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Shipping Dungeness crab live to the retail market is presently limited by high mortality rates. Mortality rates could be lowered if the container temperature was kept at or below 35 degrees Fahrenheit in the presence of 70 percent or greater relative humidity. A method to achieve lower mortality rates was successfully tested in a simulated air shipment of live Dungeness crab.

Several interrelated ideas for maintaining average final product temperature at or below 35 degrees Fahrenheit after a 19 hour shipment were developed and tested:

1. A computer program was developed to model thermal performance of existing commercial containers and suggest modifications to maintain the temperature at or below the desired maximum temperature.

2. A container was designed to optimize the efficiency of the insulation and gel ice. Design modification tests

were conducted to aid in design decisions.

3. Subcooling Dungeness crab rapidly to 30 degrees Fahrenheit before transport was tested.

Finally the optimized design box and a commercial container, both using the amount of gel ice suggested by the computer program, were tested in a 19 hour simulated shipment test with subcooled live Dungeness crab. The average temperature of the crab mass within the optimized design container remained below 35 degrees Fahrenheit while the average temperature of the crab mass within a commonly used commercial container (38.2 degrees Fahrenheit) rose only slightly above this. It was found that by maintaining the inside container temperature around 35 degrees Fahrenheit under humid conditions the mortality rate of 9.4 percent was markedly lower than the 30-50 percent commercial mortality rates reported when these conditions are not maintained.

CONTAINERIZATION FOR AIR SHIPMENT
OF LIVE DUNGENESS CRAB

by

Carol Harper Rosane

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Redacted for privacy

Head of Department of Agricultural Engineering

Redacted for privacy

Dean of Graduate School

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The pride and the gratitude I feel for my husband, Randy, and daughter, Kirsten, cannot be measured. Without their unselfishness, confidence, and help I would not have been able to do this project.

The commercial products used in this project were chosen to represent a random sampling of what is available. This thesis does not endorse nor discourage the use of any of the products mentioned therein.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CONTAINERIZATION FOR AIR SHIPMENT OF LIVE DUNGENESS CRAB

1. INTRODUCTION

1.1 Statement of Problem

The US consumption of seafood has had a record of overall increase since 1960 (Figure 1) (Vondruska, 1984).

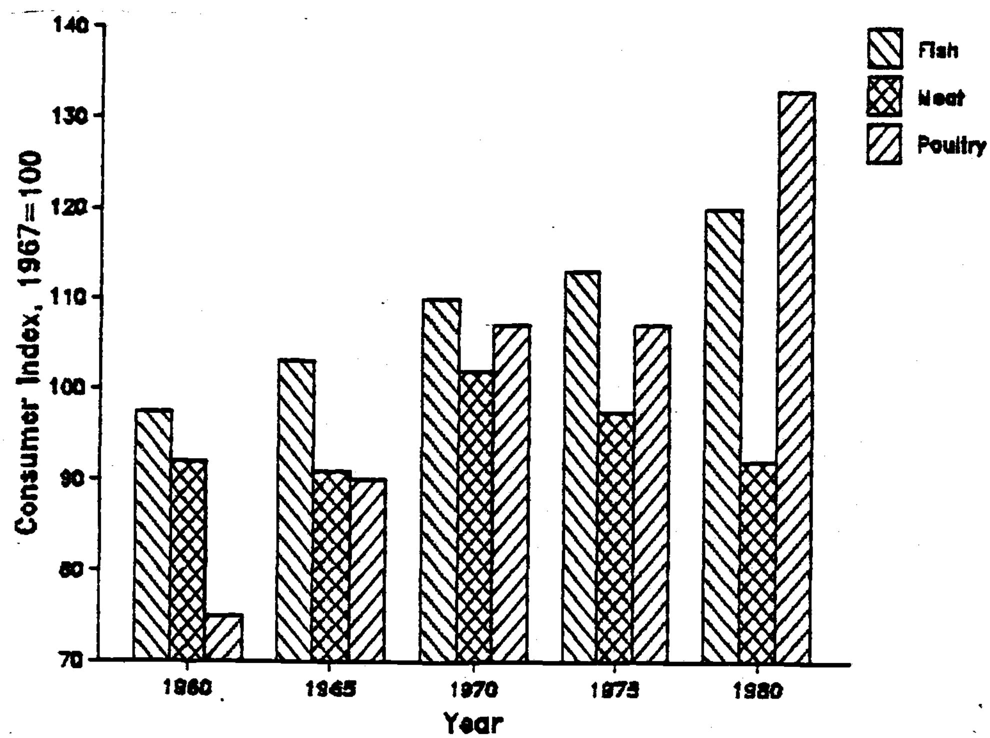


Figure 1. Indexes of U.S. per-capita consumption of meat, fish, and poultry, 1960-80.

There are several reasons for this. People have become more health conscious. They are replacing red meats in their diets with poultry and fish to reduce their intake of calories and saturated fats, a precursor to cholesterol.

The cost of red meats is steadily increasing. Rising costs force people to try alternative protein sources.

Many feel that the seafood market's volume potential has not yet been realized. Lack of quality is cited as the reason. The Food Market Institute, a trade association for supermarket operators, concluded in a recent government-funded survey that the main problem blocking increased market volume was lack of consistent seafood quality (Redmayne, 1984). Jon Rowley, in a critique of the industry by chefs and foodwriters (1983) also concurred that higher seafood quality would vastly expand the market volume. Other retailers who have been successful in their seafood operations agree that quality is more important than price in bringing the customer back (Hasselback and Stroud, 1984). Sackton (1983) lists poor quality control first in his list of three factors that hurt supermarket sales of seafood.

Two mandatory requirements for getting good quality seafood to market are temperature control of the product (Sackton, 1983), and minimizing transportation time (Rowley, 1983). According to Sackton (1985), the internal temperature of seafood should be 32-35 degrees Fahrenheit and anything over 40 degrees Fahrenheit rejected by the buyer. Chefs famous for their seafood preparations use two methods to keep transportation time at a minimum. They either buy only fish and shellfish indigenous to the area or have the product shipped in by air freight. A successful restaurateur, Larry Forgione of the River Cafe in Brooklyn, states that air freight is indispensable to stimulating both industry's and the consumer's interest in a wide variety of seafood (Rowley, 1983).

The seafood market's volume potential for growth has not been experienced because of an inconsistent product quality. Methods of rapid transportation with good temperature control need to be designed, implemented, and standardized. Air transport of temperature controlled containers is one solution. Current containers used in air shipment include a wide variety of insulated (both disposable and returnable) types.

Figure 2 compares meat, fish and poultry price indexes from 1960-80 (Vondruska, 1984). Although keeping the quality high is the main consideration, keeping the cost as low as possible while doing this would certainly be a marketing plus. An economic advantage of dealing with a live instead of processed (cooked) product is the reduced spoilage. A live seafood product has a longer shelf life than a processed one, e.g. Dungeness crab have a two to three month shelf life alive and an eight day shelf life processed (unfrozen). Spoilage loss is considerably reduced.

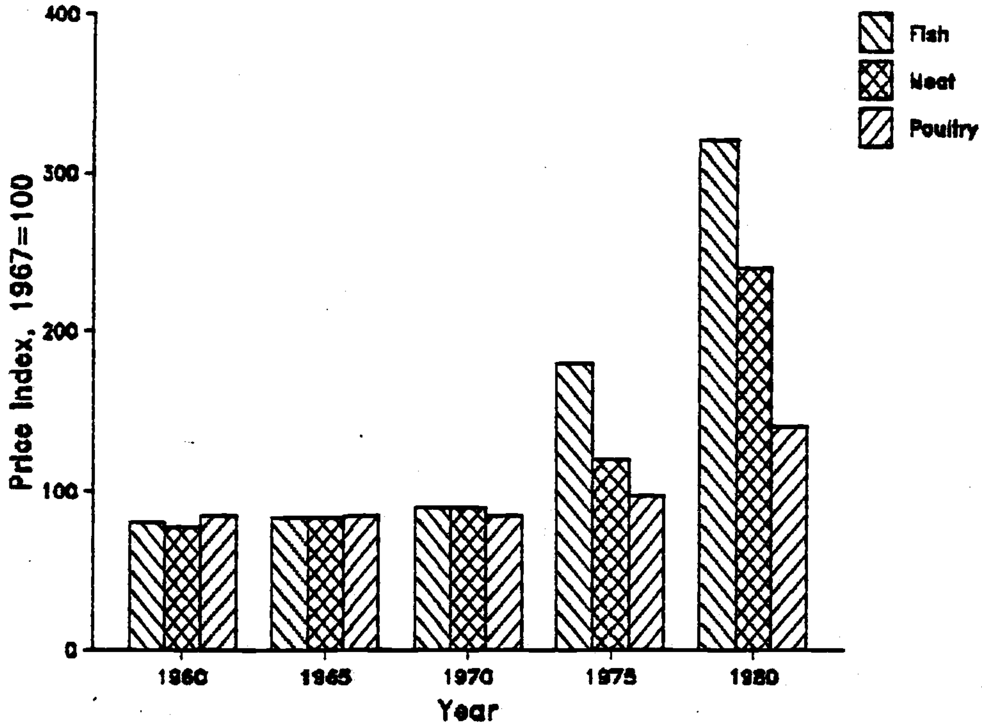


Figure 2. U.S. retail price indexes, 1960-80.

This project was promoted by the Oregon Dungeness Crab Commission because there is a need for availability of a better quality product. The live crab market has not been well developed, yet it could offer the consumer a fresher product. Current practices of live shipment need improvement. Dick Yoshimura from Mutual Fish Co., Inc. in Seattle, Washington, (1983) said in an interview that on the average approximately 1/3 to 1/2 of the Dungeness crab now shipped to him arrive dead. Fifty percent mortality rates in shipment of live Dungeness crab out of Alaska have also been reported (Paust, 1983). Harold Barnett, an authority on seafood shipment, (1985) said that although it is not well documented as industry is reluctant to admit that commercial mortality rates in live Dungeness crab shipments of 24 hours duration or less are high, the percentage of crabs arriving dead can easily be 50 percent. Shipments longer than this can have up to 100 percent mortality rates.

Once Dungeness crab die, deterioration rapidly occurs unless processed. The two main deterioration processes include the blueing of crab meat and enzymatic degradation. The blueing of crab meat may be related to the presence of polyphenoloxidases in crab (Babbitt et al., 1973a) and the subsequent oxidation and polymerization of phenols to colored melanins, particularly in the presence of metals (Cu and Fe) and under alkaline conditions (Babbitt et al., 1973b). Blue crab meat is unsalable commercially. Enzymatic degradation occurs when enzymes break down muscle proteins rapidly into peptides and amino acids. Yield is decreased and these degradation products act as nutrients for microbes causing off-flavors to develop. Other enzymes break down compounds which impart flavors associated with fresh crab meat resulting in a lack of flavor (Howgate, 1984).

Methods to prevent deterioration include natural biochemical control and immediate heat processing. Natural biochemical control means keeping the crab alive.

Immediate heat processing inactivates the enzymes and reduces the copper content of the crab (Babbit et al., 1975). Natural biochemical control has the advantage of preventing degradation longer than heat processing. This advantage is lost, however, if mortality rates are high during shipment. It is therefore important to keep the Dungeness crab alive during shipment when the crab are out of water. Conclusions drawn from a review of the literature (see Chapter 2) suggest that keeping the temperature around 35 degrees Fahrenheit, the temperature Dungeness crab cease activity, would be biologically advantageous for survival during transport.

Dungeness crab sales have the potential of being increased if the quality is raised and the prices are lowered. Air transport and good temperature control would insure high quality. Increasing the shelf life of the product by dealing with live rather than cooked merchandise and finding an effective low cost shipping container would lower prices. "Containerization for Air Shipment of Live Dungeness Crab" deals mainly with increasing the crab survival rate during transport by maintaining a maximum internal container temperature of 35 to 40 degrees Fahrenheit. Optimizing container design for minimum heat transfer, developing computer models to predict the behavior of various shipping boxes, and applying the subcooling method used in fruit and vegetable shipment to crab were methods employed to achieve this.

Shipment of only Dungeness crab was considered in this thesis. The results and conclusions, however, have broader applications. Predicting and controlling temperature is important to any seafood product (processed or live) if quality is to remain high. Optimizing container design so that heat transfer is held at a minimum is pertinent to any temperature dependent transport.

1.2 Objectives

Based on the premise that the potential crab market is underdeveloped, the general objective of this project could be thought of as increasing live Dungeness crab sales. Being able to provide a live product would guarantee freshness and successful air shipment would broaden the market area.

More specifically the aim of this project was to lower current mortality rates common to live transport by maintaining internal container temperatures optimally at 35 degrees Fahrenheit or less and not higher than 40 degrees Fahrenheit.

Three interrelated ideas were tested and combined to achieve this: (1) A computer program was developed capable of modeling container behavior when given initial and boundary conditions and then suggesting modifications (adding gel ice or insulation) needed to maintain the internal temperature at or below a desired maximum. (2) A container was designed to meet predetermined design specifications and to incorporate design modifications that increased the efficiency of the gel ice and the insulation. (3) The subcooling method, used in fruit and vegetable shipment, was applied to live Dungeness crab.

2. REVIEW OF LITERATURE

2.1 Biological Background

The sea provides a remarkably constant climate for its inhabitants, temperature changes little and slowly, and ionic concentrations and quantities of dissolved gases tend not to vary. For a crab to be able to survive in an environment other than the sea, it must not only be able to tolerate a new set of environmental levels but also be able to adapt to fluctuations greater than normally encountered in the ocean.

Crab, in general, are remarkably well prepared to adapt to a new environment. The tough exoskeleton and compact body help limit diffusion and desiccation and provide it with a means of transportation out of water. Dungeness crab's ability to adjust to fluctuations in temperature, salinity, oxygen levels and degree of immersion permits it to be a successful candidate for live transport and holding.

The American lobster, <u>Homarus americanus</u>, has been extensively studied and much appears in the literature pertinent to its biological requirements. Barnett (1983) stated that lobster are not more robust than crab and that they can both be maintained equally well under the same conditions. Therefore, consideration will also be given to the limits for survival of the American lobster. Barnett also felt it important to remember the variance of tolerances between species of crab. For example, king crab that do not tend to migrate to varying ocean environments but stay in the colder, deeper waters have different tolerance limits than Dungeness crab (that do migrate).

The four parameters; temperature, salinity, oxygen concentration, and humidity, which must be monitored for sea life to survive in and out of seawater will be explored from the perspective of Dungeness crab adaptations. The temperature and humidity parameter sections focus on what the best conditions are for live Dungeness crab shipment. The oxygen and salinity concentration sections substantiate the fact that Dungeness crab are adaptable to varying environmental conditions. This is an important factor when considering any sea life for live holding tanks.

2.1.1 Temperature

Dungeness crab have been shown to survive temperatures as low as 24 degrees Fahrenheit (Barnett, 1983). Dungeness crab have been reported to survive easily for 9 hours at temperatures as high as 70 degrees Fahrenheit and have a mean death temperature of 91 degrees Fahrenheit (Prentice and Schneider, 1978).

Temperature greatly affects metabolic rate. Prentice and Schneider (1978) developed a regression equation for Dungeness crab to determine if a relationship between thermal acclimation and respiration, a method which indicates metabolic rate, existed. The prediction formula, based upon a straight line relationship, was:

$$\text{Resp. rate} = 9.55 + 1.824(\text{test temp.}) - .015(\text{body wt.}) \quad (1)$$

Fifty percent of the variability in respiration rate was accounted for by test temperature while only 3 and .4 percent of the variability was accounted for by weight of the crab and acclimation temperature, respectively. Acclimation is how animals alter their metabolic processes to compensate for seasonal changes in temperature. It takes a week or two to occur when induced experimentally and did not appear to have much effect compared to the actual test temperature effect and so was not included in the regression equation. Environmental temperature was a major influencing factor in metabolic rate.

McLeese (1968) noticed that the American lobster was capable of only reduced activity at low temperatures (35 to 40 degrees Fahrenheit) while the spider crab, *Chionoecetes opilio*, has normal activity at these temperatures as this is the temperature range at which it normally lives. A test was run to determine if these crabs have a high rate of oxygen consumption as an adaptation for life at low temperatures. Their oxygen consumption at low temperatures did not appear to significantly differ from lobster's consumption at higher temperatures. It was concluded that oxygen requirements would not have to be increased for live storage of these cold acclimated crabs over that required for lobster. Their adaptation to lower temperatures had not resulted in a higher metabolic rate to maintain "normal" activity. The spider crab demonstrated a crustacean's basic adaptability, one that came from internal biological control rather than short term compensation for the external environmental.

Temperature also affects oxygen content of the blood. McMahon, et al, (1978) found that Dungeness crab showed decreased oxygen content of the blood with increased acclimation temperature. Oxygen content is reduced due to the combined effects of temperature and pH on oxygen affinity for hemocyanin, a blood pigment.

Lobsters of two size groups (approximately 8 1/2 inches long and approximately 11 inches long) were tested to see if high temperatures were more lethal to one group than the other (McLeese, 1955). For both size groups the temperature at which 50 percent of the animals died in 48 hours was 80 degrees Fahrenheit. Size does not seem to influence the resistance of lobsters to high temperatures.

Higher temperatures increase the metabolism of crabs and decrease the blood's affinity for oxygen. Under storage or transportation conditions higher temperatures cause production of toxic waste products, a higher oxygen demand, and greater activity of the crab. Larger animals (as proven by McLeese (1955) with lobsters) show no superiority when compared to smaller animals in resisting death from higher temperatures.

Lower temperatures combined with starvation have been shown to decrease physiological problems (Stewart, et al, 1972) of live lobster storage. Hoffman, et al, (1975) has also shown that lobsters become less aggressive at lower temperatures which results in lower commercial loss. Roach (1956) held live crabs successfully at 35 degrees Fahrenheit under aerated conditions for 12 days without changing the sea water.

