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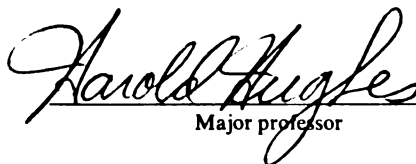
Thermal Insulated Packaging Design with S-Flute
Corrugated Board

presented by

Oranis Panyarjun

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Packaging


Major professor

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**THERMAL INSULATED PACKAGING DESIGN WITH S-FLUTE
CORRUGATED BOARD**

By

Oranis Panyarjun

A DISSERTATION

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

DOCTOR OF PHILOSOPHY

College of Agricultural and Natural Resource

2002

ABSTRACT

THERMAL INSULATED PACKAGING DESIGN WITH S-FLUTE CORRUGATED BOARD

By

Oranis Panyarjun

The objectives of this research were to evaluate suitability of S-flute corrugated shipping containers for use as insulated containers, to quantify R-values, to evaluate insulated containers made of corrugated board and other materials, to demonstrate the examples of insulating structural design providing heat transfer resistance for longer time, and also to prove that packaging structural design is a factor which affects insulating ability.

Double wall construction with an air space was included in two thermal shipping packaging designs. Each insulated container was composed of an outer box and an inner box. There were two styles of inner boxes: interlocking and folding. An RSC was used as the outer box for both designs. Artios software was used to create the prototype models.

The ice requirement method was used to evaluate different designs and other insulating materials. It gave estimated package R-values by determining the heat transfer resistance for each design and material combination including other insulating containers. Computer simulation was examined to quantify temperature distributions and R-values.

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**Dedicated to my grandfather,
Phya Sripikar Banchong (Samahn Panyarjun),
Director of Royal State Railway of Thailand (1932-1933),
and my relatives who have passed away.**

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1.0 INTRODUCTION

Heat is a form of energy which can be transferred from one item to another when the temperatures are different. The energy transportation process is known as heat transfer. Heat transfer is an area of study in several engineering disciplines. There are three distinct modes of heat transfer: conduction, convection, and radiation. Conduction (Figure 1) is the process by which heat energy is transmitted from a region of higher temperature to one of lower temperature within the same object or between objects in direct physical contact.

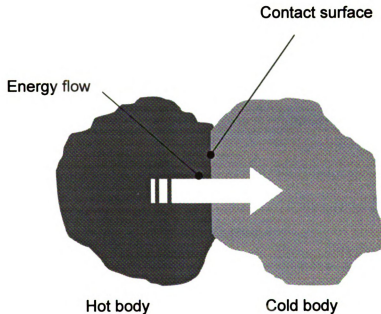


Figure 1. Heat Conduction.

Convection is the process of transferring heat through a fluid or gas through the process of bulk fluid motion (Cengel, 1998). There are two kinds of convection: natural convection and forced convection. Examples are shown in Figure 2. For natural convection, heat is transferred to air and hot air moves upward because it is less dense. Cold air moves in to replace the hot air. In forced convection, the fluid flow which carries heat away from or to an object occurs because of a mechanical action.

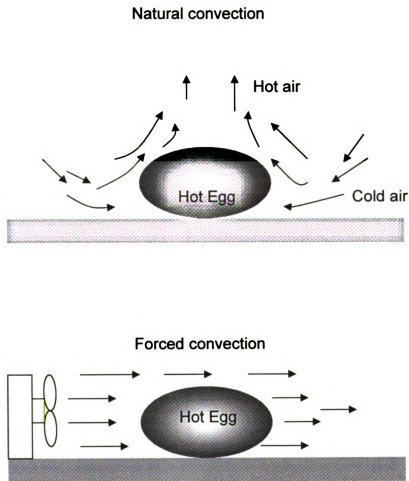


Figure 2. Heat Convection.

Radiation is the process by which heat is transported from a high temperature body to a lower temperature body by passing through a vacuum or a transparent medium. (Kreith, 1973). For example, in Figure 3, the human feels the heat of the sun, even while standing inside the building. The heat energy coming from the sun transfers through the vacuum of space and the glass windows. The person, in turn, radiates heat to cooler surfaces of the building.

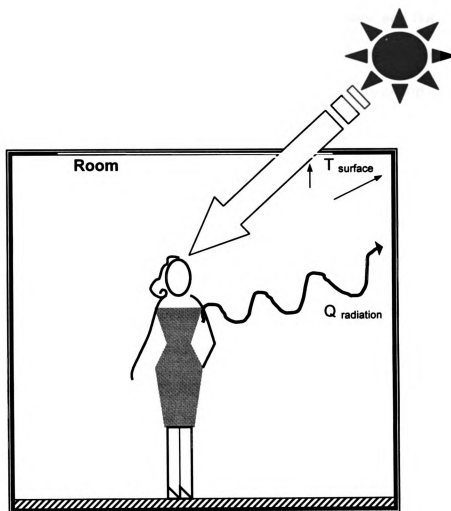


Figure 3. Heat Radiation.

Heat transfer knowledge has been applied to protect humans and objects from injury and damage due to too high or too low temperatures. Thermal insulation is a material or a combination of materials that retards heat transfer by conduction, convection, or radiation. A measure of the effectiveness of thermal insulation is the R-value (thermal resistance). Higher thermal resistance indicates more effective insulation (ASHRAE, 1997). Reasons for using insulation include energy conservation, personnel protection and comfort, maintaining process temperature, reducing temperature variation and fluctuation, fire protection and freezing protection, etc. Insulation also attenuates noise and vibration. There are many relevant properties of insulation including: thermal conductivity, density, service temperature, form, structural strength, surface reflectivity and emissivity, acoustic effects, corrosiveness, and water vapor transmission. These criteria are used to select insulation (Cengel, 1998). The following are some issues that must be considered when selecting an insulation material for a particular application:

- 1) Purpose: Why is the insulation to be used? The purpose may be to conserve energy, to reduce the surface temperature for safety, to prevent sound transmission, to minimize temperature variations or fluctuations, to prevent freezing on surface, etc.
- 2) Special Requirement: Each insulation job has its own requirements. For example, rigid boards cannot be used to insulate pipe. Flexible insulation or preformed rigid pipe insulation is necessary.

- 3) Environment: The environment and the conditions of use limit insulation choices. Insulation for underground steam pipes is different from insulation for steam pipes in a production facility. Cork, foam, and polyethylene insulation can be good choices for a moist environment.
- 4) Ease of Handling and Installation: Some insulation materials need special maintenance in storage before installation. Some insulation materials require specialists to install. Some insulation is simple to install in a single step, but other materials require cutting, wrapping, painting, etc.
- 5) Cost: The selection of insulation is often based on cost. An economic analysis should be conducted to identify the insulation type with the lowest total cost. In this process, the thickness may also be determined. Logically, the thicker the insulation, the slower heat transfers through but higher the insulation cost.

There are many factors which can contribute to the damage to temperature-sensitive products, including: inadequate insulation during package distribution, the number of steps in the distribution process because the temperature may not be controlled at some locations or times, temperature fluctuation due to various environmental conditions, stacking patterns, etc.

For example, Federal Express ships individual packages by truck and aircraft, mostly in overnight shipments (FedEx, 2001). Since there are many

different products in the packages, FedEx can't guarantee an appropriate shipping environment for each product. Handling operations involve 3 to 5 steps (ASTM D-4169, 1994). For example, in a simple case: 1) packages are loaded onto a truck, 2) packages are taken from the truck into the store, and 3) packages are bought by the consumers. During distribution, packages are exposed to various conditions with different temperatures as in Table 1.

Table 1. Distribution condition and their temperatures.

Conditions	Temperatures
Freezer	-18 to -35 °C
Refrigerator	1 to 4 °C
Freezer truck, railcar, airplane	-18 °C or below -29 °C for ice cream only
Refrigerated truck, rail car, airplane	0 to 5 °C
Outside environment: (depending on locations and seasons)	Based on ASTM D-4332-89: 20 ± 2 °C for Temperature high humidity 40 ± 2 °C for Tropical 60 ± 3 °C for Desert
	Extremes, based on FedEx: -51 °C for Carrier vehicles and open dock areas during the winter in northern climates 60 °C for Closed, parked carrier vehicles during summer in southern climates (FedEx, 2001)
	Based on the U.S. Military assuming: (the worst case) -62 °C low for Worldwide 71 °C high for Worldwide

In the frozen food business, as products move from a manufacturer to a consumer, they pass through a variety of distribution processes. For example, a typical case of frozen food may be packed and stored in a freezer before being shipped by truck to a warehouse loading dock. Eventually, the packaged products are displayed in the freezer case of a retail store. Later, the product is placed into a shopping cart and then loaded into a car, often in hot weather, before it reaches the consumers' freezer (Figure 4).

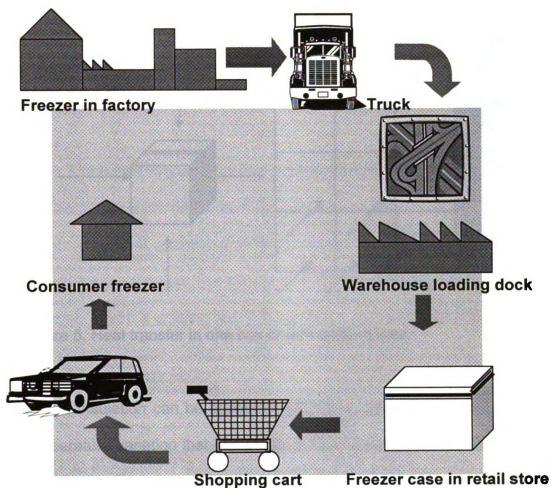


Figure 4. Distribution of frozen food.

Stacking is another factor that affects heat transfer in distribution packages. If packages are unitized onto a pallet, heat transfer rates in different locations are varied. Products in boxes on the inside of a stack keep better than products in the outside boxes. This is because the outside shipping containers of a unitized load act as insulation to prevent heat gain in the center of the unitized load (Figure 5).

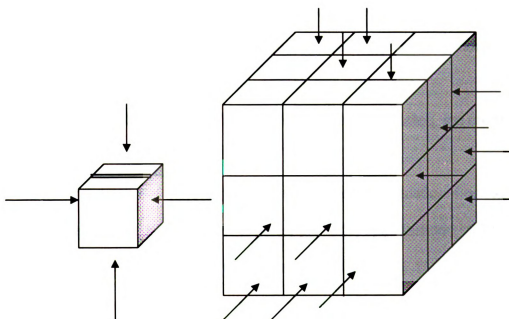


Figure 5. Heat transfer in one box or one unitized load.

Insulation can be applied in packaging systems to solve the problem of temperature variation that can cause product damage or loss. Insulated shipping containers offer more resistance to heat flow than other containers. Insulated shipping containers perform the same functions as insulation materials. Excellent insulated containers offer energy cost saving (e.g., electricity, gas, etc.), by

reducing the amount of refrigeration required and reducing the required thickness of the package wall, thereby saving space during transportation. Generally, there are five insulated shipment applications (FedEx, 2001):

1. To maintain products within allowable temperature ranges (chemicals, food, medical drugs).
2. To keep products frozen (seafood, dairy products, medical specimens, meat).
3. To prevent products from freezing (chemicals, blood specimens, seafood).
4. To minimize the effect of temperature variation (plants, flowers, live lobsters, sensitive electronics, polymers).
5. To prevent melting and thawing in hot weather (chocolates, ice cream).

Each temperature-sensitive product has own characteristics. For example, live products such as fresh fruits, vegetables, and live seafood continue to respire. Sugar is combined with O_2 to produce CO_2 and H_2O . Heat of the respiration is released. The rate of respiration depends strongly on temperature (Cengel, 1998). It is likely that if the package had excellent insulation ability, the temperature inside would rise and the respiration rate would increase correspondingly. This would cause rapid decay. Tables 2, 3, 4, 5, and 6 showed the requirements of food samples affecting consideration of their suitable shipping containers (Cengel, 1998 and ASHRAE, 1994).

Table 2. Requirements of fruits and vegetables.

Product types	Respiration	Storage Temperature, °C	Suggested shipping containers
Oranges, Lemons, Grapefruits	yes	1	Corrugated containers with vents.
Apples, Plums, Cherries, Grapes	yes	-1	
Bananas	yes	14	
Peaches, Nectarines, Apricots	yes	-0.5	
Cucumbers	yes	10-13	
Eggplants	yes	8-12	
Watermelons	yes	10-15	
Potatoes	yes	3-13	
Okra Ripe tomatoes	yes	7-10	
Sweet peppers	yes	7-13	
Cantaloupes	yes	2-3	
Green beans, Snap beans	yes	4-7	
Broccoli, sweet corn, lettuce, green peas, parsley, spinach, cabbage, mushrooms, carrots, onions	yes	0	

Table 3. Requirements of meats.

Product types	Months				Suggested shipping containers
	Temperature, °F				
	10	0	-10	-20	
Beef	4-12	6-18	12-24	12+	-No specific suggestion. -Presenting free space in a container of frozen food caused subliming and condensing ice on the package.
Lamb	3-8	6-16	12-18	12+	
Veal	3-4	4-14	8	12	
Pork	2-6	4-12	8-15	10	
Chopped beef	3-4	4-6	8	10	
Pork sausage	1-2	2-6	3	4	
Smoked ham and bacon	1-3	2-4	3	4	
Uncured ham and bacon	2	4	6	6	
Beef liver	2-3	2-4			
Cooked foods	2-3	2-4			

Table 4. Requirements for poultry products.

Product types	Ice chilling, °C	Deep chilling, °C	Freezing, °C	
	Short term	Long term	Short term	Long term
Poultry	1-2	-2	-18	Below -18
Suggested shipping containers	-No specific suggestion.			

Table 5. Requirements for fish.

Product types	Short term, °C	1 year or more, °C	Occasional storage, °C	Retail store, °C	Transported, °C
Frozen fish	-26 or below	-29	-23	-18 or below	-18
Suggested shipping containers	-Proper fit of package to the product, the surface area of the package, and the maximum used of the freezer space are important.				

Table 6. Requirements of eggs, milk, and bakery products.

Product types	Storage room, °F		Suggested shipping containers
Milk	33-40		Cases
Butter	Not above 0, preferably below -20 for several months	32-40 for short period	-Stored in bulk
Cheese	Various from 30-45, depending on the types (Assuming 45°F and 70 % RH for average conditions of American cheese)		-
Cinnamon rolls	0 for 3 weeks		-
Dinner rolls, yeast-raised, and cake doughnuts	0 for 8 weeks		-
Pound, yellow layer, chocolate layer cakes	10 for 3 weeks		-
Sponge and angel cakes	0		-

Container manufacturers have produced a variety of insulated containers. After examining the use of insulated containers from several companies, it was observed that there were two approaches to marketing temperature sensitive products: 1) mass production industries and 2) mail order or E-Commerce companies. Mass production industries use many similar sized containers which are transported by vehicles to warehouses or distribution centers and, finally, to retail stores. Mail order and E-Commerce companies tend to buy fewer containers in a range of sizes and send them directly to individual customers by small package delivery companies such as FedEx. However, even though ordered products are of different sizes, many mail order or E-Commerce companies prefer to solve this problem by adding dunnage, such as foam peanuts or scrap paper, to fill oversized packages, rather than buying correct sized packages. Consequently, in the current market place, there are many kinds of insulated containers that are used to protect products from heat and cold temperature, such as the following:

1. EPS (Expanded Polystyrene) container

An EPS box is the most common type of insulated container. The EPS box is made by injecting EPS into a mold (Figure 6). EPS containers are reusable stackable, cheap, and lightweight. They can be produced by standard technology with no special equipment. The tight interlocking joint between the base and the cover minimizes heat loss or gain. EPS containers, however, are bulky, cumbersome, and prone to cracking and leaking. Also EPS is hard to recycle.



