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Theoretical, Experimental and Computer Model for Package R-value Using Regular Ice and Dry Ice

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Gary Burgess
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THEORETICAL, EXPERIMENTAL AND COMPUTER MODEL FOR PACKAGE R-VALUE USING REGULAR ICE AND DRY ICE

By

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ABSTRACT

THEORETICAL, EXPERIMENTAL AND COMPUTER MODEL FOR PACKAGE R-VALUE USING REGULAR ICE AND DRY ICE

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Temperature sensitive products need specific containers to prevent heat loss or gain. Several containers (corrugated box, EPS cooler, molded polyurethane and VIP panels) were studied for their package insulating ability (R-value). Regular ice and dry ice were compared by performing an ice melt test at three different conditions (72°F and 50%RH, 72°F and 85%RH, and 104°F and 50% RH). Experimental R-values were compared to a fitted equation and to computer model results using a BASIC program.

The higher the R-value, the better the insulating container. The VIP was focused to be a better insulating container than molded polyurethane, followed by an EPS cooler and a corrugated box.

The experimental R-values using dry ice were higher than for regular ice because the temperature of dry ice is much lower than regular ice. This lowers the thermal conductivity and the convection heat transfer coefficient. The surface area also affects the R-value. The higher the storage temperature and relative humidity, the lower the R-value. The fitted equations agreed the experimental R-value for regular ice but not for dry ice. On the other hand, the computer model R-values fit better for dry ice.

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Introduction

1. Introduction

Temperature sensitive products such as biological materials, blood and some organ parts, pharmaceuticals, frozen foods, fresh-products, diary products and delivery pizza need specific containers (insulating packages) that can prevent the loss of heat and either keep the temperature constant during transportation or keep products from melting, thawing, or freezing. This is done by using thermal insulation. Thermal insulation is any material or combination of materials that retard heat transfer by conduction, convection or radiation (ASHRAE 1993). By retarding heat flow, thermal insulation conserves energy by reducing heat loss or gain by the product.

The most commonly used insulation packages are expanded polystyrene (EPS), rigid high-density polyurethane and reflecting surface materials (radiant barrier films) (FedEx, 2002). Sometimes, refrigerants such as gel packs or dry ice are placed in the container, especially for perishable products, to maintain the range of temperatures (cold or frozen temperature). Normally gel packs are suitable for refrigerating products in the range of 30°F (-1°C) to 60°F (16°C). Dry ice is a solid form of carbon dioxide. It has a surface temperature of –108.4°F (-78°C) and is used to keep products frozen. Regular ice is not normally used since it has many disadvantages including weight, thawing, leaking and the need for expensive water resistant packages (FedEx, 2002).

Environmental temperature and moisture affect the thermal resistance of insulating containers. When the temperature or the relative humidity increases, the thermal resistance of packages decreases (FedEx, 2002). Not only environmental temperature but changing temperature during transportation affect products as shown in

Table 1 (Panyarjun, 2002). The number of steps in the distribution process also affects products.

There are two main users of insulating packages: perishable food industries, who use specific containers for each product, and e-commerce businesses, who use several standard packages to pack all products. The distribution process starts from the factory → storage room → trucks or airplanes → warehouse → stores → customers. In e-commerce, companies will directly pack products using standard size packages, adding dunnage such as scrap paper or peanut foam to protect products and sending it to customers using FedEx, UPS or USPS.

Table 1. Distribution conditions and their temperatures

Conditions	Temperature (°C)
Freezer	-18 to -35
Refrigerator	1 to 4
Freezer truck, rail car or airplane	-18 or below
Refrigerated truck, rail car or airplane	0 to 5

Each temperature sensitive product has specific characteristics. For instance, frozen products need to maintain the frozen temperature to prevent melting or thawing. For fresh fruits or fresh vegetables that still respire, releasing heat and increasing temperature into the package would cause faster decay. On the other hand, pizza delivery needs insulation packages to maintain hot temperatures (Fava, 1999). The designs and materials for insulation packages have to meet these minimum requirements and also be inexpensive.

The thermal resistance (R-value) of packages and the amount of refrigerants has to be optimized to design for temperature sensitive products. The thermal resistance of packages varies widely. It ranges from a low R-value for a corrugated box, medium R-value for an EPS or rigid high-density polyurethane, to a high R-value for Vacuum Insulation Panels (VIP). The optimal amount of refrigerants to keep products frozen or cold depends on several factors including the product mass, inside surface area of the package, the wall thickness, and the time of transportation.

Insulating packages need to have high R-values. There are several methods to determine the insulating ability of containers: ASTM D3103 and the ice –melt test (Burgess, 1999). ASTM D3103: Standard Test Method for Thermal Insulation Quality of Packages, uses temperature indicating devices such as thermocouples to assemble the temperature profiles and determine the R-value.

In this work, the ice melt test method (Burgess, 1999) was used because it is very simple, easy to test, inexpensive (do not need any machine or sensors) and is an effective method to determine the insulating ability of a package. This method is similar to the ASTM D3103 but the R-value is calculated from equation 1. By definition,

$$R - value = \frac{A \times \Delta T}{meltrate \times latentheat} \tag{1}$$

Where R-value = thermal resistance of container wall ($\frac{ft^2.F.hr}{Btu}$)

A = inside surface area of package (ft^2)

ΔT = temperature different (°F) between outside air and refrigerant used

Melt rate= the rate that ice melts during the experiment and is equal to the weight of the ice melted divided by the melt time (lb/hr)

Latent heat = 144 Btu/lb for regular ice and 240 Btu/lb for dry ice

From equation 1, the ratio of ΔT/latent heat, depends on what refrigerant is used and the outside air temperature. Burgess (1999) fitted experimental R-values to the equation 2,

$$R - value = 3.9th + 1.5np + 3.2nf(\pm 20\% accuracy) \tag{2}$$

Where th = the average wall thickness (inch)

np = the number of plain surfaces

nf = the number of aluminium foil surfaces

In this equation, the R-value is separated into three parts: the effects of conduction, convection and radiation. Conduction depends mainly on the wall construction (th). Convection refers to heat transfer between air and surfaces so the R-value depends upon the number of surfaces in contact with air (np). Radiation refers to the emission or reflection of infrared waves and can be a significant factor. The number of aluminium foil surfaces (nf) is therefore important to R-value.

In the design of insulating packages, equation 2 can be used to determine the R-value needed. The requirement for refrigerants is found using equation 1. The R-value calculated from equation 2 is only ±20% accurate. The equation is linear but radiation is known to be a strong function of temperature. The thermal conductivity of containers also varies with temperature and relative humidity and this equation does not correct for the relative humidity. Equation 2 uses an average of thermal conductivity (k) of 0.022 Btu/h.ft.°F but k varies for different materials. For example, corrugated board is about 0.035 Btu/h.ft.°F. The thermal conductivity of materials at lower temperatures (such as dry ice) should have lower R-value due to lower k in lower temperature.

The objectives of this work were to investigate the effect of temperature and relative humidity in order to reduce the error in determining the R-value of insulating containers for each specific package and condition. There are three main objectives in this work.

1. To compare the R-value between dry ice and regular ice using the ice melted test method.
2. To compare thermal resistant (R-value) between the theory parts of heat transfer using computer simulation of the insulated containers with the ice melted test results.
3. To determine the effect of temperature and relative humidity of the corrugated box on R-value

Chapter 2

Literature Review

2. Literature Review

2.1 Insulating Packages

There are several insulating packages that are used for temperature sensitive products: Expanded Polystyrene Foam (EPS foam), Modified Corrugated board lined .EPS Foam, Molded Polyurethane, corrugated with liners or blankets, and Vacuum Insulation Panels (VIP).

Expanded Polystyrene Foam (EPS Foam)

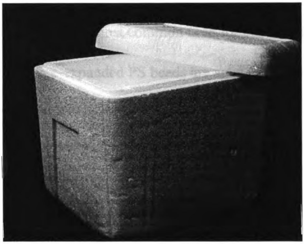

Figure 1. Expanded polystyrene foam (EPS foam)

EPS foam (Figure 1) is the most common packaging foam used for low temperature distribution. It is known to show excellent insulation capability because of its air-filled cells, EPS foam is an excellent insulator since air has particularly low heat conductivity. This is the reason why EPS foam is being used for insulation in temperature sensitive products. It is typically the least expensive packaging foam available. EPS foam is relatively chemically inert and acceptable for use in food packaging for meat and produce. EPS foam is lightweight, reusable and stackable (Hernandez, 2000). It can be produced by standard technology with no special equipment. EPS foam is produced from PS granules or beads that are impregnated with hydrocarbon blowing agent (such as pentane 5-8%) and sometimes with flame-retardants during suspension polymerization. The blowing agent produces bubbles in the plastics and forming cells. The properties of foam depend upon the amount of blowing agent and process conditions. The PS beads are pre-expanded heating to 85-96°C (185-205°F) to vaporize the pentane. The PS beads usually expand about 25 to 40 times of their original size. The density of foam varies from 13 to 48 kg/m^3, with 24 kg/m^3 most common used for cushion packaging and 16 kg/m^3 for insulation. These pre-expanded PS beads are aged to reach equilibrium then packed into a mold under heat and pressure that cause these beads to fuse together. The mold produces the final shape desired. The problem with EPS foam is that it is hard to dispose after use.

Modified Corrugated Board Lined EPS Foam

Modified corrugated board lined EPS foam consists of a corrugated core layer, which is an EPS foamed sheet, covered on both sides with a paperboard liner (Sasaki, 1999). EPS foams are used to improve heat insulation by stopping the movement of air and decrease the absorption of water. The continuous process for mass production starts from polystyrene foam. A sheet is heated and is passed through a pair of matching toothed rolls to make corrugated. Next, adhesive is applied to the top of the corrugated foamed sheet and this sheet is passed between two rolls to be formed into a cardboard sheet. This material is light and can be recycled separately from paperboard.

Molded Polyurethane

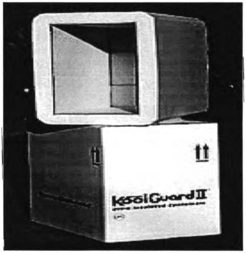

Figure 2. Molded polyurethane.

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Molded Polyurethane (Figure 2) is designed with a layer of high performance urethane foam injected between layers of corrugated fiberboard. Urethane gives a high R-value (twice the R-value per inch compared to EPS foam) insulated shipping container capable of meeting the most demanding temperature controlled requirements such as for pharmaceutical products (Cold Ice, 2002). Urethane requires less- refrigerant than EPS foam. This can be valuable for re-use options, where only some of the components, such as the outer corrugate, needs to be replaced. It is also environmentally preferable where components can be sorted for recycling. In addition, polyurethane can be injected between two corrugated boards to increase the strength of the box and also improve stability (Panyarjun, 2002).