Dungeness crab cease motor activity at 35 degrees Fahrenheit. Their metabolism is low and they are easier to handle for shipment at or below this temperature. Although the Dungeness crab is able to tolerate a large temperature range (24 to 70 degrees Fahrenheit) it appears that the lower temperature ranges (< 35 degrees Fahrenheit) are the best for live storage and transportation.

2.1.2 Salinity

Most crabs have the same concentration of salts in their body as seawater, so the problem of maintaining this concentration is not difficult as no osmotic gradient exists. If a crab is exposed to dilute seawater and it is not capable of osmoregulation it will at first gain weight rapidly by osmosis until internal and external concentrations are equal; then, more gradually, it loses weight as salts and water diffuse out of its distended body. If the drop in the crab's internal osmotic concentration is greater than 25 percent the crab dies.

A crab placed in varying dilutions and concentrations of standard seawater for live storage needs to be able to osmoregulate to survive. It has been proven (Hunter and Rudy, 1975; Engelhardt and Dehnel, 1973) that Dungeness crab is capable of both hyper- and hypo-osmoregulation. Hyper-osmoregulation is when the osmotic concentration of the blood drops below normal level but above environmental level. Hypo-osmoregulation is when the osmotic concentration of the blood stays around normal level and below environmental level. Both previously mentioned studies concluded that Dungeness crab were capable of specific ionic regulation also. Engelhardt and Dehnel (1973) showed that crab were capable of surviving in a wide range (50 to 125 percent) of dilutions and concentrations of standard seawater.

2.1.3 Oxygen Concentration

Gills are not suitable for extracting oxygen from air as they collapse and the lamellae (small membranes) stick together. At temperatures above 45 degrees Fahrenheit and relative humidities below 70 percent crab do not survive. Dungeness crab has been shown to be able to survive out of water for short periods of time (one to three days) as long as the humidity is maintained between 70 and 100 percent and the temperature kept below 45 degrees Fahrenheit (Barnett, 1982). Lower temperatures lower the metabolic rate and consequently lower oxygen demand. High humidities prevent the gills from drying out and the crab from dehydrating.

Regulators can both increase their ventilation rate and decrease their metabolic rate to compensate for low available oxygen conditions in seawater. An animal that regulates can then survive when the available oxygen concentration of seawater is not optimum. Dungeness crab are regulators. Dungeness crab increase their ventilation and oxygen extraction rates at partial pressures as low as 50 mm Hg. Stiffler and Pritchard (1972) proposed that the metabolic slow-down at partial pressures lower than 50 mm Hg is due to a receptor system sensitive to blood concentration of oxygen that slows down the heart which in turn slows down the circulation.

Dungeness crab have been shown to be far superior to snow and king crab in their ability to extract dissolved oxygen from the seawater (Hartsock, 1975). Dungeness crab appeared to utilize anaerobic metabolism more efficiently than snow and king crab. Also, the blood pigment, hemocyanin, has different affinities for oxygen in different crab species. High affinity pigments continue to take up oxygen despite low external oxygen concentration (Warner, 1977).

Feeding greatly increases the oxygen need because of increased metabolism. Starvation is suggested for 24 hours prior to a live shipment of crab (Barnett, 1969).

2.1.4 Humidity

Crabs can not effectively prevent water loss by evaporation. The crab cuticle is very permeable because it lacks a protective outer waxy layer.

High humidity must therefore be maintained to prevent desiccation and to keep the gills moist to facilitate oxygen uptake when returned to an aqueous environment. Loss of body fluids exacerbates other problems. As the crab dries out, body temperature increases due to loss of evaporative cooling potential occur and subsequently metabolic rate and oxygen demand are increased. The oxygen demand will not be able to be met if the crab is in a dry environment, and death will soon ensue.

Although imperative for survival to prevent fluid loss from the body and to keep the gills moist, keeping crabs submerged in seawater is not obligatory.

As previously mentioned, Barnett (1982) reported successfully maintaining Dungeness crab out of water for short periods of time as long as the humidity was kept over 70 percent and the temperature kept low (<45 degrees Fahrenheit). Spider crabs, Chionoecetes opilio, have been reported successfully held for four days in moist air near freezing in boxes (Miller, 1977). McLeese (1965) in a study keeping lobsters alive out of water concluded that this was possible primarily if the need for oxygen was kept at a minimum. Large body temperature reductions and starvation of the lobster before testing led to the highest rates of survival. Starvation and large temperature drops decrease metabolism. At low metabolic rates oxygen demand is minimized. If an aquatic crustacean is to be maintained out of an environment from which it can obtain oxygen it seems imperative to keep its oxygen need as low as possible.

2.2 Current Recommendations for Live Crab Holding and Transportation

Barnett (1982) in Proceedings of the First National Conference on Seafood Packaging and Shipping pointed out that much of the information available about lobster shipment is also applicable to crab transportation. He stated that much is known about the handling and shipping of live lobster. Well managed programs that were developed from a thorough knowledge of the conditions that lobsters can tolerate in and out of water were recognized to be essential if lobsters were to be marketed successfully. An existing world wide market for live lobsters is verification of the validity of this attitude. Barnett maintains that the conditions necessary for the handling and shipping of live lobsters are applicable to the handling and shipping of other shellfish, including crabs.

A review of suggestions for live American lobster storage and shipment will precede live Dungeness crab recommendations.

2.2.1 Live American Lobster, Homarus americanus, Shipping and Holding Information

Lobsters appear to be able to tolerate starvation. McLeese (1964) has held lobsters without food for seven months. The lobsters remained active and apparently healthy with no increased incidence of mortalities. Live weight did not change but meat yield was reduced by about 35 percent. Other groups of lobsters have been starved for periods up to 4 months without any increase in cannibalism. Cannibalism occurs among even well-fed lobsters.

McLeese (1964) also noted that after feeding, the oxygen consumption almost doubles and remains high for three or four days. His conclusion was to feed with caution particularly in low flow water tanks. Cornick and Stewart (1977) concluded that administering a minimal amount of food while holding at 41 degrees Fahrenheit with adequate filtration for several months maintains muscle weight longer than complete starvation.

The four parameters; temperature, salinity, oxygen, and humidity, are interrelated and the tolerance limits of one may be influenced by the others. For example, at correct salt and high oxygen concentrations lobsters can tolerate temperatures up to 87 degrees Fahrenheit. Yet by dropping the salinity 1.5 percent, 79 degrees Fahrenheit is lethal (McLeese, 1964).

Ayres and Wood (1978) warned that high concentrations of metabolic waste products, if allowed to accumulate can prove toxic. Copper, brass, bronze, lead, zinc, some formulations of stainless steel, and some insecticides are also toxic to lobsters. Care must be taken to not inadvertently expose them to these products.

During air shipment lobsters are exposed to pressure fluctuations. Biologists in Maine have shown that lobsters appear unaffected by such pressure changes. One experiment dropped the pressure from normal to the equivalent pressure at 50,000 feet in one minute without harm to the lobsters (McLeese, 1964).

2.2.2 Live Dungeness Crab, *Cancer magister*, Shipping and Holding Information

Harold Barnett of Northwest and Alaska Fisheries Center in Seattle, Washington has published several articles on live shipment of Dungeness crab and seafood in general (1969, 1973, 1982).

Barnett (1982) cited injury due to rough handling before and during packaging as one of the causes of mortalities when shipping live seafood. Careful handling from fishing vessel to retail outlet is important.

He concluded that before shipment the animals should be held in a seawater holding tank for at least 24 hours. Crab should not be fed during this time and the weak ones should be separated out. A low storage temperature recommended at 35 degrees Fahrenheit also reduces the metabolic rate and makes them easier to handle.

During shipment, temperatures must be kept low and humidity high. Once carefully packed to insure both of these conditions shipment should proceed as quickly as possible.

2.3 Air Shipment Standards

When designing a container to be used for transportation of a particular product, one must not only consider the needs of the product but also consider the demands of the transporter. Traditional air freight tonnage that existed for many years has been decreasing (Schorr, 1982). New markets needing transport are particularly attractive to airlines at this time. Transporting fresh seafood is one such market. Unfortunately there have been problems in packaging in this area which have caused economic losses for the airlines. Proper packaging is an economic necessity for both the airlines and the seafood industry. Guidelines set forth by the airlines are not meant to discourage seafood shipments but rather to make it a profitable venture for both parties. By meeting these standards the seafood industry keeps one of the fastest available avenues of transportation open to themselves.

Preventing saltwater leakage is a big concern of the air transport industry. Knowing the nature of the product being shipped is important. Heilgeist (1982) cited an example where live Dungeness crab was being shipped in styrofoam boxes from Alaska to San Francisco. The crab dug holes in the boxes and fluid leaked throughout the aircraft. Saltwater is very corrosive to many metals and it cost the company $100,000 to fix the plane. Not only does this brine damage aluminum and aluminum alloys extensively but also it eats into electrical wiring which could cause serious control problems in flight (Schorr, 1982). Fish odors cause secondary problems for the airlines, too, particularly on passenger flights.

Alaska Airlines, Continental Airlines, and Eastern Airlines all adopted similar policies in 1982 to deal with seafood shipping. Successful adherence to these requirements have resulted in profits for both the air freight and seafood industry.

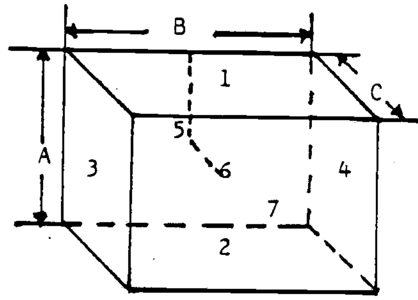
Continental Airline's policies (1982) pertinent to this project included that the product be sealed in one four-mil polyethylene bag, or two, two-mil polyethylene bags and that no wet ice should be used, only gel ice or dry ice. Other airlines' requirements and international standards also agree with these policies (IATA, 1980; Ashby, 1981).

Dry ice was not used in this project as the carbon dioxide gas released as it sublimes could prove harmful to the crab and to other live animals in the hold. Gel ice, a frozen gel consisting of a 1 percent non-ionic polymer and 99 percent water encased in a plastic pouch, was used.

3. CONTAINER EVALUATION PROGRAM

Temperature control (which is done by manipulating heat transfer) was the most important factor considered in designing and evaluating containers for live transport of Dungeness crab. It was mandatory to maintain low temperatures for crab survival. Mortalities would result in decreased product quality and monetary losses would make the whole project economically unfeasible. Before control can be exercised the correct average temperature of the thermal mass being contained must be predicted. This will ascertain if more control is desired. A computer program was developed to predict the average temperature of the contained thermal mass if initial conditions, boundary conditions and time length of shipment were known. To test the accuracy of the program an experiment was run which measured the average temperature of the contained thermal mass with thermocouples. An average thermal mass temperature was calculated so there would just be one figure with which to work. Figure 3 shows the thermocouple positions throughout the thermal mass inside the containers.

Thermocouple Positions
1. Center top of mass
2. Center bottom of mass
3. Center end of mass
4. Center end of mass
5. Center side of mass
6. Center of mass
7. Center side of mass



Container Dimensions
A. Height
B. Length
C. Width

Figure 3. Thermocouple positions used in determining the average temperature of the contained thermal mass.

A weighted average of the recorded temperatures was then used to determine an average thermal mass temperature (equation (2)).

$$T = \frac{(1+2(6)+2) + B/A(3+2(6)+4) + C/A(5+2(6)+7)}{(A+B+C)/A} \qquad (2)$$

where:

T = average temperature of the contained thermal mass, degrees Fahrenheit,

1,2,...7 = recorded temperature, degrees Fahrenheit,

A = height of container, inches,

B = length of the container, inches

C = width of the container, inches.

The experimental and computer predicted time-temperature curves were then compared. Close correlation of the curves would validate the computer model.

3.1 Development of the Container Evaluation Computer Program

The container evaluation program consists of two parts. The first section models temperature change over a given time period and calculates heat absorbed by the thermal mass during designated time intervals. Time intervals should not be longer than the time lapse that occurs during a 5 degree Fahrenheit increase in average thermal mass temperature. (Otherwise the heat transfer rate will be inaccurate and the thermal mass will not be modeled correctly.) It also sums the heat absorbed in each interval for use later in the program. The second section determines if the container is adequate to maintain the product at or below a given maximum temperature or if a modification is needed. Two modifications are given as options: adding gel ice as a refrigerant or adding a selected insulation material. If modifications are necessary the program then calculates approximately how many pounds of gel ice or how many inches of designated insulation should be added to the container. The program is able to accommodate changing ambient conditions, different temperatures and convection coefficients for varying time periods. Appendix A contains inputs and outputs of the program and a program listing.

The amount of heat that is transferred into the container is dependent upon the difference between the ambient, T(A), and inside, T(I), temperatures. The larger this difference, the larger the heat transfer rate for a given set of conditions. As the thermal mass inside the container heats up this difference lessens and a smaller rate of heat transfer occurs. This can be better visualized by looking at equation (3).

$$q = UA(T(A)-T(I)) \tag{3}$$

where:

q = heat flow, Btu/sq ft·hr,

U = overall heat transfer coefficient, Btu/sq ft·hr·F,

A = surface area, sq ft,

T(A) = ambient temperature, degrees Fahrenheit,

T(I) = average thermal mass temperature, degrees Fahrenheit.

If U and A remain constant then it can easily be seen that the larger the quantity, T(A)-T(I), the larger the value of the heat flow, q. The model used equation (3) to determine how much heat entered the container during a given time interval. (Heat flow, q, must be multiplied by a time interval in hours to determine total heat absorbed, Q.) As heat enters the container the inside temperature of the thermal mass will rise. The new average inside temperature can be calculated using equation (4).

$$T = (Q/(C_pM)) + T(o) \tag{4}$$

where:

T = new inside temperature, degrees Fahrenheit,

T(o) = old inside temperature, degrees Fahrenheit,

Q = total heat entering container for a given time period,

C_p = specific heat of thermal mass, Btu/lb.F

M = thermal mass, lbs.

A change in inside temperature causes a change in the heat transfer rate. The program returns to equation (3) and again calculates the total heat entering the container for a given time period. The loop continues until the time limit for a given set of conditions has been reached.

The mass of the containers was neglected in the program calculations as it was small (less than 10 percent) when compared to the mass of the inside product (see Table 1). The effect when the container mass was included on the final temperature was less than .5 degree Fahrenheit.

Table 1. Container mass percentage of total weight.

CONTAINER	CONTAINER MASS/TOTAL MASS, PERCENT
Tech Pak	4.1
P.E.S.	2.2
Tempress	2.2
American Dry Ice	1.9
Optimized design	9.4
Corruguard	2.3
T.L.C.	2.9
World Container	8.7

Equation (5) shows how U, the overall heat transfer coefficient, was calculated for the program.

$$U = 1/(1/H1 + L1/K1 + 1/H2) \tag{5}$$

where:

H1 = outside convection coefficient, Btu/sq.ft. hr·F,

H2 = inside convection coefficient, Btu/sq ft· hr· F,

L1=wall thickness, ft,

K1=overall thermal conductivity of container wall, Btu/ft·hr·F.

All tests were run under free or natural convection conditions in an effort to simulate conditions in air cargo holds. Free convection of gases is considered to range from 1 to 5 Btu/sq ft·hr·F (Arpaci, 1966). Convection coefficients were calculated during one of the experimental tests using the ambient temperature, the surface temperatures (inside and outside) of the container, the average thermal mass temperature, and the measured heat flow (see p. 42) (equations (6) and (7)).

$$H(O) = q/(T(AMB) - T(O)) \tag{6}$$

where:

H(O) = outside convection coefficient, Btu/sq ft.h.F,

q = measured heat flow, Btu/sq ft·hr,

T(AMB) = ambient temperature, degrees Fahrenheit,

T(O) = outside surface temperature, degrees Fahrenheit.

$$H(I) = q/(T(I) - T(AVE)) \tag{7}$$

where:

H(I) = inside convection coefficient, Btu/sq ft.h.F,

q = measured heat flow, Btu/sq ft.hr,

T(I) = inside surface temperature, degrees Fahrenheit,

T(AVE) = average thermal mass temperature, degrees Fahrenheit.

The average outside convection coefficient calculated was 1.09 Btu/sq ft.hr.F and the average inside convection coefficient calculated was 2.35 Btu/sq ft.hr.F. The inside convection coefficient included some conduction heat transfer in its measurement and was therefore larger than the outside coefficient. The temperature of the thermal mass in an insulated container is primarily influenced by the thickness and thermal conductivity of the walls. The more insulation is added, the smaller the convection effect on the temperature. Examples of two containers modeled in this project, the American Dry Ice container and the optimum design box, will be used to illustrate this point. When the outside convection coefficient was increased 500 percent (from 1 to 5 Btu/sq ft.hr.F) for the American Dry Ice container example, the ending average thermal mass temperature increased only 1.5 degrees Fahrenheit (4 percent). The optimized design container (which has a lower overall heat transfer coefficient than the American Dry Ice container) had a .9 degree Fahrenheit increase (2 percent) in the average thermal mass temperature when the outside convection coefficient was increased 500 percent. It was then decided to use the rounded values of 1 and 2 Btu/sq ft·hr·F as the outside and inside convection coefficients respectively, as an exact value was not that influential on the final average thermal mass temperature. The net rate of radiant energy exchanged between surfaces is dependent upon the temperature difference between those surfaces. As there was no radiant energy source present during the experiment the temperature differences between the containers and surrounding surfaces was small. Radiation effects were therefore not included in the program inputs. Appendix B explains how to include them when applicable by combining them with the outside convection coefficient.

The second subroutine starting with line 490 (see Appendix A) calculates the average thermal mass temperature changes in a stepwise routine until the desired total time at these conditions has elapsed. The first subroutine, starting with line 390 allows the user to switch ambient conditions as many times as desired. For instance, if the container will be outside for an hour before it is loaded on the plane, the outside convection coefficient and ambient temperature will be different in each environment. The over-all heat transfer coefficient and heat transfer rate will be different in each set of circumstances. The program takes the last average thermal mass temperature, calculates a new U using the new outside convection coefficient, and uses the new average ambient temperature and total time at this temperature in the second subroutine (beginning at line 490). Stepwise modeling is continued using the initial time intervals until the total time at this ambient temperature has been reached. The first subroutine once again gives the user the option to either quit or continue calculations dependent on whether the journey being modeled has reached completion.

