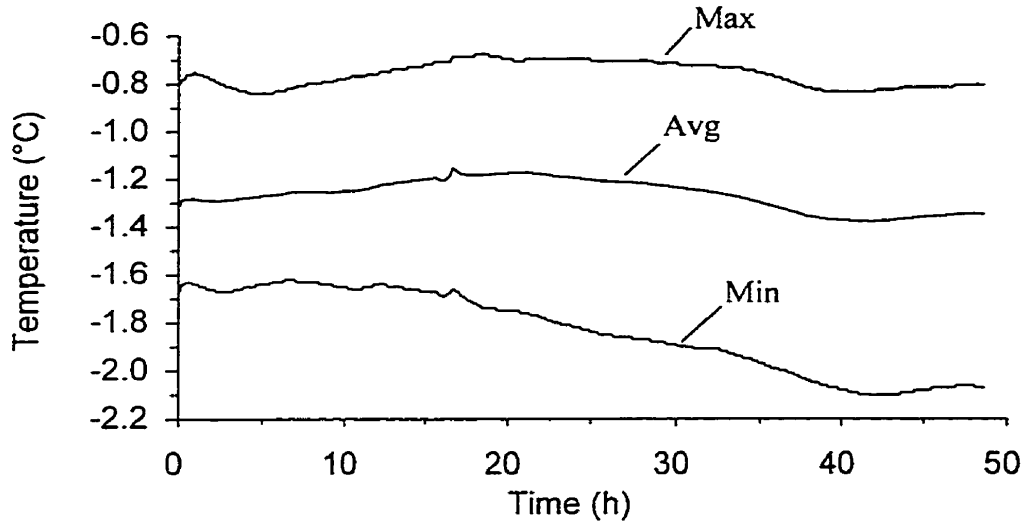

Fig. C.11. Maximum, average, and minimum temperatures (Trial 3) of meat (except 1st level) , when the container was exposed to an outside temperature of 15°C. (Control sensor temperature set at -2.60°C).

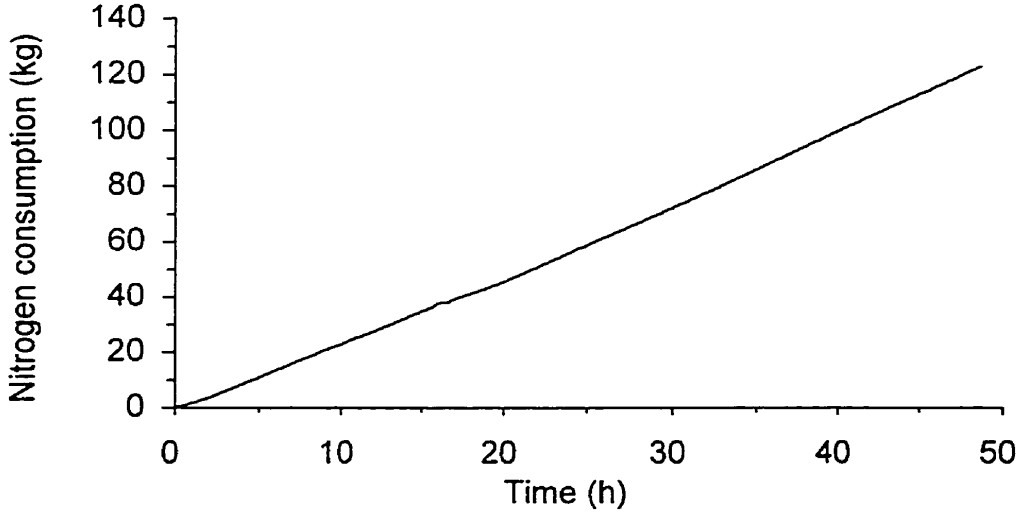

Fig. C.12. Nitrogen consumption during trial 3 (Fig. C.11).

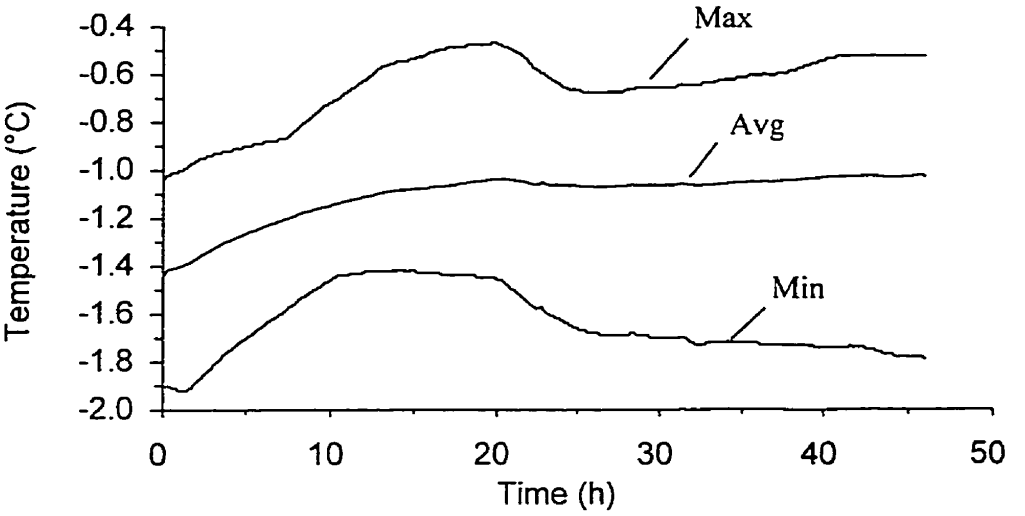

Fig. C.13. Maximum, average, and minimum temperatures (Trial 1) of meat (except 1st level) , when the container was exposed to an outside temperature of 30°C.

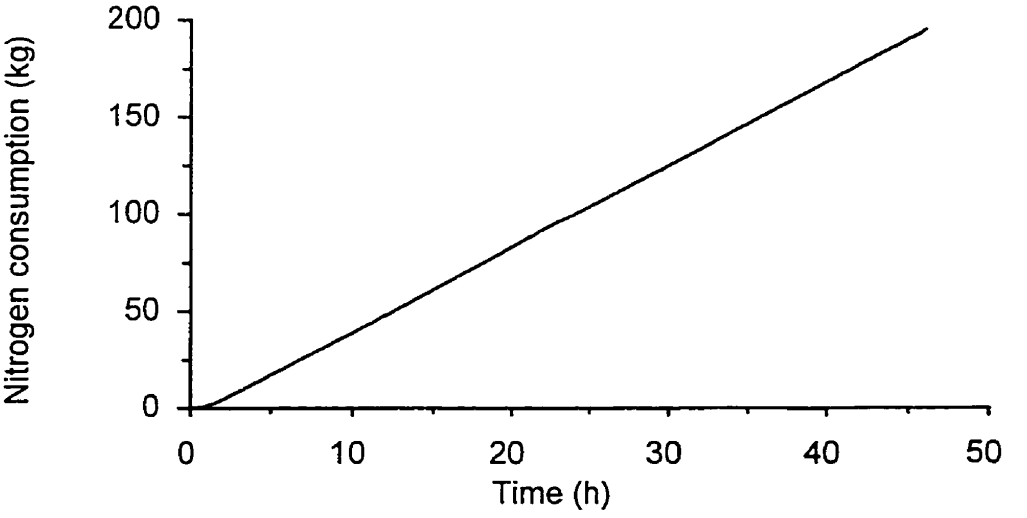

Fig. C.14. Nitrogen consumption during trial 1 (Fig. C.13).