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Vacuum Insulation Panels or VIP

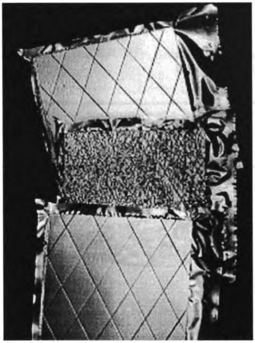


Figure 3. Vacuum insulation panels (VIP)

Vacuum Insulation is an advanced thermal insulation technology that significantly outperforms insulation materials like closed-cell foams, foam beads or fiber blankets. It removes the gases within the insulating space (Dow Chemical, 2002).

The vacuum insulation panel (VIP) in Figure 3 (Glacier Bay, 2002) is a technologically advanced product that combines a high R-value in a relatively thin panel. VIP in Figure 6 (Dow Chemical, 2002) consists of a core panel enclosed in an air-tight envelope, for which a vacuum is applied. This product provides an insulative value of three to seven times EPS (Table 2) (Dow Chemical, 2002). Figure 4 shows a filler material that is 100 percent open cell, microcellular polystyrene called a core that is encapsulated by a thin, super-barrier film, a membrane film, getters and desiccants.

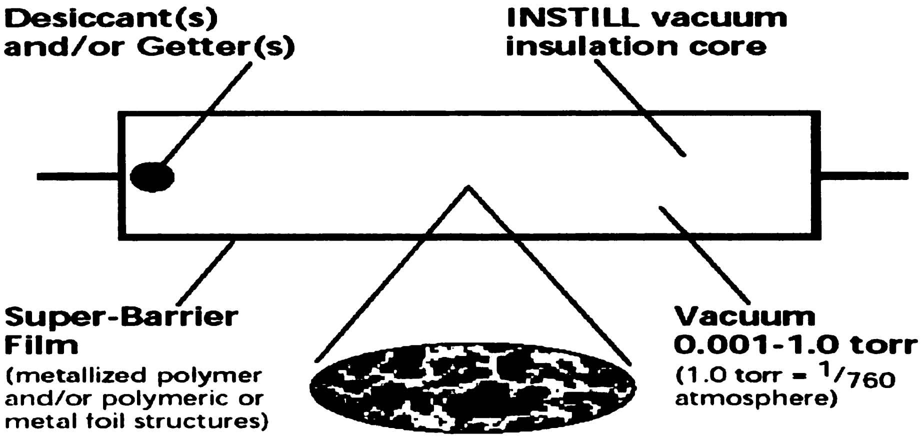


Figure 4. Components of VIP

The core material has two main functions. First, it provides physical support to the membrane or barrier film envelope so that it does not collapse in on itself when the vacuum is applied. Second, the core material acts to disrupt the flow of the molecules of gas which still remain in the evacuated space, thus reducing transfer heat between the walls of the VIP.

The membrane films are the materials which form the walls of the VIP. It is the job of the membrane film to provide an effective barrier to retard all gases and moisture so that the vacuum can be maintained. Impermeable membrane materials are glasses and metals. Unfortunately glass is too fragile. Metal can be used but significantly reduces the average insulation value of the finished panel due to the conductance of heat around the edges where the walls are joined. Also a pure metal membrane is higher in cost to form and weld to the panel.

Getters and desiccants are chemicals that absorb gases and moisture respectively. Getters and desiccants are used to extend the life of VIPs by absorbing unwanted gases and moisture to prevent a rise in pressure within the evacuated space. In order to be effective, the getters and desiccants must be thoroughly matched to the type and quantity of gas/moisture they will be expected to absorb. They must be able to effectively absorb and hold the gasses and moisture at the low pressures inside the VIP.

The insulative values are dependent upon the vacuum. The foil is fairly durable, but it is fragile. The vacuum insulated panel cannot be punctured during installation or use. Therefore, the panel must be protected by a material that is resistant to puncture such as corrugated boxes. This requires that the VIP be contained within another product such as a corrugated box or protective covering during transportation.

Table 2. Insulation performance of vacuum insulation panel (VIP) and conventional insulations

Insulations	Thermal Resistance (ft^2.hr.°F/Btu.in)
Vacuum insulation panel with instill core @ 0.1 torr or 0.13 bar	25-30
Rigid Polyurethane (close cell)	7
Extruded Polystyrene/STYROFOAM brand	5
Expanded Polystyrene (EPS)(Beadboard)	4
Fiberglass Batting	4

VIP has been tested with an R-30 for1 inch of thickness. The cost of VIP is about $3 - $5 per square foot (Toolbase, 2002) depending on the volume of the order and the precise use and life parameters. The cost of this material may be adjusted to a more competitive level. The VIP is ideal for applications which require a higher R-value but without sufficient room for conventional materials. The VIP completes the insulative envelope, where it has been difficult to insulate in the past.

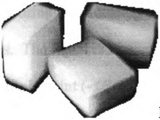
2.2 Refrigerants

There are several refrigerants to keep products frozen or cold such as regular ice, dry ice or gel pack. In this experiment, regular ice and dry ice were used to determine the R-value.

Regular Ice

Regular ice consists of water molecules joined together by hydrogen bonds in a regular arrangement. It appears that there is considerable empty space between the molecules. The density of ice is 0.92 g/cm^3 at 0°C (McCabe, 1993) and the latent heat is 144 Btu/lb.

Dry Ice



Block

Pellet

Figure 5. Forms of dry ice: block and pellet

Dry Ice is frozen carbon dioxide ($C0_2$). Carbon dioxide is a colorless, odorless, tasteless gas, about 1.5 times as heavy as air. The specific volume at atmospheric pressure (100 kilopascals) and 70°F (21°C) is 8.74 ft^3 /lb (0.546 m^3 /kg). Under normal conditions, it is stable, inert, and nontoxic.

Dry ice is available in two common forms (Figure 5): blocks and pellets (AAA Ice, 2002). Block dry ice weighs, on the average, 55 pounds. It can be cut in a variety of smaller square sizes to accommodate specific needs. Pellet ice is generally easier to handle and is the preferred choice for special effect needs. The block is better for longevity.

Dry ice is much denser and colder than traditional ice (ABC Ice house, 2002). In addition, dry ice doesn't melt. It sublimates. Sublimation is the process of a solid going directly to a gas. It is nontoxic and noncorrosive and leaves no residue. At atmospheric pressure, it sublimes at -108.4°F (-78°C), absorbing its latent heat of 240 Btu/lb.

The manufacture of dry ice from carbon dioxide gas is a chemical process (Carl, 2002). The gas is liquefied by compressing it to 900-1000 lb/in^2 (6.2-6.9 megapascals) in three stages using reciprocating compressors and then condensing it in water-cooled condensers. The liquid is expanded to atmospheric pressure where its temperature is below the triple point (- 69.9°F or -56.6°C). In the expansion there is a flash separation (at –108.4°F or -78°C) of some solid carbon dioxide "snow" which is very porous. The snow is removed from the expansion chamber and mechanically compressed into standard 50-lb (23-kg) blocks in which measure 10 by 10 by 10 in. (25 by 25 by 25 cm). Dry Ice will sublimate (change from a solid to a gas) at a rate of 10 pounds every 24-hours in a standard insulated container (ABC Ice house, 2002):

Dry ice needs to store in an insulated container (ABC Ice house, 2002). The thicker the insulation, the slower it will sublimate. Never store dry ice in a absolutely airtight container. The sublimation of dry ice to carbon dioxide gas will cause the container to expand and probably explode. Dry ice should be stored using proper air ventilation. The sublimated carbon dioxide gas will flow to low areas and substitute oxygen. This can cause suffocation if breathed exclusively. Never store dry ice in a refrigerator freezer. The extremely cold temperature will cause the thermostat to turn the freezer off. It will keep everything frozen in the freezer but it will be used up at a faster rate.

The pick up time of dry ice should be as close as possible to the time it is needed. It sublimates at 10%, or 5 to 10 pounds every 24 hours (ABC Ice house, 2002). Carry it in a well-insulated container such as an ice chest or cooler. If it is transported inside a car or van for more than 15 minutes, make sure there is fresh air. For disposal, unwrap and leav

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leave dry ice at room temperature in a well-ventilated area. It will sublimate from a solid to a gas. Do not leave dry ice unattended around children.

The primary use of dry ice is to keep perishables fresh, especially during shipment. Solid carbon dioxide made its debut as the packing material of choice for ice cream and frozen food. (Cool Quiz network, 2002). Products such as fish and meat can be shipped thousands of miles, and arrive at their destinations in good condition. Even florists take advantage of the preservative property of dry ice and can prevent flower buds from opening for up to three days by putting them in a solid carbon dioxide atmosphere. Essentially, dry ice temporarily freezes the aging process to suit our purposes.

Gel Packs:

Figure 6. Gel packs

Gel Packs in Figure 6 (FDC Packaging, 2002) are made from a non-toxic; super-absorbent powder that, when combined with water, forms a viscous gel-like product (Marko Foam Products, 2002).

Gel refrigerants are good for maintaining constant temperature for perishable products. Normally gel refrigerants are suitable for refrigerating products in the range of 30°F (-1°C) to 60°F (16°C) (FedEx, 2002). Temperature maintenance and duration are dependent on several factors such as the quality and wall thickness of the molded container, the temperature at which the product is packaged and ambient temperature. The standard ratio for gel-packs is 1 lb of gel for every 5-7 lbs of product (Marko Foam Products, 2002). Gel packs are used in floral, dairy products, meat & poultry, prepared foods, or seafood.

2.3 Heat Transfer

Heat transfer is the transport of thermal energy from one region to another, normally from the hotter to the colder. The net rate of heat flow is in the direction of decreasing temperature (Hagen, 1999). Heat transfer can occur by three distinct modes: conduction, convection and radiation.

Conduction Heat Transfer:

Conduction is the transfer of thermal energy in a solid or a liquid from higher temperature to an adjacent point of lower temperature. Equation 3 is called Fourier's law of heat conduction. The heat flux (q) is proportional to the temperature difference and inversely proportional to the thickness. The proportionality coefficient (k) is called the thermal conductivity (Middleman, 1998).