Once the inside temperature has been predicted, the next step is to decide if the container is adequate for the shipment or if it needs modifications. A maximum desired inside temperature is part of the input information at the beginning of the program. The program tells the user that the container is adequate when the inside predicted temperature is not greater than this value. If the predicted end temperature is greater than the maximum desired inside temperature, the program calculates how much gel ice is needed or how much insulation should be added to keep the temperature within the desired limit. The user may then decide which suggestion is most practical for his circumstances or add some of the suggested insulation and rerun the program to determine the quantity of gel ice subsequently necessary.

The calculations for additional insulation assumed the thermal mass had been subcooled. Because the thermal mass had been subcooled it could absorb some heat before reaching the maximum desired temperature. This acceptable amount of absorbed heat, W, is calculated in equation (8).

$$W = C_p M \, (DT - ST) \qquad (8)$$

where:

C_p = specific heat, Btu/lb.F,

M = mass, lbs,

DT = maximum desired temperature, degrees F,

ST = initial temperature of subcooled product, degrees F,

W = acceptable amount of absorbed heat, Btu's.

An overall heat transfer coefficient, U2, is then calculated using the acceptable amount of absorbed heat as the design parameter (equation (9)).

$$U2 = W/((AA-((DT+ST)/2))ATR) \tag{9}$$

where:

AA = weighted average ambient temperature, degrees Fahrenheit,

A = inside surface area, sq ft,

TR = total travel time, hrs,

(DT+ST)/2 = average inside temperature, degrees Fahrenheit

U2 = acceptable overall unit conductance, Btu/sq ft·hr·F.

From this overall heat transfer coefficient, U2, the thickness of the insulation specified to be added can be calculated (equation (10)).

$$L2 = (K2((1/U2)-(1/HO)-(1/H2)-(L1/K1)))12 \tag{10}$$

where:

K2 = thermal conductivity of insulation material to be added, Btu ft/sq ft·hr·F,

HO = weighted average outside convection coefficient, Btu/sq ft.hr.F,

L2 = thickness of insulation to be added, ft,

H2 = inside convection coefficient, Btu/sq ft.hr.F,

$L1$ = wall thickness of existing container, ft,

$K1$ = thermal conductivity of container, Btu·ft/sq ft.hr.F

The amount of gel ice to add was computed by first determining the total heat load expected (using "worst case" ambient conditions) and then dividing this heat load by the latent heat of fusion of gel ice (equations (11) and (12)). In conversations with a biochemist that developed a gel ice formulation (Fenske, 1985) it was confirmed that the latent heat of fusion is essentially the same as water. Gel ice is 99% water and 1% non-ionic polymer. The bonding between the two is weak hydrogen bonding. The weakness of the binding and inertness of the polymer lead to little shift away from the properties of water. A safety factor of 2 was used in calculating the amount of gel ice needed. During the design improvement tests it was observed that the amount of surface area exposed to the incoming heat, the thickness of the gel ice pack, and the amount of convection inside the container all influence the melting rate of the gel ice. The faster the gel ice melted the more heat it absorbed. The gel ice packs at the end of the first gel ice placement test were observed to be 40 to 60 percent melted. Roughly half of the heat absorbing potential of the gel ice was realized. Twice as much gel ice was suggested by the program as compensation. The safety factor may be altered by the user to adjust for variance of melting rates due to size and geometry of the packs and the amount of inside free convection.

$$Y = (HA-ST)UATR \tag{11}$$

where:

Y = total expected heat load, Btu's,

HA = highest ambient temperature, degrees Fahrenheit,

ST = starting temperature of thermal mass, degrees Fahrenheit,

U = overall heat transfer coefficient, Btu/sq ft.hr.F,

A = inside surface area of container, sq ft,

TR = total travel time, hr.

$$Z = (Y/143.4))2 \tag{12}$$

where:

Z = mass of gel ice needed, lbs,

143.4 = latent heat of fusion of gel ice, Btu/lb,

2 = safety factor.

The suggested amounts of gel ice and insulation to add should be considered guidelines not guarantees.

3.2 Materials

Seven commercial containers and one container developed for this project were tested to determine their time-temperature curves and thermal conductivities. A wide variety of sizes, shapes, and materials used in the containers were chosen. One container was returnable, the rest were disposable. The broader the spectrum of containers tested and successfully modeled, the more universal the applications of the program. A summary of information about the containers is shown in Table 2 and Figure 4. Inside dimensions and inside surface areas were used in the program. The wall thicknesses were weighted averages as the thickness can vary in different areas of the container.

Table 2. Container information summary.

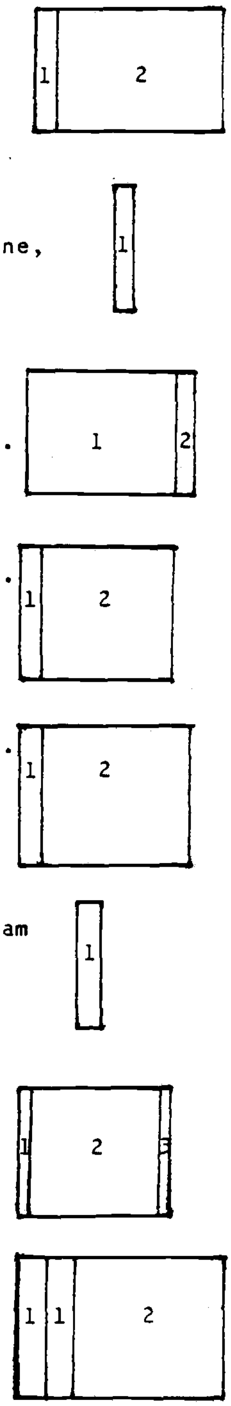
Container/ Manufacturer (Telephone)	Inside Dimensions (inches)	Inside Surface Area (sq.ft.)	Wall Thickness (inches)
Tech Pak, Inc. Chelsea, Mass. 02150 (617-884-9000)	6x14x11.5	4.5	1 1/4
P.E.S. Processing Equipment Sales, Inc. PO Box 70469 Seattle, WA 98107	26x10x8	7.6	1/8

Table 2. Container information summary. (cont'd.)

Container/ Manufacturer (Telephone)	Inside Dimensions (inches)	Inside Surface Area (sq.ft.)	Wall Thickness (inches)
T.L.C. Tom Madderon & Martin Stott Salem, Oregon (503-623-6665)	25x28x42	40.2	1 1/8
Tempress Fresh Pak Tempress, Inc. 701 South Orchard Seattle, WA 98108 (206-762-1410)	31.5x15x8	11.7	1
American Dry Ice Type E American Dry Ice 672 S. Orcas Seattle, WA 98108 (206-767-6671)	40x26x22.5	35.2	1 1/8
Corruguard Wet-lock Box Cherokee Container Co. 515 Lunt Avenue Schaumburg, Ill. 60193	29.5x15x8	11.1	5/32
World Container Keeper World Container Corporation 1 Appletree Sq Suite 1149 Minneapolis, MN 55420 (612-854-7748)	22x17x17	14.6	1
Optimum Design Box Constructed for this project.	21x22x17.5	16.9	1 3/8

CONTAINER	WALL LAYER DESCRIPTIONS
Tech Pak	1. Cardboard, 1/8 in. 2. Molded polystyrene, 1 1/8 in.
P.E.S.	1. Lightweight corrugated (3 corrugations/inch) high density polyethylene, 1/8 inch
T.L.C.	1. Asphalt based foil and isocyanate, 1 in. 2. Waxed cardboard, 1/8 in.
Tempress	1. Waxed cardboard, 1/8 in. 2. Polystyrene, 7/8 in.
American Dry Ice	1. Waxed cardboard, 1/8 in. 2. Polystyrene, 1 in.
Corruguard	1. Extruded polystyrene foam and paper, 5/32 in.
World Container	1. Polyethylene, 1/16 in. 2. Polyurethane foam, 7/8 in. 3. Polyethylene, 1/16 in.
Optimum design box	1. Corruguard, 2 sheets, 3/8 in. 2. Isocyanate between asphalt and foil, 1 in.

SCALE CROSS SECTION



outside → inside
3/4" = 1"

Figure 4. Cross sectional views of container walls.

The World Container Keeper was returnable, the rest disposable. There was no large economic advantage of one container over the rest. The returnable container was meant to be leased so the monthly cost was comparable to the disposable containers' costs.

To experimentally check the heat absorbed by a contained product over a given period of time, a thermal mass was needed that would have a known weight and specific heat. It was also important that this thermal mass simulate crab's thermal reaction and that it not freeze at the temperatures the crab would be shipped, 25 to 30 degrees Fahrenheit, so that the latent heat of fusion wouldn't be a consideration. From a practical standpoint it also needed to be inexpensive and easy to handle for the person running the tests. The larger containers would hold approximately 450 pounds of thermal mass. The specific heat of fish is .86 Btu/lb.F (Henderson and Perry, 1976), the specific heat of oysters and clams was .89 Btu/lb·F, and lobster's specific heat was .83 Btu/lb·F (ASHRAE, 1982). A 13.25 percent by weight solution of sodium chloride has a specific heat of .86 Btu/lb·F (ASHRAE, 1972). It was decided to fill surgical gloves with a 13.25 percent by weight saline solution to use as the thermal mass. The shape of the gloves would hinder fluid movement so that it would more closely mimic the thermal reaction of a solid. The saline solution would not freeze above a temperature of 15 degrees Fahrenheit and was inexpensive.

In considering these containers for shipping live Dungeness crab it was important to determine that the gloves simulated the thermal response of crab. It had been theorized that at the temperatures considered for shipment, a live crab's metabolic processes would generate negligible heat and add little to the overall thermal response of the container. A test was conducted to verify these points.

A live Dungeness crab (1.61 lbs) and two saline filled gloves (1.72 lbs each) were chilled to 37 degrees Fahrenheit. They were then moved to ambient conditions of 70 degrees Fahrenheit and free convection. Two thermocouples were inserted through the shell on the back of the crab into the main body. The heart could be observed (through the hole) beating throughout the entire experiment. Thermocouples were also placed in the middle of the gloves. The two temperatures from the crab and from the gloves were each averaged and the results plotted against time. The largest spread for the temperatures averaged was .6 of a degree Fahrenheit for the crab and 1.9 degrees Fahrenheit for the saline gloves. Figure 5 compared the thermal responses of each. The glove curve is not as smooth as the live crab curve as the glove thermocouples were accidentally moved at the time the aberration in the curve occurs. A very close correlation between the gloves and crab was shown and it was assumed that the gloves could be used to simulate the thermal response of the crab.

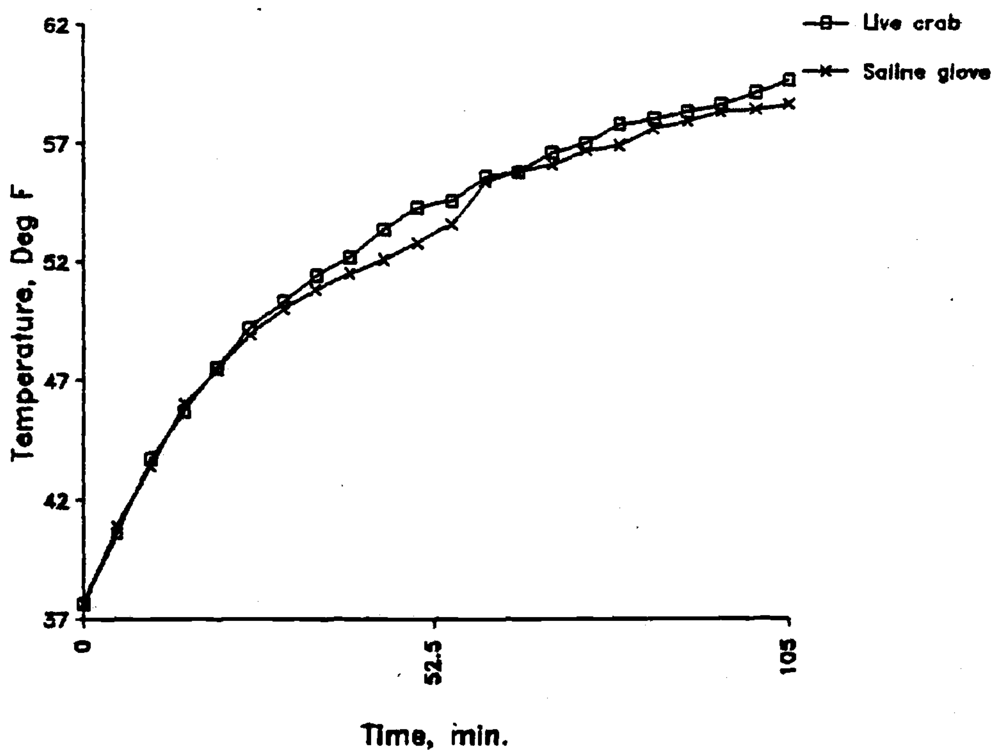


Figure 5. Live crab vs saline glove thermal response.

Measuring heat flow through the container walls was important in many aspects of the project (Figure 6). Heat flow was measured using two sensors manufactured by Concept Engineering, 43 Ragged Rock Road, Old Saybrook, Connecticut, 06475. Heat flowing through the sensors causes a slight temperature difference across the device. This temperature gradient is directly proportional to heat flux. Multiple miniature thermocouple junctions (thermopile) properly oriented within the transducer generate a millivolt output. This output was recorded on the Esterline Angus data logger. The millivolts were multiplied by a calibration constant which was furnished with each sensor. The result was heat flow in units of Btu/sq ft·hr with an accuracy of plus or minus 2 percent.

Gel ice was used as a refrigerant. Airlines require that gel ice rather than ice be used to prevent leakage problems in seafood shipments. A non-toxic polymer is mixed with water to form a gel. This gel is placed in a puncture resistant pouch. Once frozen gel ice can absorb 143.4 Btu/lb F (latent heat of fusion).

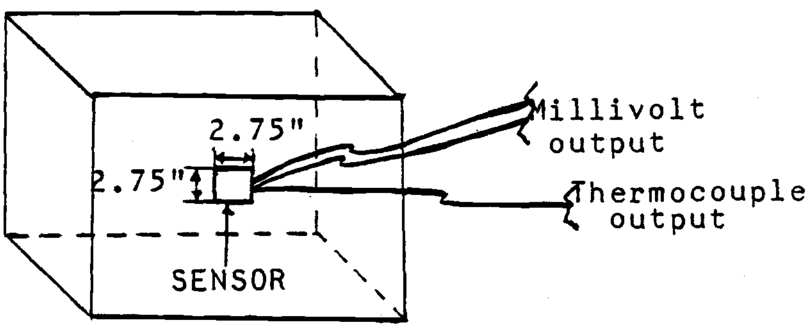


Figure 6. Heat flow sensor on a typical container wall.

3.3 Experimental Procedure

Each of the containers was filled with a known weight of surgical gloves prechilled to around 30 degrees Fahrenheit (Table 6 lists initial temperatures) that contained 13.25 percent by weight sodium chloride solution. The tests were run at room temperature (see Table 5 for average ambient temperatures). Thermocouples were placed throughout this "thermal mass" and the increasing temperatures recorded at given intervals. Ambient and surface (inside and outside) temperatures were also recorded. There was a temperature gradient with the center of the thermal mass being cooler than the edges and the bottom being cooler than the top. An example of the temperature variance of the thermal mass inside one of the medium sized containers tested (Tempress) can be seen in Table 3. Temperatures were recorded on the outside edges and center of the mass.

Table 3. Temperature variance of thermal mass in Tempress container.

TIME, HRS	RANGE (F)	AVERAGE (F)	RANGE SIZE (F)
0	31.2-32.9	31.9	1.7
1	31.8-33.5	32.1	1.7
2	32.7-34.6	33.1	1.9
3	33.3-35.0	33.7	1.7
4	33.8-35.5	34.3	1.7
5	34.3-36.4	34.9	2.1
6	35.2-37.0	35.8	1.8
7	35.7-37.6	36.4	1.9
8	36.7-38.6	37.3	1.9
9	37.2-39.1	37.7	1.9
10	37.9-39.7	38.5	1.8
11	38.6-40.2	39.0	1.6
12	39.1-40.7	39.6	1.6
13	39.5-41.4	40.3	1.9
14	39.9-41.8	40.7	1.9
15	40.6-42.1	41.1	1.5
16	41.3-42.8	41.8	1.5
17	41.7-43.5	42.5	1.8

Of the containers tested for this project, Tempress had an average insulation value. The largest range of temperatures in the thermal mass was 2.1 degrees Fahrenheit. The average thermal mass gradient divided by the difference between the average ambient and the average inside thermal mass temperature was 5.8 percent. Containers with increased insulation would have even smaller gradients within the thermal mass. Therefore it was considered acceptable to use average temperature values for the thermal masses. These average temperatures were considered to occur in the central horizontal plane in the middle of a symmetrical quarter of the length and width.

Accurate thermal conductivity values were needed for the computer model. These were determined experimentally using the heat flow sensors. The heat flow surface temperatures (inside and outside) and wall thickness were all measured and used in equation (13) to determine thermal conductivity, k.

$$k = q/A\ (x/(T(O)-T(I))) \tag{13}$$

where:

q/A = heat flow, Btu/ sq ft·F,

x=wall thickness, ft,

T(O)=outside surface temperature, degrees F,

T(I)=inside surface temperature, degrees F,

k=thermal conductivity, Btu ft/sq ft · hr · F.

These measurements were taken at the same time the inside temperature history was being recorded. The measurements were taken repeatedly at given time intervals so that both an average k value and a 95 percent range could be statistically determined (see Appendix C).