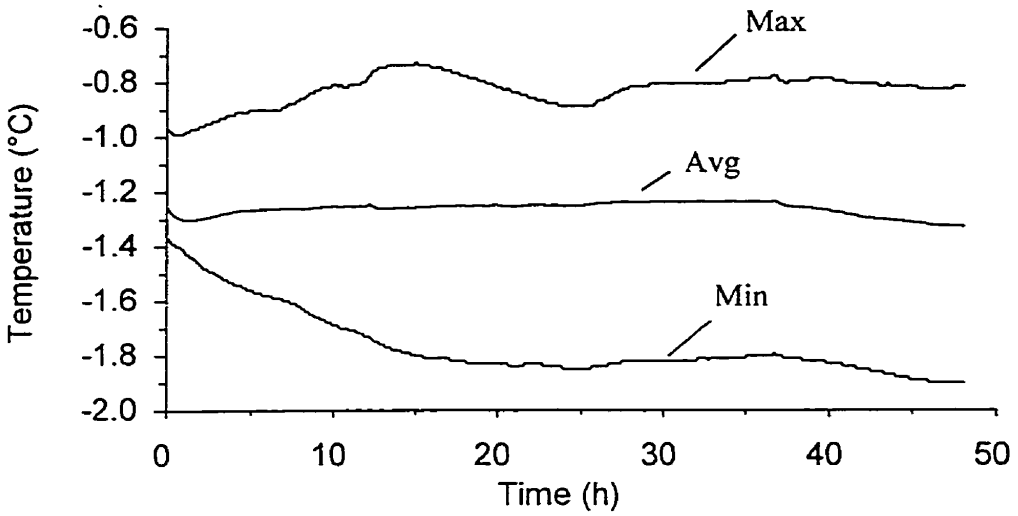

Fig. C.15. Maximum, average, and minimum temperatures (Trial 2) of meat (except 1st level) , when the container was exposed to an outside temperature of 30°C.

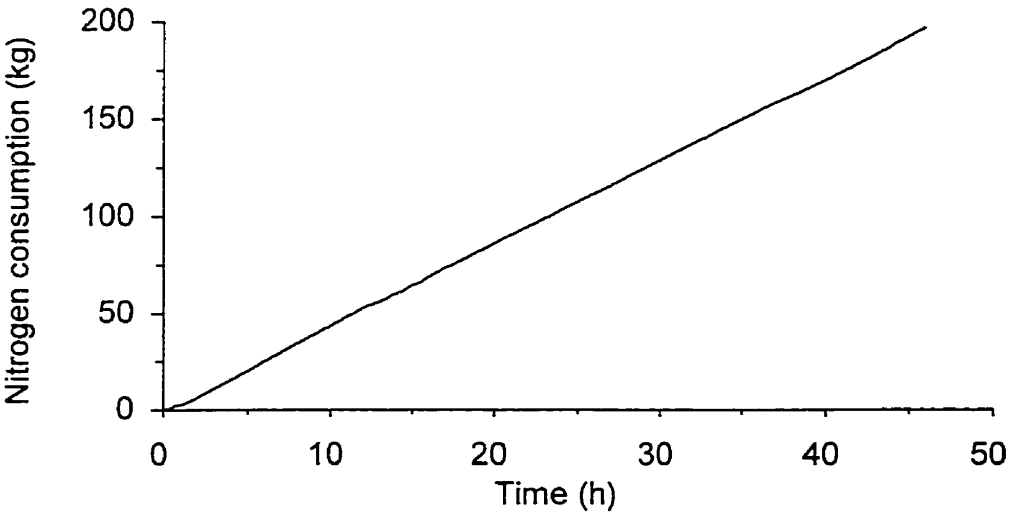

Fig. C.16. Nitrogen consumption during trial 2 (Fig. C.15).

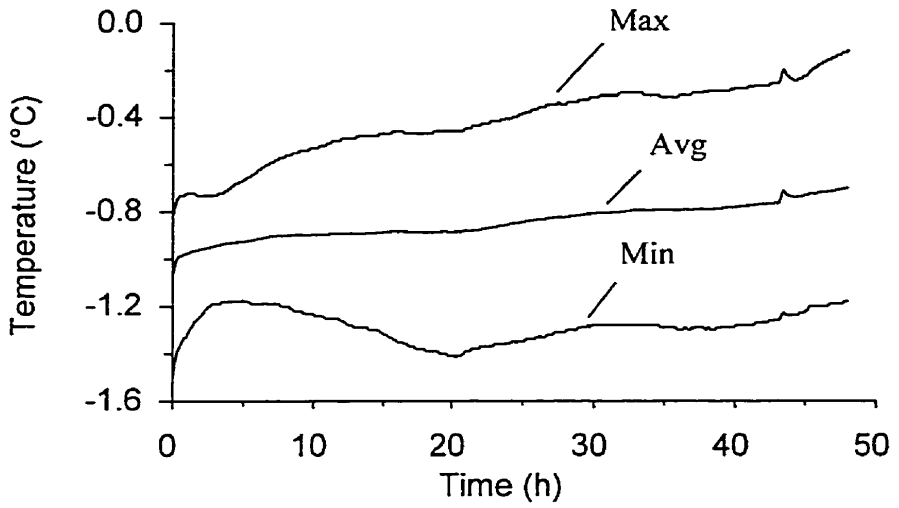

Fig. C.17. Maximum, average, and minimum temperatures (Trial 3) of meat (except 1st level) , when the container was exposed to an outside temperature of 30°C.

