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A Performance Comparison of Thermal Insulated
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A Performance Comparison of Thermal Insulated Packaging For Single Parcel Shipments

By

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ABSTRACT

A Performance Comparison Of Thermal Insulated Packaging For Single Parcel Shipments

By

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Insulated packaging is an important area of study in packaging. A large number of temperature sensitive perishable products (meat, seafood, flowers, pharmaceuticals, etc) are shipped in the single parcel shipping environment of carriers such as Fedex, USPS, and UPS. The purpose of this research was to investigate the insulation effectiveness of various commercially available and newly developed insulated packages. The packages studied included single wall corrugated containers, Box-in-Box packaging systems with an air gap, Thermal-Cor® boxes, and corrugated containers with (expanded poly styrene) EPS foam panels. Ice-melt tests were conducted both at room temperature (74°F) and at 104°F. The air temperature variation with respect to time inside the package was also measured at room temperature (74°F) and at 104°F by placing dry ice and gel ice inside the package. Temperature measurement recorders were used to record the temperature change inside the package over time. The packages were also subjected to pre-shipment tests in accordance with the International Safe Transit Association, Test Procedure 1A. Based on the results of this study, the melt rates of the box-in-box packages were found to be less compared to those of single packages. Also the time-temperature analysis inside the package showed that the foil laminated Thermal-Cor® boxes were found to slow the heat transfer process as compared with the other packaging systems tested like corrugated boxes with EPS foam panels.

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I would like to express my sincerest thanks to my advisor, Professor S Paul Singh for his support, guidance, and leadership throughout my graduate education. In addition, I would like to thank Professor Gary Burgess and Dr. Brian Feeny for serving on my Master's Defense committee.

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1 INTRODUCTION

Heat is a form of energy that can be transferred from one body to another. Heat energy flows from a higher potential to a lower potential meaning that heat transfers from a warmer body to a cooler body. This transfer takes place until both the bodies are in thermal equilibrium. There are three ways by which the transfer of heat energy takes place: 1) Conduction 2) Convection and 3) Radiation.

1.1 Conduction:

Conduction (Figure 1-1) is the transfer of heat energy in which heat is transferred from particle to particle. In other words, heat energy is transferred from one medium to another medium through atoms. The vibration of one atom in the body helps the adjacent atom to vibrate thus transferring the energy to the entire body until thermal equilibrium is reached. In conduction there is no actual movement of matter but only transfer of energy takes place.

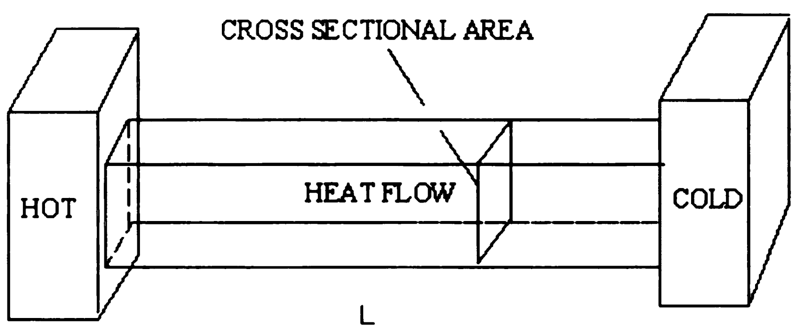


Figure 1-1 Conductive heat transfer through an I- shaped bar.

After conduction takes place both the surfaces that are in contact will have the same temperatures.

1.2 Convection:

Convention (Figure 1-2) is the transfer of heat energy by actual movement of the warmed matter. This type of transfer of heat energy occurs in gases and liquids. The hot air in a room near the hot air vent displaces, and is replaced with cool air and the cycle is repeated until equilibrium is reached.

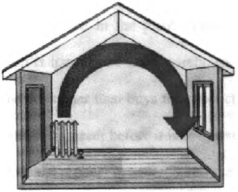


Figure 1-2 Convection heat transfer through convection in a room

1.3 Radiation:

This process of heat transfer occurs when electromagnetic waves transport energy through space (Figure 1-3). Electromagnetic waves that originate from the sun and pass through space to earth is an example of radiation heat transfer. This type of heat transfer requires no help from the medium. Radiation occurs even in vacuum.

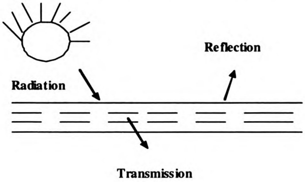


Figure 1-3 Heat transfer through radiation

A package is considered to be a good insulator when it slows down the heat transfer. Package insulation is a vital area of study in packaging because any inadequacies in insulation can result in product damage and eventually lead to monetary loss. Food products, frozen foods in particular have to pass through different temperature cycles during manufacture, storage, and distribution. For instance, a typical frozen food is manufactured in the plant and stored in the plant freezer before being shipped to a warehouse. The package then is transported from warehouse to a retail store where it is stored in a freezer case. The consumer then buys the product and takes it in a shopping cart to home where it is stored in a freezer before it is consumed. Insulation becomes very vital in the above case because the product is undergoing lot of temperature changes.

There are four main features that insulation packages should have (FedEx, 2001)

1. Keep products that are temperature sensitive within allowable temperature ranges.
2. Keep products frozen. This is applicable to products like ice cream, diary products, vegetables, meat, seafood etc.
3. Prevent products from freezing. This is applicable to products like chemicals, pharmaceuticals, blood and tissue samples, etc.
4. Attenuate the effect of temperature variation. This is applicable to electronic products, polymers, flowers etc.

There are different types of insulating containers that are available for packaging. Each combination of materials and package configuration addresses a specific need. Some of the commonly used insulated packaging systems are discussed next.

1.4 Expanded Polystyrene (EPS) Containers:

Expanded polystyrene (EPS) is the most common insulation packaging material used today (Figure 1-4). Air filled cells inside the EPS foam make it an excellent thermal insulator. This is due to the fact that air has particularly low heat conductivity. Insulation packaging from EPS helps perishable products from deteriorating over a long period of time. They also provide uniform temperature distribution within the container. The product is protected from rapid temperature changes, not only at the center of the package, but also near the walls. These containers are lightweight, durable and inexpensive. The facts that they do not produce Chloro Floro Carbons (CFC's) make them Eco-friendly packages. EPS coolers are also easily recyclable.

Figure 1-4 EPS Cooler

1.5 Gas filled bag

Gas-filled bags (Figure 1-5) are also used as good insulators. These bags are made of plastic films with internal baffles that prevent convective heat transfer. This bag is filled with air or an inert gas such as argon, krypton or xenon. The air inside the bag acts as a thermal insulator. These bags are placed inside the corrugated boxes wrapped around the product. These bags are very space-efficient when not in use, since they can be transported flat to the shippers. This saves valuable space in the warehouse and also reduces the transport costs.

Figure 1-5 Gas filled bag

1.6 Vacuum Insulation Panels

Vacuum Insulation Panels (Figure 1-6) are even more effective insulation materials compared to polyurethane or expanded polystyrene. The vacuum insulation panels have an R-value of up to 30 whereas the R-values of Polyurethane and Expanded Polystyrene range from 4 to 10. A vacuum panel is made of a core material, a metal foil or a metallized barrier film. The core material is sealed to the barrier film or foil by applying pressure in presence of vacuum. The high R-value of the vacuum panel makes it an excellent insulator.