3.4 Results and Discussion

Temperature change of the thermal mass over a given time period was monitored experimentally. The computer program determined how much heat entered the container and then predicted the temperature change of the thermal mass using the weight and specific heat of the mass. Correlation of these end temperatures validated the model.

The thermal conductivity, k, values used in the computer were determined by using the heat flow sensor. The average k values for the containers can be viewed in Table 4. Appendix C lists the 95 percent confidence ranges, standard deviations of these values, the temperature ranges in which they were measured, the averages, and an example showing how a calculated thermal conductivity value compares with an experimental measurement.

Table 4. Experimentally determined thermal conductivity values of container walls.

CONTAINER	THERMAL CONDUCTIVITY (Btu/ft·hr·F)
Tech Pak	.016
PES	.059
Corruguard	.011
Tempress	.020
TLC	.015
American Dry Ice	.020
World Container	.011
Optimized design	.012

Appendix D contains tables for each of the containers listing the average inside temperatures found experimentally and by the computer model on an hourly basis.

Ambient temperature ranged 4 to 13.9 degrees Fahrenheit during the experiments. The Tech Pak experiment showed the greatest ambient temperature range, 13.9 degrees Fahrenheit. Figure 7 shows a comparison of time temperature curves of Tech Pak using varying ambient conditions (A) and average ambient conditions (B). Results in this "worst case" example justify using average ambient temperatures in the other programs.

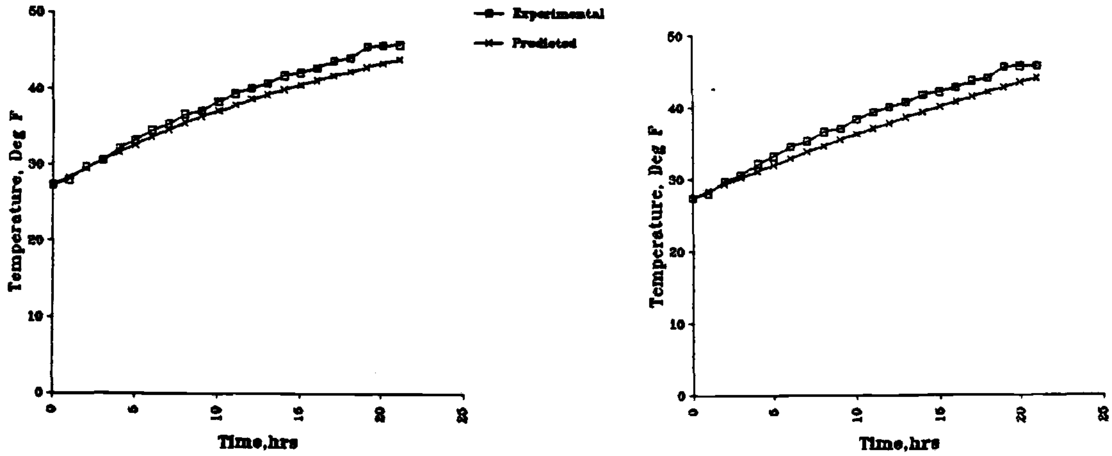


Figure 7. Tech Pak time temperature curves using varying ambient (A) and average ambient (B) temperatures in the computer program.

An average ambient temperature was calculated for each container experiment to be used in the computer program (Table 5).

Table 5. Average ambient temperatures for each container experiment.

CONTAINER	AVERAGE AMBIENT TEMPERATURE (F)
Tech Pak	70.6
PES	64.6
Corruguard	72.9
Tempress	67.8
TLC	88.0
American Dry Ice	88.0
World Container	67.8
Optimized design	67.7

The output printouts and input values for each container are compiled in Appendix A. Ambient temperature, inside starting temperature, and total length of time were determined by the experiment which they were modeling. Polystyrene was arbitrarily chosen as the insulation to add, if necessary, in each case and its thermal conductivity value used.

To further clarify how the program works a hypothetical example was run (Appendix E). It demonstrates how the program handles varying ambient conditions. It also verifies that the correct amount of insulation to keep the average thermal mass temperature at or below 35 degrees Fahrenheit was predicted.

Figures 8-15 show a comparison between the predicted and experimental average thermal mass temperature results. The predicted curves are smooth because an average ambient temperature was used. The experimental curves reflect the margin of error involved in thermocouple measurement. The important correlation to insure high product quality is that the final temperatures are close. Table 6 compares the final experimental and predicted temperatures of all containers.

Table 6. Final container temperatures of experimental and model results

CONTAINER	INITIAL TEMP (F)	FINAL TEMP, EXPERIMENTAL (F)	FINAL TEMP, MODEL (F)	TIME (HRS)
Corruguard	26.3	56.3	56.7	23
TLC	23.5	37.0	39.1	22
Tempress	31.9	42.5	42.2	17
Tech Pak	27.3	45.7	44.0	21
PES	28.4	55.8	56.4	18
American Dry Ice	26.0	41.3	42.1	21
World Container	27.0	40.6	39.8	30
Optimized design	32.0	38.6	38.9	9

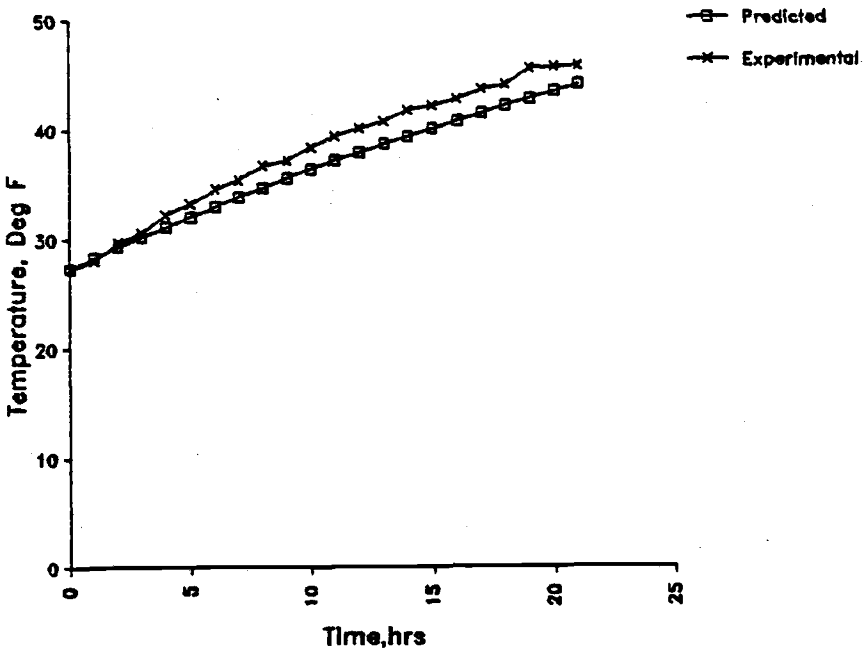


Figure 8. Time-temperature curves of Tech Pak experimental and computer model results.

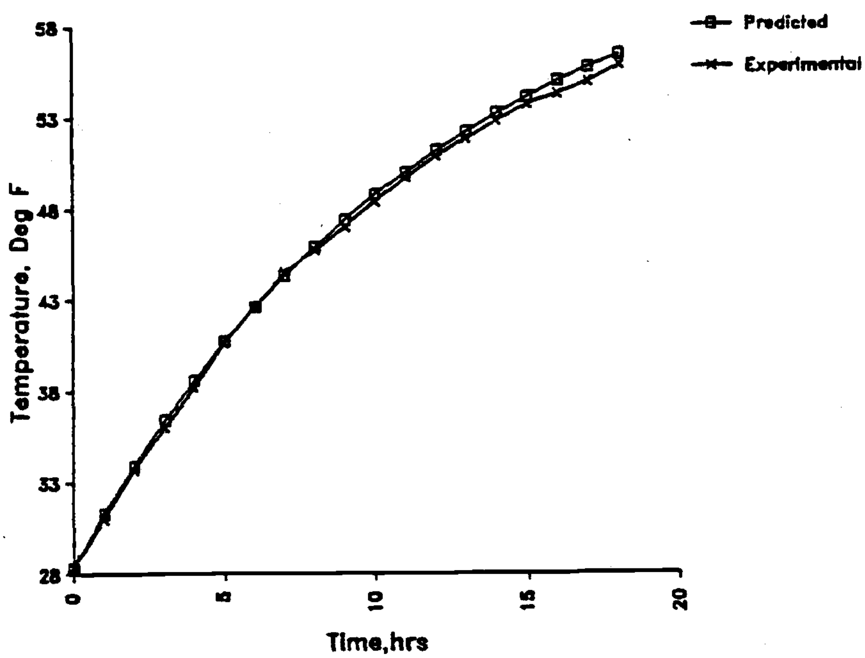


Figure 9. Time temperature curves of PES experimental and computer model results.

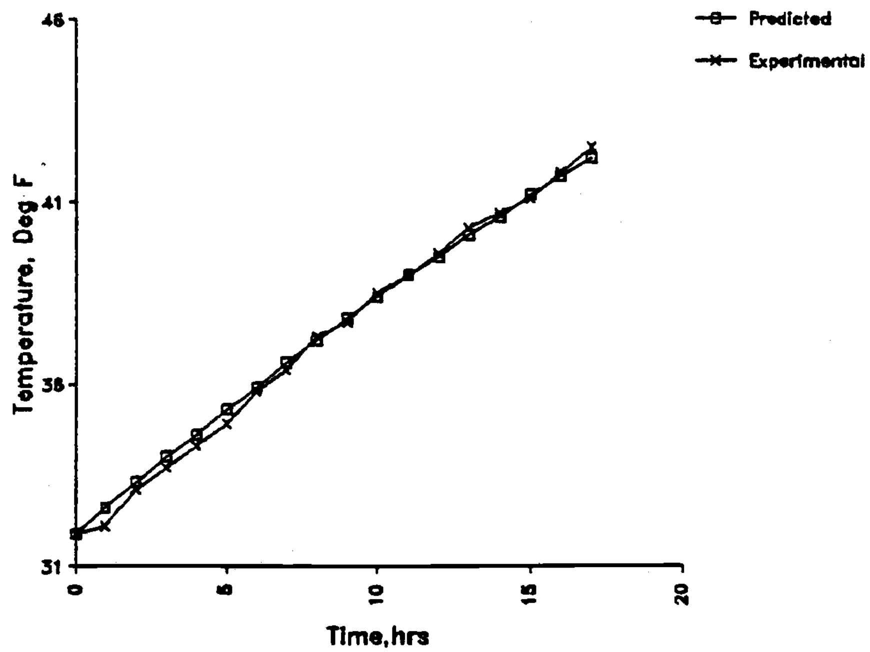


Figure 10. Time temperature curves of Tempress experimental and computer model results.

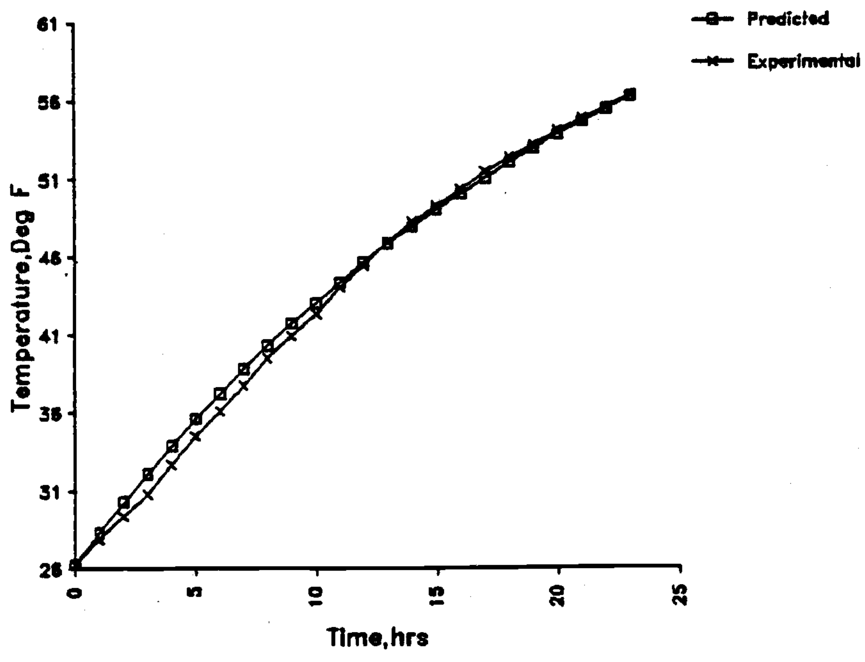


Figure 11. Time temperature curves of Corruguard experimental and computer model results.

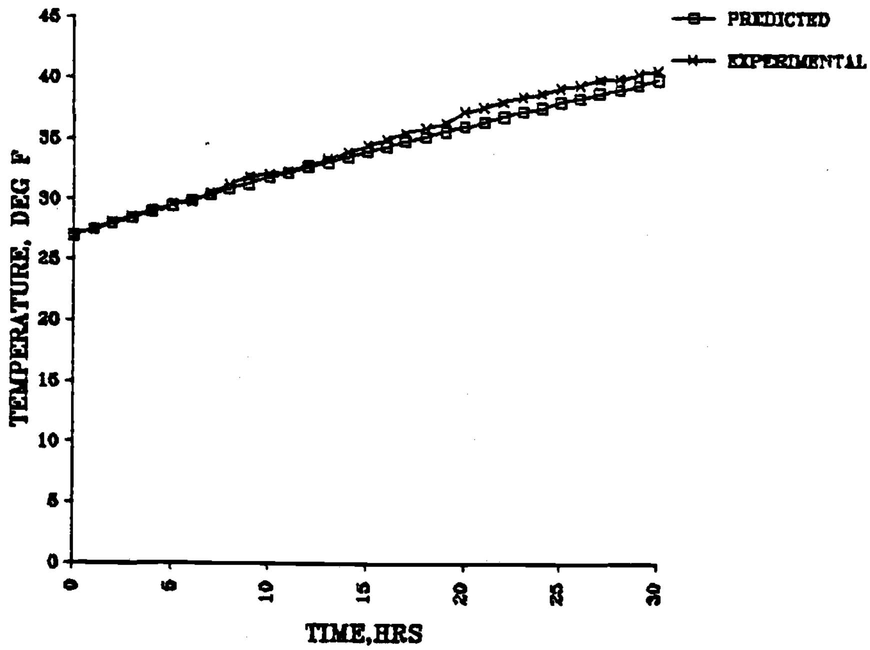


Figure 12. Time temperature curves of World Container experimental and computer model results.

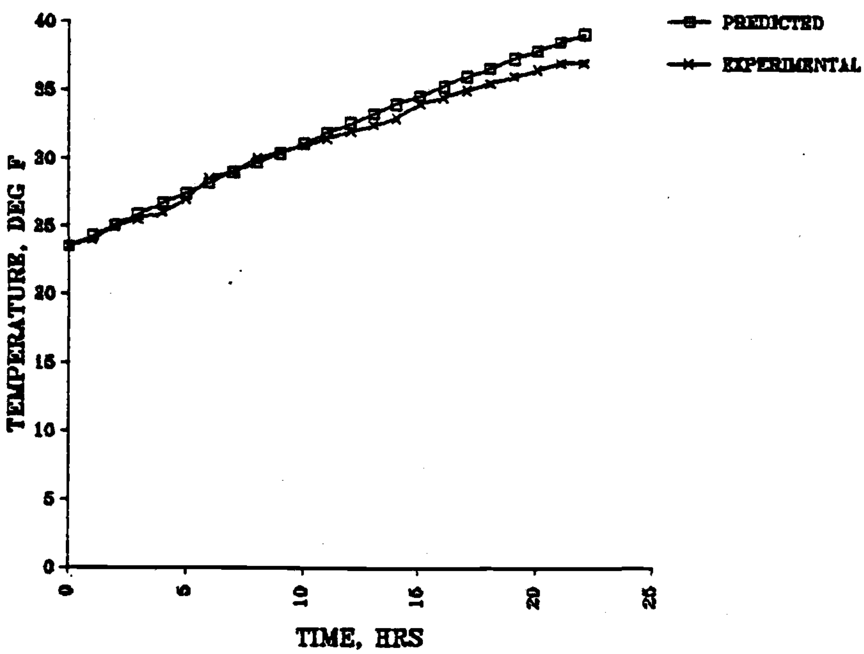


Figure 13. Time temperature curves of ~TLC experimental and computer model results.

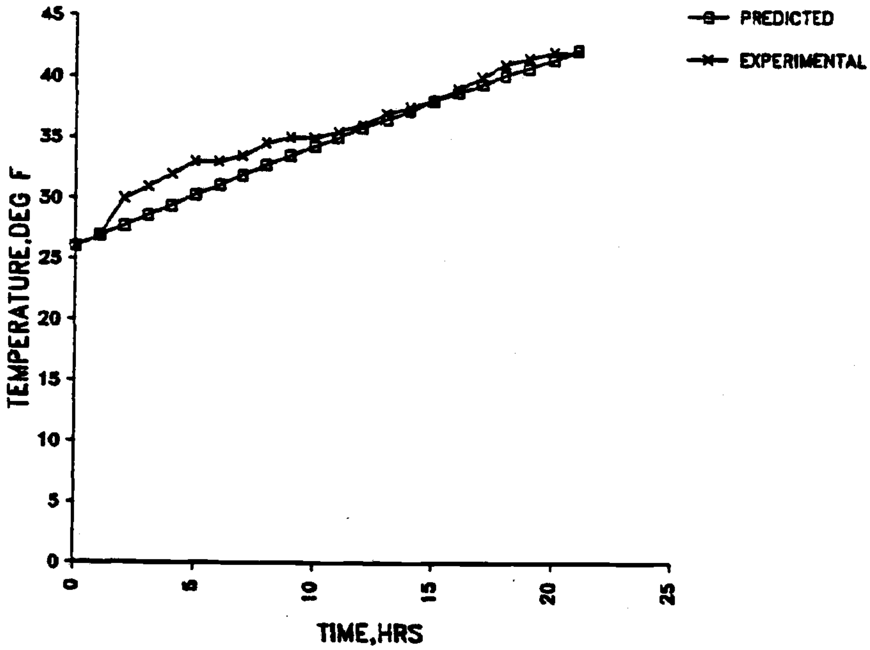


Figure 14. Time temperature curves of American Dry Ice experimental and computer model results.