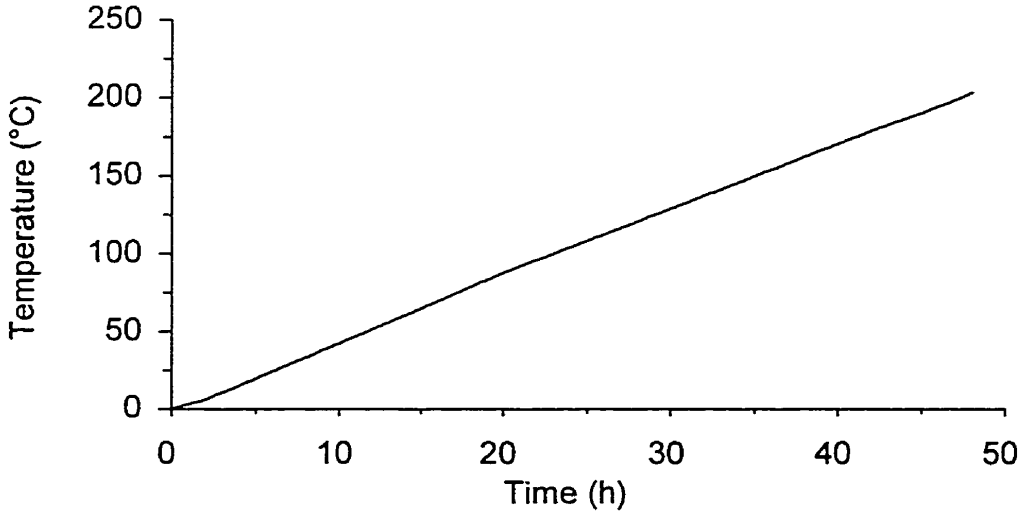

Fig. C.18. Nitrogen consumption during trial 3 (Fig. C.17).

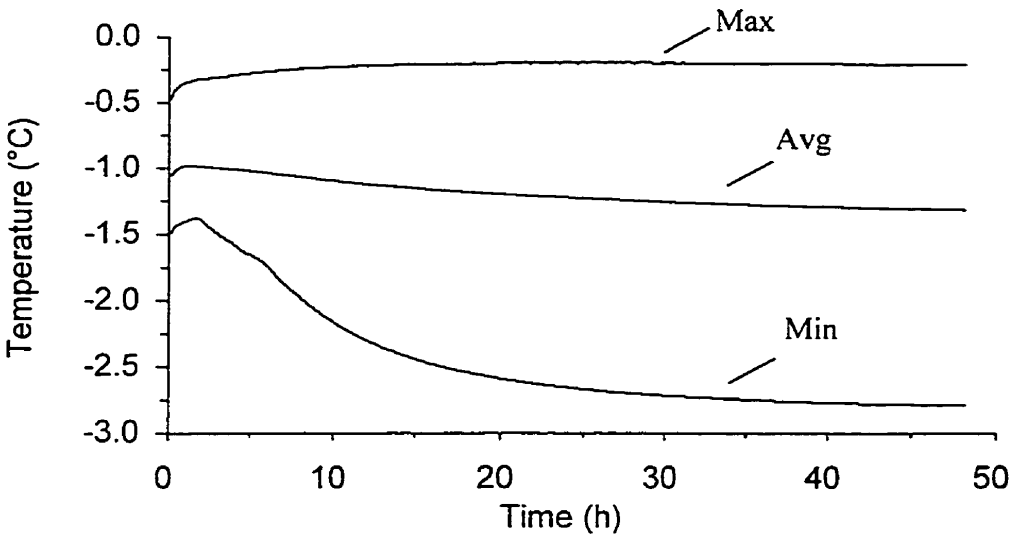

Fig. C.19. Maximum, average, and minimum temperatures (Trial 1) of meat , when the container was exposed to an outside temperature of -15°C. (Control sensor temperature set at 2.50°C).

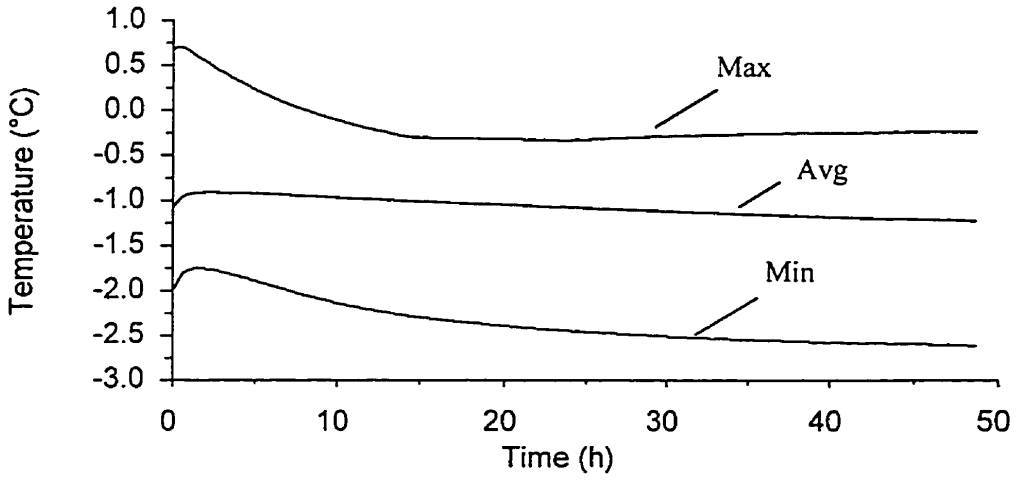

Fig. C.20. Maximum, average, and minimum temperatures (Trial 2) of meat , when the container was exposed to an outside temperature of -15°C. (Control sensor temperature set at 2.50°C).

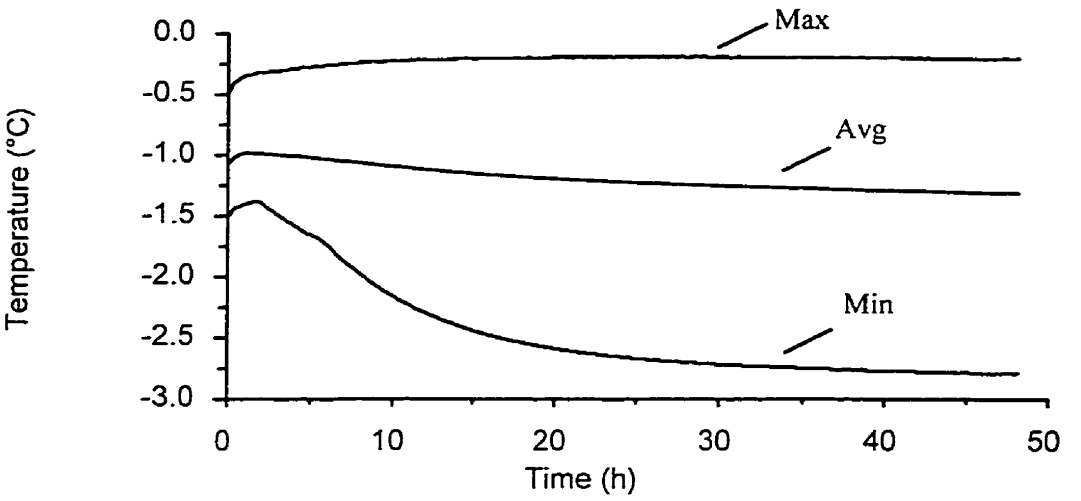

Fig. C.21. Maximum, average, and minimum temperatures (Trial 3) of meat , when the container was exposed to an outside temperature of -15°C. (Control sensor temperature set at 2.50°C).