Heat transfer through a wall

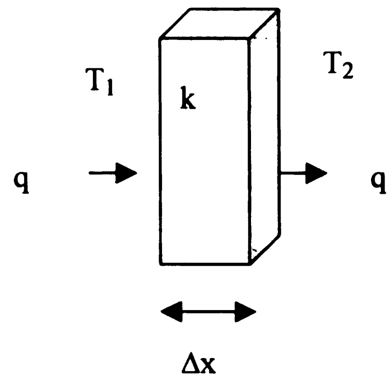

Figure 7. Diagram for heat transfer through a wall

From Figure 7, conduction heat transfer through a wall at steady state in one dimension follows equation 3. Based on the principle of heat transfer, the heat flows from higher temperature T_1 through the surface of wall to surface T_2 (lower temperature).

$$q = -k\frac{\Delta T}{\Delta x} = k\frac{(T_1 - T_2)}{\Delta x} \qquad (3)$$

q = heat flux (W/m^2 or $Btu/h.ft^2$)

k = thermal conductivity (W/m.K or Btu/h.ft°F)

ΔT = temperature different (°F or K)

Δx = thickness (ft or m)

Thermal conductivity (k) is the amount of heat transmitted through a unit area of material in a unit time through its total thickness with a unit of temperature difference between the two opposite sides (Turner, 1981) and indicates how well a material conducts thermal energy (high for metal, low for plastic) (McCabe, 1993). Thermal conductivity of metals has a broad range of values, about 10 Btu/ft.h.°F for stainless steel to 240 Btu/ft.h.°F for silver. Water has a thermal conductivity of 0.3-0.4 Btu/ft.h.°F. Gases have the lowest thermal conductivity; for air k, is about 0.014 Btu/ft.h.°F. Solids having low k values are used as insulators to minimize the rate of heat flow. Examples are polystyrene foam, urethane foam, and fiberglass. These porous insulating materials act by entrapping air and thus eliminate convection with in the cell if the diameter is less than 4 mm (Brody, 1997). Their k values are about equal to that for air.

Thermal conductivity is a function of temperature and relative humidity. When temperature increases, k increases therefore insulation value decreases as shown in equation 5. In the case of cellular foam, when the relative humidity increases, all or part of the air or gas in the foam is filled with water so the thermal conductivity of the foam will be the thermal conductivity of water (4.1 Btu.in/ft^2.hr°F at 70°F) instead of air (0.17 Btu.in/ft^2.hr°F at 70°F) (Turner, 1981), so k increases

Rearranging the equation 3:

$$q = \frac{T_1 - T_2}{\frac{\Delta x}{k}} \tag{4}$$

$$R = \frac{\Delta x}{k} \tag{5}$$

R = thermal resistance (ft^2.°F.h/Btu) is the material property that opposes the passage of energy or heat through a material (Turner, 1981). In heat flow, the driving force is the temperature difference between two bodies from one region to another region. The thermal resistance of a homogeneous body of uniform cross-section is the reciprocal of conductance as shown in equation 5 (Turner, 1981). High thermal resistance indicates more effective insulation (ASHRAE, 1993). There are several pertinent properties of insulation as well as thermal conductivity of structures: the service temperature, the relative humidity, surface emissivity, reflectivity and absorptivity, density, form and water transmission.

The reasons for using insulation materials (low thermal conductivity or high thermal resistance) are to conserve energy by reducing heat loss or gain, control surface temperature, facilitate temperature control of a chemical process in products, prevent vapor condensation at the surface with a temperature below the dew point of the surrounding atmosphere, or reduce temperature variations within a products (ASHRAE, 1993)

Heat transfer through two walls

For two walls, the heat transfer diagram is shown in Figure 8. Heat flows from T_1 (higher temperature) through the wall$_1$ (k_1, x_1), past the contact between wall$_1$ and wall$_2$ (T_2), then through wall$_2$ (k_2, x_2) to surface T_3.

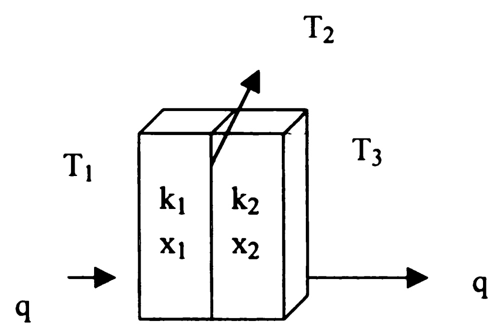

Figure 8. Diagram for heat transfer through two walls

Where q = heat flux (W/m^2 or Btu/h.ft^2)

x_1 and x_2 = thickness of $wall_1$ and $wall_2$ (ft or m)

k_1 and k_2 = thermal conductivity of $wall_1$ and $wall_2$ (Btu/hr.ft.°F or W/m.K), respectively

At steady state, the heat flux is constant so

$$q = q_{conduct\ ,wall_1} = q_{conduct\ ,wall_2}$$

$$q = \frac{k_1}{x_1}(T_1 - T_2) = \frac{k_2}{x_2}(T_2 - T_3) \qquad (6)$$

Rearranging equation 6,

$$T_1 - T_2 = \frac{qx_1}{k_1}$$

$$T_2 - T_3 = \frac{qx_2}{k_2}$$

Adding these two equations,

$$T_1 - T_3 = \frac{qx_1}{k_1} + \frac{qx_2}{k_2} = q(\frac{x_1}{k_2} + \frac{x_2}{k_2})$$

$$q = \frac{T_1 - T_3}{\frac{x_1}{k_2} + \frac{x_2}{k_2}} = \frac{T_1 - T_3}{R}$$

$$R = \frac{x_1}{k_2} + \frac{x_2}{k_2} \qquad (7)$$

The R-value for conduction heat transfer through two walls is a function of sum of thicknesses divided by the thermal conductivities.

Heat transfer through multilayered walls

For multilayered walls, the heat transfer diagram is shown in Figure 9. The heat transfers from T_1: higher temperature through $wall_1$ (k_1, x_1) then passes through the contact of $wall_1$ and $wall_2$ at T_2 and flows through wall structure until $wall_n$ and through the surface of $wall_n$ at T_{n+1}.

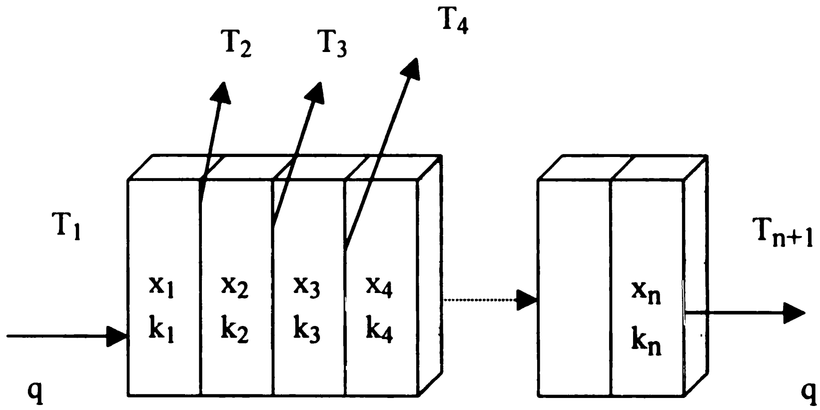

Figure 9. Diagram of heat transfer through multilayered walls

$$q = \frac{T_1 - T_n}{\frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \ldots + \frac{x_n}{k_n}} = \frac{T_1 - T_n}{R} \tag{8}$$

$$R = \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \ldots + \frac{x_n}{k_n} \tag{9}$$

The R-value for conduction heat transfer through multilayer flat materials is the sum of thicknesses divided by thermal conductivities.

Convection:

Convection is the mechanism by which thermal energy is transferred between a solid surface and a fluid moving over the surface. Heat transfer by convection is proportional to the temperature difference and surface area and is known as Newton's law of cooling (Hagen, 1999), shown in equation 10,

$$q = hA\Delta T \tag{10}$$

h = heat transfer coefficient (Btu/h.ft^2.°F or W/m^2.K)

The force that creates convection flow in fluids has two types (Hagen, 1999): natural convection and forces convection. If currents result from buoyancy forces generated by differences of density and these densities are caused by temperature gradients in the fluid mass, the action is called natural convection. If the currents are set in motion by the action of mechanical device such as fan, pump or agitator so that the flow is independent of density gradients, this is called forced convection.

The heat transfer coefficient (h) is not a thermal property (Hagen, 1999). It can be determined by several factors: type of fluid (liquid or gas), flow condition (laminar or turbulent), forced or natural convection or phase change, free-stream velocity, surface geometry and roughness, position along the surface and temperature dependence of fluid properties.

Rearranging equation 10,

$$q = \frac{T_1 - T_2}{\frac{1}{h}} \tag{11}$$

The thermal resistance R for convection is

$$R = \frac{1}{h} \tag{12}$$

In convection heat flow, the driving force is the temperature difference between two bodies. The thermal resistance is reciprocal of heat transfer coefficient as shown in equation 12 (Turner, 1981).

Combined thermal resistance both conduction and convection (no radiation)

In this system, a wall of thickness x with conductivity k is in contact with air on both sides as shown in Figure 10. The heat flows from higher temperature (T_1) from inside air to the surface of the wall (T_2) by convection and conduction through the wall to surface T_3 and convection from the wall to the air (T_4).

Heat transfer through a wall contacted with air on both sides

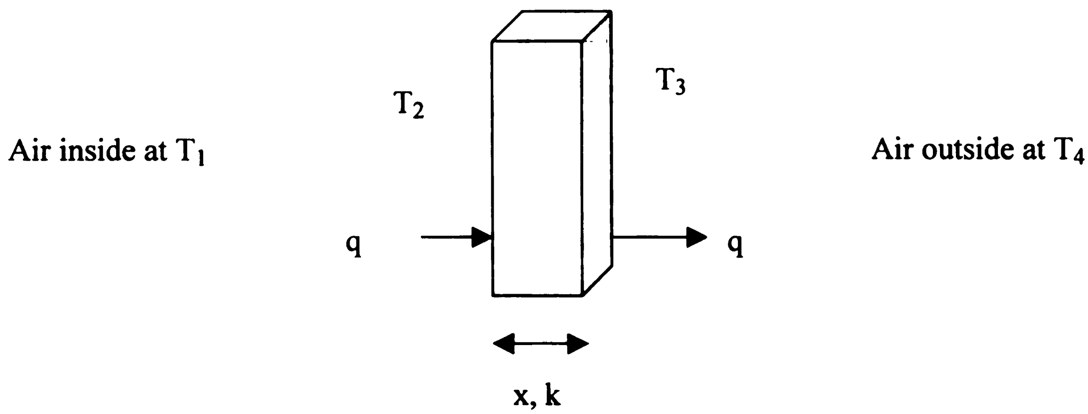

Figure 10. Diagram for heat transfer of a wall connected with inside and outside air

At steady state, the heat flux is constant so

$$q = q_{convect,inside} = q_{conduct} = q_{convect,outside}$$

$$q = h(T_1 - T_2) = \frac{k}{x}(T_2 - T_3) = h(T_3 - T_4) \qquad (13)$$

Rearranging equation 13,

$$T_1 - T_2 = \frac{q}{h}$$

$$T_2 - T_3 = \frac{qx}{k}$$

$$T_3 - T_4 = \frac{q}{h}$$

Adding these three equations,

$$T_1 - T_4 = \frac{2q}{h} + \frac{qx}{k} = q(\frac{2}{h} + \frac{x}{k})$$

$$q = \frac{T_1 - T_4}{\frac{2}{h} + \frac{x}{k}} = \frac{T_1 - T_4}{R}$$

$$R = \frac{2}{h} + \frac{x}{k} \tag{14}$$

The R-value for combined heat transfer through a wall in contact with inside and outside air depends upon the number of surfaces in contact with air, 2, the number of walls, 1, the type of walls (k), and the wall thickness (x) as shown in equation 14.