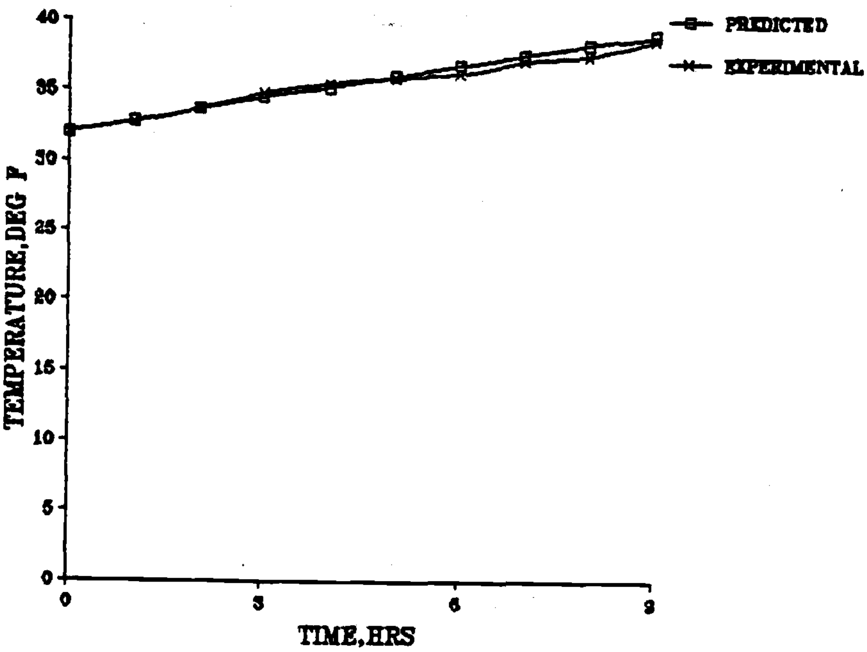


Figure 15. Time temperature curves of optimized design experimental and computer model results.

4. DEVELOPMENT OF THE OPTIMUM DESIGN CONTAINER

Airlines maintain their cargo holds around 65 degrees Fahrenheit to accommodate shipping warm blooded animals (Braniff Airlines, 1985). It was decided to design for an 18 hour flight, the time it would take for a shipment to go from Ketchikan, Alaska, to Los Angeles, California. Design considerations which influenced the development of the container created for this project then included: air shipment standards, biological requirements of crab, and a capability of maintaining an internal temperature of 35 degrees Fahrenheit for 18 hours in ambient conditions of 65 degrees Fahrenheit with free convection.

To meet airline regulation standards and biological requirements of Dungeness crab a container was developed that was leakproof and minimized heat transfer. The container evaluation program was used to ascertain that it was capable of maintaining an inside temperature of 35 degrees Fahrenheit or less for 18 hours assuming 65 degree Fahrenheit ambient conditions and free convection.

Materials for the construction of this container were chosen from the commercial disposable container materials obtained for this project. Corruguard and the isocyanate material used in the TLC container were selected because of their low thermal conductivities

(Appendix C lists thermal conductivity values). Corruguard was also picked as an outer layer because of its strength. It was needed to protect the isocyanate layer. Two layers of Corruguard were glued together for the outer layer (3/8 inch thick) and sections of isocyanate (one inch thick) cut to be placed inside for the inner layer.

The shape of the container was approximately cubic (see Figure 16).

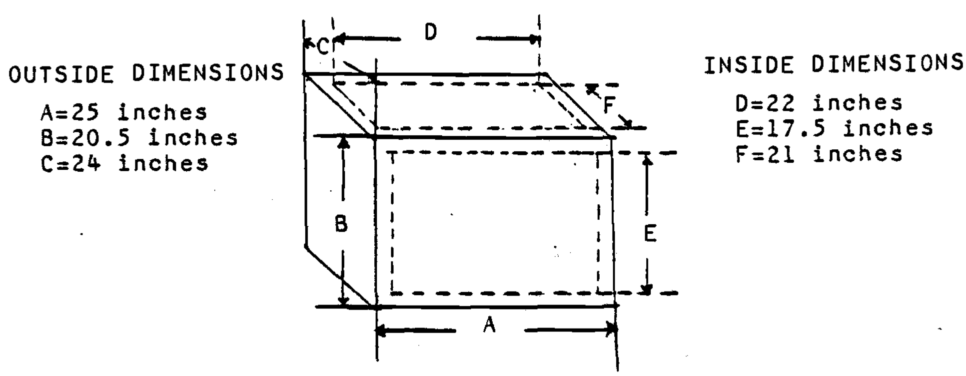


Figure 16. Dimensions of optimum design container.

A cube minimizes the surface area to volume ratio. The geometry of a cube maximizes the distance heat must be transferred to the thermal mass center. Available materials determined the final dimensions. Analysis of the centerline temperature for a slab on the Heisler charts proved that there was very little difference in the centerline temperature whether the limiting distance was 17.5 inches or 22 inches. Adherence to a strictly cubic structure was not necessary. Properties of 13.25

percent saline solution (which was shown experimentally to transfer heat at the same rate as live crab) and an 18 hour time period were used to determine the Fourier and Biot moduli (Table 7).

Table 7. Heisler chart values for 17.5 and 22 inch 13.25 percent by weight saline slabs.

Length (inches)	Fourier Modulus, $Fo=\alpha t/L^2$	1/Biot Modulus, $1/Bi=k/hL$	$\frac{T_c - T}{T_i - T}$
17.5	.1490	.09	.93
22	.0943	.07	.96

where

α = .0044 sq ft/hr,

t = 18 hrs,

k = .256 Btu/ft·hr·F

h = 2 Btu/sq ft·hr·F

T_c = centerline temperature, degrees F

T_i = initial mass temperature, degrees F

T = ambient temperature, degrees F.

Minimizing the surface area/volume ratio lowers heat transfer. The optimum design container was made as large as possible with the materials available while still maintaining an approximately cubic shape.

To insure that the container would not leak, two plastic bags were used inside. One between the isocyanate layer and the Corruguard and the other to encase the crab. This method provided a one inch layer of insulation between the crab and the last layer of water proofing. It was done to further insure saline leakage did not occur. The crab would have to penetrate a layer of plastic and one inch of insulation before reaching the outer plastic bag.

Four design improvement ideas were tested. They involved decreasing the heat flow and optimizing the efficacy of gel ice. A report of the design improvement tests and a theoretical analysis of the ideas is in Appendix F.

The first design improvement test was to determine if insulation should be added in the corners. During the experimental container evaluation tests temperatures in the inside surfaces of the corners of the thinner walled containers were observed to be higher than the other inside surface temperatures (see Appendix F). A larger temperature difference between the inside surface and the thermal mass would cause increased heat flow. Tests were run to determine if the temperature gradient was greater in the corners than along the sides. It was determined that more insulation was needed in the corners. Figure 17 diagrams the added insulation thickness in the corners of the optimum design box. The increased insulation thickness (.6 inch) reduced the overall heat transfer coefficient between the wall surfaces from .105 Btu/sq ft·hr·F to .074 Btu/sq ft·hr·F or 30 percent.

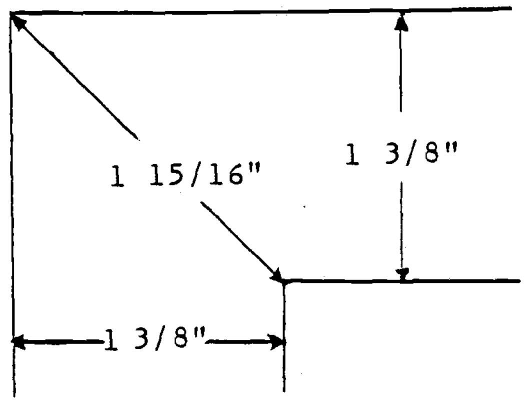


Figure 17. Corner diagram of optimum design box.

Placement locations of gel ice was another improvement test. Chattopadhyay and Bose (1979) conducted a study that proved the placement of ice in a plywood box lined with polyethylene film had an effect on the inside temperature. Varying ratios of the same total amount of ice were placed in the middle layer, on the top layer, and on the bottom layer. Conclusions were that the best icing method was with 5/8 of the ice on the top layer, 1/4 of the ice in the middle layer, and 1/8 of the ice on the bottom layer. Testing methods did not include placing all the ice on top or some on top and some on the sides. Additional placement tests were run to determine these effects. The greatest percentage of heat entering the container was absorbed by the gel ice when the gel ice was all placed on top of the thermal mass. Theoretically the largest temperature difference between the gel ice and the thermal mass would be on top of the thermal mass as heat rises. The larger the temperature gradient, the greater the heat flow. Consequently more heat would be absorbed by the gel ice. The surface area of one side of all the gel ice tested was in direct contact with the thermal mass. Placing all the gel ice directly on top of the thermal mass was used in the final simulated shipment (see Chapter 6) of live crab in both the optimum design container and the World Continer.

Compartmentalizing a container to decrease the net heat flow was a third idea tested. The theoretical and experimental results both showed that compartmentalization decreased net heat flow to the thermal mass when gel ice is not present. Placing gel ice on top of the compartments rather than directly on the thermal mass proved inferior. Compartmentalizing added insulation and decreased heat flow. However, the negative effect of putting a barrier between the gel ice and the thermal mass outweighed the benefits. The net heat flow into the thermal mass was greater in the compartmentalized container than in the control container when gel ice was present. It was determined by the container evaluation computer program that it would be necessary to include gel ice in the optimum design container for the final simulated shipment of live crab. It was therefore decided not to add compartments to the box design.

The fourth design improvement idea tested was including an air space between the encased thermal mass and the container walls. Experimentally it proved beneficial to include the air space with gel ice. Theoretically it was shown that the air space decreased heat flow into the container. It was also hypothesized that the air space increased heat absorption of the gel ice when free convection was increased. During the final simulated shipment boards were placed in the bottom of the optimum design box to create an air space between the thermal mass and the container walls (Figure 18).

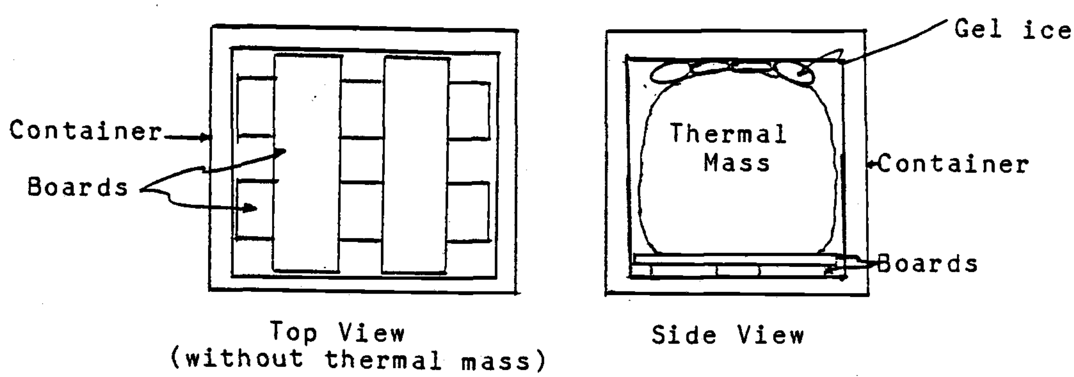


Figure 18. Optimum design container with air space surrounding thermal mass.

5. SUBCOOLING CRAB

Subcooling has been successfully used in the transport of fruits and vegetables. Theoretically prechilling a large mass a few degrees below the maximum desired temperature (subcooling) should be able to compensate for the entering heat load. The need for refrigeration units or ice which take up valuable space would then be eliminated (Lorentzen, 1979).

Subcooling the crab was not expected to absorb the entire heat load entering the container. It was assumed by the computer program that all products being transported would be subcooled. Assuming that a subcooled product would be shipped was a design condition used to determine how much insulation to add. Prechilling the product to be shipped eliminates an additional heat load on gel ice. Even if a product is not expected to compensate for part of the heat load it should always be prechilled before shipment if temperature control is important.

Dungeness crab have been reported to be able to tolerate temperatures down to 24 degrees Fahrenheit (Barnett, 1983). Below 35 degree Fahrenheit their activity ceases. Lower temperatures (<35 degrees Fahrenheit) aid in decreasing physiological problems during transport (Stewart, et al, 1972) which increases survival rates.

The crab were subcooled to 30 degrees Fahrenheit (chosen because it was as low as the available equipment could cool them) for the final simulated shipment test. Benefits of subcooling included:

1. Compensation for part of the incoming heat load
2. Bringing the crab to a good temperature biologically for survival
3. Removing an additional potential heat load from the gel ice

Although it was known Dungeness crab can tolerate temperatures as low as 24 degrees Fahrenheit, it was not known how they would tolerate the combined stress of being rapidly equilibrated to this temperature and then maintained out of water for 18 hours. The final simulated shipment test proved they could tolerate this.

6. LIVE CRAB SIMULATED SHIPMENT TEST

6.1 Procedure

A final test using the World Container and the optimum design box was run to see: (1) if the crab could survive the subcooling process and subsequent shipping, (2) if the containers and gel ice predicted by the container evaluation program would maintain the temperature within a desired range, and (3) how the thermal-time curves for the two containers would compare.

It was decided to simulate a shipment of 19 hours, the approximate time it takes to deliver a shipment from Ketchikan, Alaska to Los Angeles, California. Conditions in the hold were simulated by having an average ambient temperature of 65 degrees Fahrenheit and free convection. Simulation rather than actual shipment was done as it was the only mechanism available. The World Container was chosen for testing because it had the second lowest overall heat transfer coefficient (the optimumized design container had the lowest) and because, of the available containers, it was the closest in volume to the optimum design container. Table 8 compares different parameters of the World Container and the optimum design container.

Table 8. Comparison of the World Container and the optimum design container

CONTAINER	OVERALL HEAT TRANSFER COEFFICIENT (Btu/sq ft·hr·F)	VOLUME (cu.ft.)	INSIDE SURFACE AREA (sq. ft.)
World Container	.131	3.7	14.6
Optimum design	.101	4.7	16.9

Seventy-five pounds of live Dungeness crab were bought in Newport, Oregon. They were quickly moved to the Hatfield Marine Science Center in Newport where they were placed in seawater holding tanks that were oxygenated and continually replenished with fresh seawater. They were not fed for 48 hours before shipment.

Both containers were placed in a cold storage room, maintained at 30 degrees Fahrenheit, and allowed to come to equilibrium at this temperature. An oxygenated tank filled with seawater was also placed in this room and cooled to 30 degrees Fahrenheit. The crab (16 for each container, 25.7 pounds in the World Container and 25.9 pounds in the optimum design box) were cooled down from 60 degrees Fahrenheit to 30 degrees Fahrenheit in 15 minutes in the seawater tank. A slight elevation in seawater temperature occurred when the crab were introduced into the tank but the seawater temperature returned to 30 degrees Fahrenheit after 15 minutes. Heisler charts also predicted a 30 degree Fahrenheit crab centerline temperature after 15 minutes. The crab were placed in plastic bags in the containers in layers separated by newspapers soaked in seawater. The boxes were then moved to room temperature conditions and the plastic bags containing the crab were closed after six thermocouples were inserted throughout each "thermal mass" (Figure 19). The Biot modulus was .125 (where L was 3/8 in, k was .256 Btu/ft•hr•F, and h was 1 Btu/sq ft•hr•F) which meant the internal crab temperature gradients were small and a lumped thermal capacity approach could be used for analysis. The hourly ambient temperature change was less than one degree Fahrenheit. Although .125 Biot modulus is slightly higher (.25) than recommended for lumped analysis, the Heisler charts indicated that only a .3 degree maximum Fahrenheit difference between surface and center crab temperatures would occur. A single mass-averaged temperature for each crab was considered adequate. Due to the slow rate of temperature change, the temperature of the crab was considered to be the same as the air space temperatures which the thermocouples measured.

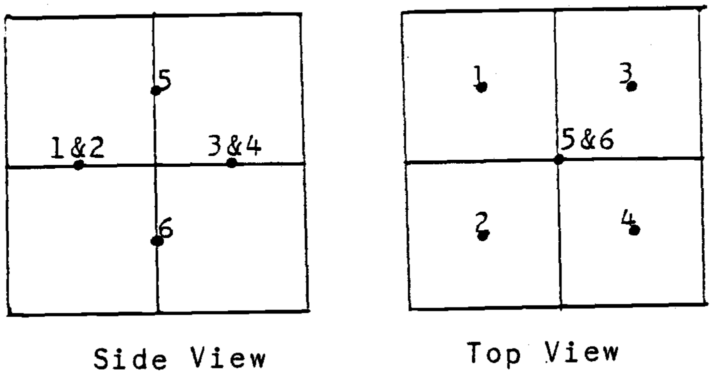


Figure 19. Six thermocouple positions throughout the thermal mass in the simulated shipment test.

Gel ice was placed directly on top of the plastic bags. Heat flux sensors were attached to the outside of the container walls. Ambient temperature was also monitored. All temperatures and heat flow readings were recorded hourly on the Esterline Angus data logger for 19 hours.

Eight crab were held as a control group in the holding tanks and fed sandshrimp to reduce cannabalism. At the end of the "simulated shipment" at room temperature the 32 crab in both containers were immediately returned to the 60 degree Fahrenheit holding tanks and fed sandshrimp. All crab were then observed for 24 hours.