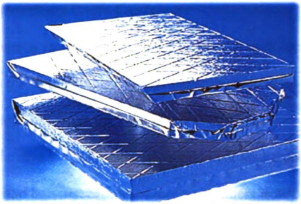


Figure 1-6 Vacuum insulation panel.

1.7 Insulated pallet blanket

Insulated pallet blankets (Figure 1-7) are another type of insulation packaging materials that are widely used for shipping perishable products like fruits, candies and medical supplies. The blankets are made of 0.25 inches of microfoam lined with aluminum foil. The microfoam is made of low-density polypropylene, which is very flexible. The reflective surface of the blanket radiates heat outward and retains inward heat.

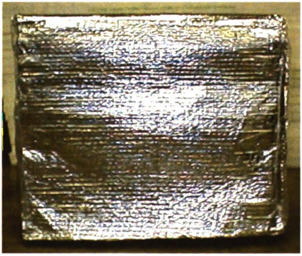


Figure 1-7 Insulated pallet blanket

1.8 Expanded Polyurethane Foam Containers:

Polyurethane foam is injected between the Regular slotted corrugated container and the insert as shown in the figure below. A rectangular cushion foam piece is used to cover the product from the top. The air filled foam inside these containers provides good barrier and delays heat transfer making these containers excellent insulators. The polyurethane foam used in the side and bottom sections of these containers is also referred to as "Foam-In-Place".

Figure 1-8 Polyurethane Foam Container

The objective of this research was to compare and analyze the insulation effectiveness of various new packaging materials. The packaging systems that were studied have been described in the materials and methods section of this thesis. The following are the specific objectives of this research:

1) To evaluate the insulation effectiveness of new packaging systems.
2) To measure and compare the R-values of various packaging systems.

3) To perform distribution testing on these package systems for single parcel shipments.

2 LITERATURE REVIEW

This chapter discusses some of the various heat transfer mechanisms that influence the performance of insulated packages.

2.1 Heat Transfer Basics

Heat Transfer occurs whenever there is a difference in temperature in a medium. If the medium is stationary and there exists a temperature difference, the type of heat transfer that occurs is called conduction. The heat conduction rate across a one-dimensional plane (Figure 2-1) of length "L", and having a temperature of T1 on one side and T2 on the other side is (Incropera, 2002):

$$H = \frac{k\,\Delta T}{L}$$

$\Delta T = T1 - T2$

L = Length of the Plane

k= Co-efficient of thermal conductivity

H= Heat flux per unit area.

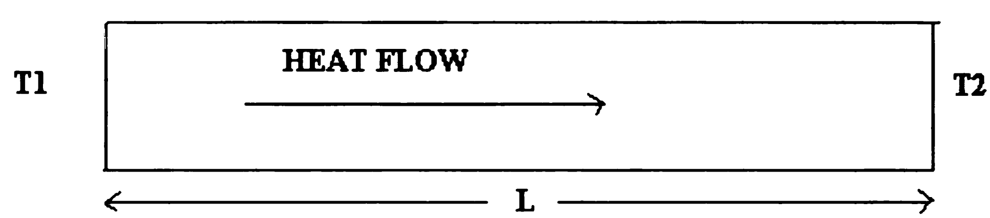


Figure 2-1 Heat transfer across two-dimensional plane

Since, H is the Heat flux per unit area, the heat rate "Q" by conduction through a plane wall of area is

$$Q = H \times A$$

Thermal conductivity (k) is the rate at which the heat flows in a material. The thermal conductivity is a material property and is constant for a particular material. Lower value of the k means the material is a better insulator. The thermal resistance, which is also, known as R-value is the reciprocal of thermal conductivity. Therefore higher R-value means the material is a good insulator. The k and R-values of different materials with a thickness of 1" and cross-sectional area of 1 sq.ft. (Table 2.1.1).

Table 2.1.1 Thermal conductivity and R-values of different materials.

MATERIAL	CONDUCTIVITY ("k")	THERMAL RESISTANCE ("R")
Copper	2712	0.00037
Aluminum (6061)	1160	0.00086
Glass	5	0.2
Polyethylene Foam	0.43	2.33
Wood (dry)	0.33	3.03
Glass Wool	0.29	3.45
Polystyrene (expanded)	0.28	3.57
Polystyrene (extruded)	0.21	4.8
PVC (Klegecell)	0.21	4.8
Polyurethane Foam	0.17	5.88
Air	0.16	6.25
BARRIER Ultra-R	0.02	50.36
Total Vacuum	0.004	250

Heat transfer through convection is caused by the motion of the fluid (liquid or gas). Depending on the nature of the flow, convection heat transfer can be classified into two categories 1) forced convection and 2) free or natural convection. Forced convection is caused by external means like winds. Free or natural convection is a result of density differences caused by temperature variations in a fluid.

The heat transfer rate equation in convection process regardless of the convection type is

$$Q = h\,(T_S - T_\alpha)$$

Q = Convective heat flux

T_S = Temperature of the surface (in °K)

T_α = Temperature of the Fluid (gas or liquid) in °K

h = Convective heat transfer coefficient ($W/m^2\,K$)

Unlike in conduction or convection, radiation does not require an intervening medium to transfer the heat. Radiation can transfer the heat even through vacuum. The corresponding equation for radiation heat transfer is

$$H = e\sigma AT^4$$

H = Radiation heat flux

e = emissivity (0-1)

σ= Stefan-Boltzmann constant = $5.67 \times 10^{-8}\ J/(s\text{-}m^2\text{-}K^4)$

A = surface area of object

T = temperature (in °K)

Heat transfer is influenced by many factors such as boundary surfaces, thickness of the air space, distance between the boundary surfaces and the direction of the heat flow. The above-mentioned factors particularly affect heat transfer through conduction and convection. The mean temperatures of the surfaces minutely affect conductive and convective heat transfers. Heat transfer through radiation is affected by surface properties of the material like its emissivity. The thickness of the air space and the direction of the heat flow have very little effect on heat transfer through radiation (ASHRAE, 1997).

Thermal resistance (R-value) in packaging depends on the wall construction and inside area of the package because that is what limits the heat transfer of the product inside the package (Burgess, 1999). The temperature difference between outside environment and inside the package also affects the R-value.

The R-values of the package systems can be measured by taking the combined effects of conduction, convection and radiation (Burgess, 1999). The contribution of conduction to the overall R-value depends on the total thickness of the package system. For example, if the package system has a corrugated container and EPS foam inside it, the thickness of the package will be the sum of thickness of corrugated container and the EPS foam.

The contribution of convection in the overall R-value depends on the number of surfaces in contact with outside environment. For instance, for a corrugated box with EPS foam panels inside it, the number of surfaces in contact will be five. The outside and inside surface of the box, the two faces of the EPS foam panels and the product.

The contribution of radiation in overall R-value depends on the number of reflective surfaces on the package. Aluminum foil laminated boxes are good examples of reflective surfaces.