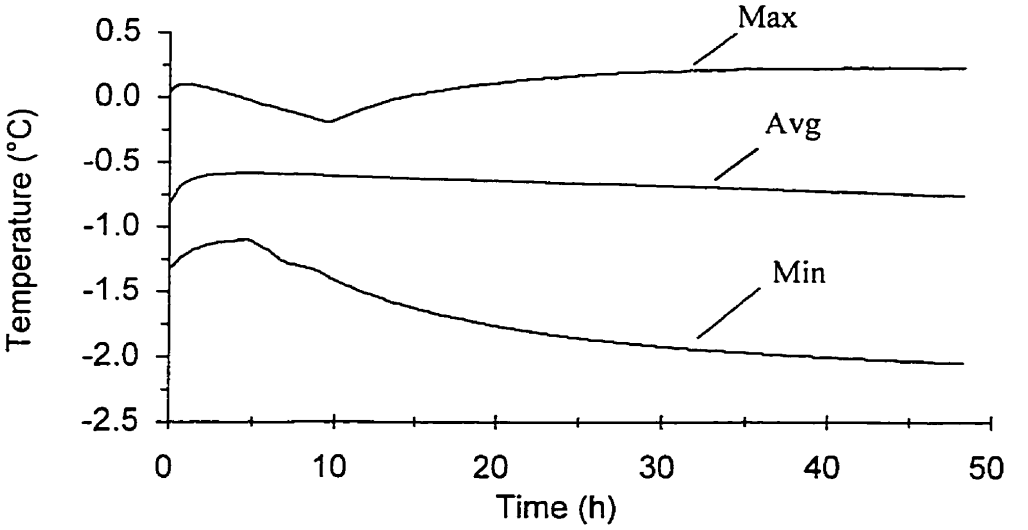

Fig. C.21. Maximum, average, and minimum temperatures (Trial 3) of meat , when the container was exposed to an outside temperature of -15°C. (Control sensor temperature set at 2.50°C).

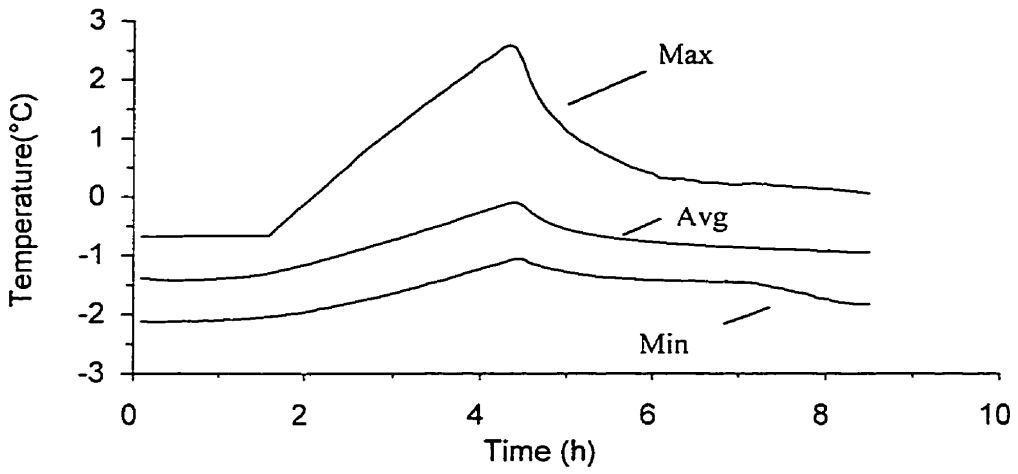

Fig. C.23 Maximum, average, and minimum temperatures (Trial 1) of meat when the container was exposed to an outside temperature of 30°C. The container was connected to the liquid nitrogen tank at 4th h to simulate delivery of the container to the retail store in the early morning and connection to the tank at store opening.

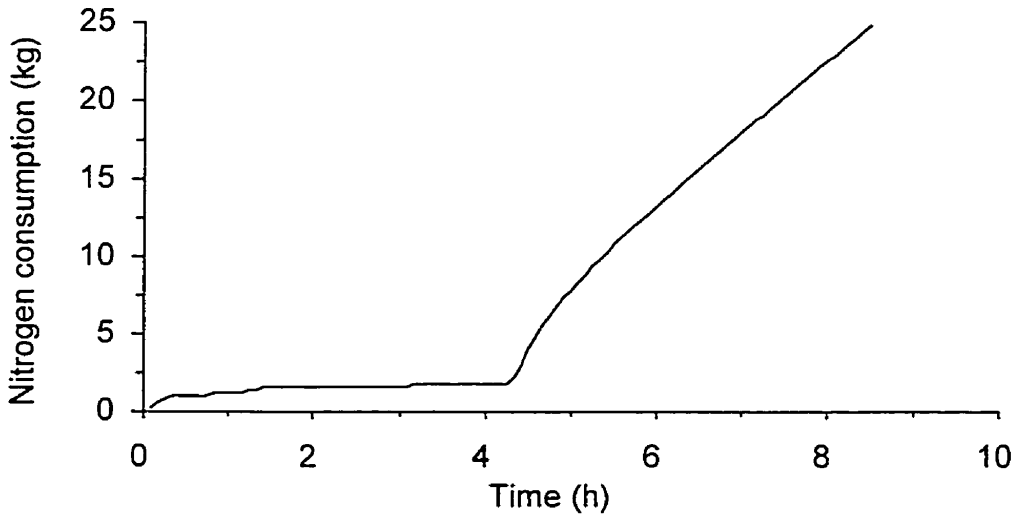

Fig. C.24. Nitrogen consumption for trial 1 (Fig. C.23).