Figure 6. EPS container.

2. Corrugated box with assembled insulation panels

This type of container is a "conventional box" with six foam panels that line the inside (Figure 7). It can be cheap and can be produced on standard equipment. It facilitates transport cost saving since box suppliers can send collapsed boxes to their customers to assemble during packing. It is simple to separate the panels from the corrugated box for recycling. However, holes at all corners of the corrugated box and joints where the panels meet allow heat loss or gain. Also the assembly process is labor intensive.



Figure 7. Corrugated boxes with EPS panels and shrink-wrapped Polyurethane panels.

3. Blanket

A blanket made of plastic film can be packed with cellulose or granulated foam to a thickness of an inch or more. For warm products, the inside of the plastic bag may be laminated with aluminum foil to reflect radiant heat energy. For cold products, the outside of the bag may be similarly laminated with aluminum foil to prevent heat gain. The product can be wrapped in the blanket and put into a corrugated container or the entire container can be wrapped in the blanket. The blanket is flexible and adjustable for use on various sizes of products. It can be reused, saves space during shipping, and generally is not damaged by water. However, it requires special technology to produce, is not stackable, and is complicated to recycle. The appearance is similar to the gas filled bag shown in Figure 8.

4. Gas-filled bag

The gas filled bag is similar to the blanket but ordinary air or inert gas is used to inflate the bag. The gas filled bag is made of plastic film with internal baffles that prevent convection heat transfer (Figure 8). The bag is used in ordinary corrugated boxes for shipping perishable products by air without refrigeration. The bags can be transported flat to shippers to save warehouse space and delivery cost as compared to other package forms. The gas filled bag is an advanced insulating approach that requires special equipment and technology. It is labor-intensive to wrap the bag around the products and assemble the corrugated container.



Figure 8. Gas-filled bag.

5. Modified corrugated board or Kraft lined EPS sheeting

Two Kraft liners with a foam core, typically EPS (Figure 9) are produced in sheets and distributed to customers who convert them into boxes. The material is light, easy to recycle, and cost saving because it is flat during shipment. It can be produced by cutting the flat pattern and assembling into the box. However, labor is required to assemble the boxes and there are holes at all corners of the box.

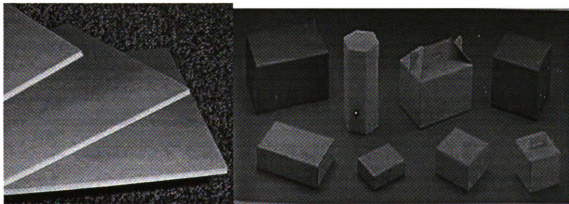


Figure 9. Kraft lined EPS sheeting.

6. Corrugated box with molded Polyurethane

A corrugated box with molded polyurethane is a corrugated container with a layer of polyurethane applied to the interior to reduce heat transfer (Figure 10). There are no holes at corners or other joints allowing heat leaks or gains. This improves insulating ability. In addition, the foam strengthens the boxes, improving stackability. The whole box, however, is hard to recycle since molded Polyurethane is on the surface of the corrugated. Also, this style of box is expensive, bulky and cumbersome to handle. Special equipment is required to inject the foam into the corrugated box.

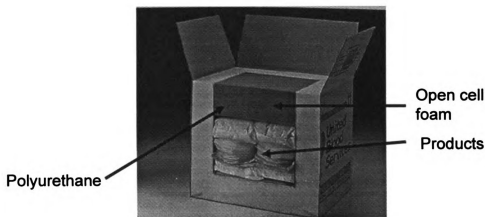


Figure 10. Corrugated box with molded Polyurethane.

7. Vacuum Panel

A vacuum panel is a core material sealed by a barrier film to keep a vacuum inside. The "microporous" core material with low thermal conductivity is used to form box structures. The material, like EPS panels, can also be used as wall liners in shipping containers to improve the insulating ability of the packages.

Vacuum panels are thin, light, durable and space saving during transportation. The insulation values are much higher than the insulating values of conventional foams. A vacuum panel container can be designed to maintain the temperature of a shipment for 1 to 5 days. However, vacuum panel containers are expensive since special technology is required to produce the panels. The panels sealed with the barrier film are complicated to recycle.

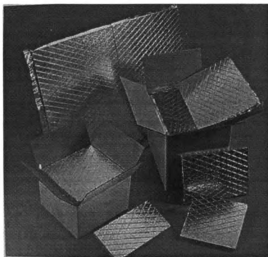


Figure 11. Vacuum panels.

Summary of container options

There are three primary considerations involved in the selection of an insulated package: 1) strength of the container, 2) insulating ability, 3) costs, and 4) knock down ratio. Corrugated boxes generally have not been able to provide a combination of strength, insulation, and cost to meet the needs of the market for an insulated container. However, corrugated has often been combined with

other insulating materials, such as EPS panels and molded Polyurethane, to provide form containers which are acceptable.

A new corrugated board, S-flute, which is thicker than any other single wall corrugated board, has recently been introduced into the market. Theoretically, the larger flute size, even with the same grammage liners, should make this board a more effective insulating material than the conventional corrugated boards, (e.g. A, B, D, and E-flute). As was noted previously, increasing the thickness of an insulating material produces an increase in the insulating ability. Before the introduction of S-flute, the highest heat transfer resistance of corrugated paperboard was provided by A-flute, followed by C-flute, B-flute, and E-flute, respectively (Thompsonson et al., 1998). Therefore, it is likely that S-flute should be able to enhance insulation effectiveness of corrugated containers.

Structural design of the packaging (e.g. shape, size, wall construction, etc.) should be another factor which influences insulating ability of corrugated containers. However, due to the fact that S-flute has only recently become available, there is little specific information available about this material and very little design work has been done using it. Therefore, the overall goals of this project were to develop new designs for thermal insulated corrugated packages made of S-flute and to compare the new designs with to existing insulated containers. The following were the specific objectives:

1. To evaluate the suitability of S-flute for thermal insulated containers.

2. To demonstrate that particular structural designs affect the length of time that a corrugated container can protect against heat gain or loss
3. To quantify and compare the R-value insulated containers of various types and materials.
4. To evaluate computer simulation as a means of determining R-value of corrugated insulating containers.

2.0 LITERATURE REVIEW

Heat Transfer Theories

The fundamental equation (Equation 1) for heat conduction through a large plane wall of thickness L and surface area A , as shown in Figure 12, is shown below (Cengel, 1998),

$$\frac{dQ}{dt} = \frac{k A \Delta T}{L} \text{ -----(1)}$$

T = the temperature difference across the insulation

L = the thickness of flat insulation

k = thermal conductivity

dQ/dt = the rate of heat transfer

A = surface area

R-value, thermal resistance of material per unit area ($^{\circ}\text{F} \cdot \text{ft}^2 \cdot \text{h/Btu}$), is a measure of insulation effectiveness. For flat insulation, the R-value is defined in Equation 2,

$$\text{R-value} = L / k \text{ -----(2)}$$

k = the thermal conductivity of the material

Whenever R-value is known, the rate of heat transfer through the insulation can be determined from,

$$\frac{dQ}{dt} = \frac{\Delta T \times A}{\text{R-value}} \text{ -----(3)}$$

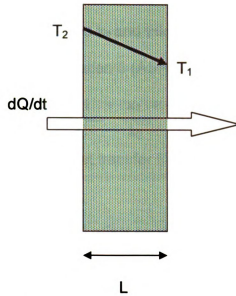


Figure 12. Heat Conduction through plane wall of thickness L

Equation (2) can not be applied directly to a box since it was developed for flat insulation, not for a box composed of flat insulated walls.

Based on the principles of heat flow, the overall thermal resistance to heat flow through a flat surface, such as a ceiling, floor, or wall, equals to the sum of the resistances (R -values) of the various parts of the construction in series as shown in Equation 4 (ASHRAE, 1997):

$$R = R_1 + R_2 + R_3 + \dots + R_n \text{ -----(4)}$$

$R_1 + R_2 + \dots + R_n$ = individual resistances of the parts

R = resistance of the construction from inside surface to outside surface

A wall with an air space of conductance C, made of two homogenous materials with conductivities k_1 and k_2 and thickness x_1 and x_2 , respectively would have resistance as shown in Equation 5 (ASHRAE, 1997).

$$R_T = \frac{1}{h_i} + \frac{x_1}{k_1} + \frac{1}{C} + \frac{x_2}{k_2} + \frac{1}{h_o} \text{-----}(5)$$

h_i and h_o = the heat transfer film coefficients

There are many factors that affect heat transfer across air spaces, such as the nature of the boundary surfaces, the thickness of the intervening air space, the orientation of the air space and the distance between the boundary surfaces, as well as the direction of heat flow. The air space conductance coefficient equals the total conductance from one surface bounding the air space to the other. It is the sum of a radiation component, a convection component, and a conduction component. The most effective arrangement is airtight. Convection and conduction are affected by the orientation of the air space, the direction of heat flow, the temperature difference across the space, and the thickness of the space but only slightly affected by the mean temperature of the surfaces. Radiation, on the other hand, is strongly affected by the temperature of the two boundary surfaces including their respective surface properties characterized by emissivity but only affected slightly by the thickness of the space, its orientation, the direction of heat flow, and the order of emittance (hot or cold surfaces) (ASHRAE, 1997).

Corrugated Shipping Container

Board Structure

Figure 13 shows how single wall corrugated board is composed of a corrugated medium sandwiched between two liners or facings.

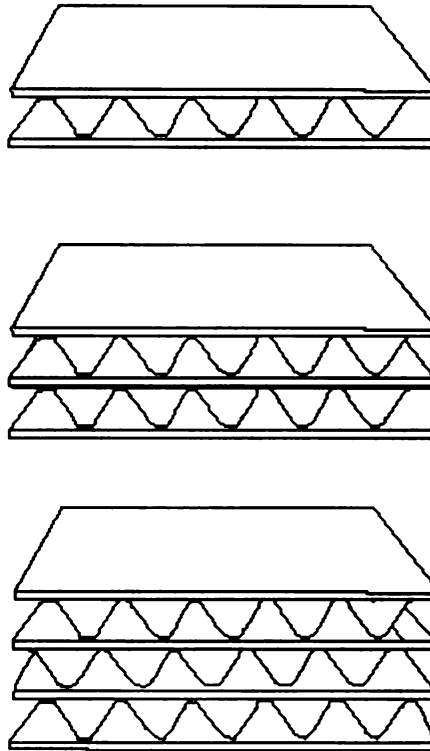


Figure 13. Single wall, double wall, triple wall.

Connected arches are formed as flutes in the corrugated medium. An arch with a proper curve, glued at both facings, can support many times its own weight. (Fibre Box Association, 1994). Double wall board is composed of two fluted medium plies and three linerboard plies while triple wall board combines three fluted medium plies and four linerboard plies (Saroka, 1995). The purpose

of the medium is to separate the facings, prevent them from sliding relative to one another and prevent localized buckling. The medium acts like a low-density core, which makes corrugated board strong and lightweight. The higher the quality of paper and process used in corrugated production, the higher the quality of board produced, (Wright, 1991). Single wall corrugated board is primarily used for manufacturing shipping containers, partitions, cushions, pads, and display stands. With its higher stacking strength, double wall board is used for heavy or bulky products such as machinery, appliances, or furniture. Large and very heavy products are mostly contained in corrugated boxes made of triple wall. Moreover, instead of using wood, triple wall board is used to construct large bulk bins and boxes.

Flute Standards

Most corrugated boards are classified into one of four standard flute sizes (Table 7).

Table 7. Standard flute configurations (Source: ASTM D 4727-91).

Type	Flutes per linear foot	Approximate height	Takeup Factor
A-flute	36 ± 3	3/16-inch	1.54
B-flute	50 ± 3	3/32-inch	1.32
C-flute	42 ± 3	9/64-inch	1.43
E-flute	94 ± 4	3/64-inch	1.27

The size of the teeth in the meshed corrugating roll used to form the medium designates the flute size (Muldoon, 1984). The thickest flute is A,

followed by C, B, and E-flute. In general, the bigger flutes provide greater stacking strength and compression strength, but the smaller flutes provide greater puncture resistance (Saroka, 1995).

In selecting the correct flute for each packaging transport purpose, a carrier classification should be used. C-flute is usually a good for starting point since it is a common size. E-flute is typically not used for shipping containers. Replacing paperboard is a main purpose of E-flute. A-flute is thicker than the other flutes. Theoretically, the highest thickness should offer the best stacking strength. However, there are exceptions. For example, A-flute with 26-pound medium is hard to transport without damaging the flute structure. Therefore, A-flute is mostly used for cushions or triple wall board. With the highest flat crush strength, B-flute is a good choice for packaging such heavy rigid goods as cans or bottles since a high stacking strength is not needed. C-flute gives better stacking strength than B-flute. Corrugated shipping containers made of C-flute use less space than equipment containers made of A-flute. Table 8 illustrates characteristics of each flute (Soroka, 1995).

Materials

Generally, natural Kraft fibers are used for linerboards. Recycled or secondary fiber can be used to produce either linerboards or mediums. Corrugated boards, made of recycled fiber, can be made to the same specifications as virgin fiber containerboard. Sometimes, recycled board is

produced with slightly greater thickness if there is a concern about weaker recycled fiber.

Table 8. Comparison of corrugated board characteristics.

Characteristic	A-flute	B-flute	C-flute	E-flute
Stack strength	best*	fair	good	Poor
Printing	poor	good	Fair	best
Die cutting	Poor	Good	Fair	Best
Puncture	Good	Fair	Best	Best
Storage space	Most	Good	Fair	Least
Score/bend	Poor	Good	Fair	Best
Cushioning	Best	Fair	Good	Poor
Flat crush	poor	good	fair	fair

*Subject to flat crush limitations

A-flute is subject to the limitations of flat crush when a light medium is used.

Typically, recycled board has lower coefficient of friction than virgin Kraft; therefore, its surface looks smoother. Because of this property, a good recycled board offers an excellent printing surface. A disadvantage of recycled board is that it absorbs water more rapidly than virgin Kraft. Due to the lower stiffness of virgin Kraft, it is a good choice for wraparound cases (Soroka, 1995).

Corrugated board grades

Grammage, weight in grams per square meter, and “Basis Weight”, weight in pounds per 1,000 square feet (lb/MSF), are used to categorize fiberboard grades (Table 9 and 10). Component grammage starts from the outside, the smoother finish, to the inside, where embossed lines from the corrugating rolls are visible. Thus, 205/127C/161 consists of the following components: outside liner of 205 grams per square meter, medium of 127 grams per square meter, formed to a C-flute, and inside liner of 161 grams per square (Soroka, 1995).

Table 9. The most commonly used linerboard grades.

North American Grades		European Grades
Grammage	Basis weight	Grammage
127 g	26 lb	125 g
161 g	33 lb	150 g
186 g	38 lb	
205 g	42 lb	200 g
—	—	225 g
—	—	250 g
337 g	69 lb	300 g
Other grades	—	400 g
—	—	440 g

Table 10. The most commonly used corrugating medium weights.