The overall R-value, which takes into account, the heat transfer through conduction, convection and radiation, can be calculated by using the equation below (Burgess, 1999).

$$\text{Package R-value} = 3.9\,\boldsymbol{th} + 1.5\,\boldsymbol{np} + 3.2\,\boldsymbol{nf}$$

where ***th*** is the overall thickness of the package in inches, ***np*** is the number of plain surfaces and ***nf*** is the number of reflective surfaces. The above equation can predict R-value with 20% accuracy. Surfaces are considered plain if they are not covered with aluminum foil or any other reflective surface. The main advantage of the above equation is to estimate approximate amounts of ice that would be needed to keep the product cool inside the package. The equation below is used to calculate the approximate amount of ice needed.

$$\text{Amount of ice (lb)} = \frac{\text{(Inside area of the box) (temperature difference) (hours exposed)}}{\text{(R-value) (Latent heat)}}$$

For instance a corrugated container having an inside dimensions of 12 x 12 x 12 inches and a R-value of 6, if exposed for 24 hours at 72°F, would require

$$= \frac{(6)\,(72\text{-}32)\,(24)}{(6)\;(144)}$$

$$= 6.7 \text{ lbs of ice}$$

So, it would take 24 hours for 6.7 lbs of ice to melt inside the corrugated container having a product. After the 6.7 lbs of ice has melted, the temperature of the product would start to rise gradually. If the product is frozen prior to packing and contains water in it, it will contribute to the ice requirement. For example, 5 lbs of a frozen food product has about 2 lbs of water in it. Therefore, in the example above, only 4.7 lbs of ice would be required (Burgess,1999).

3 MATERIALS AND METHODS

The different materials and package types that were evaluated in this study are described in this section.

3.1 Phase I: Prototype Boxes:

During the first phase of this study, prototype packages were constructed from the test materials and preliminary heat transfer characteristics compared. Based on the performance of this data, production run containers were tested in the second phase to validate the performance. The prototype packages are described below.

3.1.1 Package A:

This package was made of a single wall C-flute corrugated board with inside dimensions of 12 x 12 x 12 inches. This corrugated container was a full overlap type (FOL). Six foam panels made of Expanded Polystyrene (EPS) were placed inside the package as shown below in Figure 3-1. The thickness of the EPS foam panels was 0.5 inch. The bursting strength of the fiberboard was 200 psi.

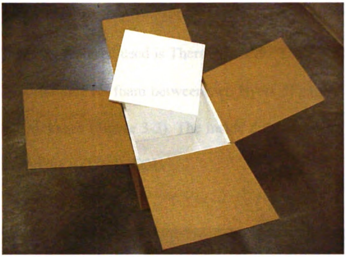


Figure 3-1: Package A

3.1.2 Package B:

This package was similar to Package A, but used a 0.75 inch EPS foam panels. It was also made from single wall C-flute corrugated board with inside dimensions of 12 x 12 x 12 inches. This corrugated fiber box was also a full overlap type (FOL).

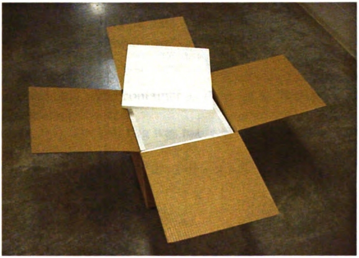


Figure 3-2: Package B

3.1.3 Package C:

In this package, the material used is Thermal-Cor®. The Thermal-Cor® material is manufactured by extruding EPS foam between two layers of paper. The material was then formed into test packages (Figure 3-3). The inside dimensions of the box were also 12 x 12 x 12 inches, and the style was FOL.

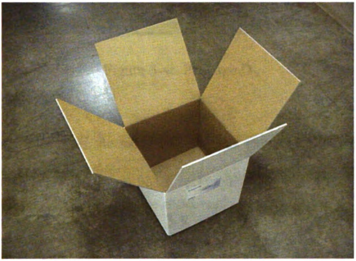


Figure 3-3: Package C.

3.1.4 Package D:

This package uses the same container as Package C, but in addition had a foil bag inside the box (Figure 3-4). The foil bag was made of an aluminum laminate. The product that is to be packaged was placed inside the foil bag before the container is sealed.

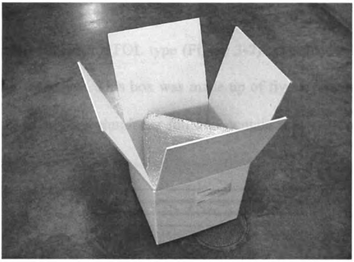


Figure 3-4: Package D

3.1.5 Package E:

The package also uses the same container as Package C but in addition to the Thermal-Cor® container, the system has a rectangular Thermal-Cor® tube, which was placed, inside the box as shown in Figure 3-5. The Thermal-Cor® tube was made of the same material as the box.

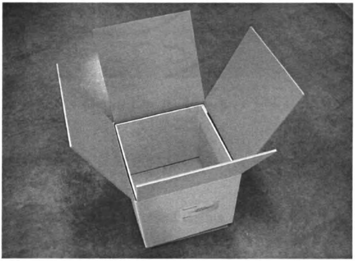


Figure 3-5: Package E

3.1.6 Package F:

This container was also a FOL type (Figure 3-7). The inside dimensions of this box were 12 x 12 x 12 inches. This box was made up of five layers as shown in Figure 3-6. The two outer layers are aluminum foil and contain a three layer Thermal-Cor® structure sandwiched in between.

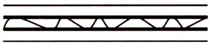


Figure 3-6 Graphic Representation of Aluminum Foil Laminate Structure

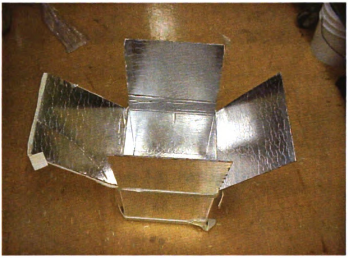


Figure 3-7: Package F

3.2 Phase II: Production Boxes:

The second phase of the project involved testing production run fabricated boxes. The second phase of boxes were made based on the test performance data of Phase I.

3.2.1 Package G:

This type of package system contains a Thermal-Cor® box inside another Thermal-Cor® box. There was a gap of 0.5 inches between the two boxes. Small square pieces of EPS foam cushion were glued in the middle of all the faces of the outside surface on the inner box as shown in the (Figure 3-8). The internal dimensions of the inside box were 11 x 11 x 11-5/8 inches.

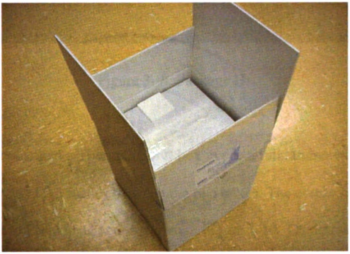


Figure 3-8: Package G.

3.2.2 Package H:

This type of package system contained a foil laminated Thermal-Cor® box inside another Thermal-Cor® box. There was a gap of 0.5 inches between the two boxes. The box-in-box was constructed similar to Package G and is shown in Figure 3-9. The internal dimensions of the inside box were 9 x 9 x 9-5/8 inches. The internal dimensions of the outside box are 10-9/16 x 10-9/16 x 11-13/16 inches.

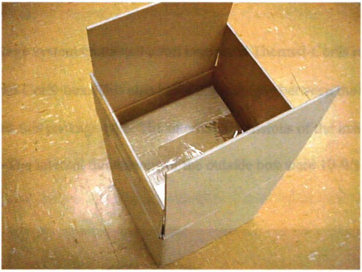


Figure 3-9: Package H.