Heat transfer through two flat materials connected with inside and outside air:

In the system shown in Figure 11, there are two walls in contact with the air inside and outside.

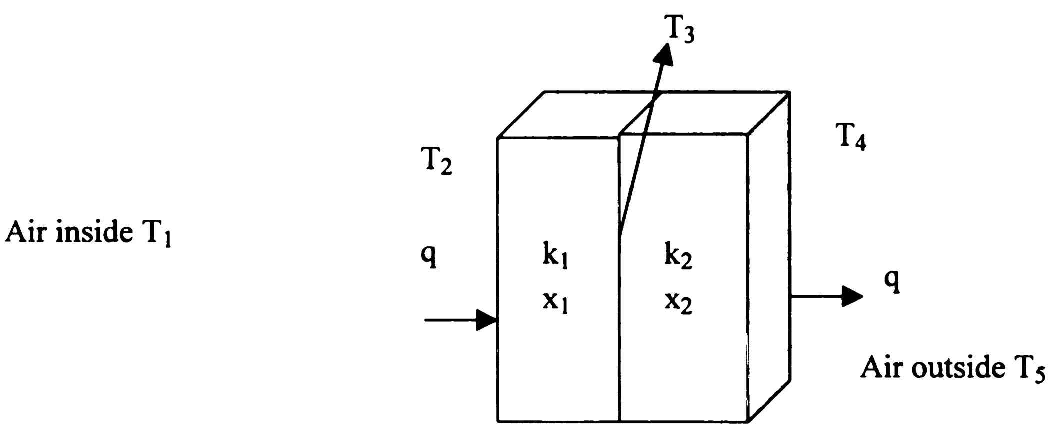

Figure 11. Diagram for heat transfer through two walls connected with inside and outside air

$$q = \frac{T_1 - T_5}{\frac{2}{h} + \frac{x_1}{k_1} + \frac{x_2}{k_2}} = \frac{T_1 - T_5}{R} \tag{15}$$

$$R = \frac{2}{h} + \frac{x_1}{k_1} + \frac{x_2}{k_2} \tag{16}$$

The R-value for combined conduction and convection heat transfer through two walls in contact with inside and outside air depends upon the number of surfaces in contact with air, 2, number of walls, 2, the type of walls (k_1, k_2), and the wall thickness (x_1, x_2) is shown in equation 16.

Heat transfer through multilayered walls in contact with inside and outside air

In multiple walls, there are "n" connected walls in which $wall_1$ is in contact with inside air and $wall_n$ is in contact with outside air. Heat flows from higher temperature (T_a) to $wall_1$ by convection at surface T_1 then conduction from $wall_1$ through $wall_n$ until surface of $wall_n$ and convection from $wall_n$ to air outside at T_b.

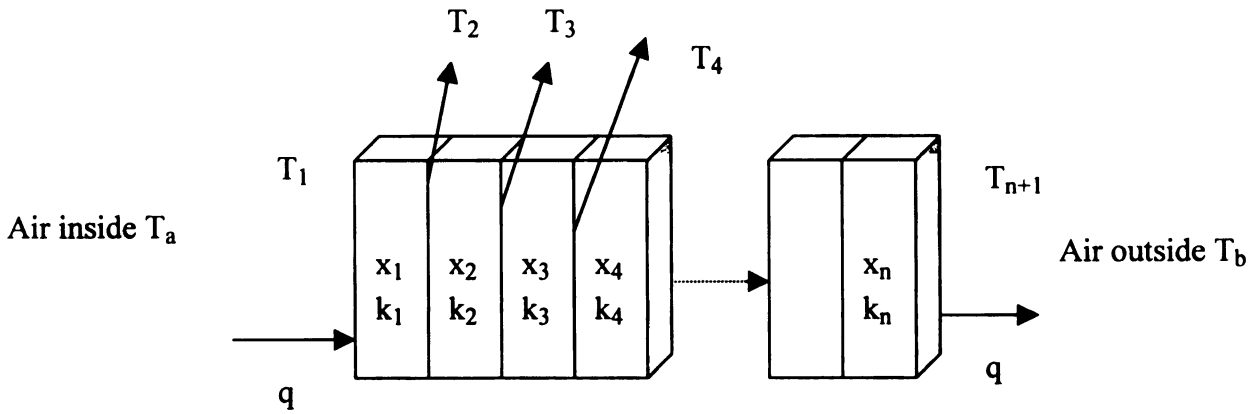

Figure 12. Diagram of heat transfer through multilayered walls in contact with inside and outside air

$$q = \frac{T_a - T_b}{\frac{2}{h} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \ldots + \frac{x_n}{k_n}} = \frac{T_a - T_b}{R} \tag{17}$$

$$R = \frac{2}{h} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \ldots + \frac{x_n}{k_n} \tag{18}$$

The R-value for heat transfer through multiple walls in contact with inside and outside air depends upon the number of surfaces in contact with air, 2, the number of walls, n, the type of walls ($k_1, k_2, \ldots, k_n$), and the wall thickness ($x_1, x_2, \ldots, x_n$) is shown in equation 18.

Radiation

Radiation is thermal energy transfer by electromagnetic waves at the speed of light (2.998×10^8 m/s). It does not require a medium, so radiation can transmit energy through a vacuum (Middleman, 1998). Thermal radiation lies in the range of wavelengths from about 0.1 to 100 μm. (Hagen, 1999)

All bodies with a surface temperature above absolute zero emit thermal radiation. The maximum radiation which a body can emit is given by the Stefan-Boltzmann law (Hagen, 1999) as shown in equation 19.

$$E_b = \sigma T^4 \qquad (19)$$

where E_b = blackbody emissive power (Btu/h.ft^2)

σ = Stefan-Boltzmann constant $= 0.1714 \times 10^{-8}$ Btu/h.ft^2.°R

T = absolute temperature (°R)

A body that emits radiation according to equation 19 is an ideal radiator. Real surfaces do not emit radiation following the Stefan-Boltzmann law. Instead, the emission power (E) is given by equation 20

$$E = \varepsilon \sigma T^4 \qquad (20)$$

E = emissive power

$$\varepsilon = \text{emissivity} = \frac{E}{E_b} \qquad (21)$$

Emissivity (ε) is a surface property that is used to compare the emissive power of a real surface with a blackbody at the same temperature. Emissivity varies between 0 to 1 and it is dimensionless (Hagen, 1999). Emissivity is a function of surface temperature and the wavelength and direction of the emitted radiation. Emissivity is a strong function of the surface condition so emissivities of polished metals are low, in the range 0.03 to 0.08. For nonmetals such as paper, boards and building materials, emissivity is in the range of 0.65 to 0.95 (McCabe, 1993).

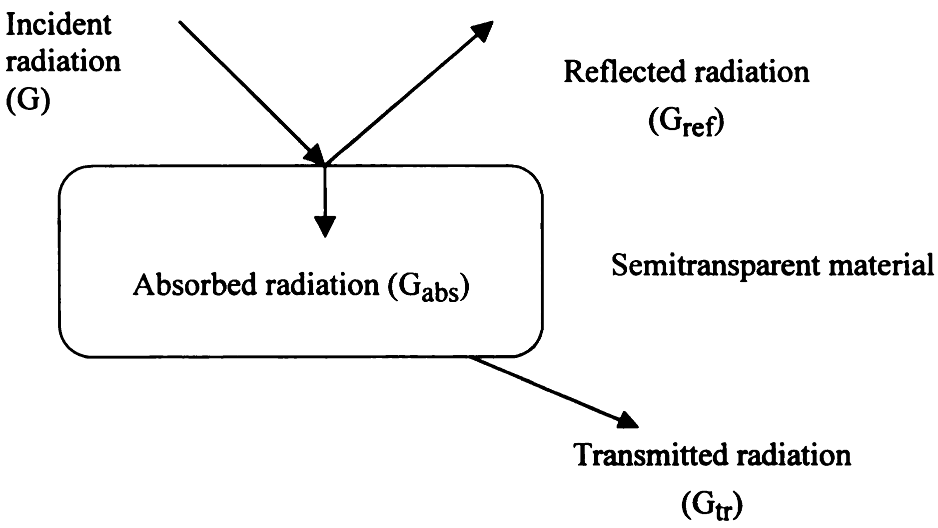

Figure 13. Radiation incident on a surface can be absorbed, reflected and transmitted

Irradiation (G) is the radiant heat flux upon a surface (Btu/h.ft^2) as shown in Figure 13 (Hagen, 1999). Thermal radiation is principally a surface phenomenon. When radiation impinges on a surface, a fraction of the incident radiation can be absorbed, called absorptivity (α), reflected, called reflectivity (ρ), and/or transmitted, called transmissivity (τ). The amounts absorbed, reflected and transmitted depend on material properties and may vary with the wavelength or frequency of the incident radiation.

These radiation properties can be defined as fractions of the irradiation as shown in the following equations 22-24:

$$\alpha = \frac{G_{abs}}{G} \tag{22}$$

$$\rho = \frac{G_{ref}}{G} \tag{23}$$

$$\tau = \frac{G_{tr}}{G} \tag{24}$$

where G_{abs}, G_{ref}, G_{tr} are the absorbed, reflected and transmitted portions of the irradiation G, respectively

Absorptivity, reflectivity and transmissivity are dimensionless numbers that are range between 0 to 1. According to the first law of thermodynmics, energy is conserved so the radiation incident on the surface must equal to the sum of the radiation absorbed, reflected and transmitted (Hagen, 1999) as shown in equation 25,

$$G = G_{abs} + G_{ref} + G_{tr} \tag{25}$$

Dividing equation 25 by G:

$$\alpha + \rho + \tau = 1 \tag{26}$$

If the material is opaque, $\tau = 0$ and the equation 26 becomes,

$$\alpha + \rho = 1 \tag{27}$$

The radiation properties defined by absorptivity, reflectivity and transmissivity are total hemispherical properties that are averaged over all wavelengths and directions.