Grammage	Basis Weight
127 g	26 lb
147 g	30 lb
161 g	33 lb
195 g	40 lb

(Conversion: Basis weight in pounds x 4.885 = grammage)

Manufacturer's joint

Corrugated boxes are assembled by gluing, taping, stapling, and stitching (Fiber Box Association, 1994). Glued joints are common and strong and can be produced at high speed. Taping, stapling, and stitching are semiautomatic, so they are slower operations.

Box style

1. Slotted styles

Slotted style boxes are formed from a single piece of corrugated fiberboard which is scored and slotted for folding into a box. At the manufacturer's joint, one side panel and one end panel are brought together and held by glue, tape, or stitching. The examples of slotted boxes include RSC (Regular Slotted Container), OSC (Overlap Slotted Container), FOL (Full-Overlap Slotted Container, CSSC (Center Special Slotted Container). The most common slotted style is the RSC (Regular Slotted Container) (Figure 14). All flaps on an RSC are the same depth. This style is the most economic design since it produces the least production waste (Fibre Box Association, 1994).

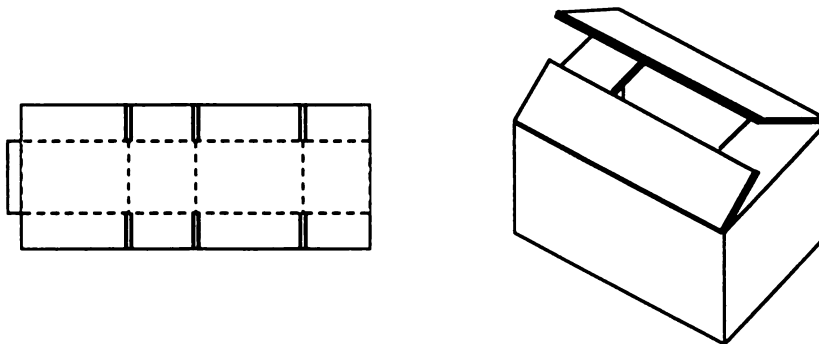


Figure 14. Regular Slotted Container.

2. Telescope boxes

Telescope boxes are composed of more than one part. For example, one piece can be the separate top or cover and the other piece can be the body. The cover slides onto the body. There are many telescope boxes such as FTD (Full-Telescope Design-Style Box), FTHS (Full-Telescope Half-Slotted Box), PTD (Partial-Telescope Design-Style Box), and PTHS (Partial telescope Half-Slotted Box). The FTD, which is a common style, produces the least manufacturing waste (Figure 15).

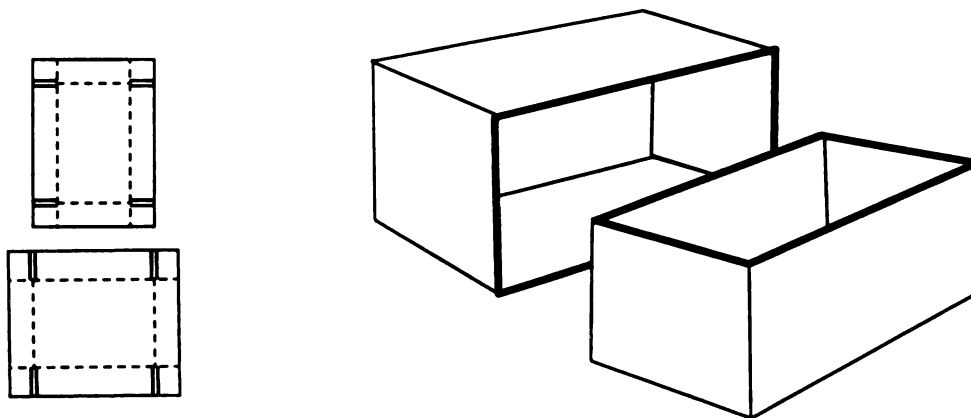


Figure 15. Full-Telescope Design-Style Box.

3. Folders

Folders are made of one or more pieces of fiberboard that fold around a product. Folders include 1PF (One-Piece Folder), 2PF (Two-Piece Folder, 3PF (Three-Piece Folder), FPF (Five-Panel Folder), wrap-around blank, self-locking tray, tuck folder, etc. A 1PF (one-piece folder) (Figure 16) uses one piece of

corrugated board, scored to form the sides and ends, and extensions of the side flaps to form the top.

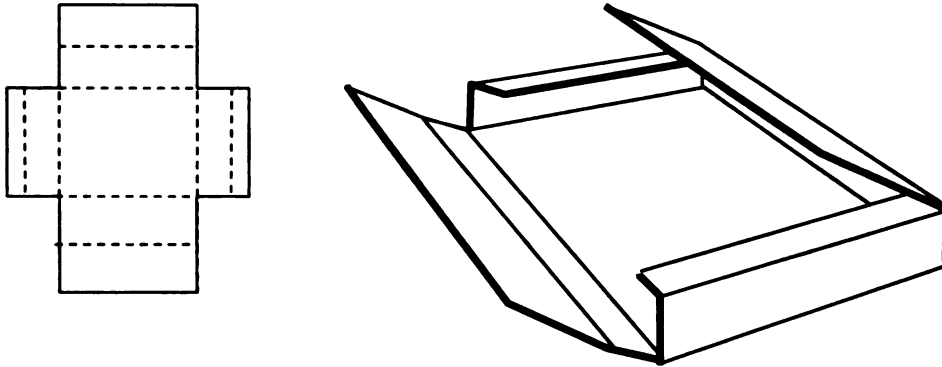


Figure 16. One-piece folder.

A five-panel folder (FPF) (Figure 17) is composed of five panels which are slotted and scored. The fifth panel is the closing flap that covers one side panel. The FPF is appropriate for long products. Penetration of the end is prevented by several layers of the FPF flaps (Fibre Box Association, 1994).

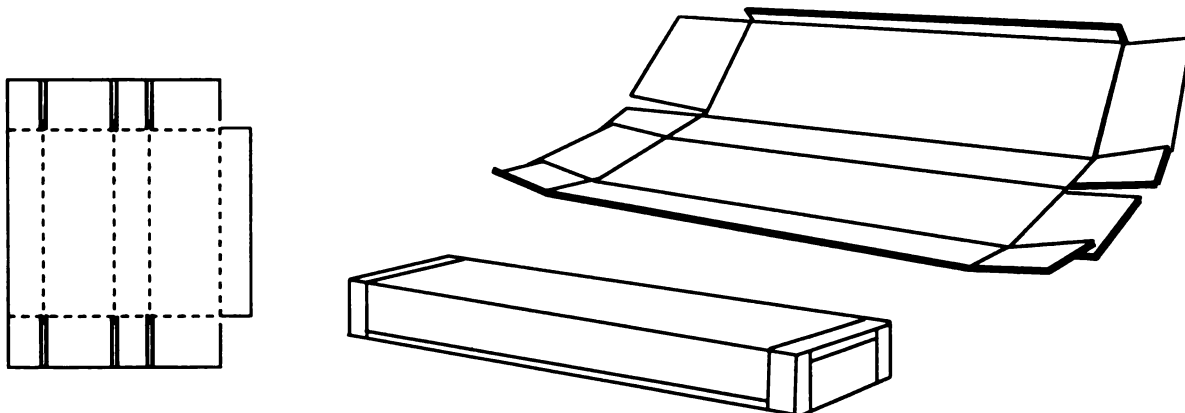


Figure 17. A five-panel folder.

4. Slide-type boxes

A slide-type box is an outer tube and an inner shell which are formed from two rectangular and scored pieces of board. The tube slides onto the shell. It is very easy to close or open the box. The examples of slide-type boxes include DS (Double-Slide Box) and TS (Triple-Slide Box). A DS (Double-Side Box) (Figure 18) is two shells made of two pieces of board that slide onto each other. The two thicknesses of four sidewalls provide stacking strength (Fibre Box Association, 1994).

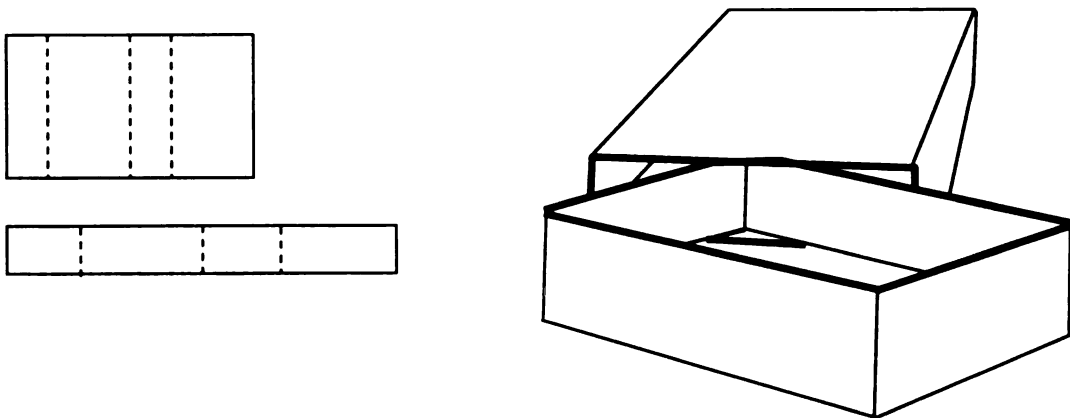


Figure 18. Double-Side Box.

5. Rigid boxes

Rigid boxes are made of three pieces of fiberboard. Two identical end panels have flaps to attach to a body which is made from one piece of the fiberboard folded to form the two side panels. The examples of rigid boxes are Recessed-End box, No.2 Bliss Box and No.4 Bliss Box. Figure 19 showing a

No.2 Bliss Box is made from one scored piece formed to be the body and two end pieces with four flaps to provide good stacking strength. Seams are formed on the body panels (Fibre Box Association, 1994).

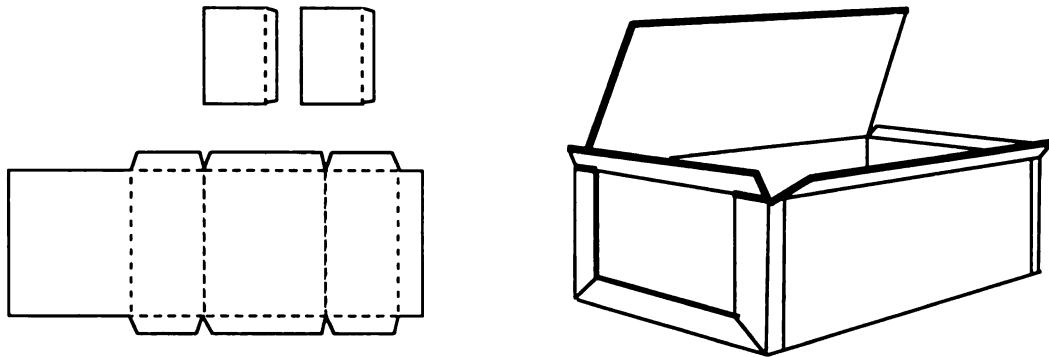


Figure 19. Bliss Box.

6. Self-erecting boxes

Self-erecting boxes are made of one piece of die-cut board with slit-scored bottom flaps. Two pairs of bottom flaps are designed to be fastened to each other when forming the joint. Self-erecting boxes are appropriate for small-volume shippers who load automatic set-up equipment. Self-erecting boxes (Figure 20) have two pairs of adjacent bottom flaps that slide together to form the bottom while four panels with top flaps are similar as a regular slotted container (Fibre Box Association, 1994).

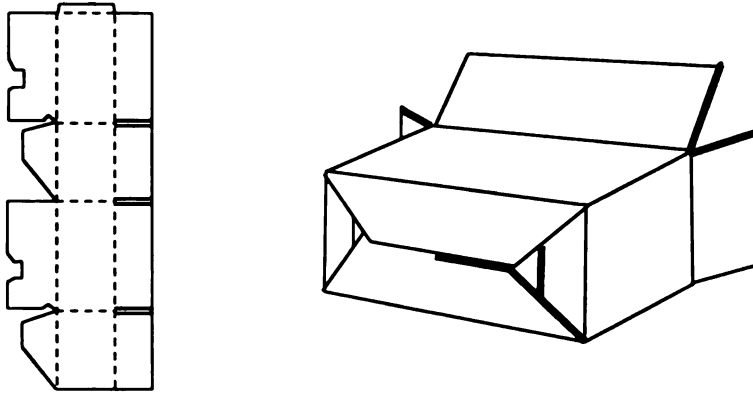


Figure 20 Self-erecting Box.

Shapes of corrugated boxes

The shape and style of a corrugated box is determined by the size, weight, and shape of the products inside. The shape of the box is defined by the ratio of the length of the longest side to the length of the shortest side and by the ratio of the length of the intermediate side to the length of the shortest side. The ratios, L/W and D/W , where L = box length, W = box width and D = box depth give the proportions of the box as in Figure 21 (Wright, 1991).

Sizes of corrugated boxes

In the fiberboard box industry, the manufacturer states inside box dimensions in the order of length, width and depth. The definitions of length, width, and depth are based on which panel side is the opening. Even though two boxes have the same size, it doesn't mean that they have the same dimensions as well (Figure 22). The longer dimension of the opening is the length and the

length of the shorter side is the width. The depth is determined by the distance perpendicular to the innermost surface of opening (Muldoon, 1984).

End Proportions

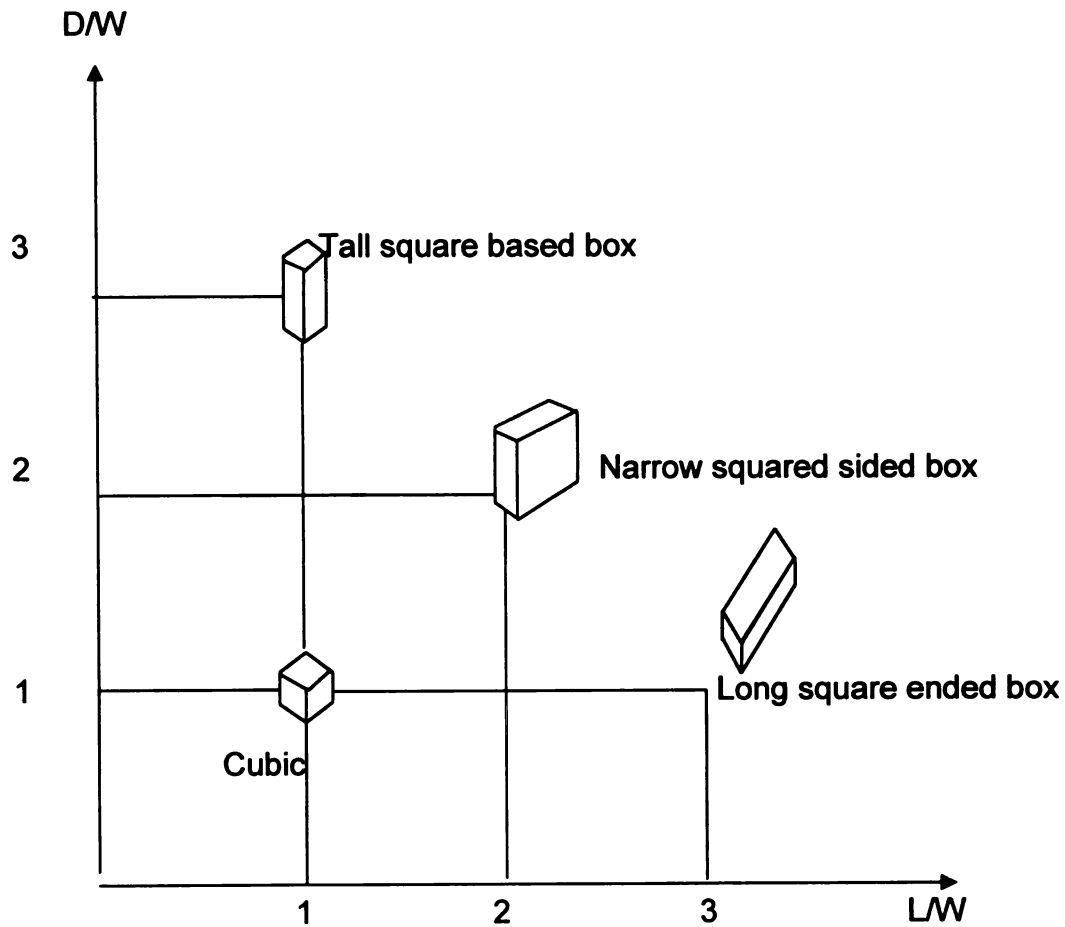


Figure 21. The proportion of the box.