3.2.3 Package I:

Package I contained a Thermal-Cor® box inside a foil laminated Thermal-Cor® box. There was a gap of 0.5 inches between the two boxes. The construction of the box-in-box was similar to Package G and is shown in Figure 3-10. The internal dimensions of the inside box were 9 x 9 x 9-5/8 inches.

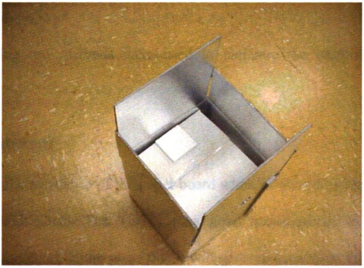


Figure 3-10: Package I.

3.2.4 Package J:

This package system contained a foil laminated Thermal-Cor® inside another foil laminated Thermal-Cor® box. This also had a 0.5-inch gap between the two boxes. Figure 3-11 shows this package type. The internal dimensions of the inside box were 9 x 9 x 9-5/8 inches. The internal dimensions of the outside box were 10-9/16 x 10-9/16 x 11-13/16 inches.

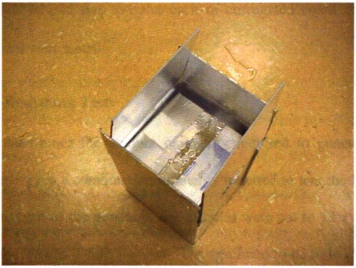


Figure 3-11: Package J.

3.3 Test Methods:

The following test methods were used to compare the performance of these containers.

3.3.1 Edge Crush Test:

In this test the resistance of the paper board when subjected to edge crushing was measured. The Edge Crush Test (ECT) is a good measurement to determine the performance of a container, in the sense that it will give an assessment with regard to the stacking strength and the bending stiffness of the corrugated walls.

Rectangular specimens of 2 inches width and approximately 1-¼ inches in height were taken and placed in a compression tester in accordance with TAPPI T 811 standard. The load is applied perpendicular to the flutes of the specimen and the largest amount of force the specimen can withstand without being crushed is determined. This force calculated per unit length of the specimen is the edge crush strength of the board. The results of this test are discussed in the next chapter. Ten samples were tested for the new Thermal-Cor® material and five samples each of corrugated board and foil-laminated Thermal-Cor® board were tested.

3.3.2 Puncture Resistance Test:

This test determines the amount of energy required to puncture a corrugated fiberboard. This energy is a combination of energy required to tear the board and energy to bend the material out of the puncture. Six samples were cut to 12 x 12 inches size in accordance with the TAPPI T 803 standard. The specimen to be tested is mounted and a latch is pulled to release the impacting pendulum mass. Before releasing the pendulum, sufficient amount of weights should be put on the stud so that the pointer will stop within the scale reading. The values obtained in this test are in Beach Puncture Units, which can be converted into in-lb using a multiplying factor of 0.265.

3.3.3 Thermal Analysis:

In this experiment, the temperature change inside a test package is measured with respect to time. The heat transfer in the test packages was evaluated in an environmental chamber at 104° F and at room temperature (72°F) for 48 hours.

Replicates of packages were prepared and 5 pounds of gel ice was placed inside the packages and Time Temperature Indicators (TTI's) (Figure 3-12) were placed inside the test packages. These TTI's were activated before placing them inside the package. The TTI's record the temperature inside the package every 60 seconds. The recorders are equipped with a memory chip, which stores this data. This data can be erased and the TTI can be reused. When the temperature recorders were placed inside the package, great care was taken to make sure that tip of the recorder was not in contact with gel ice pouches or dry ice during storage. Only the air temperature inside the package was monitored. The packages were then sealed with a foam tape. The boxes, EPS foams, foil bags, inserts and gel ice used in this process were pre-conditioned for 24 hours at frozen temperatures (20° F) prior to testing.

The above experimental procedure was repeated by using 5 lbs of dry ice. The TTI's were placed in the packages the same way as they were placed in the above case with gel ice. The boxes, inserts and foil bags used in this process were also conditioned at frozen temperatures (20°F). Unlike gel ice, dry ice was not preconditioned for 24 hours in the freezer.

After 48 hours the packages were taken out from the environmental chamber and the ambient room conditions. The packages were then opened and time temperature indicators were taken out and were connected to the computer to obtain the temperature profile data of the boxes for 48 hours. Microsoft Excel Spread Sheet was used to import the data from the TTIs. Graphs were plotted to evaluate the temperature profile of all the packages.

Figure 3-12: Time Temperature Indicator (Sensitech Inc.)

Table 3.3.1: TTI Specifications (Source: www.sensitech.com)

Operating Range	-22°F to +185°F (-30°C to +85°C)
Sensing Options	Ambient, SS Probe Flex Probe Pulp Probe (16,000 data pts only)
Sensor Accuracy	±2°F from -22°F to 0°F (±1°C from -30°C to -18°C) ±1°F from 0°F to +122°F (±0.5°C from -18°C to +50°C) ±2°F from +122°F to +185°F (±1°C from +50°C to 85°C)
Memory Size	2,000 or 16,000 Data Points
Temperature Alarms	Red/Green LED Alarm
Start-Up Delay	Minimum - 0 Minutes Maximum - 20 Days
Measurement Interval	Minimum - 30 Seconds Maximum - 120 Minutes 2k data points Maximum - 32 minutes 16k data points
Sensor Resolution	0.1° (1/10°)

3.3.4 R-Value Measurement:

R-value measurements (Burgess, 1999) were conducted to measure the thermal resistance of each package. The packages were stored at two different temperatures: 74°F and 104°F. In this procedure sufficient quantity of ice was taken in a bucket and was preconditioned for several hours until some of the ice starts melting. The water was then drained out and the bucket and remaining ice was placed inside the package (Figure 3-13), sealed and stored in both the environmental chamber (104°F) and ambient room (74°F). The packages were checked every five hours to see if most of the ice melted. This was done by slightly shaking the packages. If a rattling sound was heard, it indicated the presence of ice that had not melted. The packages were then taken out of the storage conditions and opened. The ice was removed and the remaining water weighed. The length of the storage time and weight of ice melted was used to determine the melt rate. This was used to calculate the R-Value of the package system using the equation:

$$\text{System R-value} = \frac{\text{(Inside area) (Temperature difference)}}{\text{(Melt rate) (Latent heat)}}$$

Melt rate is the amount of the ice melted divided by the storage period. Latent heat is the amount of heat energy required for 1 lb of a substance to change its phase from solid to liquid or liquid to gas without changing its temperature. The energy required to melt 1 lb of ice is 144 Btu. The temperature difference is the difference in the temperature of the storage environment (74°F or 104°F) and the temperature inside the package (32°F).

Figure 3-13 Experimental setup of R-value measurement.