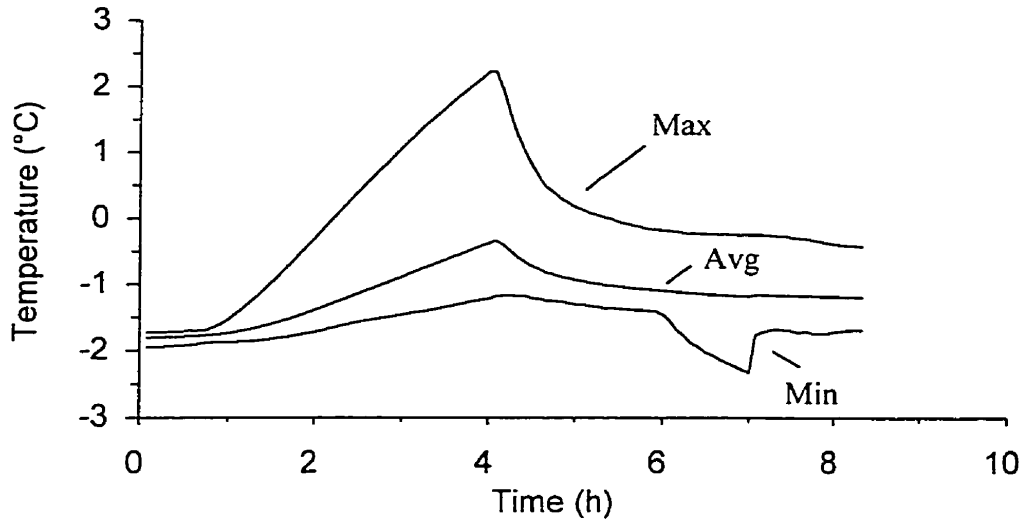

Fig. C.25. Maximum, average, and minimum temperatures (Trial 2) of meat when the container was exposed to an outside temperature of 30°C. The container was connected to the liquid nitrogen tank at 4th h to simulate delivery of the container to the retail store in the early morning and connection to the tank at store opening.

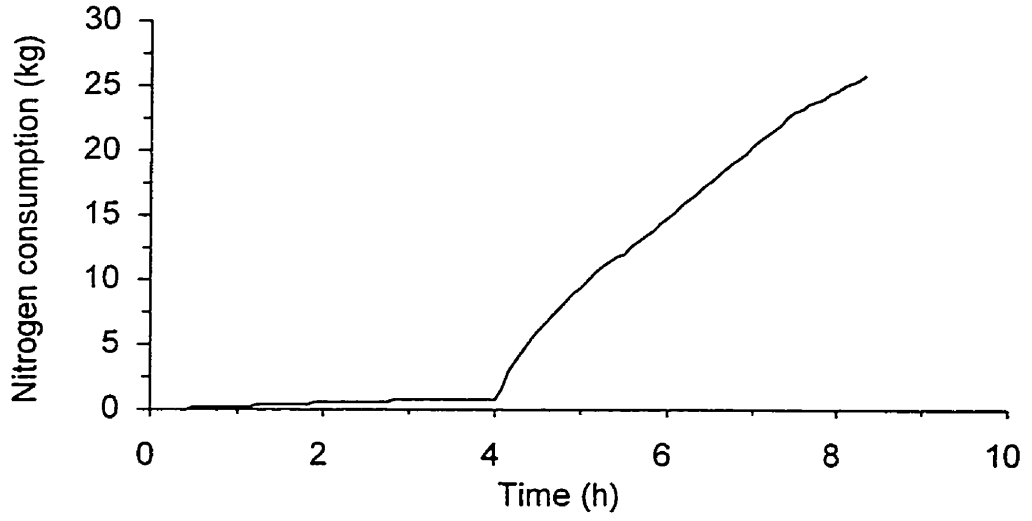

Fig. C.26. Nitrogen consumption for trial 2 (Fig. C.25).

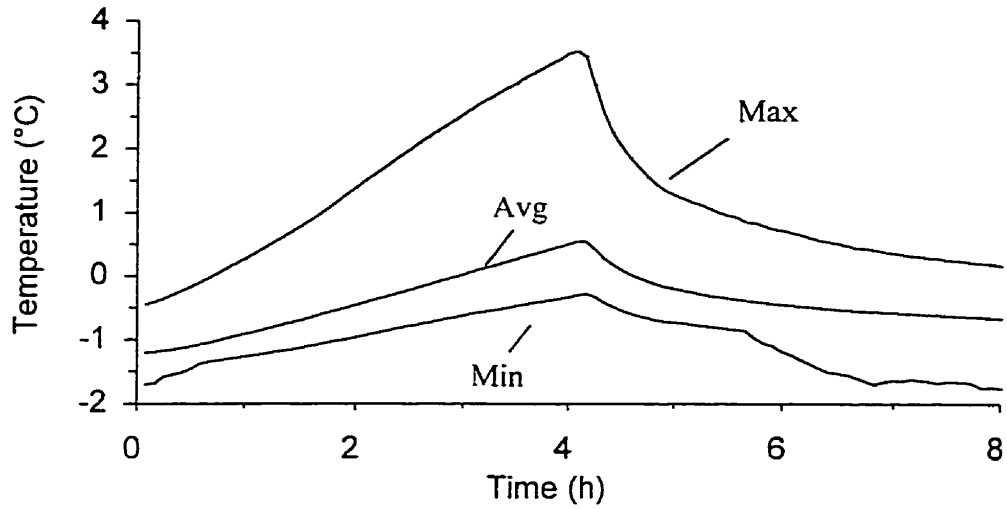

Fig. C.27. Maximum, average, and minimum temperatures (Trial 3) of meat when the container was exposed to an outside temperature of 30 °C. The container was connected to the liquid nitrogen tank at 4th h to simulate delivery of the container to the retail store in the early morning and connection to the tank at store opening.

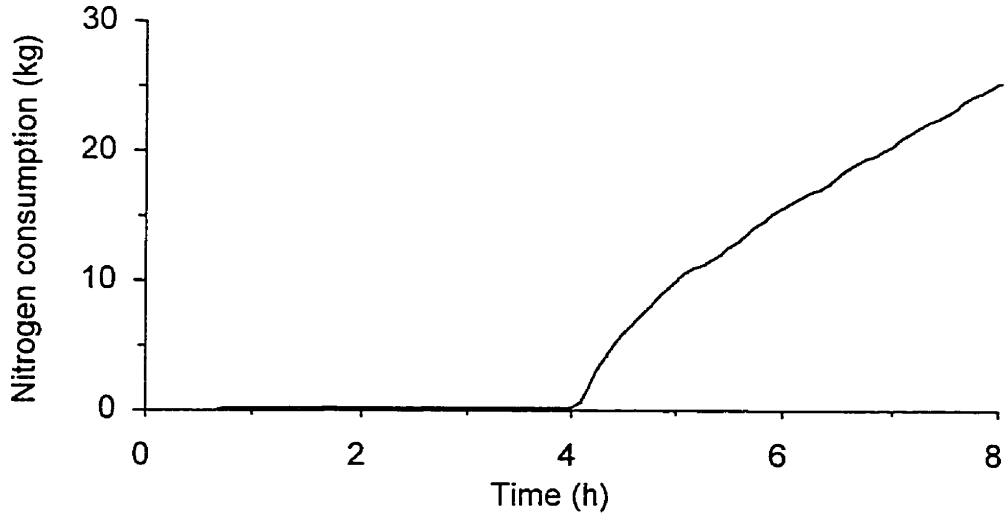

Fig. C.28. Nitrogen consumption for trial 3 (Fig. C.27).