6.2 Results and Discussion

A simulation run of the shipment was modeled with the containerization evaluation program (Appendix G). The suggested amounts of gel ice, 24 pounds for the World

Container and 27.3 pounds for the optimized design box, had been added to each shipment. The final average temperature of the thermal mass in the World Container was 38.2 degrees Fahrenheit which was 3.2 degrees Fahrenheit above the maximum desired temperature. The final average temperature of the thermal mass in the optimized design box was 34.2 degrees Fahrenheit, lower than the 35 degree Fahrenheit desired maximum temperature. Table 9 shows the ranges and standard deviations of the six recorded temperatures within each container.

Table 9. Ranges and standard deviations of the hourly recorded temperatures during the final simulated shipment of live crab for the optimum design box and the World Container.

Time, hrs	Optimum design Range (F)	Optimum design Standard Deviation (F)	World Container Range (F)	World Container Standard Deviation (F)
1	30.0-31.4	.5	29.1-32.2	1.1
2	30.3-30.9	.2	29.8-33.0	1.3
3	29.7-31.1	.6	29.9-33.8	1.4
4	29.7-31.9	.7	29.6-34.1	1.5
5	29.7-31.8	.8	30.0-34.8	1.6
6	29.4-32.1	1.0	30.6-35.1	1.5
7	29.6-32.4	1.1	30.3-35.5	1.7
8	29.9-32.7	1.1	31.0-36.3	1.7
9	29.7-33.4	1.3	31.5-36.4	1.6
10	29.6-33.6	1.4	32.2-36.8	1.5
11	30.0-33.7	1.3	32.5-37.2	1.5
12	30.4-33.9	1.4	32.3-37.7	1.7
13	30.9-34.3	1.3	32.6-38.3	1.8
14	30.9-34.5	1.3	33.6-38.9	1.7
15	31.0-34.5	1.3	33.9-39.4	1.7
16	31.0-35.2	1.5	34.3-39.2	1.6
17	31.6-35.0	1.3	34.5-39.9	1.7
18	32.6-35.1	1.4	34.6-40.0	1.7
19	31.6-35.3	1.4	35.2-40.5	1.7

Table 10 lists the live crab simulated shipment results.

Table 10. Simulated shipment results with live crab.

Time lapse, hrs.	World Container Temp of thermal mass, deg F	Optimized design Temp of thermal mass, deg F	Ambient Temp., deg F
0	30.2	30.4	70.0
1	30.4	30.5	66.7
2	31.1	30.6	66.2
3	31.3	31.0	65.8
4	32.0	31.1	65.2
5	32.7	31.3	64.2
6	32.9	31.5	64.7
7	33.7	31.8	64.4
8	34.1	32.0	64.0
9	34.6	32.0	63.8
10	35.1	32.3	63.6
11	35.1	32.6	63.8
12	35.6	33.0	63.5
13	36.3	33.2	63.8
14	36.8	33.3	64.1
15	36.9	33.5	65.6
16	37.2	33.7	65.8
17	37.4	34.0	66.2
18	38.1	34.1	66.6
19	38.2	34.2	67.0

Of the 45 crab purchased two died the first 24 hours after purchase, two died in the following 24 hours, and one was sacrificed during the 48 hour interval between purchase and simulated shipment. After the 19 hour simulated shipment there was one crab dead in the optimized design container and two dead in the World Container. None of the control group died during the simulated shipment time. Feeding the control group was an error as the crab undergoing the simulated shipment were not fed, too. Lobster have been held without food for seven months without increased incidence of mortalitites (McLeese, 1964). Feeding the crab probably didn't affect the results. Before the shipment ever occurred 8.4% of the crab had died. A 9.4% mortality rate of the 32 shipped crabs might not have been much increase over what was occurring without shipment conditions. After the simulated shipment each group was returned to their holding tank and fed. One day later three more were dead from the World Container and one more was dead from the optimized design box group. This increased incidence of deaths of crabs held in the World Container when compared to crab deaths from the optimum design box indicate that the higher holding temperature was detrimental to survival.

Although relative humidity was not experimentally recorded, newspapers saturated with salt water and enclosed with wet crab in a plastic bag could be expected to yield close to saturated conditions (100 percent relative humidity). The crab absorbed more heat (177 Btu) in the World Container than the crab in the optimized design box (85.2 Btu). The heat flow (measured by the heat flow sensors) entering each of the containers appeared approximately equal, 1106.4 Btu entered World Container and 1102.3 Btu entered the optimized design box. The gel ice absorbed 84% of the incoming heat load in the World Container and 92.3% of the heat load in the optimized design box. Including an air buffer layer around the thermal mass in the optimized design box when placing all the gel ice on top of the thermal mass appears to have increased the efficiency of the gel ice thereby decreasing the heat absorption of the thermal mass. Figure 20 gives the internal temperatures of both containers and the ambient temperature changes.

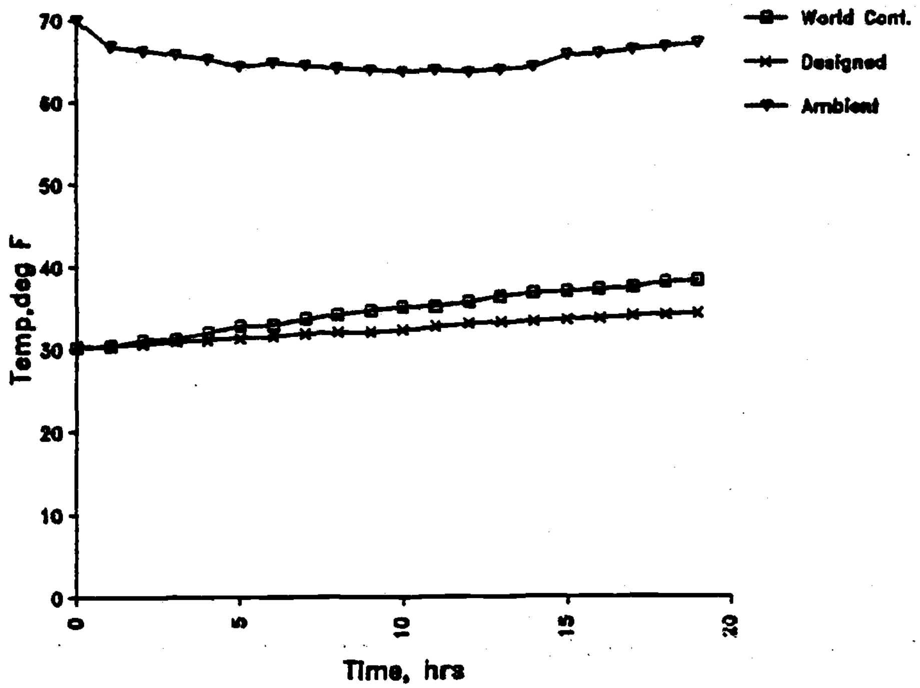


Figure 20. Measured average time-temperature curves of a simulated shipment of live Dungeness crab in the World Container and the optimized design box.

7. CONCLUSIONS

Several interrelated ideas for maintaining the temperature at or below 35 degrees Fahrenheit were developed and tested:

1. A computer program was developed to model thermal performance of existing commercial containers and suggest modifications to maintain the temperature at or below the desired maximum temperature.

2. A container was designed to optimize the efficiency of the insulation and the gel ice. Design modification tests were conducted to aid in design decisions.

3. The theory of subcooling before transport, which is used in fruit and vegetable shipment, was tested on Dungeness crab to see if it could be successfully applied. Not only would this "biologically optimize" the crab for transport but also it would remove a potential additional heat load from the gel ice and help compensate for the incoming heat load.

The accuracy of the modeling section of the computer program was evaluated by comparing curves of the temperatures predicted by the model with actual experimental curves. Close correlation of the experimental and model curves validated the model (Table 11). A single curve to describe both experimental and predicted results was fit using the mean of both numbers in the least square method. A correlation coefficient for each data set was then calculated. Correlation coefficients range from 0 to 1. The closer to 1.0 the better the fit.

Table 11. Straight line curves and correlation coefficients for experimental and predicted data of containers where y=degrees F and x=hours.

CONTAINER	CURVE EQUATION $y = a + bx$	CORRELATION COEFFICIENTS Predicted	Experimental
Tech Pak	$y = 28.23 + .84x$	.97	.96
PES	$y = 31.97 + 1.49x$	.96	.96
Tempress	$y = 32.02 + .62x$	1.00	1.0
Corruguard	$y = 28.4 + 1.31x$	.98	.98
TLC	$y = 23.95 + .68x$	.99	.98
American Dry Ice	$y = 27.13 + .74x$	.99	.95
World Container	$y = 27.35 + .45x$	.99	.99
Optimum design	$y = 32.2 + .73x$	.99	.97

The optimized design box was developed to satisfy biological requirements of Dungeness crab, airline container recommendations, and a selected set of design ambients. These specified requirements to maintain the inside temperature at or below 35 degrees Fahrenheit for 18 hours with 65 degree Fahrenheit ambient temperature. Conclusions from the design modification tests led to placing all the gel ice on top of the product and decreasing heat flow into the container by separating the product from the container walls with an air space.

Dungeness crab were shown to be able to tolerate the effects of subcooling to 30 degrees Fahrenheit. Their temperature was dropped from 60 to 30 degrees Fahrenheit in fifteen minutes and 19 hours later raised from 35 to 60 degrees Fahrenheit in approximately the same time period; less than 10% died.

In the final test the optimized design box and a commercial container, both using the amount of gel ice suggested by the computer program, were tested in a 19 hour simulated shipment test with subcooled live Dungeness crab. The temperature of the optimized design container remained below 35 degrees Fahrenheit while the temperature of the World Container rose only slightly above this (38.2 degrees Fahrenheit). It was found that by maintaining the inside container temperature around 35 degrees Fahrenheit under humid conditions the mortality rate (9.4%), when compared to some commercial shipping mortality rates (30 to 50%) of live Dungeness crab, was markedly lower.

Although these ideas were combined to increase the survival rate of live Dungeness crab during air shipment, they could also be individually applied to various shipment problems involving a need for better temperature control.

Suggestions for further studies include developing gel ice packs that melt more rapidly. Altering the size and shape of the package and adding an antifreeze agent are suggestions for testing. The melting point of gel ice can be lowered by adding antifreeze (propylene glycol). The curve is shifted but the heat of fusion is the same. If melting began at 25 degrees Fahrenheit instead of 32 degrees Fahrenheit perhaps a greater percentage of the incoming heat would be absorbed by the gel ice. The amount of heat absorbed per hour by the gel ice (the melting rate) would then be increased. Further modification tests to optimize container design could include comparing heat absorbed by the thermal mass both in a container with compartments large enough to contain gel ice next to the thermal mass and a non-compartmentalized control container with gel ice.

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APPENDICES

APPENDIX A

"Containerization Evaluation" Computer Program

Variables Used in Input

H1= outside convection coefficient, Btu/sq ft.hr.F

H2= inside convection coefficient, Btu/sq ft.hr.F

K1= container thermal conductivity, Btu/ft·hr·F

K2= added insulation's thermal conductivity,
Btu/sq ft·hr·F

TA= starting ambient temperature, F

DT= maximum desired inside temperature, F

ST= starting inside temperature, F

HA= highest ambient temperature expected, F

AA= weighted average ambient temperature, F

TT= total time at the beginning ambient temperature, hrs

TL= time interval, hrs.

CP= specific heat, Btu/lb·F

LB= weight of product, lbs

L1= thickness of wall, ft

TR= total travel time, hrs

A= inside surface area, sq ft

HO=weighted average of outside convection coefficient,
Btu/sq ft·hr·F

Program Output

1. Calculate time/temperature data for container

2. Calculate total heat energy that will enter container

3. Calculate amount of gel ice or the amount of added insulation needed to keep container and product at or below the maximum desired input temperature

Table 12. Input data used in container evaluation program. (Units shown in variable input list on previous page.)

CONTAINER:	TECHPAK	PES	CORRUGUARD
H1	2	2	2
H2	1	1	1
K1	.016	.059	.011
K2	.021	.021	.021
TA	70.6	64.6	72.9
ST	27.3	28.4	26.3
TT	21	18	23
LB	27.9	62.9	86
L1	.107	.016	.021
A	4.48	7.61	11.1

CONTAINER:	TLC	AMER.DRY ICE	WORLD
H1	2	2	2
H2	1	1	1
K1	.015	.02	.011
K2	.021	.021	.021
TA	88	88	67.8
ST	23.5	26	27
TT	22	21	30
LB	453.8	453.8	150
L1	.1	.1	.08
A	40.2	35.2	14.6

"CONTAINERIZATION EVALUATION" PROGRAM LISTING

```
10  PRINT "CONTAINERIZATION EVALUATION"
20  PRINT : PRINT
30  INPUT "ENTER STARTING CONVECTION COEFFICIENTS OUTSIDE AND INSIDE RESPECTIVELY, AND THE THERMAL CONDUCTIVITY COEFFICIENTS OF THE CONTAINER AND OF MATERIAL TO BE ADDED IF NECESSARY (IN BTU/FT*HR*F)";H1,H2,K1,K2
34  PRINT : PRINT
35  INPUT "ENTER WEIGHTED AVERAGE OUTSIDE CONVECTION COEFFICIENT";HO
40  PRINT : PRINT
50  INPUT "ENTER THE STARTING AMBIENT TEMPERATURE, MAXIMUM DESIRED TEMPERATURE, THE STARTING INSIDE TEMPERATURE OF THE BOX, THE AVERAGE AMBIENT TEMPERATURE, AND THE HIGHEST AMBIENT TEMPERATURE, ALL IN DEGREES FARENHEIGHT";TA,DT,ST,AA,HA
60  PRINT : PRINT
70  INPUT "ENTER THE TOTAL TIME AT THIS AMBIENT TEMPERATURE AND THE TIME INTERVALS DESIRED FOR CALCULATION, BOTH IN HRS";TT,TL
80  PRINT : PRINT
90  INPUT "ENTER SPECIFIC HEAT OF PRODUCT (BTU/LB/F),LBS OF PRODUCT, THICKNESS OF WALL (FT), TOTAL TRAVEL TIME (HRS), AND INSIDE AREA (SQ FT)";CP,LB,L1,TR,A
100  PRINT
110  PRINT
120  PRINT "--------------------------------------------------------------------------------"
130  PRINT "TIME,HRS  ";"HEAT ABSORBED,BTU  ";"TEMP CHANGE,DEG F  ";"INSIDE TEMP,DEG F"
140  PRINT "________________________________________________________________________________"
150  PRINT
160  PRINT
170  PRINT "0"; SPC( 47);ST
180 SUM = 0
190 U = 1 / ((1 / H1) + (L1 / K1) + (1 / H2))
200 TI = ST
210  GOSUB 390
220  PRINT
230  PRINT "--------------------------------------------------------------------------------"
240  PRINT
250  PRINT "THE TOTAL AMOUNT OF HEAT ABSORBED IS ";SUM;" BTU."
260 X = DT - TI
270  IF X < 0 THEN  GOTO 290
280  GOTO 370
290  PRINT "TO KEEP INSIDE TEMP AT OR BELOW ";DT;" DEG F"
300 Y = (HA - ST) * U * A * TR
310 Z = (Y / 143.4) * 2.0
311 Z =  INT (Z * 10 + .5) / 10
320  PRINT "THE MASS OF GEL ICE NEEDED IS ";Z;" LBS"
330 W = CP * LB * (DT - ST)
335 U2 = W / ((AA - ((DT + ST) / 2)) * A * TR)
340 L2 = (K2 * ((1 / U2) - (1 / HO) - (1 / H2) - (L1 / K1))) * 12
341 L2 =  INT (L2 * 10 + .5) / 10
350  PRINT "OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS ";L2;" INCHES."
360  GOTO 380
370  PRINT "CONTAINER IS ADEQUATE TO MAINTAIN PRODUCT AT OR BELOW ";DT;" DEG F."
380  END
```

```
390  REM ***SUBROUTINE TO ALLOW FOR AMBIENT TEMPERATURE CHANGES***
400  GOSUB 480
410  INPUT "IF DONE ENTER 0, IF NOT ENTER 1,";B
420  IF B > 0 GOTO 440
430  GOTO 470
440  PRINT : PRINT
450  INPUT "ENTER AMBIENT TEMP, TOTAL TIME AT THIS TEMP, AND OUTSIDE CON
    VECTION COEFFICIENT";TA,TT,H1
455 U = 1 / ((1 / H1) + (L1 / K1) + (1 / H2))
460  GOTO 400
470  RETURN
480  REM ***SUBROUTINE TO CALCULATE INSIDE TEMPERATURE CHANGE AND BTU'S
    ABSORBED***
490  FOR I = TL TO TT STEP TL
500 Q = U * (TA - TI) * A * TL
501 Q =  INT (10 * Q + .5) / 10
510 DF = Q / (CP * LB)
511 DF =  INT (10 * DF + .5) / 10
520 TI = TI + DF
521 TI =  INT (10 * TI + .5) / 10
530 SUM = SUM + Q
540  PRINT I,Q,DF,TI
550  NEXT I
560  RETURN
```

COMPUTER MODEL OUTPUT FOR TECHPAK

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			27.3
1	23.8	1	28.3
2	23.2	1	29.3
3	22.7	.9	30.2
4	22.2	.9	31.1
5	21.7	.9	32
6	21.2	.9	32.9
7	20.7	.9	33.8
8	20.2	.8	34.6
9	19.8	.8	35.4
10	19.3	.8	36.2
11	18.9	.8	37
12	18.5	.8	37.8
13	18	.8	38.6
14	17.6	.7	39.3
15	17.2	.7	40
16	16.8	.7	40.7
17	16.4	.7	41.4
18	16	.7	42.1
19	15.7	.7	42.8
20	15.3	.6	43.4
21	14.9	.6	44

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 400.1 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 8.5 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 2.9 INCHES.