3.3.5 Pre-shipment Test: ISTA Project 1A

The package systems were subjected to vibration and drop testing to evaluate their performance during transportation and distribution. Sand was filled in bags and was properly taped to secure sand from coming out of the bags. The bags were then placed in the packages as shown in the Figure 3-14. The bags were secured in the packages using foam-in-place packaging. The package was then placed on a vibration table (Figure 3-15) for 60 minutes at a frequency of 4 Hz. The procedure used in this test was in accordance with ISTA (International Safe Transit Association) Procedure 1A. The test duration can be determined by using the following equation:

$$\text{Test Duration in Minutes} = \frac{\text{14,200 vibratory impacts}}{\text{Cycles per second (Hz)} \times 60}$$

$$= \frac{\text{14,200 vibratory impacts}}{4 \times 60}$$

$$= 59.16 \text{ (approximately 60 minutes)}$$

Figure 3-14 Setup of Packages for Vibration and Drop Test.

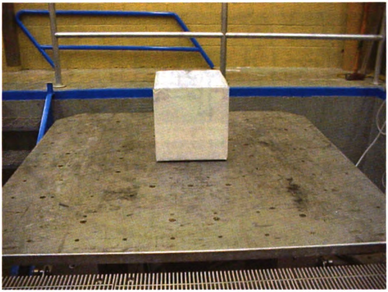


Figure 3-15 Vibration Test Setup.

After the vibration test, the packages were dropped from 30 inches height using a drop test machine (Figure 3-16). The following ten-drop sequence was used to drop the packages.

Table 3.3.2 Drop Sequence in Accordance with ISTA Procedure 1A.

Sequence Number	Orientation	Specific Edge or corner
1	Corner	Most fragile face-3 corner, if not known, use 2-3-5 corner
2	Edge	Shortest edge radiating from the corner
3	Edge	Next longest edge radiating from the corner
4	Edge	Longest edge radiating from the corner
5	Face	One of the smallest faces
6	Face	Opposite small face
7	Face	One of the medium faces
8	Face	Opposite medium face
9	Face	One of the largest face
10	Face	Opposite large face.

After performing the ten-drop sequence above, the packages were visually inspected for any failure.

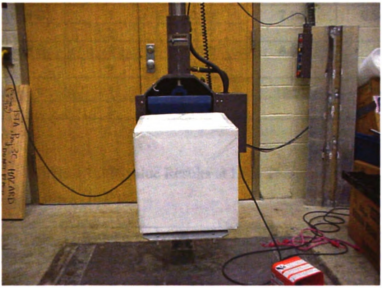


Figure 3-16 Drop Test Setup

4 RESULTS AND DISCUSSION

4.1 R-value of Phase I Packages:

The five packages were tested for R-values in accordance with the procedure described in 3.3.4. The results of the test are shown in Table 4.1.1 and Table 4.1.2 and graphically shown in Figure 4.1.1.

Table 4.1.1 R-value Results at Room Temperature

Room Temperature (74°F)

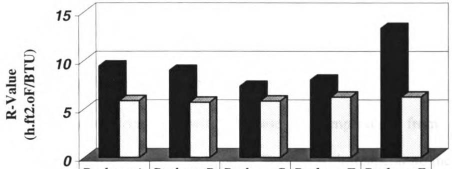
System Type	Sample #	R-value	Average	St.Dev
Package A	1	8.88	9.43	0.7778
	2	9.98		
Package B	1	8.00	8.99	1.4
	2	9.98		
Package C	1	8.00	7.34	0.9404
	2	6.67		
Package E	1	8.00	8.00	0
	2	8.00		
Package F	1	13.33	13.33	N/A
	2	N/A		

Table 4.1.2 R-value Results at High Temperature.

High temperature (104°F)

System Type	Sample #	R-value	Average	St.Dev
Package A	1	6.28	5.87	0.587
	2	5.45		
Package B	1	5.55	5.7	0.2
	2	5.84		
Package C	1	5.84	5.84	0
	2	5.84		
Package E	1	6.25	6.25	0
	2	6.25		
Package F	1	6.26	6.26	N/A
	2	N/A		

Average R-value plot for Room Temperature(74°F) and High temperature (104°F)



	Package A	Package B	Package C	Package E	Package F
■ *Room Temperature*	9.43	8.99	7.34	8.00	13.33
□ *High Temperature (104°F)*	5.87	5.7	5.84	6.25	6.26

Type of package systems

Figure 4-1 R-value Comparison of Phase I Packages.

4.1.1 R-value of Package Systems at Room Temperature:

The R-value average of Package A obtained in the results was greater than that of Package B (Figure 4-1). The thickness of the EPS foam used in Package A is 0.5 inch whereas the thickness of the EPS foam used in Package B is 0.75 inches. The R-value depends on property of the material, density and its thickness. Since, the material used in both the systems was EPS of the same density, the thickness dictates the system R-value. The greater the thickness, greater is the R-value. The R-value of Package E was greater than that of Package C. This is due to the fact that in former there is a Thermal-Cor® tube inside the package, which acts, as an extra layer of protection whereas in the latter, there is no such additional thermal barrier.

Package F has a greater R-value based on the data in Table 4.1.1 and Table 4.1.2. This is attributed to the aluminum surfaces that act both as convection and radiation barriers (Burgess, 1999).

4.1.2 R-value of Package Systems at High Temperature

The system R-value decreased with increase in temperature from room temperature to 104 °F. The same decreasing trend of R-value with temperature increase has also been found in other insulating materials such as Terrafoam, which is a closed cell Expanded polystyrene foam manufactured by Beaver Plastics, Canada. The graph (Figure 4-2) below illustrates how the R-value of Terrafoam changes with respect to temperature.

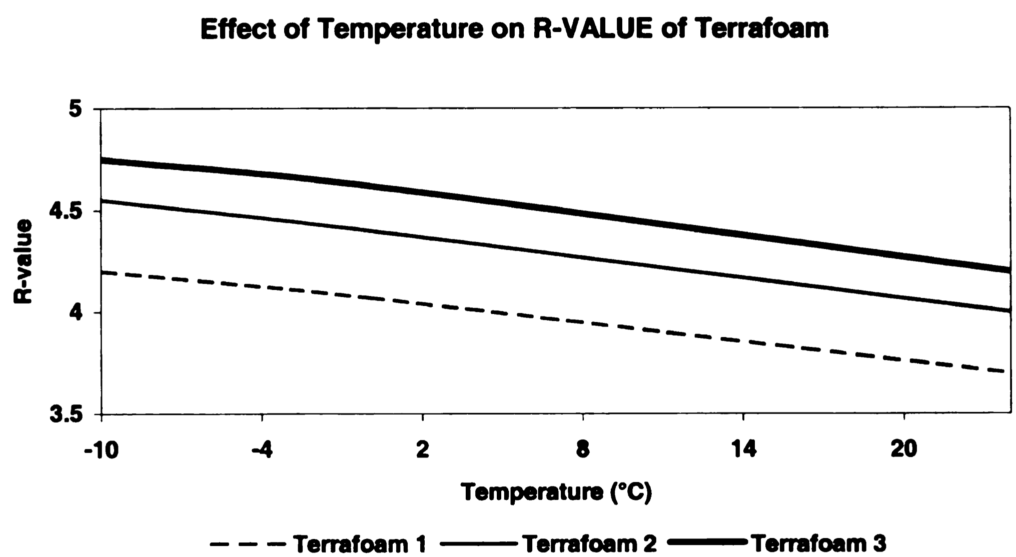


Figure 4-2 Effect of Temperature on R-value (Source: www.beaversplastics.com)

From the results it can be seen that the R-value of Package F is slightly higher as compared to other package types.