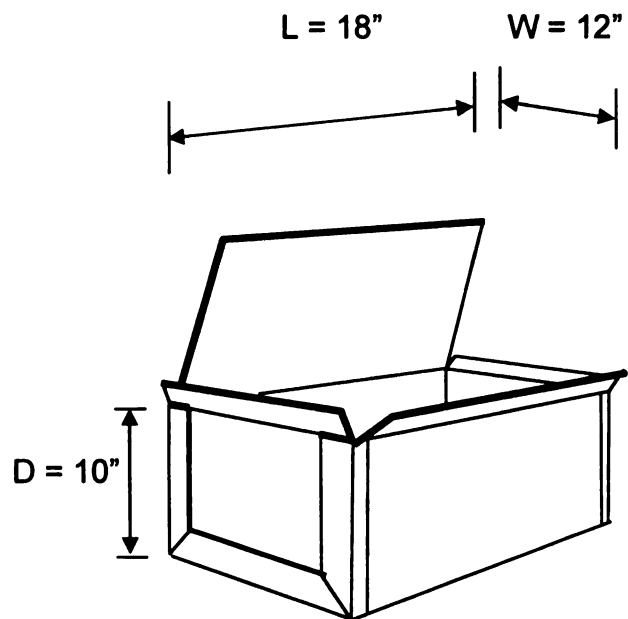
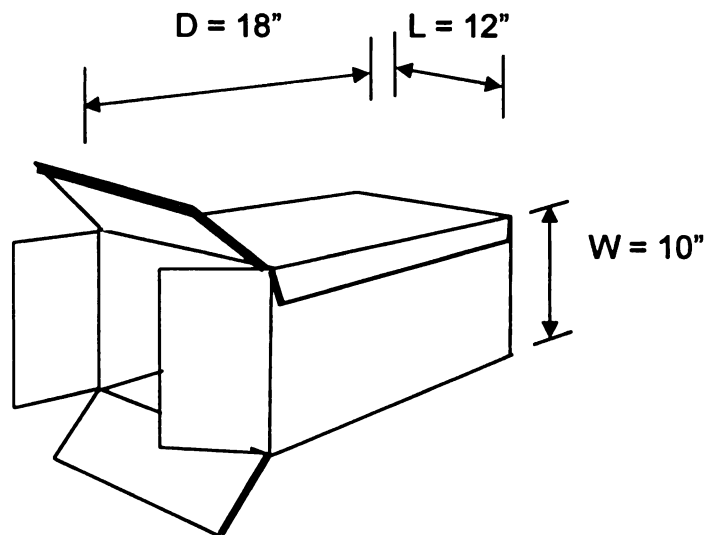


Figure 22. Box dimensions.

Thermal resistance of corrugated board

The same heat transfer principles apply to corrugated board as other materials. There are two types of heat resistance: the surface resistances and the material resistance (Thomson et. al, 1998). If the exterior temperature is higher than the interior temperature, heat transfers from the outside environment to a liner surface by conduction, convection, and/or radiation. Heat then passes through the liner by conduction. The heat transfers through the air spaces of the flute section by convection and radiation. The heat conducts from the inner liner to the product if they are in contact. There may also be radiation and/or convection (Ramaker, 1974).

Ramaker (1974) developed a mathematical model to estimate the thermal resistance of corrugated fiberboard by adding the thermal resistances of the individual components: facing and fluted section. ASTM C 518 was conducted to determine the thermal resistances of different linerboards and mediums. The study concluded that reducing the weight of the corrugated medium increased the thermal resistance while reducing the weight of linerboard decreased the thermal resistance.

Thomson, Robertson, and Cleland (1998) searched for an inexpensive, simple, and quick method to measure the thermal conductivity of packaging paperboard. Instead of using ASTM C177: Standard Method of Test for Thermal Conductivity of Materials by Means of the Guarded Heat Plate, requiring complicated apparatus and considerable time for the measurement, the method of Cleland and Earle (1976) was used to measure time-temperature data at the

surface of a semi-infinite slab for a short period of time after the onset of cooling or heating.

The overall heat transfer coefficients ($1/h$), obtained by calculating, were plotted against the number of sheets of packaging. The slope of this plot was the heat transfer resistance (R_p) of a single packaging layer. Therefore, the heat transfer resistance for the corrugated paperboards that were tested could be estimated (Table 11).

Table 11. Heat transfer resistance (R_p) of corrugated paperboard samples
(Thomson et. al, 1998).

Flute	Grammage	R_p	95% Confidence Limit
E	160/120/160	0.026	0.007
	220/120/220	0.031	0.003
	220/120/220	0.032	0.005
	290/120/290	0.037	0.006
	290/120/290	0.036	0.006
B	160/120/160	0.064	0.009
	220/120/220	0.058	0.008
	220/120/220	0.058	0.005
	290/160/220	0.057	0.004
C	120/120/120	0.078	0.003
	220/120/220	0.075	0.006
	220/120/220	0.072	0.007
	290/160/220	0.077	0.006

Recent work by this Thomson 's team was focused on developing a model for predicting the thermal resistance of a broad range of corrugated paperboards

for industrial applications. Overall resistance to heat transfer across a corrugated board equals the sum of a series of resistance as in Equation 7, 8, and 9:

$$R_{pk} = R_{liner1} + R_{fl} + R_{liner2} \text{ -----(7)}$$

$$= \left[\frac{x}{\lambda} \right]_{Liner1} + R_{fl} + \left[\frac{x}{\lambda} \right]_{Liner2} \text{ -----(8)}$$

R_{liner} = thermal resistance of corrugated liner

R_{fl} = thermal resistance of corrugated flute

x = wall thickness

λ = thermal conductivity of test material

From equation 7, thermal resistance of the flute section can be determined as:

$$R_{fl} = R_{pk} - \left[\frac{x}{\lambda} \right]_{Liner1} - \left[\frac{x}{\lambda} \right]_{Liner2} \text{ -----(9)}$$

Heat transfer resistance of common liner and medium paper for manufacturing corrugated paperboard was measured and shown in Table 12 (Thomson et. al, 1998).

Table 12. Measured heat transfer resistances of common liner and medium papers used to manufacture corrugated paperboard.

Paper Grade	Nominal Grammage (g m-2)	Average Thickness (mm)	Number of Samples Tested	Mean Heat Transfer Resistance R_{liner} (m ² KW ⁻¹)
1	120	0.175	1	0.0022
2	160	0.236	2	0.0030
3	220	0.332	3	0.0042
6	290	0.437	2	0.0056

This study concluded that increasing flute thickness increased heat transfer resistance.

S-flute Corrugated Board

General information

Steel Stack, trade name, provides 23% greater stacking strength than 275# single wall, 10% greater stacking strength than 275# double wall, 60% greater shock absorption than single wall, and also 10% greater shock absorption than double wall (Curley, 1993).

Specification

Flute Count:	24 per lineal foot
Take up Factor:	about 1.58 (slightly above A-flute at 1.52-1.54)
Thickness:	0.25 inches
Medium:	36# medium

Application and Development Research

levans (2000) stated that S-flute, a large size corrugation, was developed by Bobst and used by the Greater New York Box Co. It was tested and evaluated by Smurfit for the application in laminated bulk boxes at Ravenna. Reports of research on S-flute to improve the compression strength of laminated bulk boxes have been included in Appendix A.

S-flute with a specific basis weight and board combination was tested by Smurfit (1998). The results are shown in Table 13.

Table 13. Tested results for S-flute (Smurfit, 1998).

Test	Testing Method	Units	Identification
Board Caliper	Tappi T411 Om89	mils	252.06
ECT	Tappi T839 Pm-95	lbs./in.	63.6
Flexural Stiffness MD	Tappi 820 cm-85	lbs. in.	207.07
Flexural Stiffness CD	Tappi 820 cm-85	lbs. in.	156.57
Flexural Stiffness GEO. MEAN	Tappi 820 cm-85	lbs. in.	180.06
Flat crush	Tappi T825 Pm-86	Psi	No end point
Comb. BD. Basis weight	Tappi T410 om-93	lbs/MSF	222.1
Basis weight Double Back	Tappi T410 Om-93	lbs/MSF	79.2
Basis weight Medium (S-flute)	Tappi T410 om-93	lbs/MSF	42.3
Basis weight Single Face	Tappi T410 Om-93	lbs/MSF	78.4

Thermal Testing Approaches for Packaging

There are several test procedures, for estimating the rate of heat transfer for insulated containers such as ASTM D 3103-92 (ASTM, 1994) and ISTA 3G (ISTA, 1999). Some companies and researchers have developed other testing standards and methods. Examples of each type are discussed in the following sections.

ASTM Standard

The objective of ASTM D 3103 is to determine thermal insulation capability of a package with or without various refrigerants and with or without interior packaging. Temperature indicating devices such as thermocouples are used to measure the interior temperatures. A package with constant interior area (12 x 12 x 12 in.) enclosing the actual items or a dummy load is used as a single specimen. ASTM suggested that the interior cavity should be surrounded by a 1-in thickness of solid insulation and a 14 x 14 x 14 in. container.

The sensors are inserted into the package with or without the contents inside in different locations. In the case of packages designed with interior walls separating product and refrigerant, more thermocouples are needed. Refrigerants are weighed, measured, and placed into the package. Temperatures of water ice or refrigerant gel are recorded at the beginning of testing. The package is sealed and put on a wooden shelf in the chamber or test environment. The date, time, and temperature are recorded for each period of time (ASTM, 1994).

ISTA Standard

ISTA 3G: *Development Test for Thermal Performance of Insulated Transport Packaging* is used to test individual packaged-products shipped through a parcel delivery system for protection against temperature extremes. In addition, the ISTA procedure can measure the ability of the package to protect a product by exposing it to test cycles that simulate extreme temperature

conditions. Samples should be the untested actual packages and the product substitutes should have properties as similar as possible to actual items such as inside content, composition, thermal mass, consistency, specific heat, and other physical properties. Replicate testing is recommended. The procedure should be performed five or more times, using new packages with each test. The packages are tested by following the sequence in Table 14. The atmospheric test is conducted by choosing the cycle (Table 15, 16, or 17) which is closest to the conditions the packaged-product will be exposed to during transportation (ISTA, 1999).

Table 14. Test sequences (ISTA, 1999).

Sequence #	Test Category	Test Type	For ISTA Certification
1	Atmospheric**Preconditioning	Temperature	Optional
2	Shock Conditioning	Drop	Optional
3	Atmospheric**	Temperature	Required
4	Vibration Conditioning	Random	Optional
5	Atmosphere**	Temperature	Required
6	Shock Conditioning	Drop	Optional
7	Atmospheric**	Temperature	Required

**Equipment required for Atmospheric Test are Draft-free chamber and temperature indicators complying with the apparatus section of ASTM D 3103-92.

The extremes of winter and summer transport conditions within the United States

Table 15. 24 hour domestic express small package freight transport (Air)

Winter Profile		Summer Profile	
Cold Shipping & Cold Receiving		Hot Shipping & Hot Receiving	
Temperature	Hours	Temperature	Hours
18°C (65°F)	0-4	22°C (72°F)	0-4
-10°C (14°F)	4-6	35°C (95°F)	4-6
10°C (50°F)	6-18	30°C (86°F)	6-18
-10°C (14°F)	18-24	35°C (95°F)	18-24

Table 16. 48 hour domestic express small package freight transport (Air)

Winter Profile		Summer Profile	
Cold Shipping & Cold Receiving		Hot Shipping & Hot Receiving	
Temperature	Hours	Temperature	Hours
18°C (65°F)	0-4	22°C (72°F)	0-4
-10°C (14°F)	4-6	35°C (95°F)	4-6
10°C (50°F)	6-42	30°C (86°F)	6-42
-10°C (14°F)	42-48	35°C (95°F)	42-48

The extremes of winter and summer transport conditions for international shipments from the United States

Table 17. 72-hour international expedited airfreight transport.

Winter Profile		Summer Profile	
Cold Shipping & Cold Receiving		Hot Shipping & Hot Receiving	
Temperature	Hours	Temperature	Hours
18°C (65°F)	0-4	22°C (72°F)	0-4
-10°C (14°F)	4-10	35°C (95°F)	4-10
10°C (50°F)	10-66	30°C (86°F)	10-66
-10°C (14°F)	66-72	35°C (95°F)	66-72

Table 18. 72-hour international expedited airfreight transport.

Winter Profile		Summer Profile	
Cold Shipping & Cold Receiving		Hot Shipping & Hot Receiving	
Temperature	Hours	Temperature	Hours
18°C (65°F)	0-4	22°C (72°F)	0-4
-10°C (14°F)	4-10	35°C (95°F)	4-10
10°C (50°F)	10-42	30°C (86°F)	10-42
22°C (72°F)	42-66	35°C (95°F)	42-66
35°C (95°F)	66-72	-10°C (14°F)	66-72

Other methods

Krebs (1994) examined the relationship between rising temperatures in a trailer and the corresponding rise in temperature of a packaged product. He exposed computers to simulated trailer temperatures in the laboratory and observed the insulating effect of packages. He placed the sample packaged product in a temperature controlled chamber. He located four temperature

probes at different locations: inside the unit, on the outer surface of the unit, inside the carton but not on the unit, and outside the carton as shown in Figure 23.