Under steady state conditions, thermal equilibrium exits between objects and their enclosure. The energy emitted and absorbed by the object is

$$A\varepsilon(T)\sigma T^4 = A\alpha(T)\sigma T^4 \qquad (28)$$

Dividing equation 28 by $A\sigma T^4$,

$$\varepsilon(T) = \alpha(T) \qquad (29)$$

Equation 29 is known as Kirchhoff's law (Hagen, 1999). It states that the total hemispherical emissivity of a surface at temperature T equals to the total hemispherical absorptivity for radiation arriving from a surface at the same temperature.

2.4 Thermal Testing Approaches for Insulating Packages

There are several procedures to estimate the rate of heat transfer for insulated packages. One is the American Society for Testing and Materials (ASTM) D3103-92 (ASTM, 1997). Some researchers and companies have developed other testing for insulated containers.

ASTM D3103-92

This standard is used to determine the thermal insulation capability of a package with or without interiors or refrigerants. Temperature indicating devices such as thermocouples, thermistors, bi-metals recorders, or portable recorders are used to determine temperatures. For small packages (volume is less than 1 ft^3), at least three thermocouples are used to measure the temperature profile. For packages with interior walls (separate product and refrigerant) more thermocouples may be desired to adequately measure temperature. For the bigger packages (inside volume more than one

ft^3), at lease 10 thermocouples need to determine the locations of the coldest and warmest spots to get the temperature profile.

Using refrigerants, the weights of refrigerants and temperatures are recorded before being put into the package and during all testing until the temperatures are above the maximum or below the temperature dictated by the product. This package is sealed tightly and put on a wooden shelf at the test condition. The date, hour of the start and finish of testing are collected.

Other testing methods

The ice melt test (Burgess, 1999) was used in this research to estimate the thermal resistance (R-value) of insulating packages varying in the size between 0.5 to 5 ft^3. Regular ice was used as the refrigerant for testing. R-values were calculated using equation 1. The data was converted into equation 2. Equation 2 is used to estimate the R-value of an insulating packaging at an accuracy about ±20%. This is an easy method to determine the R-value of containers and to approximate the amount of ice required to maintain temperature in the packages.

Chapter 3

Experimental Design and Results

3. Experimental Design and Results

3.1 Materials:

1. Ice (cubed) from Quality Dairy (QD)
2. Dry ice (cubed) from Chemistry Department, Michigan State University
3. Gray paint buckets made from HDPE, 8″×6.5″ (diameter×height)
4. Mass Balance: Mettler PM 2000

Box Samples:

1. Regular Slotted Container (RSC) C-flute corrugated box, inside dimensions (L×W×D) = 13″×9″×14″
2. Regular Slotted Container (RSC) C-flute corrugated box, inside dimensions = 15″×12″×10″
3. Expanded polystyrene cooler (EPS cooler), 1.5 inch thick and inside dimensions = 12″×9″×10″
4. Expanded polystyrene cooler (EPS cooler), 1inch thick and inside dimensions = 14″×11″×8.5″
5. Molded Polyurethane box: one inch polyurethane injected between two corrugated boards, inside dimensions = 10″×10″×10″ and one open cell foam cover as shown in Figure 14.
6. Vacuum Insulation Panel (VIP) in C-flute corrugated box: six VIP panels placed inside box, inside dimensions = 10″×10″×10″(L×W×D) as shown in Figure 15.

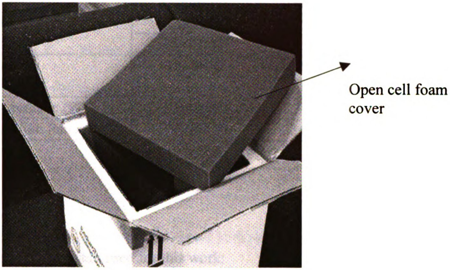

Figure 14. Molded polyurethane with open cell foam

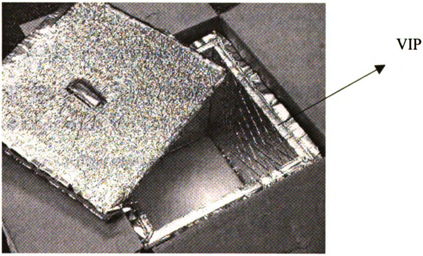

Figure 15. VIP in a corrugated box

Table 3. Summary specifications for insulation materials

Samples	Inside Dimensions (in×in×in)	Thickness (in)	Inside Surface Area (ft^2)
1.RSC (C-flute)	13×9×14	0.156	5.90
2.RSC (C-flute)	15×12×10	0.156	6.25
3.EPS Cooler	12×9×10	1.500	4.42
4. EPS Cooler	14×11×8.5	1.000	5.09
5.Molded polyurethane (PU)	10×10×10	1.312	4.17
6.Vacuum Insulation Panel (VIP)	10×10×10	1.156	4.17

3.2 Methods

Three conditions were used for this work:

1. Standard conditions: 72°F and 50 % RH
2. 72°F and 85%RH (to compare %RH at the same temperature)
3. 104°F and 50 % RH (to compare temperature at the same %RH)

Standard conditions were tested for all sample boxes (Table 3). Conditions 2 and 3 were tested for only C-flute corrugated boxes (samples 1 and 2) to compare the effect of board moisture content and temperature.

In this experiment, the ice melt test (Burgess 1999) in Figure 16 was performed to estimate the thermal resistance (R-value) of these insulating packages. There were three replicates for each package per condition.

Preconditioning

Box samples were put in the conditioning room for at least 24 hrs prior to testing. A quantity of regular ice (as much as possible to reduce the error associated with water on ice left from preconditioning) was placed into a bucket. The package was loosely closed and stored in the conditioning room for several hours to ensure that all the surface of the ice was covered by water. This was done to make the temperature of the ice equal to 32°F (not the store temperature of ice of about 0°F). The ice will hold this temperature until all the ice is melted. The water was drained and discarded after this step. Dry ice did not need to be preconditioned because it evaporates to a gas at –108.4°F.

Procedure:

The ice melt test is shown in Figure 16. The bucket is placed back into the center of the box and the box flaps are tightly sealed with tape. Sealing is important so no heat loss occurs through openings. The box sits until almost all the ice melts (to reduce the error from preconditioning that it has some water left on the surface of the ice). Finally, the amount of water that melts is measured and the melt time is recorded.

The dry ice test is shown in Figure 17. Dry ice is put into the bucket and weighed. The box is sealed tightly with tape. The box sits until almost all of the dry ice sublimates. Finally, the remaining dry ice is weighed and subtracted from the original weight. This would be the amount of dry ice sublimated. The time is noted. The experimental R-value is then calculated from the experimental results using equation 2, as shown below

$$R_{\exp} = \frac{A \times \Delta T}{meltrate \times latentheat}$$

Where R_{exp} = thermal resistance of container wall ($\frac{ft^2.F.hr}{Btu}$)

A = inside surface area of box (ft^2)

ΔT = temperature difference (°F) between the outside air and the melting point of the refrigerant used

Melt rate= the rate that ice melts during the experiment (equal to the weight of the ice melted divided by the melt time (lb/hr))

Latent heat = 144 Btu/lb for regular ice and 240 Btu/lb for dry ice

The predicted R-value (Burgess, 1999) was calculated from the following fitted equation

$$R_P = 3.9th + 1.5np + 3.2nf \quad (\pm 20\% \text{ accuracy})$$

Where th = the average wall thickness (inch)