4.2 R-value comparison of Phase II Packages

Table 4.2.1 and Table 4.2.2 below show the 12-hour and 24-hour R-value tests of all box-in-box package systems tested in Phase II.

4.2.1 12 Hour R-value testing

Table 4.2.1: 12-Hour R-value Results of Box-in-Box Package Systems.

Package system	Sample #	Inside Box Surface area (sq.ft)	System R-value (sq.ft x °F x h/ BTU)	Average R-value
Package G	1	5.23	7.267	7.3
	2		7.267	
Package H	1	3.53	9.8	9.8
	2		9.8	
Package I	1	3.53	8.4	8.4
	2		8.4	
Package J	1	3.53	9.8	9.8
	2		9.8	

4.2.2 24 Hour R-value testing

Table 4.2.2: 24-Hour R-value Results of Box-in-Box Package Systems.

Package system	Sample #	Inside Box Surface area (sq.ft)	System R-value (sq.ft x °F x h/ BTU)	Average R-value
Package G	1	5.23	7.93	7.9
	2		7.93	
Package H	1	3.53	9.8	9.8
	2		9.8	
Package I	1	3.53	8.407	8.4
	2		8.407	
Package J	1	3.53	9.06	9.1
	2		9.06	

Table 4.2.3 Specifications of Different Box-in-Box Packaging Systems.

Package system	Outer box type	Inside box type	Outer box dimensions (inside)	Inside box dimensions (inside)	Gap
G	Thermal-Cor®	Thermal-Cor®	12-9/16 X 12-9/16 X13-13/16	11 X 11 X 11-5/8	1/2 "
H	Thermal-Cor®	Thermal-Cor®Foil Laminated	10-9/16 X 10-9/16 X11-13/16	9 X 9 X 9-5/8	1/2 "
I	Thermal-Cor® Foil Laminated	Thermal-Cor®	10-9/16 X 10-9/16 X11-13/16	9 X 9 X 9-5/8	1/2 "
J	Thermal-Cor®Foil Laminated	Thermal-Cor®Foil Laminated	10-9/16 X 10-9/16 X11-13/16	9 X 9 X 9-5/8	1/2 "

From the above Table 4.2.1 and Table 4.2.2, it can be seen that the R-value of Package G is lower compared to the other package types. Both the inside and the outside box in this package are made of Thermal-Cor®. These systems are known to have less insulation effectiveness compared to foil laminated Thermal-Cor® systems. The outside and inside box in Package J is made of Thermal-Cor® foil laminated materials and has greater R-value compared to the other systems. Package H has greater R-value than Package I. This could be due to the fact that in Package H the inside box is a Foil Laminated Thermal-Cor®, whereas in Package I, the inside box is made of Thermal-Cor®. The R-Values of 12-hour and 24-hour tests showed the same trend.

4.3 Thermal Analysis of Package Systems with Dry Ice and Gel Ice

4.3.1 Gel Ice at Room Temperature (74°F)

There was a steep rise in temperature inside the box for the first few hours inside all packages (Figure 4-3). The Package D reached equilibrium with outside temperature faster than the other packages. The temperature change in Packages A and B was slower because of the presence of EPS foams, which act as good insulators. The package E, which has a Thermal-Cor® tube inside was also effective in terms of slowing the heat transfer. It can be seen from Figure 4.3 that by the end of first 24 hours of storage, temperature inside the Packages A, B, E and F were a few degrees less as compared to Packages C and D. All the packages reached equilibrium with outside temperature after 48 hours.

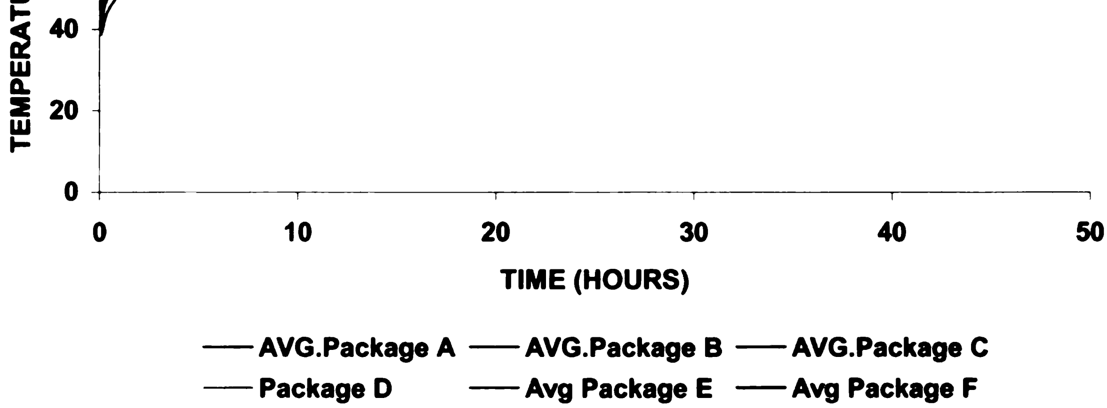


Figure 4-3 Plot of Thermal Analysis of Packages with Gel Ice at Room Temperature.

4.3.2 Gel Ice at High Temperature (104°F)

During the first few hours of storage the temperature rise was steep like the Gel Ice stored at room temperature (Figure 4-4). Although the rates of heat transfer in Packages A, C, D and E were different; all packages reached equilibrium with chamber temperature at the end of the first 24 hours. It can be seen from the graph that the temperature inside Package A was closer to 118°F after 20 hours of storage and then the temperature dropped down and was in equilibrium with chamber temperature after a few hours. The temperature inside the package cannot be more than the chamber temperature but this probably occurred because of sensor overshoot. The temperature change in Package F was slower compared to all the other packages.