COMPUTER MODEL OUTPUT FOR PES

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			26.3
1	154.6	2.1	28.4
2	147.7	2	30.4
3	141	1.9	32.3
4	134.7	1.8	34.1
5	128.8	1.7	35.8
6	123.1	1.7	37.5
7	117.5	1.6	39.1
8	112.2	1.5	40.6
9	107.2	1.4	42
10	102.5	1.4	43.4
11	97.9	1.3	44.7
12	93.6	1.3	46
13	89.3	1.2	47.2
14	85.3	1.2	48.4
15	81.3	1.1	49.5
16	77.7	1.1	50.6
17	74	1	51.6
18	70.7	1	52.6
19	67.4	.9	53.5
20	64.4	.9	54.4
21	61.4	.8	55.2
22	58.7	.8	56
23	56.1	.8	56.8

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 2247.1 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 57.2 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 3.3 INCHES.

COMPUTER MODEL OUTPUT FOR CORRUGUARD

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			28.4
1	155.4	2.9	31.3
2	143	2.6	33.9
3	131.8	2.4	36.3
4	121.5	2.2	38.5
5	112.1	2.1	40.6
6	103	1.9	42.5
7	94.9	1.8	44.3
8	87.2	1.6	45.9
9	80.3	1.5	47.4
10	73.8	1.4	48.8
11	67.8	1.3	50.1
12	62.3	1.2	51.3
13	57.1	1.1	52.4
14	52.4	1	53.4
15	48.1	.9	54.3
16	44.2	.8	55.1
17	40.8	.8	55.9
18	37.4	.7	56.6

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 1513.1 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 55.6 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 2.7 INCHES.

COMPUTER MODEL OUTPUT FOR TEMPRESS

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			31.9
1	73.5	.7	32.6
2	72.1	.7	33.3
3	70.6	.7	34
4	69.2	.7	34.7
5	67.8	.7	35.4
6	66.3	.6	36
7	65.1	.6	36.6
8	63.9	.6	37.2
9	62.6	.6	37.8
10	61.4	.6	38.4
11	60.2	.6	39
12	59	.6	39.6
13	57.7	.6	40.2
14	56.5	.5	40.7
15	55.5	.5	41.2
16	54.4	.5	41.7
17	53.4	.5	42.2

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 1069.2 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 23.3 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 3.8 INCHES.

COMPUTER MODEL OUTPUT FOR TLC

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			23.5
1	315.9	.8	24.3
2	312	.8	25.1
3	308.1	.8	25.9
4	304.1	.8	26.7
5	300.2	.8	27.5
6	296.3	.8	28.3
7	292.4	.7	29
8	289	.7	29.7
9	285.5	.7	30.4
10	282.1	.7	31.1
11	278.7	.7	31.8
12	275.2	.7	32.5
13	271.8	.7	33.2
14	268.4	.7	33.9
15	265	.7	34.6
16	261.5	.7	35.3
17	258.1	.7	36
18	254.7	.7	36.7
19	251.2	.6	37.3
20	248.3	.6	37.9
21	245.4	.6	38.5
22	242.4	.6	39.1

IF DONE ENTER 0, IF NOT ENTER 1, 0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 6106.3 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 99.9 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS .8 INCHES.

COMPUTER MODEL OUTPUT FOR AMERICAN DRY ICE

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			26
1	343.2	.9	26.9
2	338.3	.9	27.8
3	333.3	.9	28.7
4	328.3	.8	29.5
5	323.9	.8	30.3
6	319.4	.8	31.1
7	315	.8	31.9
8	310.6	.8	32.7
9	306.2	.8	33.5
10	301.7	.8	34.3
11	297.3	.8	35.1
12	292.9	.8	35.9
13	288.4	.7	36.6
14	284.6	.7	37.3
15	280.7	.7	38
16	276.8	.7	38.7
17	272.9	.7	39.4
18	269.1	.7	40.1
19	265.2	.7	40.8
20	261.3	.7	41.5
21	257.4	.7	42.2

IF DONE ENTER 0, IF NOT ENTER 1, 0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 6266.5 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 103.8 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 1.4 INCHES.

COMPUTER MODEL OUTPUT FOR WORLD CONTAINER

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			27
1	65.3	.5	27.5
2	64.5	.5	28
3	63.8	.5	28.5
4	63	.5	29
5	62.2	.5	29.5
6	61.4	.5	30
7	60.6	.5	30.5
8	59.8	.5	31
9	59	.5	31.5
10	58.2	.5	32
11	57.4	.4	32.4
12	56.7	.4	32.8
13	56.1	.4	33.2
14	55.5	.4	33.6
15	54.8	.4	34
16	54.2	.4	34.4
17	53.6	.4	34.8
18	52.9	.4	35.2
19	52.3	.4	35.6
20	51.6	.4	36
21	51	.4	36.4
22	50.4	.4	36.8
23	49.7	.4	37.2
24	49.1	.4	37.6
25	48.5	.4	38
26	47.8	.4	38.4
27	47.2	.4	38.8
28	46.5	.4	39.2
29	45.9	.4	39.6
30	45.3	.4	40

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 1644.3 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F

COMPUTER MODEL OUTPUT FOR OPTIMIZED DESIGN

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			32
1	53	.8	32.8
2	51.8	.8	33.6
3	50.6	.8	34.4
4	49.4	.8	35.2
5	48.2	.8	36
6	47.1	.7	36.7
7	46	.7	37.4
8	45	.7	38.1
9	43.9	.7	38.8

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 435 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 8.9 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 4 INCHES.

APPENDIX B

Radiant Heat Transfer Coefficient Calculations and Combined Heat Transfer Coefficient Equation

If radiant heat proves to be an ambient factor needing to be included in the "Container Evaluation" program input it may be combined with the outside convection coefficient. Large temperature differences between the outside container surface and the average surface temperature of the surrounding surfaces indicate need for inclusion.

The radiant heat transfer coefficient (Fogiel, 1984) is given by

$$h(r) = .1714 \times 10^{-8} \varepsilon (T(sc) + T(so))(T(sc)^2 + (T(so)^2)$$

where:

$.1714 \times 10^{-8}$ = Stefan-Boltzman constant, Btu/sq ft·hr·R^4,

ε = emissivity of the surfaces, $1/(1/\varepsilon(sc) + 1/\varepsilon(so) - 1)$

T(sc) = temperature of the container surface, degrees Rankine,

T(so) = temperature of the surrounding outside surfaces, degrees Rankine,

h(r) = radiant heat transfer coefficient, Btu/sq ft·hr·R.

The combined heat transfer coefficient (Threlkeld, 1970), h(o), is then

$$h(o) = h(c) + ((h(r))((T(sc)-T(so))/(T(sc)-T(a))))$$

where:

h(c) = convective heat transfer coefficient,

h(r) = radiant heat transfer coefficient,

T(sc) = temperature of the container surface,

T(so) = average temperature of the outside surfaces,

T(a) = outside air temperature.

This may then be used as input for the outside convection coefficient in the "Containerization Evaluation" program when applicable.

APPENDIX C

Table 13. Measured thermal conductivity values for containers.

Container	Average Thermal Conductivity Btu/ft hr F	Standard Deviation Btu/ft hr F	95 Percent Confidence Range Btu/ft hr F	Evaluation Temperature Range Deg F
Corruguard	.0109	.0004	.0101-.0118	27.9-56.3
PES	.0591	.0222	.0157-.1026	28.4-55.8
Tempress	.0197	.0014	.0169-.0225	32.0-42.0
TLC	.0153	.0003	.0146-.0160	24.0-38.0
American Dry Ice	.0199	.0014	.0171-.0226	26.0-41.0
World Container	.0109	.0014	.0095-.0123	27.0-40.6
Optimized design	.0116	.0004	.0109-.0124	33.3-36.6

EXAMPLE OF CALCULATED A THERMAL CONDUCTIVITY, K, VALUE FOR OPTIMIZED DESIGN CONTAINER

Determining the thermal conductivity for the optimized design container was done by two methods, measurement with the heat flow sensor and theoretical analysis. The experimental results from the measurement readings are in Table 13. The analysis consisted of first finding the U factor for a composite wall consisting of a 3/8 inch Corruguard layer and a 1 inch TLC layer, then multiplying U by the total thickness of the wall (1 3/8 inches) to obtain an average thermal conductivity for the optimized design container.

U = 1/((L1/K1) + (L2/K2)) = .1203 Btu/sq ft•hr•F

k(optimized) = (U)(L3) = .0138 Btu/ft•hr•F

where:

K1 = thermal conductivity of Corruguard, .0109 Btu/ft•hr•F,

L1 = thickness of Corruguard layer, .0312 ft,

K2 = thermal conductivity of TLC, .0153 Btu/ft•hr•F,

L2 = thickness of TLC layer, .0885 ft,

L3 = L1 + L2, .1146 ft.

The calculated thermal conductivity of the optimized container is outside the experimentally determined 95% confidence range (.0109-.0124 Btu/ft•hr•F). The evaluation temperature ranges of the Corruguard and TLC materials were not the same as the evaluation range of the optimum design box. As thermal conductivity varies linearly with temperature the range which best simulates the expected shipment range would be the best indicator of the correct thermal conductivity. In this case that would be the experimentally determined optimized design box value of .0116 Btu/ ft•hr•F.

APPENDIX D

Table 14 . Time-temperature curve data for experimental and computer model results of Tech Pak.

	TECHPAK Temperature, Deg F	
Time,hrs	Predicted Results	Experimental Results
0	27.3	27.3
1	28.3	28
2	29.3	29.7
3	30.2	30.6
4	31.1	32.2
5	32	33.2
6	32.9	34.5
7	33.8	35.3
8	34.6	36.6
9	35.5	37.1
10	36.3	38.3
11	37.1	39.3
12	37.8	40
13	38.6	40.7
14	39.3	41.7
15	40	42.1
16	40.7	42.7
17	41.4	43.6
18	42.1	44
19	42.7	45.5
20	43.4	45.6
21	44	45.7

Table 15. Time-temperature curve data for experimental and computer model results of PES.

PES
Temperature, Deg F

Time,hrs	Predicted Results	Experimental Results
0	28.4	28.4
1	31.3	31
2	33.9	33.7
3	36.4	36
4	38.6	38.2
5	40.7	40.6
6	42.6	42.6
7	44.3	44.5
8	45.9	45.7
9	47.4	47
10	48.8	48.4
11	50	49.7
12	51.2	50.9
13	52.2	51.8
14	53.2	52.8
15	54.1	53.7
16	55	54.3
17	55.7	54.9
18	56.4	55.8

Table 16. Time-temperature curve data for experimental and computer model results of Tempress.

	TEMPRESS Temperature, Deg F	
Time,hrs	Predicted Results	Experimental Results
0	31.9	31.9
1	32.6	32.1
2	33.3	33.1
3	34	33.7
4	34.6	34.3
5	35.3	34.9
6	35.9	35.8
7	36.6	36.4
8	37.2	37.3
9	37.8	37.7
10	38.4	38.5
11	39	39
12	39.5	39.6
13	40.1	40.3
14	40.6	40.7
15	41.2	41.1
16	41.7	41.8
17	42.2	42.5

Table 17. Time-temperature curve data for experimental and computer model results of Corruguard.

	CORRUGUARD Temperature, Deg F	
Time,hrs	Predicted Results	Experimental Results
0	26.3	26.3
1	28.3	27.9
2	30.3	29.4
3	32.1	30.8
4	33.9	32.7
5	35.6	34.5
6	37.2	36.1
7	38.8	37.7
8	40.3	39.5
9	41.7	40.9
10	43	42.3
11	44.3	44
12	45.6	45.4
13	46.8	46.9
14	47.9	48.2
15	49	49.2
16	50	50.3
17	51	51.4
18	52	52.3
19	52.9	53.1
20	53.8	54
21	54.6	54.8
22	55.4	55.5
23	56.2	56.3

Table 18. Time-temperature curve data for experimental and computer model results of TLC.

	TLC Temperature, Deg F	
Time,hrs	Predicted Results	Experimental Results
0	23.5	23.5
1	24.3	24
2	25.1	25
3	25.9	25.5
4	26.7	26
5	27.4	27
6	28.2	28.5
7	29	29
8	29.7	30
9	30.4	30.5
10	31.1	31
11	31.9	31.5
12	32.6	32
13	33.3	32.5
14	34	33
15	34.6	34
16	35.3	34.5
17	36	35
18	36.6	35.5
19	37.3	36
20	37.9	36.5
21	38.5	37
22	39.1	37

Table 19. Time-temperature curve data for experimental and computer model results of American Dry Ice.

	AMERICAN DRY ICE Temperature, Deg F	
Time, hrs	Predicted Results	Experimental Results
0	26	26
1	26.9	27
2	27.7	30
3	28.6	31
4	29.4	32
5	30.3	33
6	31.1	33
7	31.9	33.5
8	32.7	34.5
9	33.5	35
10	34.3	35
11	35	35.5
12	35.8	36
13	36.5	37
14	37.2	37.5
15	38	38
16	38.7	39
17	39.4	40
18	40.1	41
19	40.7	41.5
20	41.4	42
21	42.1	42

Table 20. Time-temperature curve data for experimental and computer model results of World Container.

	WORLD CONTAINER Temperature, Deg F	
Time, hrs	Predicted Results	Experimental Results
0	27	27
1	27.5	27.5
2	28	28.1
3	28.5	28.6
4	29	29.1
5	29.5	29.6
6	29.9	29.8
7	30.4	30.5
8	30.9	31.2
9	31.3	31.9
10	31.8	32.1
11	32.2	32.3
12	32.7	32.8
13	33.1	33.4
14	33.5	33.9
15	34	34.5
16	34.4	35
17	34.8	35.5
18	35.2	35.9
19	35.6	36.3
20	36	37.2
21	36.4	37.6
22	36.8	38
23	37.2	38.4
24	37.5	38.7

Table 21. Time-temperature curve data for experimental and computer model results of optimized design box.

OPTIMUM DESIGN BOX
Temperature, Deg F

Time, hrs	Predicted Results	Experimental Results
0	32	32
1	32.8	32.725
2	33.7	33.65
3	34.5	34.825
4	35.2	35.525
5	36	35.875
6	36.8	36.175
7	37.5	37.075
8	38.2	37.425
9	38.9	38.575

APPENDIX E

Hypothetical Computer Example Using Varying Ambient Conditions and Adding Suggested Insulation

The PES container is exposed to 90 degree Fahrenheit conditions for two hours, zero degree Fahrenheit conditions for one hour and 65 degree Fahrenheit conditions for four hours. After the program gives the predicted results for these conditions the suggested amount of insulation will be hypothetically added to the walls and the program rerun for the same ambient conditions to see if the insulation is adequate.

```
ENTER STARTING CONVECTION COEFFICIENTS OUTSIDE AND INSIDE RESPECTIVELY, AND THE
THERMAL CONDUCTIVITY COEFFICIENTS OF THE CONTAINER AND OF MATERIAL TO BE ADDED I
F NECESSARY (IN BTU/FT*HR*F) 1,2,.059,.021

ENTER WEIGHTED AVERAGE OUTSIDE CONVECTION COEFFICIENT 1

ENTER THE STARTING AMBIENT TEMPERATURE, MAXIMUM DESIRED TEMPERATURE, THE STARTIN
G INSIDE TEMPERATURE OF THE BOX, THE AVERAGE AMBIENT TEMPERATURE, AND THE HIGHES
T AMBIENT TEMPERATURE, ALL IN DEGREES FARENHEIGHT 90,35,28,65.9,90

ENTER THE TOTAL TIME AT THIS AMBIENT TEMPERATURE AND THE TIME INTERVALS DESIRED
FOR CALCULATION, BOTH IN HRS 2,1

ENTER SPECIFIC HEAT OF PRODUCT (BTU/LB/F),LBS OF PRODUCT, THICKNESS OF WALL (FT)
, TOTAL TRAVEL TIME (HRS), AND INSIDE AREA (SQ FT) .86,63,.016,7,7.6

--------------------------------------------------------------------------------
TIME,HRS   HEAT ABSORBED,BTU   TEMP CHANGE,DEG F   INSIDE TEMP,DEG F
--------------------------------------------------------------------------------

0                                                  28
1              266                4.9              32.9
2              245                4.5              37.4
IF DONE ENTER 0, IF NOT ENTER 1, 1

ENTER AMBIENT TEMP, TOTAL TIME AT THIS TEMP, AND OUTSIDE CONVECTION COEFFICIENTO
,1,1
1              -160.5             -3               34.4
IF DONE ENTER 0, IF NOT ENTER 1, 1

ENTER AMBIENT TEMP, TOTAL TIME AT THIS TEMP, AND OUTSIDE CONVECTION COEFFICIENT
65,4,1
1              131.3              2.4              36.8
2              121                2.2              39
3              111.6              2.1              41.1
4              102.6              1.9              43
IF DONE ENTER 0, IF NOT ENTER 1,0
--------------------------------------------------------------------------------

THE TOTAL AMOUNT OF HEAT ABSORBED IS 817 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 26 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS .8 INCHES.
```