np = the number of plain surfaces

nf = the number of aluminium foil surfaces

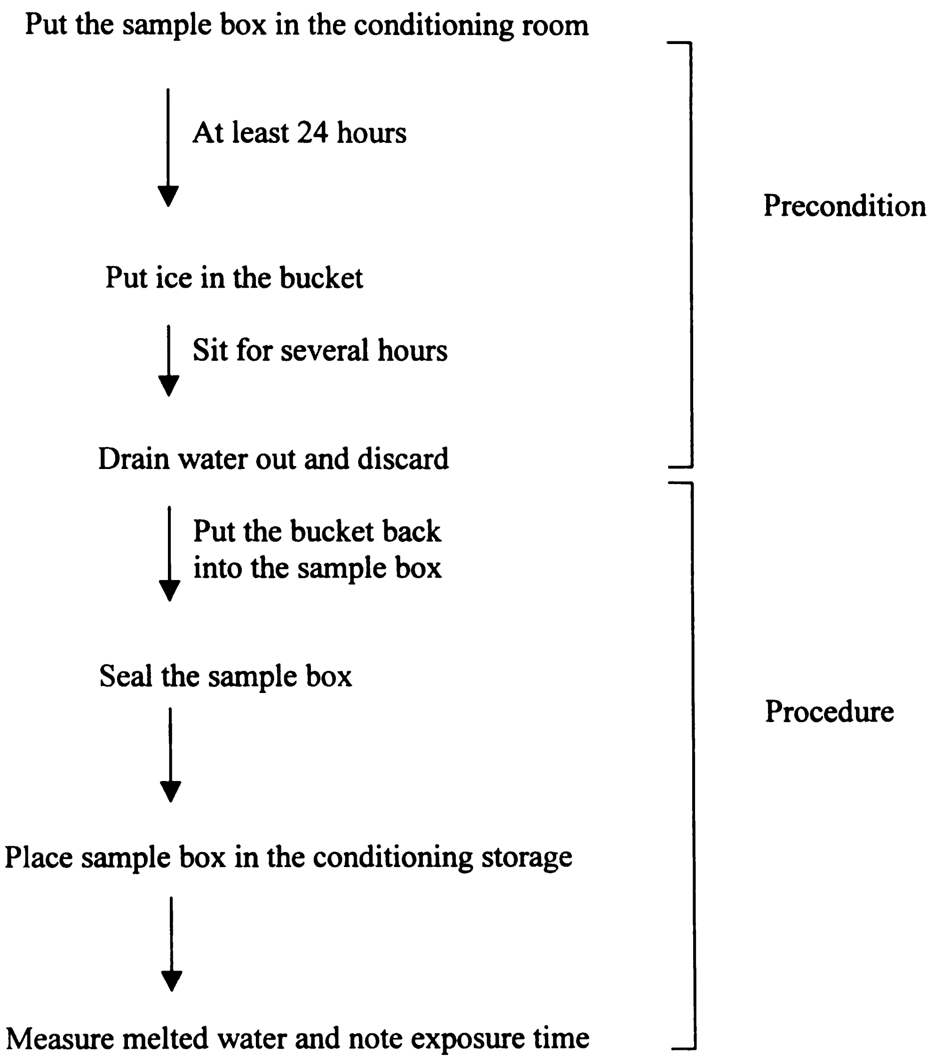

Figure 16. The procedure for the regular ice melt test

Put the sample box in the conditioning room

↓ At least 24 hours

Put dry ice into the bucket

↓

Weigh dry ice and bucket and put into the sample box

↓

Seal the sample box

↓

Place sample box in the conditioning room

↓

Open box, check weight and note the time

Figure 17. The procedure for the dry ice melt test

3.3 Results

The predicted R-value (R_p) and the experimental R-values (R_{exp}) were compared. The results in Tables 4 and 5 show the experimental results for regular ice and dry ice respectively. There was no significant difference between the theoretical R-values using regular ice under the three different conditions of the relative humidity and temperature. The R-value for the corrugated box is less than the R-value for the EPS cooler, which is less than the R-value for molded polyurethane, which is less than the R-value for the VIP. The results for VIP for regular ice from ice melt test in Table 4 are lower than the R-value (12.66) that the company quotes (25-30). The results for VIP for dry ice from the ice melt test in Table 5 have an average about of 26 which does match with what the company quotes. These prove that the same container can have different R-values using different refrigerants. The temperature and the surface area of the product affect the R-value too. Different materials used in these insulating packages can affect the R-value depending on the thermal conductivity of the materials as shown in Table 6 (type, structure or density), heat transfer coefficient, surface area and thickness.

R-values from ice melt test using regular ice and dry ice at 72°F and 50%RH

Table 4. R-values of insulating packages from regular ice melt test at 72°F and 50%RH

Samples	Ice Melt Wt (lb)	Melting Time (hr)	R-value Experimental	Average	Stdev	R-value Predicted	% Error R-value
1	4.39	14	5.23	5.44	0.19	5.11	-6.07
	4.19	14	5.48				
	4.1	14	5.60				
2	4.14	13	5.45	5.68	0.21	5.11	-9.98
	3.94	13	5.73				
	3.86	13	5.85				
3	4.74	39.25	10.17	9.86	0.50	10.35	5.01
	4.76	39.25	10.12				
	5.29	40	9.28				
4	4.37	25.5	8.25	8.25	0.27	8.4	1.86
	4.32	26	8.51				
	4.25	24	7.98				
5	4.06	38	10.84	10.73	0.11	9.62	-10.37
	4.25	39	10.63				
	4.32	40	10.73				
6	4.59	51	12.87	12.66	0.36		
	4.32	48	12.87				
	4.54	48	12.25				

Table 5. . R-values of insulating packages from dry ice melt test at 72°F and 50%RH

Samples	Ice Melt Wt (lb)	Melting Time (hr)	R-value Experimental	Average	Stdev	R-value Predicted	% Error R-value
1	7.54	22	12.94	12.92	0.36	5.11	-60.44
	7.07	20	12.55				
	6.69	20	13.26				
2	4.91	10.5	10.04	12.37	2.04	5.11	-62.69
	7.09	20	13.25				
	6.8	20	13.82				
3	6.02	29	16.00	17.16	1.13	10.35	-39.67
	5.79	30	17.21				
	6.55	36	18.26				
4	6.83	23	12.88	14.06	1.13	8.4	-40.27
	6.74	25	14.19				
	7.34	29	15.12				
5	5.61	28.33	15.83	16.23	0.84	9.62	-40.73
	6.00	30	15.67				
	5.43	30	17.19				
6	8.19	72.5	27.75	26.43	1.34		
	5.00	40	25.08				
	8.17	69	26.47				

Table 6. Thermal conductivity of materials

Materials	Thermal Conductivity (Btu/hr.ft^2.°F) at 70°F
Air	0.015
Water	0.346
Corrugated board	0.035
EPS foam	0.022
Polyurethane	0.018

The effect of the relative humidity on the R-value

The relative humidity also affects the R-value since thermal conductivity is a function of relative humidity, especially for insulating packages using corrugated boxes that trap humidity with air. The thermal conductivity will be between the thermal conductivity of pure water (0.346 Btu /ft.hr°F at 70°F) and air (0.015 Btu /ft.hr°F at 70°F) (Hagen, 1999). So the conductivity should increase as the relative humidity increases. When the relative humidity increases as shown in Tables 7 and 8, the R-values of packages are decreased.

Table 7. R-value of C-flute corrugated box at 72°F and 85%RH using regular ice

Samples	Ice Melt Wt (lb)	Melting Time (hr)	R-value Experiment	Average	Stdev	R-value Predicted	% Error R-value
1	3.31	7	3.47	3.35	0.52	5.11	52.39
	3.02	7	3.80				
	4.7	8	2.79				
2	3.28	7	3.71	3.52	0.41	5.11	45.17
	3.2	7	3.80				
	4.56	8	3.05				

Table 8. R-value of C-flute corrugated box at 72°F and 85%RH using dry ice

Samples	Ice Melt Wt (lb)	Melting Time (hr)	R-value Experiment	Average	Stdev	R-value Predicted	% Error R-value
1	8.27	18.5	9.92	10.71	0.79	5.11	-52.29
	8.17	19.75	10.72				
	7.62	19.75	11.49				
2	8.66	20	10.85	11.42	0.63	5.11	-55.24
	8.21	19.75	11.30				
	7.67	19.75	12.10				

The effect of temperature on the R-value

Thermal conductivity is a function of temperature. The thermal conductivity of insulating materials normally increases with increasing temperature (ASHRE, 1993) so when the temperature increases, the R-value decreases as shown in Tables 9 and 10.

Dry ice has a much lower temperature (-108.4°F) than regular ice (32°F). The thermal conductivity of the material and the heat transfer coefficient for carbon dioxide decreases so the R-values for dry ice are somewhat higher than for regular ice in the same containers.

Table 9. R-value for regular ice at 104°F at 50% RH in a corrugated box

Samples	Ice Melt Wt (lb)	Melting Time (hr)	R-value Experiment	Average	Stdev	R-value Predicted	% Error R-value
1	4.19	5.5	2.15	2.18	0.03	5.11	134.40
	4.12	5.5	2.19				
	4.10	5.5	2.20				
2	3.95	5.0	2.20	2.18	0.05	5.11	134.05
	4.30	5.5	2.22				
	4.48	5.5	2.13				

Table 10. R-value of dry ice at 104°F at 50% RH in a corrugated box

Samples	Ice Melt Wt (lb)	Melting Time (hr)	R-value Experiment	Average	Stdev	R-value Predicted	% Error R-value
1	5.71	9.67	7.51	7.36	0.23	5.11	-30.57
	5.99	9.58	7.09				
	5.63	9.50	7.48				
2	6.11	9.83	7.55	7.70	0.16	5.11	-33.61
	6.12	10.00	7.68				
	5.83	9.75	7.86				

Both the relative humidity and temperature affect R-values. The higher the relative humidity and storage temperature, the lower the R-value as shown in Tables 11 and 12.

Table 11. Summary of the R-values for three conditions (regular ice)

Samples	R-value 72°F, 50%RH	R-value 72°F, 85%RH	R-value 104°F, 50%RH
1	5.44	3.35	2.18
2	5.68	3.52	2.18

Table 12. Summary of the R-values for three conditions (dry ice)

Samples	R-value 72°F, 50%RH	R-value 72°F, 85%RH	R-value 104°F, 50%RH
1	12.92	10.71	7.36
2	13.70	11.42	7.70

Chapter 4

Analysis and Discussion

The predicted and experimental R-values of insulating containers were compared in Chapter 3. The simulation model shown in the Appendix was developed using BASIC to predict the R-value. The model considers conduction, convection and radiation to solve the heat transfer problem shown in Figure 18.

The theory of heat transfer by conduction, convection and radiation requires radiation balances and energy balances. Solving these equations to determine the heat transfer rate allows us to calculate the R-value.

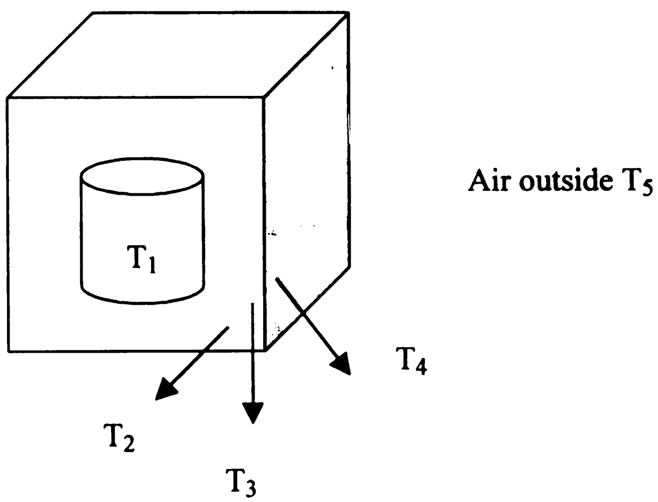

Figure 18. Performing ice melted test of ice or dry ice in a insulating container

The following equations are used in the energy and radiation balances:

T_1 = temperature of product (using ice =32°F or dry ice =-108.4°F)

T_2 = temperature of air between product and inside wall (°F or K)

T_3 = temperature of inside wall (°F or K)

T_4 = temperature of outside wall (°F or K)

T_5 = temperature of air outside (°F or K)

A_1 = surface area of product (ft^2 or m^2)

A_3 = surface area of inside wall (ft^2 or m^2)

A_4 = surface area of outside wall (ft^2 or m^2)

Q = input energy

G_1, G_3, G_4 = irradiation on product surface, inside box surface and outside box surface respectively

σ = Stefan-Boltzmann constant =0.1714×10^{-8} Btu/h.ft^2.°R

ε_1, ε_2, ε_3 = emissivity of product, inside box surface and outside box surface respectively

α_1, α_2, α_3 = absorptivity of product, inside box surface and outside box surface respectively

ρ_1, ρ_2, ρ_3 = reflectivity of product, inside box surface and outside box surface respectively

k's = the thermal conductivity of wall

h's = heat transfer coefficient of air

Radiation balances:

1. At the product surface (A_1):

$$G_1 A_1 = (\varepsilon_3 \sigma A_3 T_3^4 + \rho_3 G_3 A_3)(\frac{A_1}{A_3}) = \varepsilon_3 \sigma A_1 T_3^4 + \rho_3 G_3 A_1 \qquad (30)$$