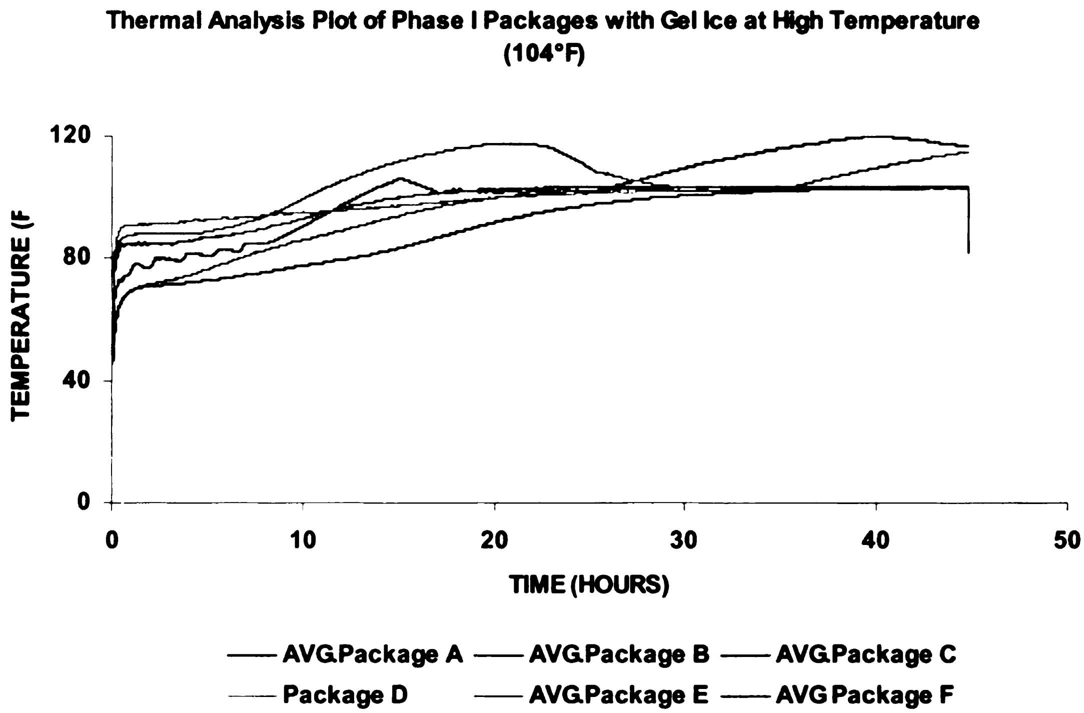


Figure 4-4 Plot of Thermal Analysis of Packages with Gel Ice at High temperature.

4.3.3 Dry Ice at Room Temperature (74 °F)

Unlike gel ice at room temperature, the temperature inside the packages dropped drastically for the first few hours with dry ice (Figure 4-5). This is probably because the dry ice changes its phase from solid to gas (sublimes) and convective heat transfer will take place resulting in dropping of temperatures for the first few hours. In other words, when the dry ice becomes gas it cools down the temperature inside the package until the temperature inside the package becomes constant and from that point the temperature starts rising to get in equilibrium with outside chamber temperature.

The Thermal-Cor® tube inside Package E acts as a barrier, which delays the rise in temperature. The aluminum lamination in Package F acts against convective heat transfer resulting in slow temperature rise. All the packages reached equilibrium after 48 hours.

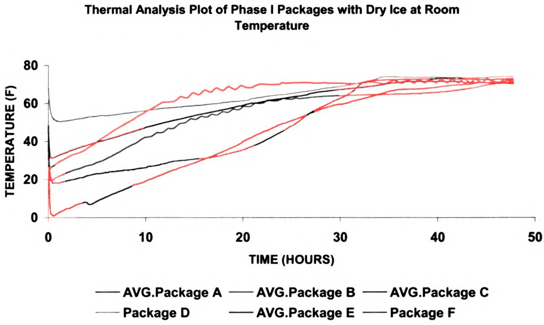


Figure 4-5 Plot of Thermal Analysis of Packages with Dry Ice at Room Temperature.

4.3.4 Dry Ice at High temperature (104°F)

The temperature inside Package F decreased for the first few hours (Figure 4-6). It was discussed earlier that aluminum foil acts as a convective and radiation barrier. So, the temperature fell down for few hours while the dry ice sublimed. The heat transfer through F was much less compared to the other packages. At the completion of 48 hours storage, the temperature inside package F was much lower than the other packages tested. Packages A and B reached equilibrium with chamber temperature within first 15 hours of storage while C, D and E took almost 30 hours to reach equilibrium with chamber temperature.

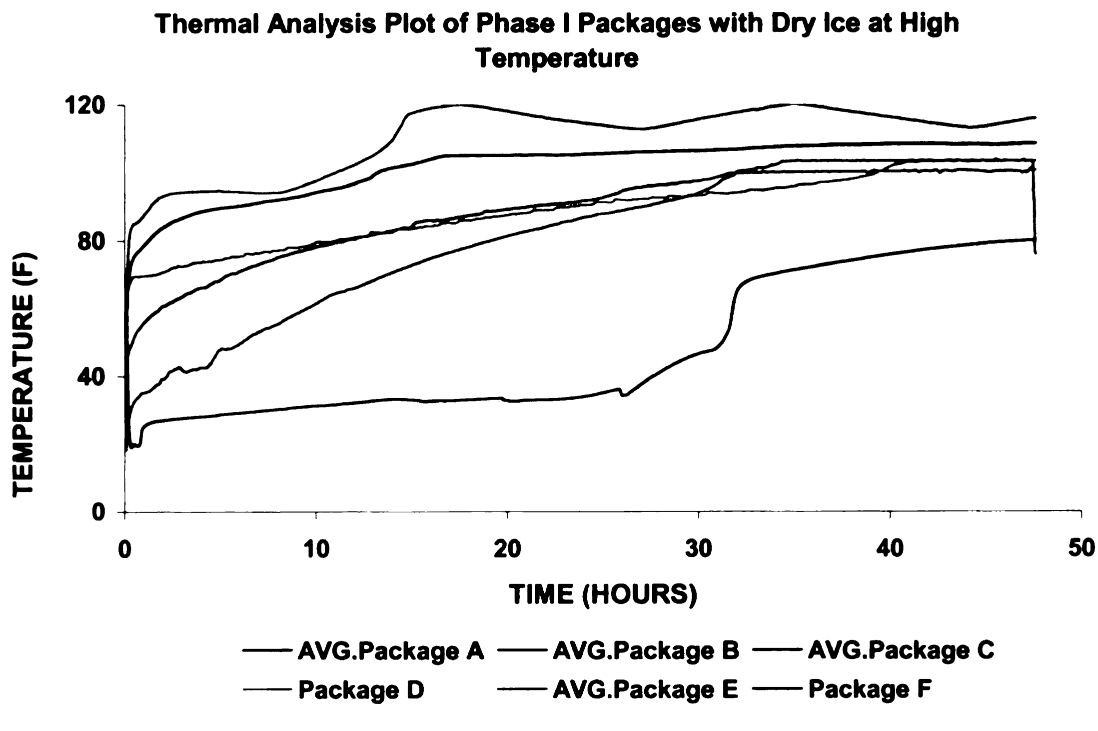


Figure 4-6 Plot of Thermal Analysis of Packages with Dry Ice at High Temperature.

4.3.5 Puncture Resistance Test

In the puncture resistance test, the results were obtained in beach units. The values were converted into inches-pound (in-lb) by multiplying with a factor of 0.265. It can be seen from the Table 4.3.1 that the puncture resistance of Thermal-Cor® was higher compared to that of corrugated samples and aluminum foil laminated board. The resistance of corrugated board and Foil Laminated Thermal-Cor® were found to be similar.

Table 4.3.1 Puncture Resistance Test Results.

Sample Type	Sample Number	Beach Unit	in.-lb.
Thermal-Cor® (Packages C,D,E)	1	445	117.93
	2	445	117.93
	3	445	117.93
	4	450	119.25
	5	455	120.58
	6	445	117.93
Average		**447.5**	**118.59**
ST.Dev		**4.2**	**1.1**
	Sample	**Beach Unit**	**in.-lb.**
Corrugated Box (Packages A & B)	1	355	94.08
	2	355	94.08
	3	365	96.73
	4	360	95.40
	5	365	96.73
	6	360	95.40
Average		**360.0**	**95.40**
ST.Dev		**4.5**	**1.2**
	Sample	**Beach Unit**	**in.-lb.**
Foil laminated Box (Package F)	1	355	94.08
	2	355	94.08
	3	385	102.03
	4	355	94.08
	5	355	94.08
	6	355	94.08
Average		**360.0**	**95.40**
ST.Dev		**12.2**	**3.2**

4.3.6 Edge Crush Test

The Edge Crush Test results obtained from the test were in lb/2 inches because the load was applied on a sample, which was 2 inches wide. The results were divided by two to get the force applied per inch. The ECT of Thermal-Cor® was almost 2.5 times greater than that of corrugated board and aluminum foil laminated board (Table 4.3.2).