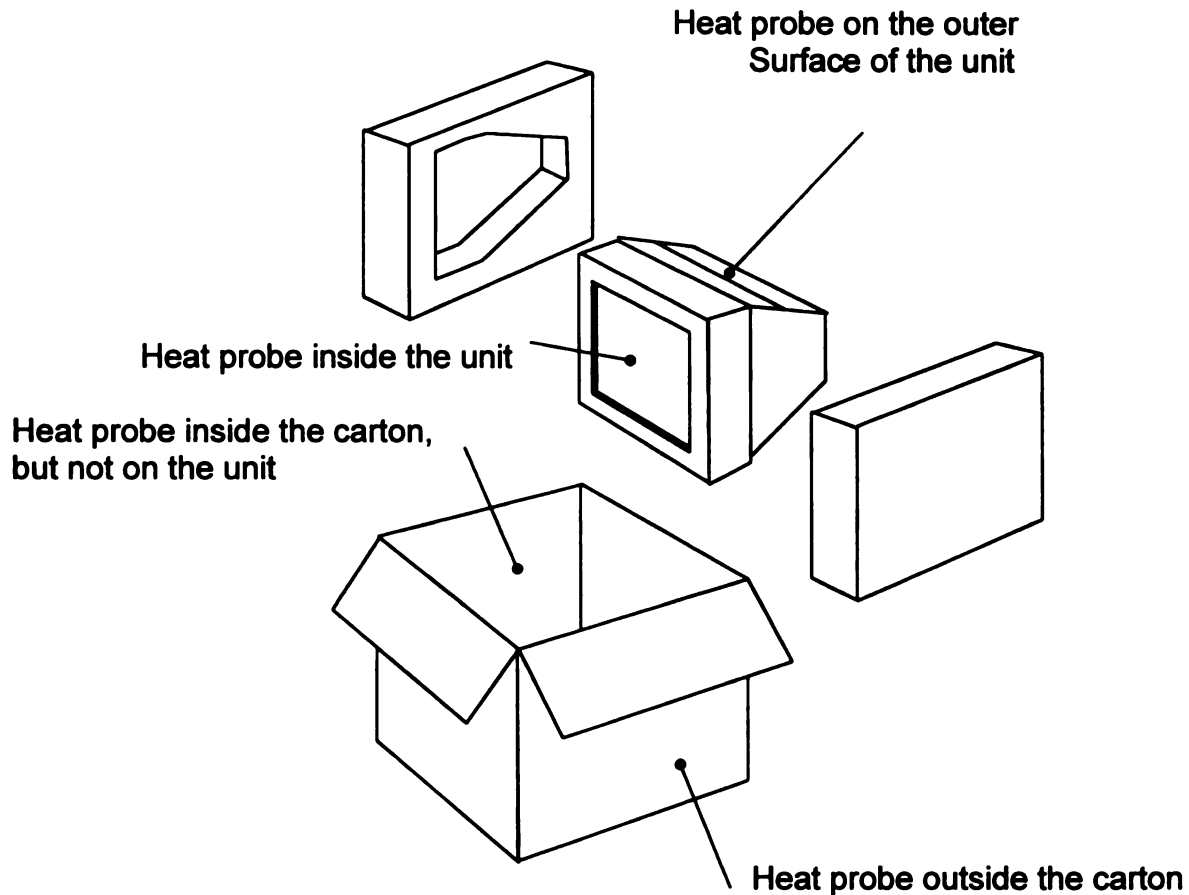


Figure 23. Illustration of packaging components (Krebs, 1994).

The packaged-product was preconditioned at 73 °F and placed in a heat chamber at 107 °F. The heat chamber temperature was increased from 107 °F to 138 °F for 8 hours to simulate the conditions inside a trailer. The results of this experiment showed that the temperature inside the cartons increased at the same rate as the chamber temperature. The outer surface temperature of the

display terminal cover, which increased with the heat chamber temperature, lagged behind by 30 °F while temperature inside the computer with insulated foam end cap cushions and the plastic display cover lagged behind by an average of 40 °F. This study showed that insulated corrugated boxes with foam cushioning materials can protect a product exposed to the extreme temperature of 138 °F.

Fava, Piergiovanni, and Pagliarini (1999) demonstrated that a new package with expanded polystyrene and water-absorbing polymer provided better thermal insulation than a conventional corrugated container for pizza. Consumers desire pizza to have the characteristics with which it left the oven: warm and not softened. They tested water absorption, WVTR, thermal insulation, and sensory profile. Four sheet materials were tested: single-wall corrugated board, Expanded polystyrene (EPS), Ultra-high density polyethylene (UHDPE), and Absorbent paper. Tested pizza was delivered from the Pizza store within 10 minutes.

Six needle-shaped thermocouples, placed in three different locations on the pizza (bottom, crust, and topping), recorded temperature every 8 seconds for 15 minutes from the time the Pizza was placed in the box. A panel of 20 subjects who tested pizza with different temperatures (from 90 to 50 °C) determined the palatability was between 65 °C and 80 °C. A critical temperature of 60 °C was selected as a reference. Time to reach the critical consumption temperature is of importance. They found that pizza in the new container stayed warm for more

than 10 minutes (more than the transport time). In the corrugated box, the crust was cold within 4 minutes.

Sasaki and Kato (1999) studied a new insulated cardboard composed of a corrugated foamed polystyrene core with paperboard liners on both side. (Figure24).

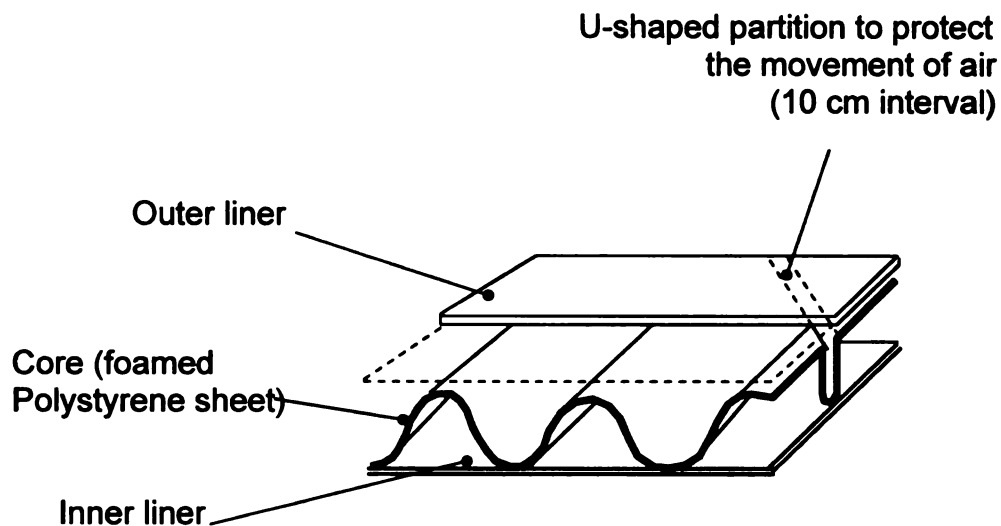


Figure 24. Cross-sectional structure of new heat insulating cardboard (Sasaki and Kato, 1999).

Sasaki and Kato tested calorific value, insulation ability, decorative capacity, and recyclability. For heat transfer testing, cut flowers and a processed marine product were used to test hot insulation and cold insulation. Roses were preconditioned at the same temperature of shipment for transportation. The temperature rise inside the package, the ratio of weight loss, the flowering progression, and durability in storage were determined. For processed marine

products, young sardines at -50°C , were placed at room temperature. The temperature change versus time was recorded. They found that the new heat insulated cardboard box could prevent heat gain and heat loss better than common cardboard box. The inside temperatures were 1 to 2°C higher than the Styrofoam package.

The ice requirement procedure (Burgess, 1999) was conducted to estimate the thermal resistance (R-value) of each package. Various packages with sized ranges of 0.5 to 5 cubic feet in volume and various wall constructions were tested in two storage temperatures: 72°F and 104°F . A known quantity of preconditioned ice (at 32°F uniformly) was put into a package. The package was sealed and stored it on the shelf or other surface off the floor in a draught free constant temperature chamber. At least once a day, the package was checked to determine when most of the ice, but not all, had melted. Interior and exterior temperatures were constant throughout the testing period. When the box was opened, the water was weighed and the time was noted.

The length of time and the quantity of ice that had melted in each package were determined and used to calculate the melt rate which was used in Equation 9:

$$\text{System R-value} = \frac{(\text{interior area}) (\text{temperature difference})}{(\text{melt rate}) (\text{latent heat})} \text{ ----- (10)}$$

The latent heat was 144 Btu of heat energy to melt 1 lb of ice. Melt rate is the proportion of water melt weight divided by period of time. The study concluded that R-value depended on the wall construction.

Camus and Veaux (1984) studied “isothermic bags and boxes such as multi-ply special paper bags, isothermal containers, and isolated bags in plastic materials or transportable isothermic boxes for transport of frozen foods from shops to households/restaurants”. They analyzed the temperature variation in selected isothermic packages by placing thermocouples in boxes of ice cream at locations 3 cm from the walls. Temperatures in cars from August to December and selling places of frozen foods were recorded. Initial temperature of product was -20°C and Test cycles were 30 min at 20°C and 15 min at 40°C . Camus and Veaux determined whether the package was suitable to use by placing a certain quantity of ice cubes into a corrugated board box instead of ice cream. The amount of melting water after a certain time was the measured parameter. If the volume of the water was lower than a predetermined limit, the package was approved.

Cambridge Refrigeration Technology (2000) did thermal testing on refrigerated and insulated containers, trailers, and van bodies to determine heat leakage in environmental chambers. The chamber temperature was maintained in the range of 0°C to 10°C . The internal insulated test unit was held at a constant temperature of at least 20°C by a metered electrical heater. Mean external and mean internal temperatures were detected and calculated by twelve external temperature sensors and twelve internal sensors when the steady state was

reached. External and internal dimension of the test unit determined the root mean area. Equation 10 and 11 were used to calculate the thermal heat leakage and overall heat transfer coefficient,

$$\text{Thermal heat leakage} = \frac{\text{measured heat input}}{\text{Mean temperature difference}}, \text{ w/k} \text{ -----(11)}$$

$$\text{Overall heat transfer coefficient} = \frac{\text{thermal leakage}}{\text{Mean area}^{\frac{1}{2}}}, \text{ W/m.k} \text{ -----(12)}$$

3.0 DESIGN AND DEVELOPMENT PROCESS

Air is a good insulation and wall thickness as well as wall construction affect insulating ability of packages. Therefore, double wall construction with a core of air space was suggested for integration into two new thermal corrugated packaging designs: 1) interlocking design and 2) folding design as shown in the following sections.

Inspiration

Interlocking design

The idea for the interlocking design came from papercraft (Figure 25). Single square patterns were used to create the modular structure (Figure 26).

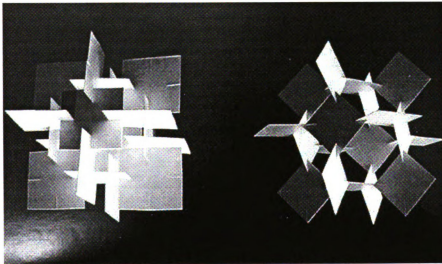


Figure 25. Modular structure.



Figure 26. Single square patterns.

Folding Design

The idea for the folding design came from the ethnic Thai food package, which is made by folding banana leaves (Figures 27 and 28).



Figure 27. Traditional Thai food packages.

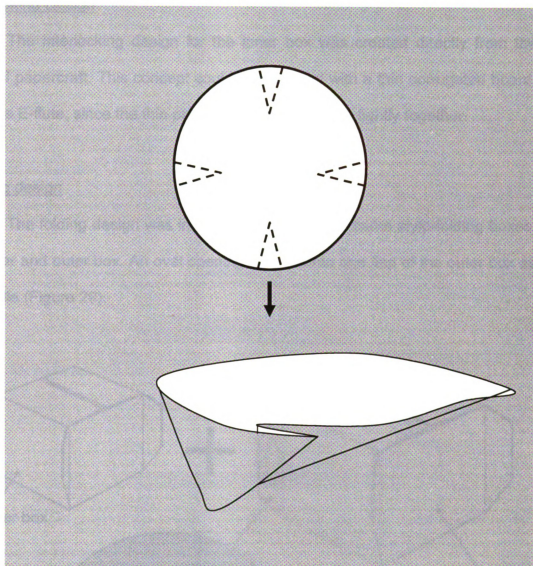


Figure 28. Folding pattern.

Design Development

Interlocking Design

The interlocking design for the inner box was created directly from the original papercraft. This concept could not be used with a thin corrugated board, such as E-flute, since the thin panels could not interlock tightly together.

Folding design

The folding design was initially created with two same style-folding boxes: an inner and outer box. An oval opening was cut into one flap of the outer box as a handle (Figure 29).

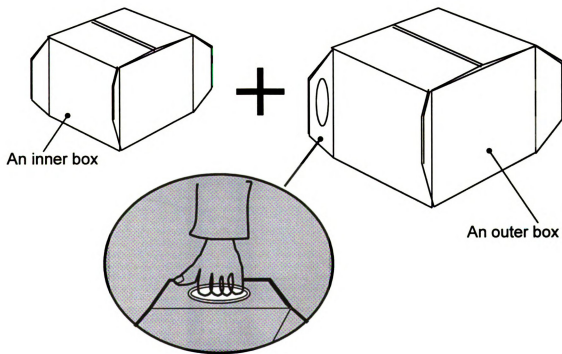


Figure 29. Development of the folding design.

Final Design

Interlocking design

The interlocking design is shown in Figure 30 and 31.

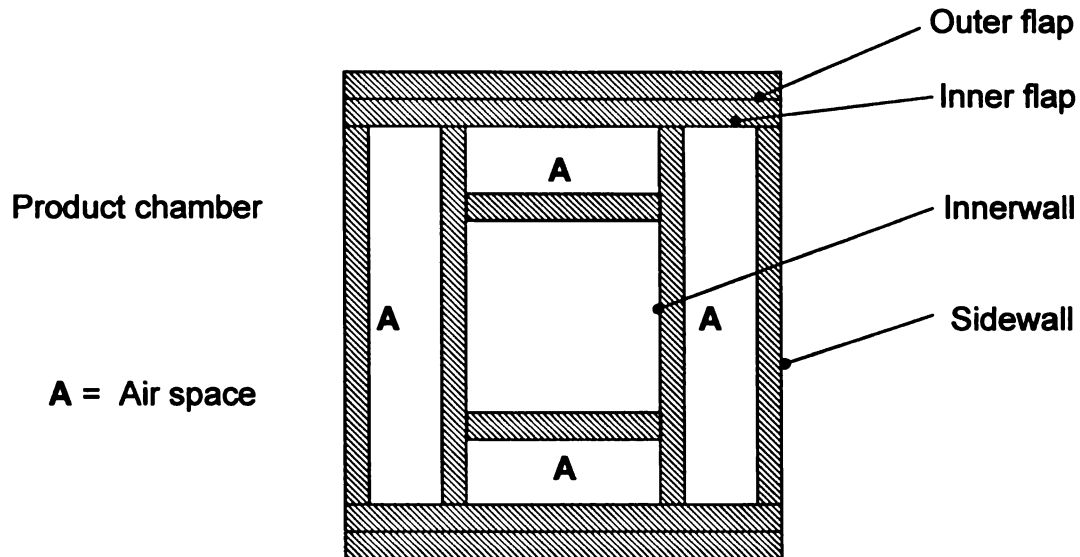


Figure 30. Side section elevation.