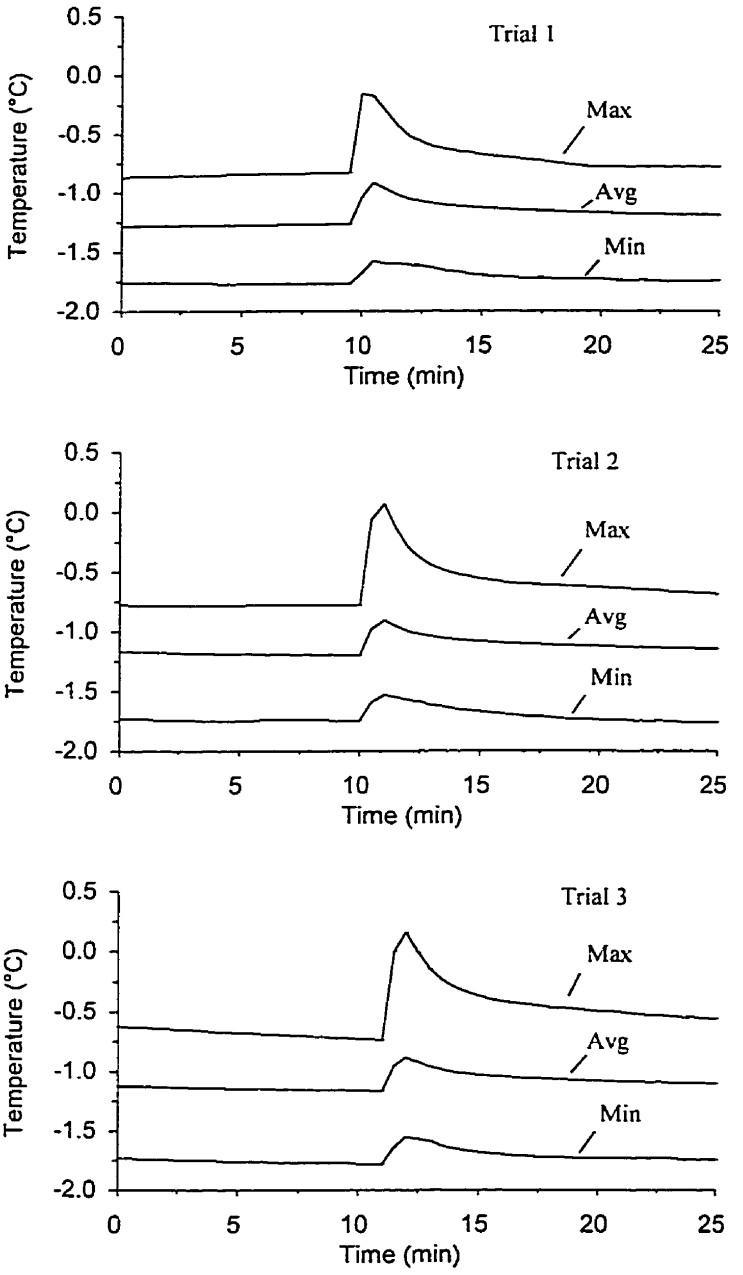

Fig. C.29. Maximum, average, and minimum temperatures of meat resulting from the container door being opened for 15 s and exposed to an outside temperature of 15°C.

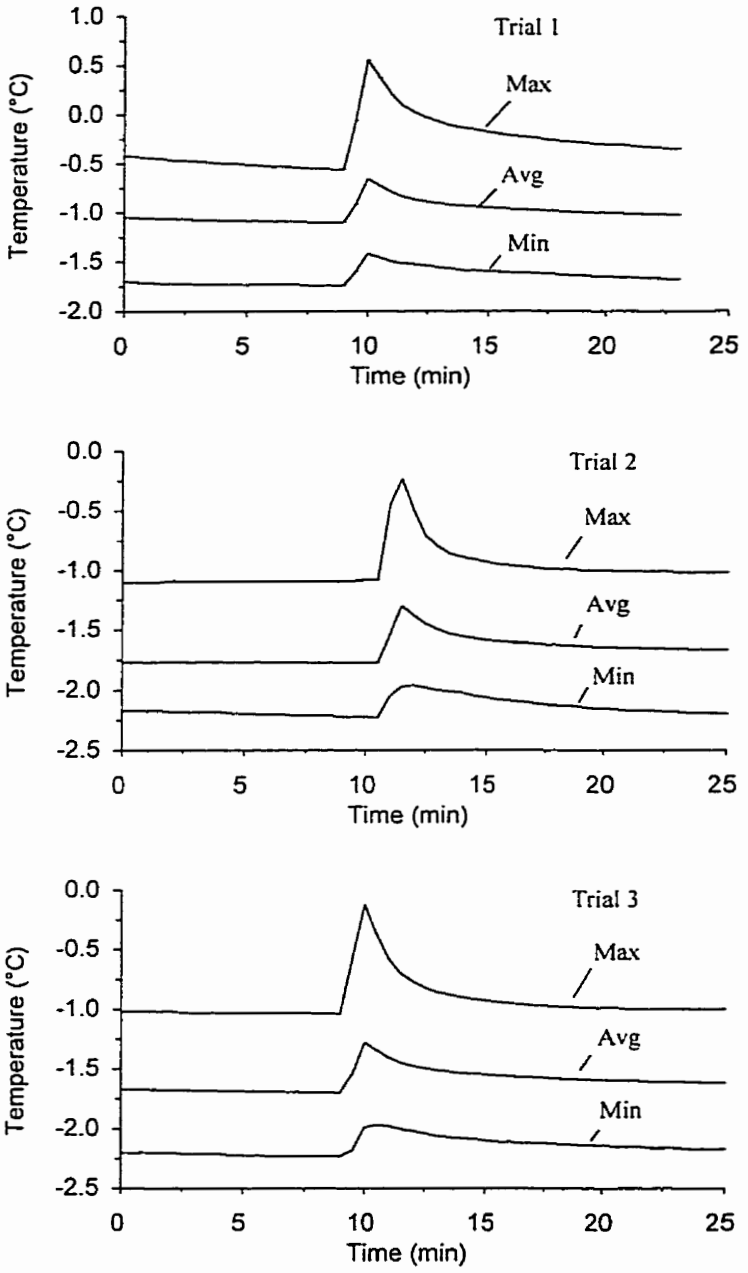

Fig. C.30. Maximum, average, and minimum temperatures of meat resulting from the container door being opened for 25 s and exposed to an outside temperature of 15 °C.