2. On the inside surface of the box (A_3)

$$G_3A_3 = \varepsilon_1\sigma A_1T_1^4 + \rho_1G_1A_1 + (\varepsilon_3\sigma A_3T_3^4 + \rho_3G_3A_3)(1 - \frac{A_1}{A_3})$$

$$G_3A_3 = \varepsilon_1\sigma A_1T_1^4 + \rho_1G_1A_1 + \varepsilon_3\sigma A_3T_3^4 + \rho_3G_3A_3 - \varepsilon_3\sigma A_1T_3^4 - \rho_3G_3A_1 \quad (31)$$

3.On the outside surface of the box (A_4)

$$G_4A_4 = (\varepsilon_5\sigma A_5T_5^4 + \rho_5G_5A_5)(\frac{A_4}{A_5}) = \varepsilon_5\sigma A_4T_5^4 + \rho_5G_5A_4 \quad (32)$$

Energy balances:

4. Product:

$$Q + G_1A_1\alpha_1 = \varepsilon_1A_1\sigma T_1^4 + hA_1(T_1 - T_2) \quad (33)$$

5. Inside box wall

$$hA_3(T_2 - T_3) + \alpha_3G_3A_3 = \frac{k_3A_3}{\Delta x}(T_3 - T_4) + \varepsilon_3\sigma A_3T_3^4 \quad (34)$$

6. Outside box wall

$$\frac{k_3A_3}{\Delta x}(T_3 - T_4) + \alpha_4G_4A_4 = hA_4(T_4 - T_5) + \varepsilon_4\sigma A_4T_4^4 \quad (35)$$

7. Air between product and inside box wall

$$hA_1(T_1 - T_2) = hA_3(T_2 - T_3) \quad (36)$$

In these equations, G_1, G_3, G_4, Q, T_2, T_3 and T_4 are unknown. These unknowns were found using an iteration method in BASIC. The R-value is determined as the temperature different, T_5 -T_1, divided by Q times A_3.

The thermal conductivity, heat transfer coefficient and surface area of products (regular ice and dry ice) are needed for the computer model. The heat transfer coefficient is a function of temperature. The temperature of air for regular ice at the wall is taken as the average or "film"temperature (T_f) between ice (32°F) and the storage temperature (72°F), which is equal to 52°F (284 K). When the storage condition is 104 °F, the average temperature (T_f) is equal to 68°F (293 K). From these temperatures, the properties of air at atmospheric pressure are as shown in Table 13.

Table 13. Properties of air at 284 and 293 K (Holman, 1986)

T (K)	$\nu \times 10^6$ (m^2/s)	k (W/m°C)	Pr
284	14.29	0.025	0.712
293	15.08	0.026	0.71

The heat transfer coefficient (h) of air was estimated from the product of the Grashof and Praudtl numbers, G_rP_r. G_r can be calculated from equation 37 and P_r from Table 13. Then, $\overline{Nu_f}$ is calculated using equation 38 and h was found in equation 39.

g = acceleration velocity (9.8 m/s^2) and l = height of container (m). For l = 10 in = 0.254 m. h can calculate from the following equations:

$$G_r = \frac{g \times \beta \times \Delta T \times l^3}{\nu^2} \qquad (37)$$

$$= \frac{9.8 \times \frac{1}{284} \times (295 - 273) \times 0.254^3}{(14.29 \times 10^{-6})^2}$$

$$G_r = 6.1 \times 10^7$$

$G_rP_r = 6.1\times10^7 \times 0.712 = 4.34\times10^7$

From Table 14 (Holman) using vertical planes and cylinders at G_rP_r between 10^4-10^9

$$\overline{Nu_f} = C(Gr_f \Pr_f)^m \tag{38}$$

$$\overline{Nu}f = 0.59(G_rP_r)^{\frac{1}{4}} = 0.59(4.34\times10^7)^{\frac{1}{4}} = 47.9$$

$$h = \frac{\overline{Nu_f}\times k}{l} \tag{39}$$

$$= \frac{47.9\times0.025}{0.254}$$

$$\mathrm{h} = 4.71\ \frac{W}{m^2K} = 0.83\ \frac{Btu}{ft^2.hr.°F}\ \text{for air}$$

Table 14. Constants for use in the equation 38.

Geometry	Gr_fPr_f	C	m
Vertical planes and cylinders	10^4-10^9	0.59	1/4
	10^9-10^{13}	0.021	2/5
	10^9-10^{13}	0.1	1/3

In this experiment, the height of samples 1 and 2 (corrugated boxes) are 14 and 10 inches respectively and k and h are shown in Tables 15 and 16 for 284 and 293 K respectively. The heat transfer coefficient depends on thermal conductivity and length (k/l) and temperature difference.

Table 15. Summary of k and h at length 10 and 14 inches at 284 K for air

L (in)	A_l (ft^2)	k (Btu/ft.hr.°F)	h (Btu/ft^2.hr.°F)
14	5.90	0.0144	0.77
10	6.25	0.0144	0.83

Table 16. Summary of k and h at length 10 and 14 inch at 293 K for air

L (in)	A_l (ft^2)	k (Btu/ft.hr.°F)	h (Btu/ft^2.hr.°F)
14	5.90	0.015	0.89
10	6.25	0.015	0.97

The results for the R-value show that the thermal conductivity affects the R-value very little as shown in Table 17. When the thermal conductivity changes from 0.035 to 0.0144 Btu/hr.ft.°F, R slightly changes from 21.58 to 22.22. On the other hand, the R-value rapidly decreases when the product surface area increases from 0.2 to 0.4 ft^2. It goes from 21.58 to 12.09.

The product (ice) surface area affects the R-value more than the thermal conductivity and heat transfer coefficient. The surface area for the regular ice used in the experiment can be calculated from the surface area of the bucket that had a size d×h = 8×6.5 in×in, so the surface area = $2\pi r^2 + 2\pi rh = 1.83$ ft^2. When the regular ice melts, water and regular ice are mixed so the surface area does not change during melting.

Table 17. Results for R-value from the computer model using regular ice at T5 (72 °F) and 50%RH at k=0.035, 0.025 and 0.0144 Btu/hr.ft°F.

	A_3 (5.9 ft^2)			A_3 (6.25 ft^2)		
A_1 ft^2	R (k=0.035)	R (k=0.025)	R (k=0.0144)	R (k=0.035)	R (k=0.025)	R (k=0.0144)
0.5	21.58	21.76	22.22	20.98	21.16	21.62
1.0	12.09	12.26	12.72	11.78	11.96	12.42
1.5	9.02	9.20	9.66	8.68	8.86	9.32
2.0	7.45	7.62	8.08	7.20	7.38	7.84
2.5	6.48	6.65	7.11	6.28	6.46	6.92
3.0	5.86	6.03	6.49	5.66	5.84	6.30
3.5	5.43	5.61	6.07	5.21	5.38	5.84
4.0	5.10	5.27	5.73	4.88	5.06	5.52

The R-values from the computer model show the effect of storage conditions (72 and 104°F). The higher temperature (104°F) has a lower R-value than at 72°F as shown in Table 18. The higher the thermal conductivity, the faster the heat transfer, so the lower the R-values.

Table 18. Results for R-value from the computer model for regular ice at 72 and 104°F and 50%RH

	A_3(5.90 ft^2)		A_3(6.25 ft^2)	
A_1 ft^2	R-value T_5 =72°F	R-value T_5 =104°F	R-value T_5=72°F	R-value T_5 =104°F
0.5	21.58	17.24	20.98	16.69
1.0	12.09	9.84	11.78	9.48
1.5	9.02	7.33	8.68	7.06
2.0	7.45	6.11	7.20	5.86
2.5	6.48	5.35	6.28	5.16
3.0	5.86	4.86	5.66	4.67
3.5	5.43	4.52	5.21	4.32
4.0	5.10	4.25	4.88	4.07

The surface area, the thermal conductivity and the heat transfer coefficient were varied for dry ice. The surface area of dry ice can be calculated from the total weight of dry ice put into the bucket divided by the weight of dry ice for one rod shown in Figure 19. We assume that the dry ice rods were packed as a block (L=W=D).

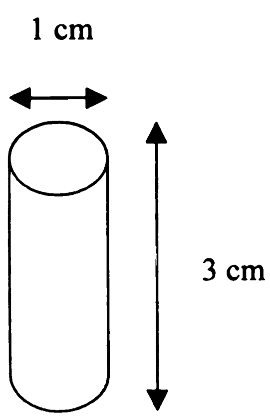

Figure 19. Dry ice rod

Weight of dry ice per rod = 14 g

Size of dry ice = d×h = 1cm×3 cm

$V = \pi r^2 h = 3.142\times0.5^2\times3 = 2.36\ cm^3$

V= Volume per rod

Weight of dry ice put into the bucket = 3800 g

So how many rods were put in the bucket

= 3800 g/14 g = 271 rods

Volume for all dry ice = 271×2.36 = 640 cm^3

Volume for all dry ice $= (L \times W \times D) = L^3$

$L^3 = 640\ cm^3$

L = 8.62 cm

Surface area of dry ice = 6×(8.62×8.62) = 446 cm^3 = 0.48 ft^2

When the dry ice sublimates, the size of the dry ice decreases, so the surface area also decreases. The R-value therefore increases when the size of dry ice decreases.

The properties of carbon dioxide gas at 245 K (T_f =(195+295)/2) and 254 (T_f=(195+313)/2) K are shown in Table 19. The results for the heat transfer coefficient for carbon dioxide gas at the storage temperatures 72°F and 104 °F are shown in Tables 20 and 21. The calculations are the same as for air.

Table 19. Properties of carbon dioxide gas at 245 and 254 K

T (K)	$\nu \times 10^6$ (m^2/s)	k (W/m°C)	Pr
245	5.59	0.0125	0.797
254	6.01	0.0132	0.791

Table 20. Summary of k and h at length 10 and 14 inch at 245 K of carbon dioxide gas

L (in)	A_l (ft^2)	k (Btu/ft.hr.°F)	h (Btu/ft^2.hr.°F)
14	5.90	0.0072	0.99
10	6.25	0.0072	0.96

Table 21. Summary of k and h at length 10 and 14 inch at 254 K of carbon dioxide gas

L (in)	A_1 (ft^2)	k (Btu/ft.hr.°F)	h (Btu/ft^2.hr.°F)
14	5.9	0.0083	1.04
10	0.0072	0.0083	1

The surface area of the dry ice affects the R-value more than the thermal conductivity as shown in Table 22. The R-value rapidly decreases when the surface area increases from 0.2 to 0.4 ft^2 at k = 0.0211 Btu/hr.ft.°F, that is 33.13 to 17.67. The surface area of dry ice from the experiment is about 0.5 ft^2 that the results from the computer model at k = 0.0211 Btu/hr.ft.°F are about 15.09. This is better than the predicted result calculated from equation 2.