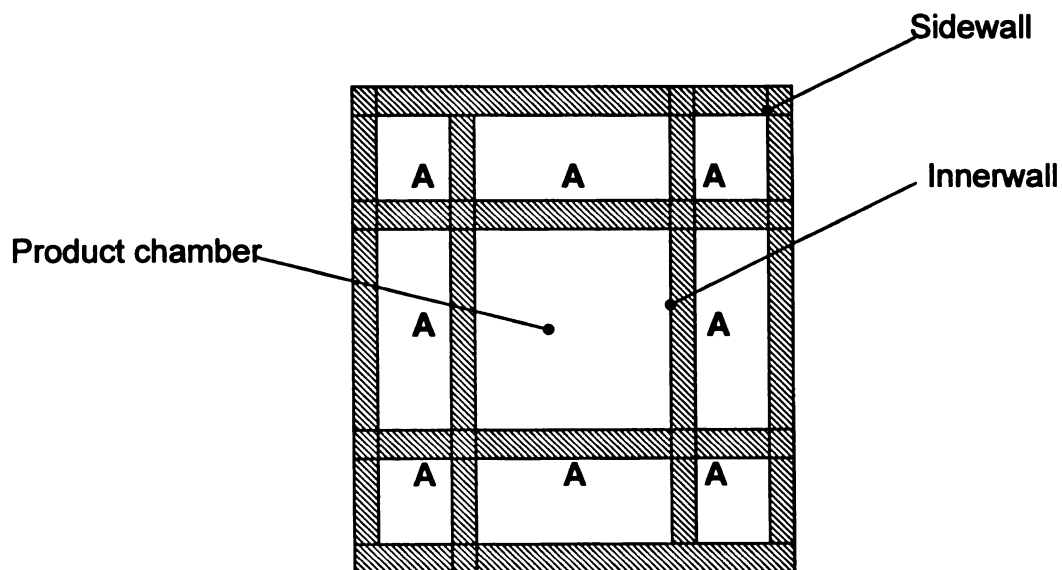


Figure 31. Top section elevation.

Assembly parts

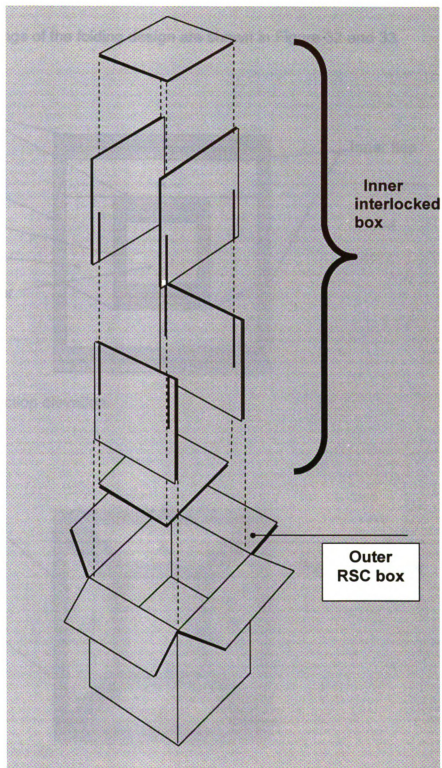


Figure 32. Assembly parts of the interlocking design.

Folding design

The drawings of the folding design are shown in Figure 32 and 33.

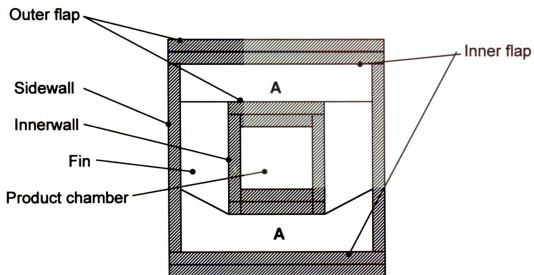


Figure 33. Side section elevation.

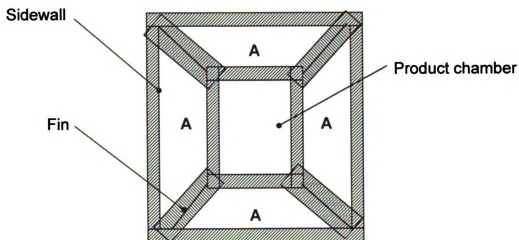


Figure 34. Top section elevation.

Assembly parts

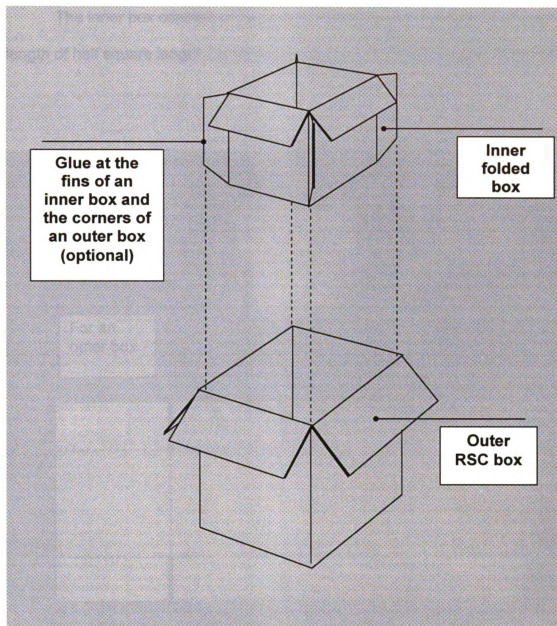


Figure 35. Assembly parts of the folding design.

Die Cut Pattern

Interlocking design

The inner box consists of four square patterns with two slots that have a length of half square length. Outer box consists of one RSC pattern (Figure 36).

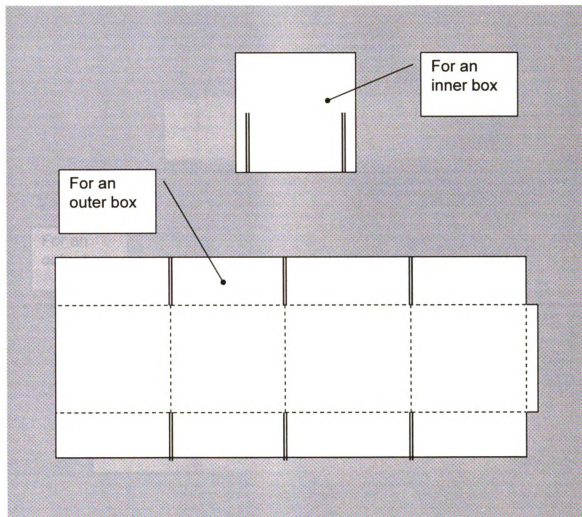


Figure 36. Die cut pattern of the interlocking design.

Folding design

The inner box is made from one die cut pattern. The outer box consists of one RSC (Figure 37).

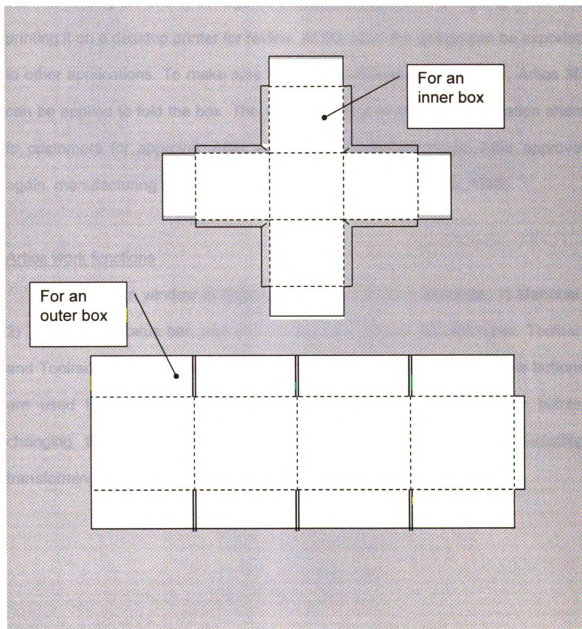


Figure 37. Die cut pattern of the folding design.

ArtiosCAD Software

Basic concept of ArtiosCAD

The purpose of using ArtiosCAD is to change creative thoughts into business with high speed, efficiency, and accuracy. The steps of making boxes such as folding cartons or corrugated containers begin from designing a box and printing it on a desktop printer for review. At this point the design can be exported to other applications. To make sure that all dimensions work together, Artios 3D can be applied to fold the box. The next process is to send a specification sheet to customers for approval. After approval, samples are made. After approval again, manufacturing tools for the box are made (BARCO Artios, 1999).

Artios work functions

The design window in ArtiosCAD consists of four elements: 1) Menubar, 2) Toolbar, 3) Status bar, and 4) Drawing area (Figure 38). Menubar, Toolbar, and Toolrack provide all command buttons available (Figure 39). These buttons are used to command drawing elements such as lines, shapes, or paints, changing the view, such as zooming in or zooming out, and including transforming such as moving, copying, or rotating design elements.

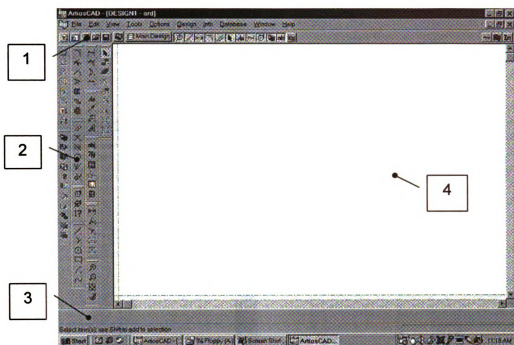


Figure 38. ArtiosCAD window.

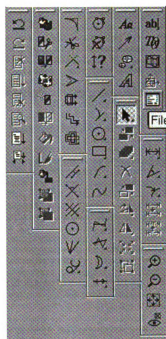


Figure 39. Toolbar.

Users can choose to draw their design by themselves or select some designs from the Artios standard catalog (Figure 40).

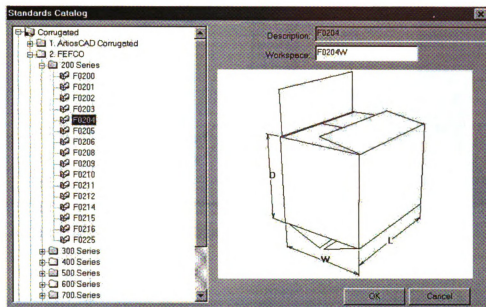


Figure 40. Standard catalog.

After selecting the box style from the standard catalog, the specification from the dialog boxes of that box style are shown for users to proceed in step by step such as inside dimensions (Figure 41), box details (Figure 42), allowances (Figure 43).

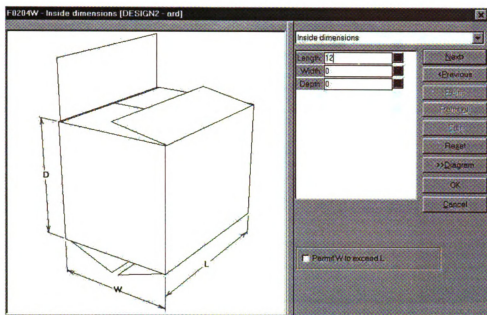


Figure 41. The inside dimension box.

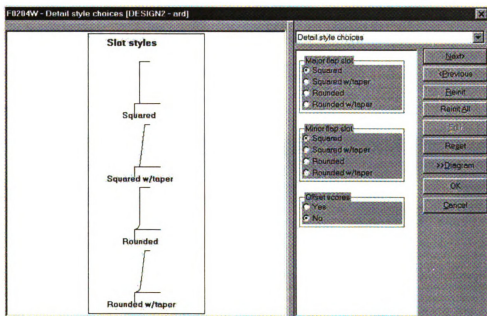


Figure 42. The detail style box.

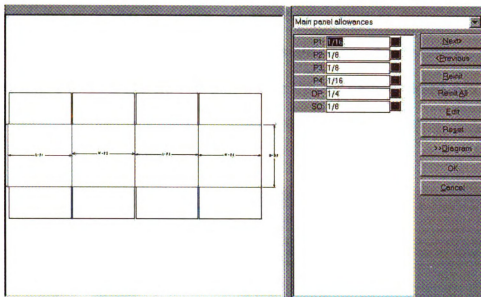


Figure 43. The allowance box.

No matter what users choose, to draw their own design or select the standard design, the single design setting dialog box is displayed automatically to ask about the kind of paperboard to be used (Figure 44).

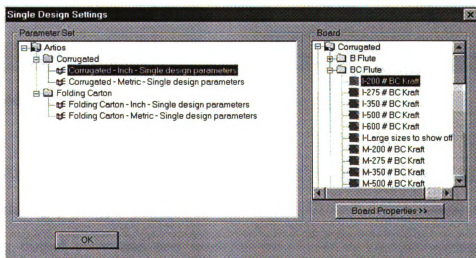


Figure 44. Single design setting box.

Drawing a design in ArtiosCAD is different than in AutoCAD or other drawing programs. Users specify which line is cut or creased by selecting a line element and choosing the type of that line in the Properties dialog box (Figure 45).

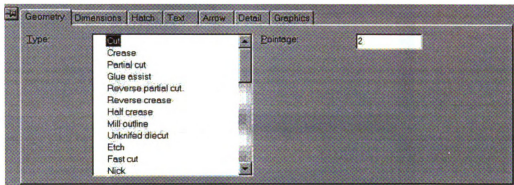


Figure 45. The properties box.

While drawing a line, the Status bar displays its length, angle, and direction (Figure 46).



Figure 46. Status bar with a drawing tool.

After finishing the work, the design has to be saved in a file of type .ARD as a drawing prototype and saved in a file of type .ACM for a cutting table by opening output command and selecting the mode of "sample cutting" to be compatible with the sample-cutting machine.

Entering information into DataCenter

DataCenter is another database program used to store and find specific information about ArtiosCAD. It consists of six main areas: design, manufacturing, embedded design, company, person, and board (Figure 47).

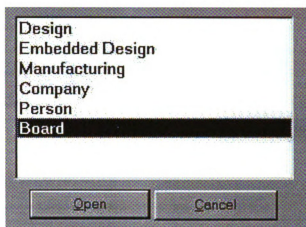


Figure 47. Six areas in Artios database.

To use the new corrugated board 'S-flute', the new board information was configured in DataCenter by clicking the Open button on the toolbar and selecting the Board browser. The  Add Record button and the  Delete Current Record button on the toolbar (Figure 48) were used to add and remove information in the Board browser.

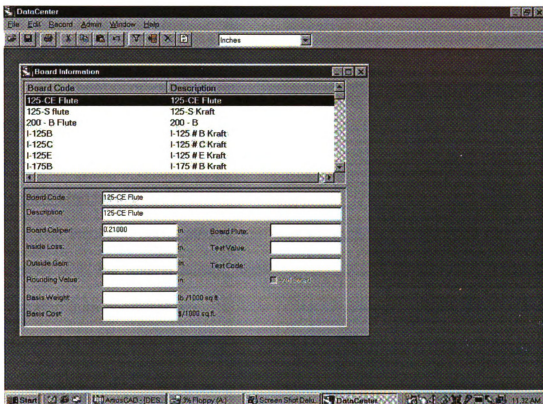


Figure 48. Board information in DataCenter.

4.0 MATERIALS AND METHOD

Part I Experiment

Test materials

Four materials used in this study were corrugated board with different flutes and flute combinations, an Expanded Polystyrene container, ISC container – a corrugated box with injected polyurethane foam and open cell foam as a cover, and Thermocor - a cored Polystyrene foam with two laminated paperboard liners.

1. Corrugated boxes

The insulated corrugated boxes, one type with an interlocking design and the other with the folding design, were developed and constructed of different corrugated flute combinations. The flute types are shown in Table 19. The space between the walls was 1.5 inches. The inside dimensions of the inner boxes were 9 x 9 x 9 in. in Figure 49 and 50.

Table 19. Corrugated boards used in the experiment.

Type	Thickness, in
B	0.12
C	0.18
E	0.07
S	0.294
BC	0.264
CE	0.215

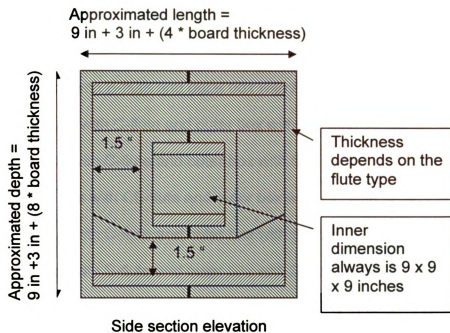


Figure 49. Dimensions of the folding design corrugated box.