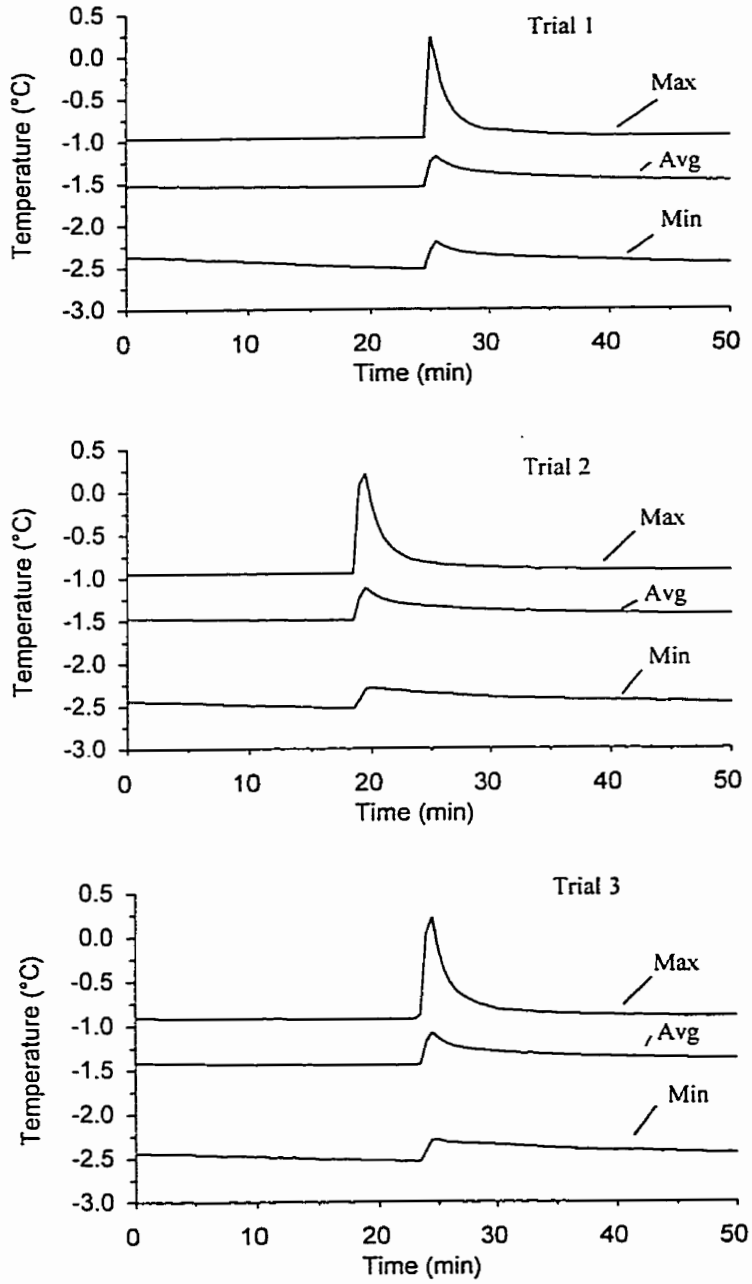

Fig. C.31. Maximum, average, and minimum temperatures of meat resulting from the container door being opened for 35 s and exposed to an outside temperature of 15°C.

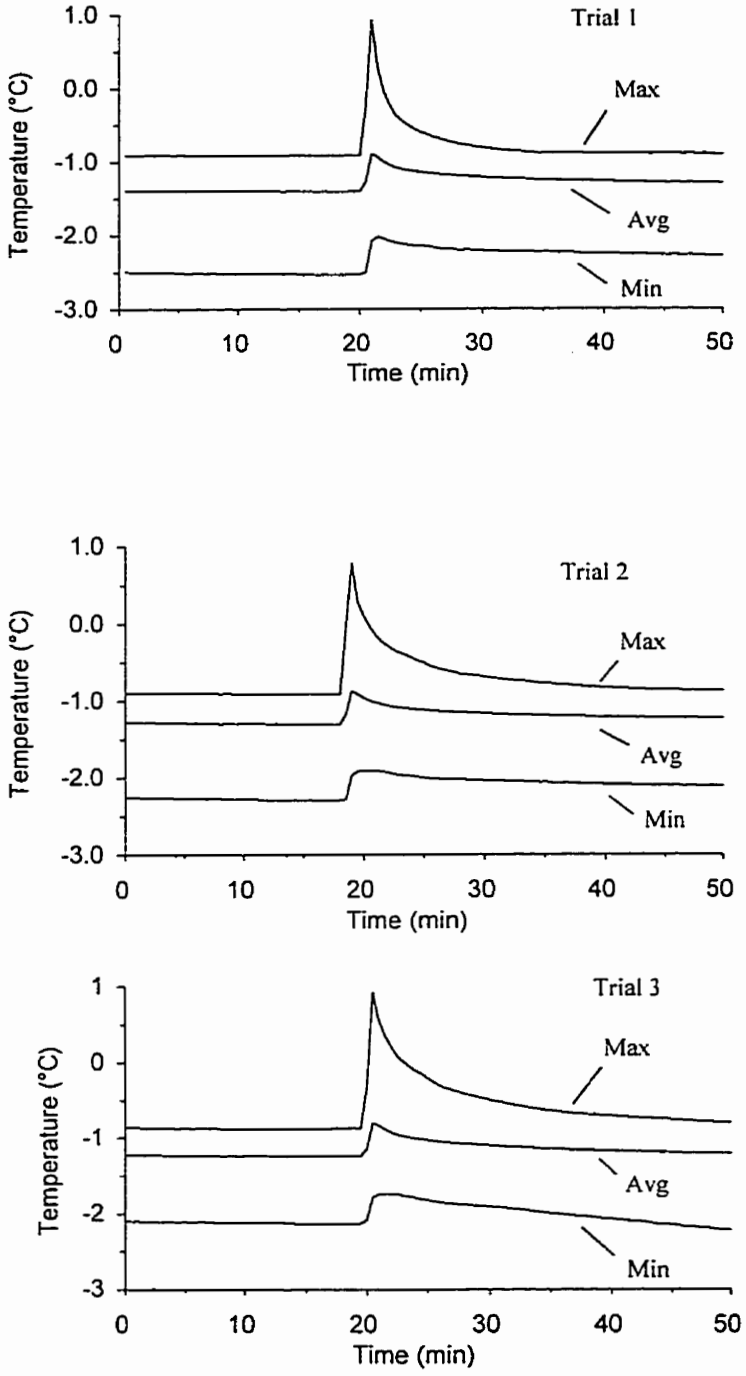

Fig. C.32. Maximum, average, and minimum temperatures of meat resulting from the container door being opened for 15 s and exposed to an outside temperature of 30°C.