Table 22. Effect of the thermal conductivity of dry ice on the R-value

	A_3 (5.9 ft^2)			A_3 (6.25 ft^2)		
A_1 ft^2	R (k=0.035)	R (k=0.0211)	R (k=0.0072)	R (k=0.035)	R (k=0.022)	R (k=0.0072)
0.2	32.85	33.09	34.30	35.79	36.04	37.26
0.4	17.41	17.66	18.84	18.92	19.17	20.39
0.6	12.25	12.50	13.70	13.28	13.53	14.74
0.8	9.68	9.92	11.12	10.46	10.71	11.93
1	8.13	8.38	9.59	8.77	9.02	10.24
1.2	7.11	7.36	8.56	7.65	7.90	9.12
1.4	6.37	6.62	7.82	6.85	7.10	8.32
1.6	5.82	6.07	7.27	6.25	6.50	7.71
1.8	5.39	5.64	6.83	5.78	6.03	7.24

The R-values from the computer model show little effect of the storage conditions (72 and 104°F). The higher temperature (104°F) has a lower R-value than at 72°F as shown in Table 23. The higher the thermal conductivity and heat transfer coefficient, the lower the R-values.

Table 23. R-values from the computer model using dry ice at 72 and 104°F and 50%RH

	A3(5.90 ft^2)		A3(6.25 ft^2)	
A_1 ft^2	R-value T_5 =72°F	R-value T_5 =104°F	R-value T_5=72°F	R-value T_5 =104°F
0.2	33.09	31.43	36.04	34.54
0.4	17.66	16.76	19.17	18.33
0.6	12.50	11.85	13.53	12.94
0.8	9.92	9.40	10.71	10.23
1	8.38	7.95	9.02	8.62
1.2	7.36	6.97	7.90	7.54
1.4	6.62	6.26	7.10	6.77
1.6	6.07	5.74	6.50	6.19
1.8	5.64	5.33	6.03	5.74

The R-values from experiment fit well with the predicted R-values for regular ice as shown in Table 24 since the predicted R-values were obtained using regular ice. The computer model still needs to be modified to have a better fit for regular ice.

Table 24. Experimental, computer model and predicted R values for regular ice at 72°F and 50%RH

Samples	R-value Experiment	R-value Computer model	R-value Predicted
1	5.44	8.16	5.11
2	5.68	7.88	5.11

The R-values from the computer model fits better for dry ice than the predicted R-value as shown in Table 25. The surface area of dry ice affected the R-value the most. This is not mentioned in the predicted R-value.

Table 25. Experimental, computer model and predicted R values for dry ice at 72°F and 50%RH

Samples	R-value Experiment	R-value Computer model	R-value Predicted
1	12.92	15.09	5.11
2	13.70	16.36	5.11

The relative humidity also affected to the R-values in the experiment (Tables 11 and 12). The disadvantage of the computer model is that it does not include the relative humidity, so this model still needs to be developed. The predicted R-value also does not include the relative humidity.

Chapter 5

Conclusions and Future Studies

5.1 Conclusions

The experimental results from the ice melt tests showed that the sizes of the R-value were VIP>molded polyurethane>EPS cooler>corrugated box. The higher the R-value, the better the insulating package.

Thermal conductivity is function of temperature and relative humidity. When the temperature and the relative humidity increase, the thermal conductivity increases. Therefore, the R-value decreases. The convection heat transfer coefficient is also a function of temperature. As the temperature increases, it increases and the R-value decreases. The surface area of the product affects the R-value more than the thermal conductivity and the heat transfer coefficient.

The experimental R-values for dry ice were much higher than for regular ice since the temperature of dry ice is much lower than regular ice. These lower both the thermal conductivity and convection heat transfer coefficient, which raises the R-value. But the effect of product surface area is even greater.

The experimental R-values fit well with the predicted R-values for regular ice since the predicted R-values were based on regular ice. The computer model still needs to be developed to get an even better fit for regular ice.

The R-values from the computer model fit better for dry ice than the predicted R-value, because the computer model accounts for the surface area of dry ice. The surface area was not accounted for the predicted R-value.

The computer model needs to be modified to include the effect of relative humidity. The theoretical R-value also needs to be developed to include both the relative humidity and the surface area of products.

5.2 Future Studies

It is recommended that further studies on more variety and sizes of packages using different materials such as Al-foil or combination of materials. The effect of openings in the packages should be considered. Other refrigerants such as gel packs should be investigated too. The R-value should be compared with the regular ice and dry ice.

The computer model should be developed to include the relative humidity and also to optimize the properties of containers with cost. The warm up times also should be studied the simulation model.

Appendix

The computer model was developed using the BASIC program to calculate for the R-value of the insulating containers. The program has 73 lines from 10-730 as shown below. There are six categories: first is input data from lines 20-120 (giving data). Second is "find k value" from lines 140-280 (depending on the structure of containers). Third is guesses and variable parameters from lines 300-350 (varied T_1, T_5 and A_1). Fourth, is the setup system of equations from lines 370-430 (equations 30-36). Fifth, is the solved system from equations 450-570 (made in matrix form and solved using iteration). Finally, are the solutions from line 590-730 (got some results and printing statement). G1, G3, G4, T2, T3, T4, Q and R were solved from this model.

Computer Model

```
10 REM Solve for G1, G3, G4, T2, T3, T4, Q and R
20 REM: Users might change to line 50,60,80,110,120,140,190,320,330,340
30 '**************input data**************
40 DIM C(7,8)  'matrix to get R-value by iteration
50 A3= 4.42 'ft^2
60 A4= 7.375 'ft^2
70 S=1.714*10^-9 'Stefan-Boltzman constant (btu/h.ft^2.R^4)
80 EM1=.985: M3=.9 : EM4=.9 'emmissivities of surfaces 1,3,4
90 AB1=EM1 : AB3=EM3 : AB4=EM4 'absorptivities
100 RE1=1-EM1 : RE3=1-EM3 : RE4=1-EM4 'reflectivities
110 X=.125 'overall thickness of wall (ft)
120 H=1 'convection heat transfer coeff (btu/h.ft^2.F)
130 '********************find k value*******************
140 N=1
150 DIM A(N), B(N)
160 SUM=0
170 FOR M=1 TO N
180 READ A(M), B(M)
190 DATA 0.125, 0.022
200 SUM=SUM+A(M)/B(M)
210 NEXT M
220 K=SUM
230 SUMA=0
240 FOR M=1 TO N
```

```
250 SUMA=SUMA+A(M)
260 NEXT M
270 L=SUMA
280 K3=L/K
290 '*********guess and variable parameters******
300 T2OLD=0: T3OLD=0: T4OLD=0
310 G1OLD=0: G3OLD=0: G4OLD=0: QOLD=0
320 FOR A1 = 2 TO 4 STEP .5
330 FOR T1=460-108 TO 460+32 STEP 140
340 FOR T5=460+72 TO 460+104 STEP 32
350 T2=460+43: T3=460+47 :T4=460+63
360 '*************setup system of equations********
370 C(1,1)=A1:C(1,2)=-RE3*A1:C(1,5)=-EM3*S*A1*T3^3
380 C(2,1)=-RE1*A1:C(2,2)=A3-RE3*A3+RE3*A1: C(2,5)=EM3*S*T3^3*(A1-
A3):C(2,8)=EM1*S*A1*T1^4
390 C(3,3)=A4: C(3,8)=EM4*S*A4*T5^4
400 C(4,1)=A1*AB1: C(4,4)=H*A1: C(4,7)=1: C(4,8)=EM1*A1*S*T1^4+H*A1*T1
410 C(5,2)=AB3*A3: C(5,4)=H*A3: C(5,5)=-
(H*A3+(K3*(A3+A4)/2/X)+EM3*S*A3*T3^3): C(5,6)=K3*(A3+A4)/2/X
420 C(6,3)=AB4*A4: C(6,5)=K3*(A3+A4)/2/X: C(6,6)=-
((K3*(A3+A4)/2/X)+H*A4+EM4*S*A4*T4^3): C(6,8)=-H*A4*T5
430 C(7,4)=-H*(A1+A3): C(7,5)=H*A3: C(7,8)=-H*A1*T1
440 '*************solve system of equations*********
450 FOR I=1 TO 7 : PVT=I
460 FOR K=I+1 TO 7
470 IF ABS(C(K,I))>ABS(C(PVT,I)) THEN PVT=K
480 NEXT K
490 FOR J=I TO 8
500 CHG=C(I,J) : C(I,J)=C(PVT,J) : C(PVT,J)=CHG
510 NEXT J
520 FOR K=1 TO 7 : IF K=I THEN 550
530 F=C(K,I)/C(I,I)
540 FOR J=I+1 TO 8 : C(K,J)=C(K,J)-F*C(I,J) : NEXT J
550 NEXT K
560 NEXT I
570 FOR K=1 TO 7 : C(K,8)=C(K,8)/C(K,K) : NEXT K
580 ' *******done with solutions***********
590 T2=C(4,8): T3=C(5,8): T4=C(6,8)
600 G1=C(1,8):G3=C(2,8): G4=C(3,8): Q=C(7,8)
600 G1=C(1,8):G3=C(2,8): G4=C(3,8): Q=C(7,8)
610 R=A3*(T1-T5)/Q
620 QTY=ABS(T2-T2OLD)+ABS(T3-T3OLD)+ABS(T4-T4OLD)+ABS(G1-
G1OLD)+ABS(G3-G3OLD)+AB
S(G4-G4OLD)+ABS(Q-QOLD)
630 T2OLD =T2: T3OLD=T3: T4OLD=T4
640 G1OLD=G1: G3OLD=G3: G4OLD=G4: QOLD=Q
```

```
650 IF QTY<=.1 THEN GOTO 690
660 FOR I=1 TO 7 :FOR J=1 TO 8: C(I,J)=0
670 NEXT J: NEXT I
680 GOTO 370
690 'PRINT:PRINT"T1=";T1-460" T2=";T2-460;"T3=";T3-460;"T4=";T4-
460;"T5=";T5-460
700 'PRINT:PRINT"G1=";G1; "G3=";G3; "G4=";G4; "Q=";Q ;"R=";R
710 'PRINT : PRINT A1       T1        T5        R
720 PRINT"A1=";A1,    "T1="; T1-460     ,"T5="; T5-460 ,     "R=";R
730 NEXT T5: NEXT T1: NEXT A1
```

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