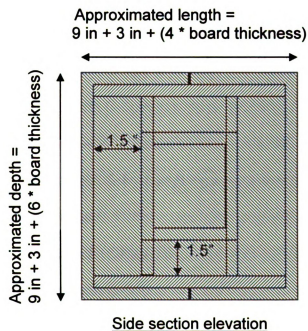


Figure 50. Dimensions of the interlocking design corrugated box.

Due to a combination of two boxes in one design (i.e. outer box and inner box), there were seven flute combinations for the interlocking design, designated as:

1. Ib-Ob : inner box with B-flute and outer box with B-flute
2. Ic-Oce : inner box with C-flute and outer box with CE-flute
3. Ic-Oc : inner box with C-flute and outer box with C-flute
4. Ice-Oce : inner box with CE-flute and outer box with CE-flute
5. Ic-Os : inner box with C-flute and outer box with S-flute
6. Is-Os : inner box with S-flute and outer box with S-flute
7. Ibc-Obc : inner box with BC-flute and outer box with BC-flute

Similarly, the nine flute combinations for the folding design were:

1. Ice-Oce : inner box with CE-flute and outer box with CE-flute
2. Ie-Os : inner box with E-flute and outer box with S-flute
3. Is-Os : inner box with S-flute and outer box with S-flute
4. Ic-Os : inner box with C-flute and outer box with S-flute
5. Ie-Oce : inner box with C-flute and outer box with CE-flute
6. Ic-Oc : inner box with C-flute and outer box with C-flute
7. Ic-Oce : inner box with C-flute and outer box with CE-flute
8. Ie-Oe : inner box with E-flute and outer box with E-flute
9. Ib-Ob : inner box with B-flute and outer box with B-flute

There were three replications of each type. For example, there were 3 interlocking corrugated boxes with a combination of an inner box with B-flute and an outer box with S-flute (Ib-Os).

2. EPS containers

The selected EPS containers (Figure 51) had inside dimensions of $11 \frac{1}{8} \times 8 \frac{1}{2} \times 9 \frac{1}{8}$ in. with a wall thickness of $1 \frac{1}{2}$ in. This was the closest fit to the corrugated boxes that was commercially available. Replication was provided by using three boxes.



Figure 51. EPS container.

3. ISC containers

An ISC container is shown in Figure 52. As was the case with the EPS container (above), the dimensions of the ISC could not be matched exactly to the

corrugated boxes. The dimensions of the selected ISC boxes (Table 20) were the closest match that was available.

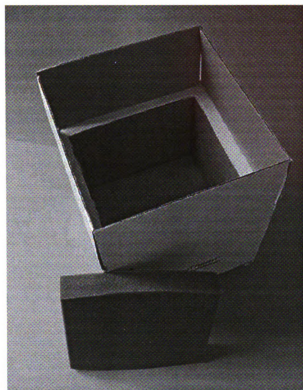


Figure 52. ISC container.

Table 20. Dimensions of the ISC containers.

Wall thickness, in	Inside dimension			Outside dimension			Unit wt. lbs.
	Length, in	Width, in	Depth, in	Length, in	Width, in	Depth, in	
1	10	10	8	12 ³ / ₄	12 ³ / ₄	12 ¹ / ₄	3.03

4. Thermocor containers

Thermocor boards were cut on the sample table and formed into boxes with the same styles and similar dimension of the corrugated boxes (Figure 53 and 54). Again each design was replicated 3 times.

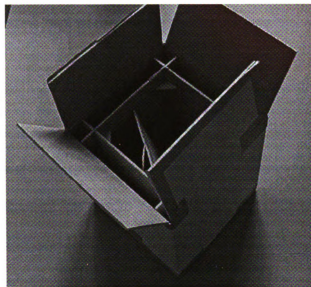


Figure 53. Thermocor container of the interlocking style.

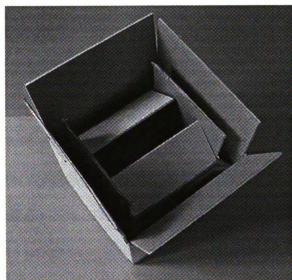


Figure 54. Thermocor container of the folding style.

Conditioning

Conforming to the 'Ice Requirement' method, the ice used in the experiment was conditioned at standard conditions of 73 °F and 50% relative humidity until the ice started to melt. That assured that the ice temperature was at 32 °F. The environmental chamber was controlled at 72 °F and 50% RH. Corrugated boxes were kept at room temperature before the experiment.

Test Method

The ice requirement procedure (Burgess, 1999) was conducted to estimate the thermal resistance (R-value) of each package. Approximately 3 pounds of preconditioned ice (at 32 °F) was put into each package. The actual weight was measured and recorded. The melt water was drained off and the ice was packed in a plastic bag. The package was sealed with tape to exclude airflow and stored on a shelf in a draught free constant 75 °F temperature room. At least once a day, the package was checked to determine when most of the ice, but not all, had melted. This assured that the interior and exterior temperatures were constant throughout the testing period. The experiment would have failed if the package had been opened after all of the ice had melted since the interior temperature would not have been constant at 32 °F. When the box was opened, the water was weighed and the time was noted.

The period of time for the ice to melt in each package was used to calculate the melt rate which was substituted into Equation 9 to obtain the system R-value,

$$\text{System R-value} = \frac{(\text{interior area}) (\text{temperature difference})}{(\text{melt rate}) (\text{latent heat})} \text{-----} (13)$$

Part II Simulation

Two computer simulation programs used in this study were GAMBIT and Fluent 5.0. They were used for computational fluid dynamics (CFD) analysis. GAMBIT generates a designed drawing, creates a mesh, and assigns boundary conditions: pressure, temperature, mass flux, etc. Fluent 5.0 solves heat transfer problems. The programs' functions were to determine the R-values of the insulated packages and expressing temperature distributions in 2 and 3-D form. The simulation programs were not available in the School of Packaging so a student expert from the College of Engineering operated the programs.

Part III Cost Estimation

The cost estimation process for the corrugated containers referred to "The Yellow Sheet" as shown in Table 21 (Official Board Market, 2001). Price ranges listed are per short ton (2000 lbs). The North Central Region was chosen. To calculate the box cost, it was necessary to know the area of corrugated board to be cut and assembled into a box. The Kraft linerboard had a basis weight of 42# per msf. Therefore, when the total area used was known, its weight could be determined and the cost could be calculated from the price per ton as shown in Table 21. There were two linerboards for one corrugated board.

Table 21. Corrugated prices.

Type	Northeast	East Central	Southeast/ South Central	North Central	West
42# Fourd. Kraft Linerboard	425-435	430-440	435-445	430-440	445-455
26#.009 Semi chemical Medium	400-410	410-420	410-420	410-420	415-425

The medium was 26# per msf Kraft paperboard. The price per ton for 26# per msf in the North Central Region was selected. The calculation of total medium cost was the same as for Linerboard except, there was only one ply for the medium and the area was multiplied by an expansion factor for that flute size. Total cost was the material cost divided by 0.45 (45% of material and 55% of labor and manufacture) (Hughes, 2001).

5.0 RESULTS AND DISCUSSION

R-value of all specimens from the experiment

There were 5 types of the R-value results depending on different designs and materials. These samples were tested according to Ice requirement procedure.

Corrugated boxes: Interlocking design

Table 22. R-value of 'interlocking' corrugated box with various board combinations.

Type	Ice melt wt, lbs	Time, hr	R-value, h.ft ² .°F/Btu	Average	Stdev.
lb-Ob (N)1.1	2.66	14.64	5.3	5.25	0
lb-Ob (N)1.2	2.70	14.70	5.2		
lc-Oce 1.1	2.72	14.64	5.3	5.22	0.1
lc-Oce 1.2	2.71	14.65	5.3		
lc-Oce 1.3	2.68	14.77	5.4		
lc-Oc 1.1	2.87	14.58	4.9	5.06	0.2
lc-Oc 1.2	2.65	14.43	5.2		
lc-Oc 1.3	2.77	14.63	5.1		
lce-Oce1.1	2.57	14.40	5.4	5.27	0.3
lce-Oce1.2	2.53	14.41	5.5		
lce-Oce1.3	2.83	14.67	5.0		
lc-Os 1.1	2.63	14.35	5.2	5.15	0.1
lc-Os 1.2	2.64	14.34	5.2		
lc-Os 1.3	2.76	14.34	5.0		
ls-Os 1.1	2.51	14.37	5.5	5.65	0.1
ls-Os 1.2	2.44	14.34	5.6		
ls-Os 1.3	2.39	14.44	5.8		
lbc-Obc 1.1	2.40	14.60	5.8	5.87	0
lbc-Obc 1.2	2.35	14.46	5.9		
lbc-Obc 1.3	2.38	14.51	5.8		

Corrugated boxes: Folding design

Table 23. R-value of 'folding' corrugated box with various board combinations.

Type	Ice melt wt, lbs	Time, hr	R-value, h.ft ² .°F/Btu	Average	Stdev.
Ice-Oce 2.1	2.77	13.93	4.8	4.75	0.1
Ice-Oce 2.2	2.74	13.17	4.6		
Ice-Oce 2.3	2.69	13.40	4.8		
le-Os 2.1	3.08	14.85	4.6	4.56	0.1
le-Os 2.2	3.10	14.80	4.6		
le-Os 2.3	3.04	14.13	4.5		
ls-Os 2.1	2.87	13.46	4.5	4.88	0.5
ls-Os 2.2	2.70	13.30	4.7		
ls-Os 2.3	2.39	13.42	5.4		
lc-Os 2.1	2.92	14.66	4.8	4.74	0.1
lc-Os 2.2	2.90	14.63	4.8		
lc-Os 2.3	2.99	13.92	4.6		
le-Oce 2.1	3.08	14.64	4.6	4.66	0.1
le-Oce 2.2	2.97	14.71	4.8		
le-Oce 2.3	3.04	14.76	4.7		
lc-Oc 2.1	2.91	14.46	4.8	4.76	0.1
lc-Oc 2.2	2.89	14.56	4.8		
lc-Oc 2.3	3.05	14.76	4.6		
lc-Oce 2.1	2.81	14.86	5.1	4.73	0.3
lc-Oce 2.2	3.04	14.55	4.6		
lc-Oce 2.3	3.11	14.59	4.5		
le-Oe 2.1	3.16	15.01	4.6	4.54	0.1
le-Oe 2.2	3.25	14.98	4.4		
le-Oe 2.3	3.13	15.07	4.6		
lb-Ob (n)2.1	2.74	15.20	5.3	5.27	0.1
lb-Ob (n)2.2	2.72	14.77	5.2		
lb-Ob (nn)1	2.93	13.96	4.6	4.54	0.8
lb-Ob (nn)2	3.00	14.07	4.5		

ISC containers

Table 24. R-value of # E - 46 ISC containers.

Type	Ice melt wt, lbs	Time, hr	R-value, h.ft ² .°F/Btu	Average	Stdev.
ISC 1	1.38	13.37	9.3	9.30	2.8
ISC 2	2.31	22.36	9.3		

EPS coolers

Table 25. R-value of SL 10 - EPS coolers.

Type	Ice melt wt, lbs	Time, hr	R-value, h.ft ² .°F/Btu	Average	Stdev.
EPS 1	2.64	26.61	9.7	9.38	0.4
EPS 2	2.69	26.59	9.5		
EPS 3	2.82	26.35	9.0		

Thermocor boxes

Table 26. R-value of Thermocor containers.

Type	Ice melt wt, lbs	Time, hr	R-value, h.ft ² .°F/Btu	Average	Stdev.
THR 1-1*	2.01	13.24	6.3	6.34	1.5
THR 1-2*	2.00	13.22	6.4		
THR 2-1**	2.11	13.33	6.1	5.96	0
THR 2-2**	2.19	13.32	5.8		

* Interlocking design

**Folding design

The data from the preceding tables has been summarized in Figure 55.

R-value of the ISC containers was as high as the EPS containers. R-value of the Thermocor containers was close to R-values of corrugated containers with a combination of S-flute and a combination of BC-flute.

R-values of all samples

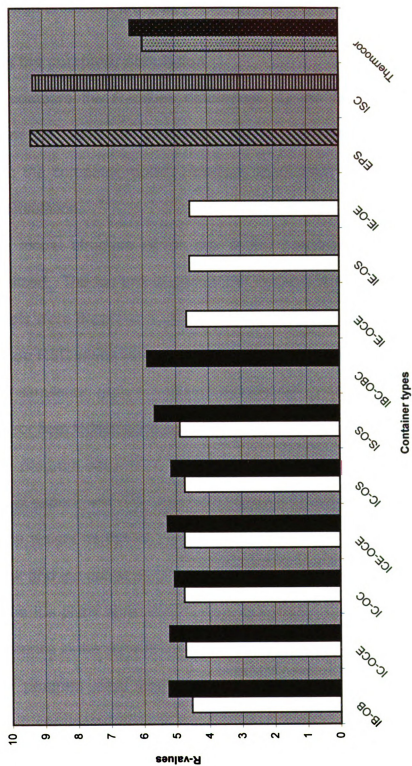


Figure 55. Comparison of R-value with both designs and other containers.



The R-values of the ISC container were as high as for the EPS containers. The R-values of the Thermocor containers were close to R-values of corrugated containers with Is-Os and lbc-Obc.

Evaluating the computer simulation

To compare the R-values determined by the experiments and the R-values from the computer simulation, the experimental conditions must be provided to the computer model. However, there were limitations on using the computer simulation.

1. The model structure of the box in the computer simulation had to be idealized. The top and bottom of the box was drawn as two layers. Other panels were drawn as a single layer. This conformed to the structure of a square RSC which has two layers of flaps and single walls.
2. The simulation program cannot account for joints or holes causing heat gain or heat loss in the actual box.
3. The program cannot simulate the shape of the ice cubes used in the actual experiment. The approach used was to create an ice plank with the same weight as the ice cubes. Although the actual ice volume of the ice plank and ice cubes were still the same, the space volume inside the box of the ice plank was less than the ice cubes. But there was an obvious difference in the surface area of the cubes and the phank.
4. The program used experimentally determined thermal conductivity of tested corrugated boards. It needed the velocity and pressure conditions of the test environment but these could not be measured accurately.

5. The program could not simulate the three-dimensional objects in this case.
6. There appeared to be a flaw in the program code itself that did not allow accurate representation of solid to liquid phase changes.

The effect of different flute combinations and insulating materials

With assistance from Dow Chemical, the R-value of each tested corrugated board was determined and is shown in Table 27. The result indicated that the relationship between R-value and board thickness was linear as illustrated in Figure 56. The higher board thickness produced higher R-values. From the graph, the prediction model was determined to be (Equation 14)

$$y = 2.6103 x + 0.032 \text{ with } R^2 = 0.981 \text{ -----(14)}$$

Table 27. R-value of each corrugated flute type.