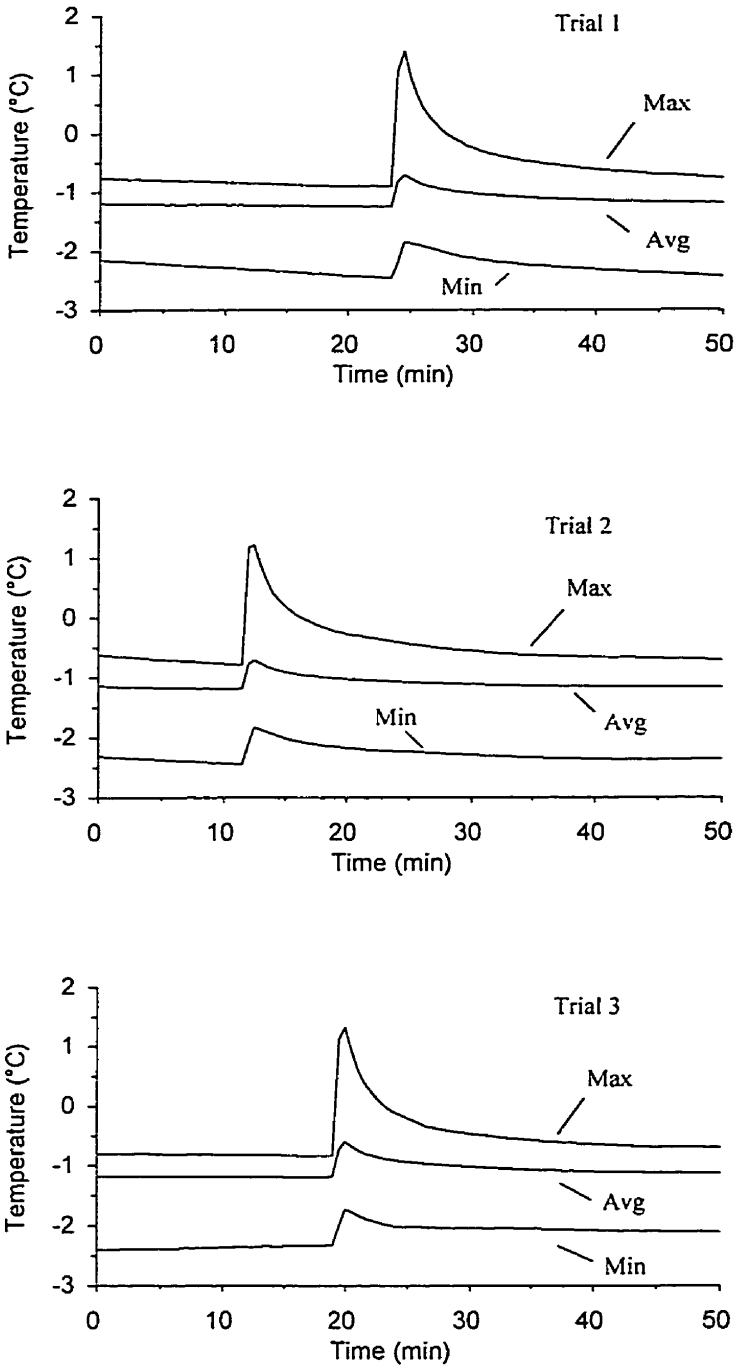

Fig. C.33. Maximum, average, and minimum temperatures of meat resulting from the container door being opened for 25 s and exposed to an outside temperature of 30°C.

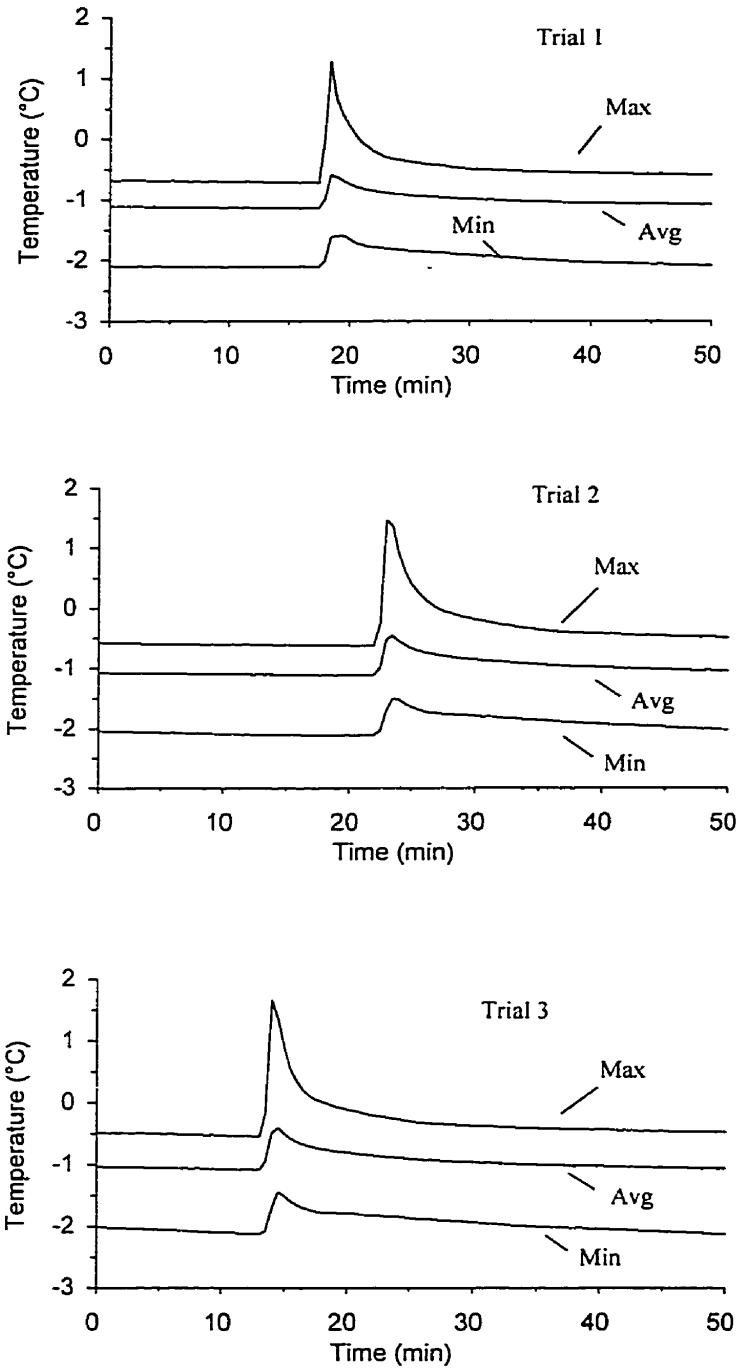

Fig. C.34. Maximum, average, and minimum temperatures of meat resulting from the container door being opened for 35 s and exposed to an outside temperature of 30 °C.