An inch (a thickness commercially available) of polystyrene was added to the walls of the container. A new thermal conductivity value, .024 Btu/ft·hr·F, and a new wall thickness, .1 ft, were used in the program.

```
k(new)/l(new)=1/(.083/.021
                + .016/.059)
              =.237

        l(new)=.083 + .016
              =.1 ft

        k(new)=.237 * l(new)
              =.024 Btu/ft·hr·F
```

```
--------------------------------------------------------------------------------
TIME,HRS  HEAT ABSORBED,BTU  TEMP CHANGE,DEG F  INSIDE TEMP,DEG F
--------------------------------------------------------------------------------

0                                               28
1               83.3             1.5            29.5
2               81.2             1.5            31
IF DONE ENTER 0, IF NOT ENTER 1, 1

ENTER AMBIENT TEMP, TOTAL TIME AT THIS TEMP, AND OUTSIDE CONVECTION COEFFICIENT
0,1,1
1               -41.6            -.8            30.2
IF DONE ENTER 0, IF NOT ENTER 1, 1

ENTER AMBIENT TEMP, TOTAL TIME AT THIS TEMP, AND OUTSIDE CONVECTION COEFFICIENT
65,4,1
1               46.7             .9             31.1
2               45.5             .8             31.9
3               44.5             .8             32.7
4               43.4             .8             33.5
IF DONE ENTER 0, IF NOT ENTER 1, 0
--------------------------------------------------------------------------------

THE TOTAL AMOUNT OF HEAT ABSORBED IS 303 BTU.
CONTAINER IS ADEQUATE TO MAINTAIN PRODUCT AT OR BELOW 35 DEG F.
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APPENDIX F

1. CORNER INSULATION TEST

During container evaluation testing, temperatures of the inside surface in the corners of the thinner walled containers were at least 4 degrees Fahrenheit higher than other inside surface areas (Table 22).

Table 22. Comparison of inside corner surface temperatures and inside central surface temperatures in thin walled containers.

Container	Average corner temperature, deg F	Average central surface temperature, deg F
Corruguard	35.5	31.0
PES	39.0	31.0

Further testing was done to determine if insulation added to the corners would reduce heat flow into the container.

Any added insulation would help decrease heat flow. These tests were to determine if placing the insulation specifically in the corners was of justifiable benefit.

The PES container was filled with chilled saline filled surgical gloves. Thermocouples were placed in the central horizontal plane along the inside surface of the wall and in a line parallel to the wall thermocouples in the thermal mass (Figure 21). A plastic spacer board was used to position the thermocouples in the thermal mass. Temperatures were recorded hourly by a recording potentiometer over a 25 hour time period.

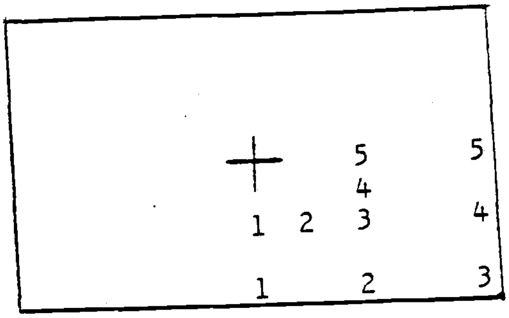

Figure 21. Thermocouple positions for 10 thermocouples in the corner effect test, top view.

Figure 22 shows a plot of the average of the temperatures recorded for the thermal mass, an average of the temperatures recorded by thermocouples 1,2,4 and 5 on the inside surface of the container, and the temperatures recorded by inside surface thermocouple 3 in the corner.

There was a larger temperature difference between the wall in the corner and the thermal mass than between the rest of the wall and the thermal mass. This would cause a greater heat flow. Adding corner insulation was decided to be beneficial in reducing heat flow into the container.

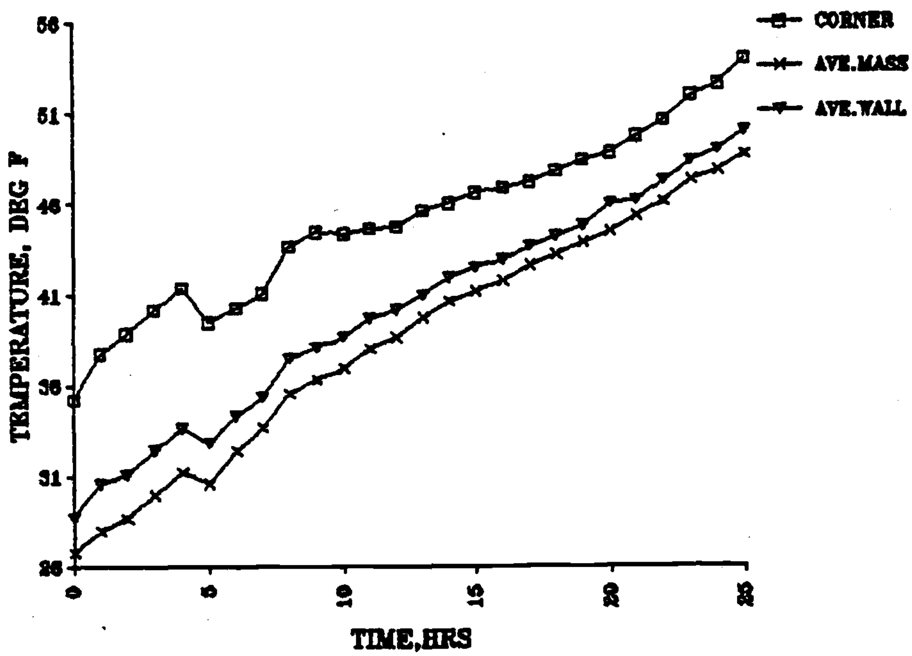

Figure 22. Corner temperature test results.

2. GEL ICE PLACEMENT

Four different methods of gel ice distribution (Table 23 and Figure 23) were tested. Ninety pounds of chilled saline filled surgical gloves were placed in the randomly chosen World Container for each of the three tests and held at room temperature. The frozen gel ice (9 pounds or six 1.5 pound bags) was then distributed according to whichever method was being tested. The average thermal mass temperature (temperature range was less than 3 degrees Fahrenheit and no gradient was detected), inside and outside surface temperatures of the container walls, and ambient temperatures were then recorded hourly. These temperatures were used to determine total heat energy entering the container, amount of heat absorbed by the mass, and percent of heat entering that was absorbed by the gel ice. The method in which gel ice absorbed the largest percent of entering heat was considered the best of alternatives tested.

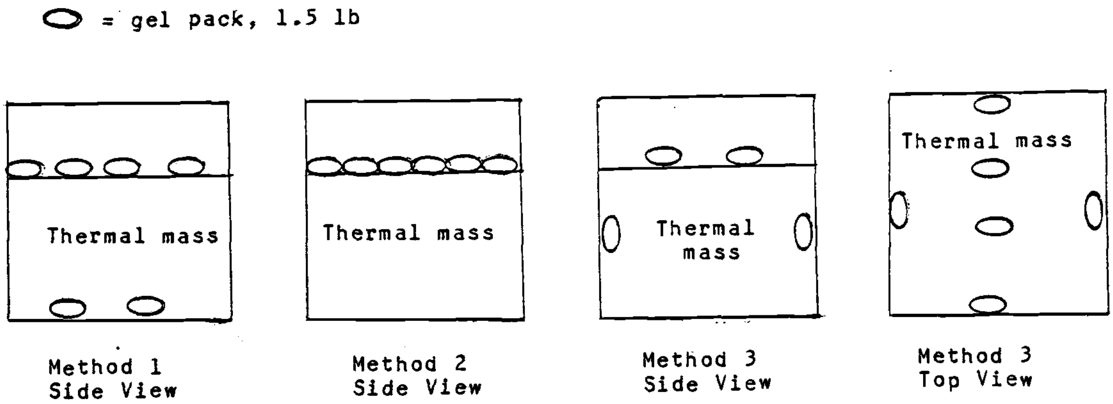

Figure 23. Diagram of methods of gel pack distribution.

Table 23 . Gel pack placement methods tested.

Method	Number of 1.5 lb gel ice bags	Position
1	4	Top layer
	2	Bottom layer
2	6	Top layer
3	2	Top layer
	4	Sides (one flat against the middle of each side)

Total heat entering the container was calculated hourly and then summed. Heat flow was calculated by multiplying the inside surface temperature and outside surface temperature difference by the thermal conductivity of the World Container divided by the wall thickness. Total heat absorbed by the gloves was found by taking the total temperature change and multiplying it by the specific heat and the weight. Heat absorbed by the ice was found by subtracting the heat absorbed by the gloves from the total heat entering the container. This answer was divided by the total heat entering the container to determine the percentage of heat absorbed by gel ice. The experimental data and a summary of these results are in Tables 24 and 25. Method 2, placing all the gel ice on top, was found to be the best method.

Table 24. Experimental data of inside container temperature changes from gel ice placement tests.

Time, hrs.	Method 1 Temp, F	Method 2 Temp, F	Method 3 Temp, F
0	29.4	27.4	27.4
1	30.0	28.1	28.5
2	30.9	28.8	29.2
3	31.6	29.4	29.8
4	31.9	30.4	30.1
5	32.9	30.9	30.7
6		31.2	31.1
7		31.4	

Table 25. Compiled results from gel ice placement tests.

Method	Heat absorbed by gloves (Btu)	Total heat entering container (Btu)	% of heat absorbed by gel ice	Ranking of methods by gel ice efficiency (1=Best)
1	270.9	462.4	41.4	2
2	307.7	535.8	42.6	1
3	290.3	425.2	31.7	3

There was a 1.2 percent difference in the gel ice placement results for Method 1, placing 2/3 of the gel ice on top and 1/3 on the bottom, and Method 2, placing all the gel ice on top. Prior to this final test another test using all three methods had been run. The results of the first test proved inconclusive because the same size gel packs were not used throughout the test. Smaller gel packs were used when testing Method 3. The same size gel packs were used for Method 1 and Method 2, however, and the results, too, showed that Method 2 was superior. The air space between the gel ice and the top of the container may have increased the heat transfer to the gel ice on top by convection in the second set of tests. The first set of tests, however, had no air space at the top present. There was no air space between the thermal mass and the walls on the sides and bottom in any of these tests. On the basis of both test results it was concluded that smaller packages of gel ice placed on top of the thermal mass enhanced gel ice's refrigerant effect.

3. COMPARTMENTALIZATION

Two tests were conducted to determine if compartmentalization would decrease heat flow to the thermal mass. Both tests used two Tech Pak containers, one as a control and one with compartments inside. One test did not use gel ice and one test did. Figures 24 and 25 show diagrams of the test containers. Each container was filled with chilled saline filled gloves. The temperature of the thermal mass was monitored and the amount of heat absorbed by each mass calculated by multiplying the specific heat of the saline solution, the mass of gloves contained, and the total change in temperature together.

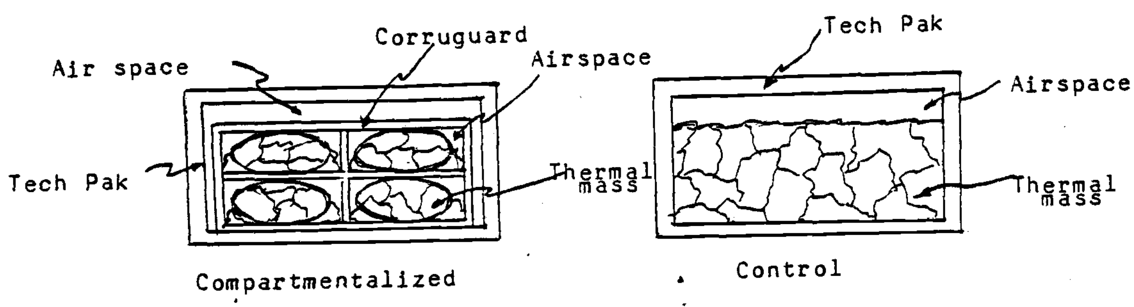

Figure 24. Diagram of compartmentalization test containers without gel ice.

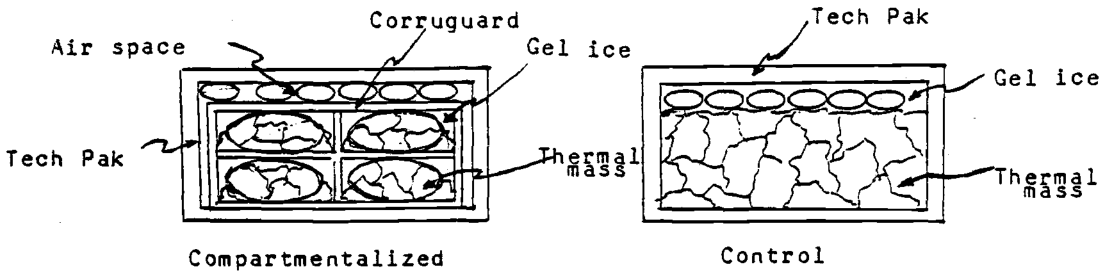

Figure 25. Diagram of compartmentalization test containers with gel ice.

Table 26 summarizes these calculations. The methods for which the least amount of heat was absorbed by the thermal mass were considered superior. Results showed that it is better to compartmentalize when gel ice is not required for shipment. However when gel ice is needed, it is better not to compartmentalize.

Table 26. Calculations for compartmentalization tests.

Method	A Mass, pounds	B C_p, Btu/lb·F	C Temp. change, degrees F	Heat absorbed by thermal mass, (A)(B)(C), Btu
No gel ice				
Compart.	8.5	.86	9.5	69.4
Control	8.3	.86	10.4	74.2
Gel ice				
Compart.	9.1	.86	6.0	47.0
Control	8.9	.86	4.3	32.9

4. Air Buffer Layer

Having a layer of air separating the thermal mass from the container walls was the fourth design improvement test. Figure 26 shows diagrams of the control and test containers. Chilled saline-filled gloves were placed in plastic bags in Tech Pak containers (one mass surrounded by air the other not) and the thermal mass temperatures monitored. The amount of heat absorbed by each thermal mass was calculated (Table 27). Including an air space between the thermal mass and the container wall proved beneficial and was included in the optimum design container.

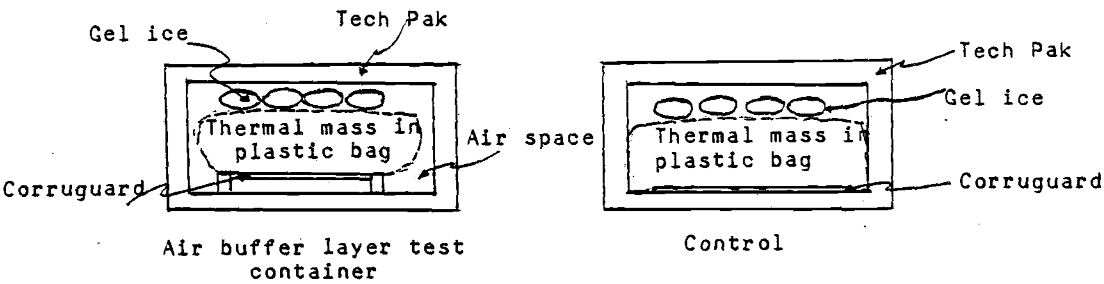

Figure 26. Diagram of containers used for the air buffer layer test.

Table 27. Calculations of heat absorbed by the thermal mass for the air buffer layer test.

Container	A Mass, lbs	B C, Btu/lb·F	C Temp change, deg F	Heat absorbed by thermal mass (A)(B)(C), Btu
Test	16.2	.86	8	111.5
Control	15.9	.86	9.4	128.5

Theoretically the overall heat transfer coefficients predicted a greater heat flow into the control container. Only the side and bottom U factors were calculated as the top U factors were equal. Symmetry permitted analyzing only half the container.

<u>Test container</u>

$U(side) = 1/(L1/K1 + 1/C + L2/K2) = .1148$ Btu/sq ft·hr·F

$U(bottom) = 1/(L1/K1 + 1/C + L2/K2 + L3/K3)$
$= .095$ Btu/sq ft·hr·F

where:

L1 = thickness of Tech Pak wall, .11 ft,

K1 = thermal conductivity of Tech Pak, .016 Btu/ft·hr·F,

C = thermal conductance of an air space, includes radiation and convection transfer, 1.2 Btu/sq ft·hr·F (Threlkeld, 1970),

L2 = thickness of Corruguard, .02 ft,

K2 = thermal conductivity of Corruguard, .011 Btu/sq ft·hr·F,

L3 = bunched thickness of two plastic bags, .02 ft,

K3 = thermal conductivity of plastic, .02 Btu/sq ft·hr·F (Chattopadhyay and Bose, 1979).

U(test) = .1148 + .095 = .2098 Btu/sq ft·hr·F

Control container:

U(bottom) = 1/(L1/K1 + L2/K2 + L3/K3)
= .1032 Btu/sq ft·hr·F

U(side) = 1/(11/K1 + L2/K2) = .1270 Btu/sq ft·hr·F

U(control) = .1270 + .1032 = .2302 Btu/sq ft·hr·F

APPENDIX G

COMPUTER OUTPUT FROM LIVE DUNGENESS CRAB TEST FOR WORLD CONTAINER

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			25
1	63.8	3	28
2	59	2.7	30.7
3	54.7	2.5	33.2
4	50.7	2.4	35.6
5	46.9	2.2	37.8
6	43.4	2	39.8
7	40.2	1.9	41.7
8	37.1	1.7	43.4
9	34.4	1.6	45
10	31.9	1.5	46.5
11	29.5	1.4	47.9
12	27.3	1.3	49.2
13	25.2	1.2	50.4
14	23.3	1.1	51.5
15	21.5	1	52.5
16	19.9	.9	53.4
17	18.5	.9	54.3
18	17.1	.8	55.1

IF DONE ENTER 0, IF NOT ENTER 1,0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 644.4 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 24 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 14.3 INCHES.

COMPUTER OUTPUT FROM LIVE DUNGENESS CRAB TEST FOR OPTIMIZED DESIGN BOX

TIME,HRS	HEAT ABSORBED,BTU	TEMP CHANGE,DEG F	INSIDE TEMP,DEG F
0			25
1	72.5	3.4	28.4
2	66.3	3.1	31.5
3	60.7	2.8	34.3
4	55.6	2.6	36.9
5	50.9	2.4	39.3
6	46.5	2.2	41.5
7	42.6	2	43.5
8	38.9	1.8	45.3
9	35.7	1.7	47
10	32.6	1.5	48.5
11	29.9	1.4	49.9
12	27.3	1.3	51.2
13	25	1.2	52.4
14	22.8	1.1	53.5
15	20.8	1	54.5
16	19	.9	55.4
17	17.4	.8	56.2
18	15.9	.7	56.9

IF DONE ENTER 0, IF NOT ENTER 1, 0

THE TOTAL AMOUNT OF HEAT ABSORBED IS 680.4 BTU.
TO KEEP INSIDE TEMP AT OR BELOW 35 DEG F
THE MASS OF GEL ICE NEEDED IS 27.3 LBS
OR THE AMOUNT OF INSULATION NEEDED TO BE ADDED TO THE WALL IS 16.8 INCHES.