Table 4.3.2 Edge crush test results

Sample Type	Sample	ECT (lb/in)
Thermal-Cor® (Packages C,D,E)	1	43.6
	2	42.9
	3	46.9
	4	47.6
	5	44.6
	6	46
	7	41.4
	8	44.7
	9	47.1
	10	40.5
Average		44.5
ST.Dev		2.4
	Sample	ECT (lb/in)
Corrugated Container (C1 and C2)	1	21
	2	17.6
	3	11.9
	4	21.5
	5	15.5
Average		17
ST.Dev		3.8
	Sample	ECT (lb/in)
Aluminum laminated foil Box	1	18.8
	2	17.3
	3	16.4
	4	18.5
	5	16
Average		17.3
ST.Dev		1.1

4.4 Pre-shipment Test: ISTA Project 1A

All the packages passed the fixed displacement vibration test and drop test. There was no product leak or failure during vibration or during the ten-drop sequence.

5 SOURCES OF ERROR

This chapter focuses on the sources of error of the R-value measurements of packages.

5.1 Sources of Error in the R-value measurement:

1) A plastic bucket is used in R-value measurement. This bucket is placed inside the package with ice inside it. This bucket provides extra insulation for the ice. But since the bucket is used in every package type, this effect is the same for all packages containing the same amount of ice to start with.

2) The formula for R-Value measurement seems to hold good for single packages. It does not seem to be good for box-in-box systems like the once discussed in Phase II of this thesis. The equation takes into account the inside surface area of the inside box but a single corrugated container having the same inside dimensions may have comparable R-value to a Box-in-Box package with smaller area. The air gap is not accounted for in the performance of the box-in-box systems when using the R-value equation.

6 ENVIRONMENTAL ISSUES AND RECYCLABILITY

Environmental Protection Agency (EPA) is encouraging businesses to practice 3 Rs (Reduce, Reuse and Recycle) before considering materials for packaging their products.

Reduce: Source reduction (also called waste prevention) reduces the consumption and discarding of materials. This includes purchasing durable, long-lasting materials and seeking products and packaging that are free of toxic substances. It may involve redesigning a product to use fewer raw materials in production, choosing materials that have a longer life, or reusing the products. Source reduction decreases waste generation and is the most preferable method of waste management that can go a long way toward protecting the environment.

Reuse: Reusing materials by reprocessing them, donating them to charity and community groups, or selling them will help reduce waste generation into the environment. Use a product more than once, either for the same purpose or for a different purpose. Reusing, if possible, is preferable to recycling because the material/product does not need to be reprocessed before it is used.

Recycle: Recyclability is a vital issue in considering the material for insulation packaging. The materials used should be recyclable after their usage. The recyclability of EPS and corrugated fiberboard, which were used extensively in this research, are discussed in this chapter.

EPS being a thermoplastic can be continuously melted and reformed which makes it an excellent recyclable material. Low levels of residual styrene found in EPS are environmentally safe for the use of material in packaging. Food and Drug Administration (FDA) has approved Expanded Polystyrene for use in food contact packaging. Health organizations encourage the use of EPS, as it does not support the growth of bacteria.

However, because of its lightweight, the volume by weight ratio of EPS is so large that it would take several trucks to transport couple of tons of EPS. This will increase the transportation costs and accounts for half the recovery costs. Several companies have explored new ways to recycle EPS in an economic way. One such procedure is by dissolving EPS in d-limonene. d-limonene, which is also known as orange terpenes, is a bio-degradable solvent and can dissolve large blocks of the material in a very short time. The d-limonene and EPS mixture occupies only 5% volume of the original EPS foam. This mixture can then be economically transported to the recycling plants.

EPS when incinerated will yield about 17000 to 18000 BTU of energy, which is more than coal. Complete combustion of EPS produces carbon dioxide and water vapor makes it a good source of fuel. The only organic volatile gas that is found in EPS is 3-6% by weight of pentane. Usually manufacturers collect and destroy it according to local and federal regulations.

Recycled EPS foam can be used to make a number of versatile materials and end products that include:

1) Remolded foam, which can be used in loose fill packaging.

2) Plastic applications such as stationary products, coat hangers etc.

3) Extruded applications such as furniture etc.

4) EPS can be reused as lightweight concrete material and may also be mixed with cement for insulating structures like swimming pools, floors, roofs etc

Corrugated containers are extensively used in packaging industry and this makes them a major component in the waste stream by weight. At the same time, corrugated containers are easily recyclable making them the most recycled packaging material by weight. Used corrugated containers are also called “Old Corrugated Containers” (OCC) in the recycling industry.

In this present research, the materials used were mostly fiberboard and EPS. However, in some packages EPS was sandwiched between fiberboards. The Packages A and B, which have corrugated containers and EPS foam panels are easily recyclable as compared with the other packages as there is no separation of the materials involved but Package A and B use more material compared to the other packages and this will not contribute to the objective of source reduction. However, EPS foams and corrugated fiberboard in the packages can be reused. Packages C, E and F are hard to recycle and expensive because the fiberboard and EPS have to be separated from each other. This separation process may leave EPS contaminants in the fiberboard and fiberboard contaminants in the EPS, which makes the recycling process more complicated. However, these packages use less material and contribute towards the goal of source reduction. The packages can also be reused.

Packages G, H, J and I are box-in-box systems and these packages are very expensive to recycle and do not contribute much to source reduction because there is a lot of material involved. In some of these packages, boxes are laminated with foil adding one more step to the recycling process and also the scope for contamination is increased. In fact, in some cases, boxes with plastic extrusions and laminates are not recycled.

7 CONCLUSIONS

The following conclusions were reached in this study:

1) The R-value of Package F was found to be the highest. This means that it is an effective insulator compared to the other packages tested. This container is made of aluminum foil lamination, which makes it a convective and radiative barrier. The R-values of Package A and B were comparable and were found to be better insulators compared to that of Package C and E which are made of Thermal-Cor® material. The EPS foam panels inside A and B seem to be more effective compared to the Thermal-Cor® material.

2) The thermal analysis test of packages at both room and high temperatures with dry ice and gel ice shows that the rate of heat transfer through Package F was slower as compared to the other packages tested thus making it a better insulator.

3) As regards Box-in-Box packaging systems, the R-values of Packages H, I and J are comparable because they have the same inside box surface areas. There was no significant difference found in the R-value of Packages H and J. The R-value of Package I was found to be lower than that of the other two systems. Unlike in the other two packages, where the inside box is aluminum foil laminated type, Package I has a Thermal-Cor® inside box and aluminum foil laminated Thermal-Cor® is a better insulator as compared to Thermal-Cor®.

4) The air inside the Box-in-Box packages seems to be acting as a good thermal insulator. The melt rates in these packages were found to be lower as compared with the single packages.

5) The R-value comparison tests should use all containers with the same inside dimensions to provide relative performance of insulating properties based on the method recommended by Burgess (1999).

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