Flute type	R-value F*ft ² *h/Btu	Thickness, in
B	0.3713	0.122
C	0.4809	0.177
BC	0.7618	0.264
CE	0.6079	0.215
E	0.1946	0.070
S	0.7558	0.294

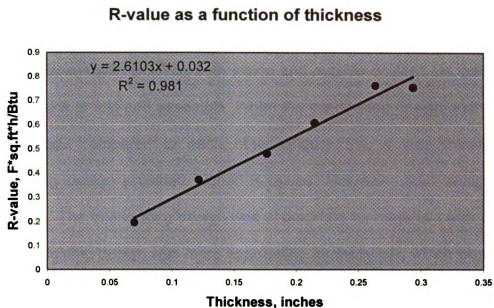


Figure 56. R-value as a function of board thickness.

For the interlocking design (Figure 57), corrugated boxes with an inside box of BC-flute and an outside box of BC-flute had the highest R-value.

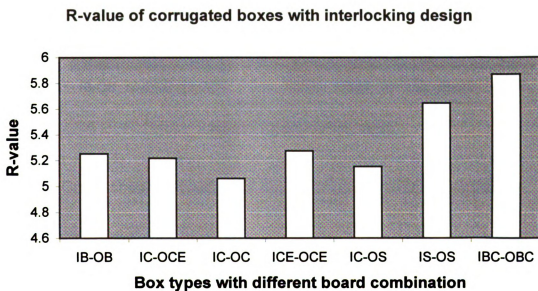


Figure 57. Graph showing R-values of corrugated boxes with interlocking design.

For the folding design (Figure 58), the corrugated boxes with a combination of S-flute inside and S-flute outside provided the highest R-value. Insulated boxes with BC-flute both inside and outside couldn't be made since it was too thick to fold and assemble. When the interlocking design and the folding design were compared to each other (Figure 59), it was found that the interlocking design provided higher R-values. However, both designs had a limitations. The interlocking design was appropriate for materials with thick walls while the folding design was more appropriate for materials, which were thin and easy to fold.

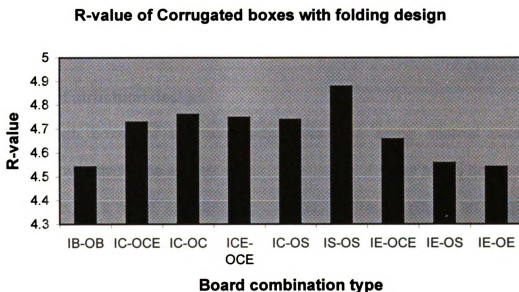
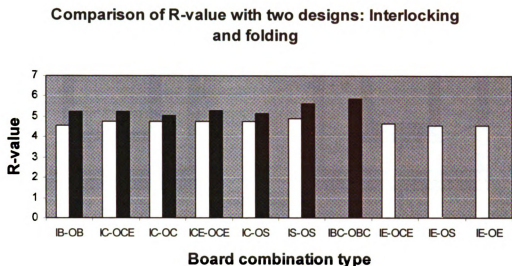


Figure 58. Graph showing R-values of corrugated boxes with folding design.



represents folding design
 represents interlocking design

Figure 59. Graph comparing R-values of both designs.

The effect of structural design

Although boxes of the two designs had the same internal package dimensions, wall thickness and air space, R-values for the two styles boxes were not the same. As a result, it could be concluded that design played an important role in preventing or reducing heat transfer. The interlocking design offered more insulating ability than the folding design. As discussed in Chapter 2, there are three heat transfer modes: conduction, convection, and radiation. In this experiment, inner surface areas, the thicknesses, the dimensions, the same material, the interior temperature and exterior temperature were controlled. Therefore, heat transfer from outside of three modes were the same. Heat transfer inside the package was different as shown in Figure 60.

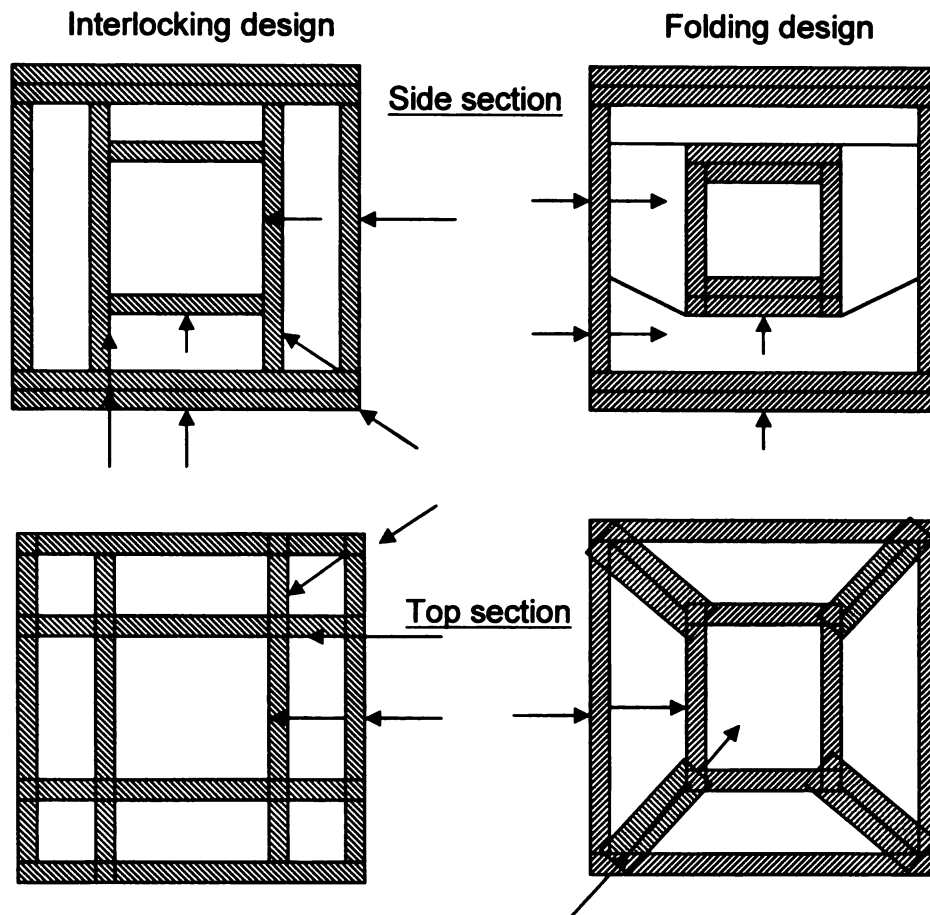


Figure 60. Heat transfer through the interlocking design and the folding design.

There was heat leakage or heat gain from holes or voids at the joints of flaps, side joints, and corners. The only way that heat could be conducted from the outer side walls to the inner walls, was along the support structures, which were made of corrugated boards. Convection could occur in the air spaces between the inner and outer walls, inside corrugated flutes, and inside the product chambers. Radiation could occur everywhere in the package. It could be concluded that combinations of the three heat transfer modes produced different R-values but it was not possible to be specific about how much and where they

were. It is likely that there was more obstruction to convection in the interlocking design than the folding design since the interlocking design provided six large air pockets around the inner box while the folding design provided only one pocket (Figure 61).

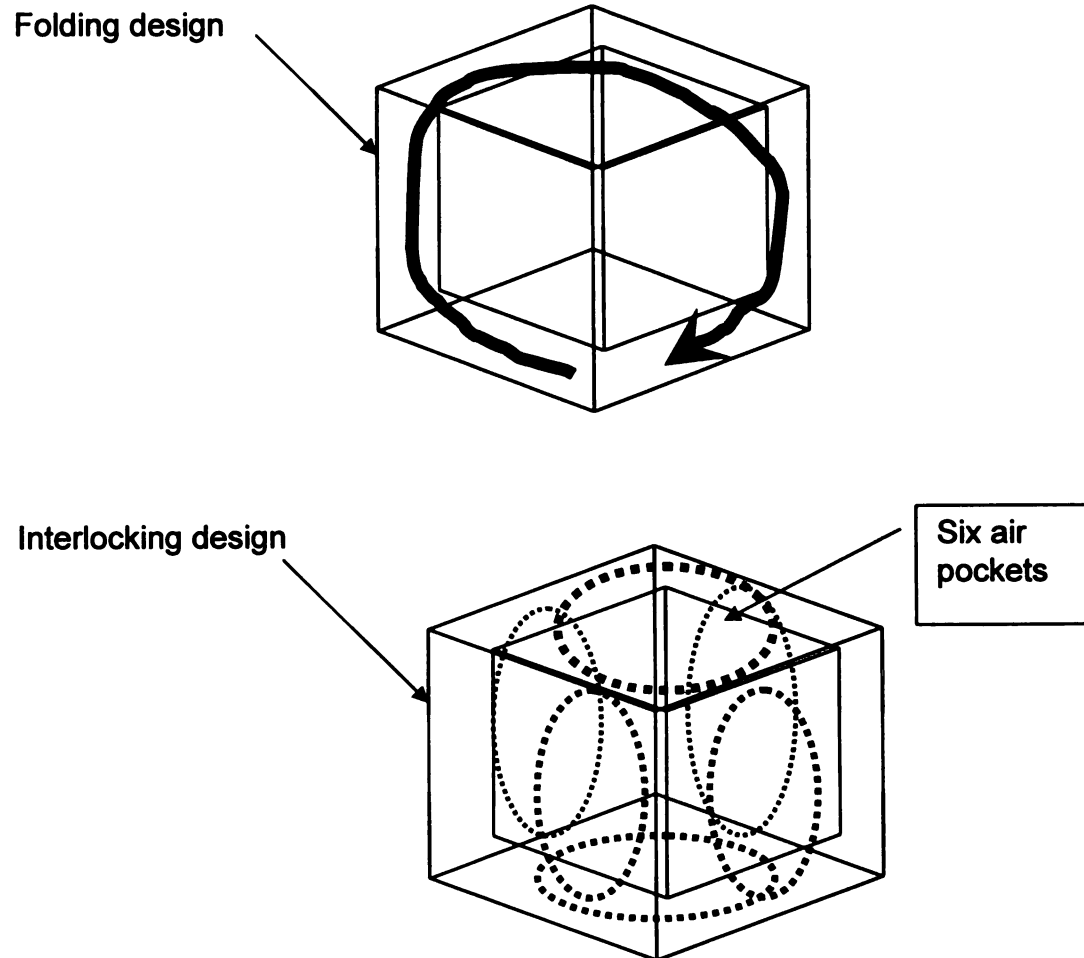


Figure 61. Comparison between convection inside two different designs.

Cost Estimation

To compare the total cost of different packages, there were two alternative shipping companies: UPS (United Parcel Service) and USPS (United State Postal Service). Distribution costs depended on distance, package and product weight, and package dimensions. If the box girth plus its length was less than 84 inches, the shipping cost depended only on weight and shipping distance. It was assumed that the tested packages were sent from Haslett, MI, 48840 to Tampe, Arizona, 85280 by the ground service to a commercial address. Cost estimations of two shipping companies and the material cost of various packages were shown in Table 28, 29, 30, and 31 (UPS, 2002 and USPS, 2002).

Table 28. Cost estimation using the package weight only.

Types	Outside dimension, in	Wt., lbs.	Shipping cost		Material cost,\$
			UPS,\$	USPS,\$	
Int. S-flute	13 x 13 x 13	2.89	5.85	4.81	0.95
Fol. S-flute	13 x 13 x13	2.97	5.85	4.81	0.9
ISC	12 ¾ x 12 ¾ x 12 ½	3.03	6.13	6	16.95
EPS	14 1/8 x 11 ½ x 12 1/8	0.82	5.01	3.45	2.2
Int. Ther	12.8 x 12.8 x 12.8	1.97	5.01	3.45	4.92
Fol.Ther	12.8 x12.8 x12.8	1.93	5.01	3.45	4.72

Int. S-flute = Interlocking design with a combination of S-flute

Fol. S-flute = Folding design with a combination of S-flute

Int. Ther = Interlocking design with Thermocor

Fol.Ther = Folding design with Thermocor

Table 29. Cost estimation using the package weight plus 5 lbs of the product inside.

Types	Outside dimension, in	Wt., lbs.	Shipping cost		Material cost,\$
			UPS,\$	USPS,\$	
Int. S-flute	13 x 13 x 13	7.89	6.07	10.74	0.95
Fol. S-flute	13 x 13 x13	7.97	6.07	10.74	0.9
ISC	12 ¾ x 12 ¾ x 12 ½	8.03	6.4	11.99	16.95
EPS	14 1/8 x 11 ½ x 12 1/8	5.82	5.57	8.25	2.2
Int. Ther	12.8 x 12.8 x 12.8	6.97	5.79	9.49	4.92
Fol.Ther	12.8 x12.8 x12.8	6.93	5.79	9.49	4.72

Table 30. Cost estimation using the package weight plus 10 lbs of the product inside.

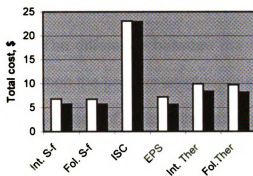
Types	Outside dimension, in	Wt., lbs.	Shipping cost		Material cost,\$
			UPS,\$	USPS,\$	
Int. S-flute	13 x 13 x 13	12.89	8.34	16.1	0.95
Fol. S-flute	13 x 13 x13	12.97	8.34	16.1	0.9
ISC	12 ¾ x 12 ¾ x 12 ½	13.03	8.84	17.05	16.95
EPS	14 1/8 x 11 ½ x 12 1/8	10.82	7.34	14.2	2.2
Int. Ther	12.8 x 12.8 x 12.8	11.97	7.85	15.15	4.92
Fol.Ther	12.8 x12.8 x12.8	11.93	7.85	15.15	4.72

Table 31. Cost estimation using the package weight plus 15 lbs of the product inside.

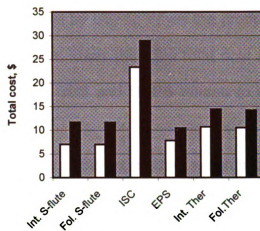
Types	Outside dimension, in	Wt., lbs.	Shipping cost		Material cost,\$
			UPS,\$	USPS,\$	
Int. S-flute	13 x 13 x 13	17.89	10.78	19.19	0.95
Fol. S-flute	13 x 13 x13	17.97	10.78	19.19	0.9
ISC	12 ¾ x 12 ¾ x 12 ½	18.03	11.26	19.66	16.95
EPS	14 1/8 x 11 ½ x 12 1/8	15.82	9.81	18.2	2.2
Int. Ther	12.8 x 12.8 x 12.8	16.97	10.3	18.72	4.92
Fol. Ther	12.8 x12.8 x12.8	16.93	10.3	18.72	4.72

Total cost included the shipping cost and the material cost. Calculation of Thermocor boxes costs was based on the same principle of 45% for material cost and 55% for manufacturing cost. Total cost comparison by UPS and USPS for various types of the tested packages with different product weight were shown in Figure 62.

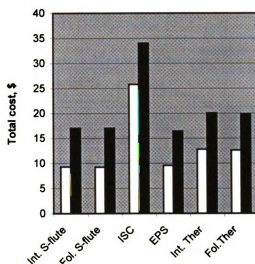
Total cost comparison by UPS and USPS on using only the package weight



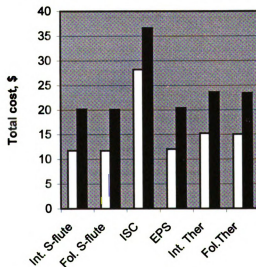
Total cost comparison by UPS and USPS on using 5 lbs of the product



Total cost comparison by UPS and USPS on using 10 lbs of the product



Total cost comparison by UPS and USPS on using 15 lbs of the product



UPS
 USPS

Figure 62. Total cost comparison by UPS and USPS with various packages and product weights.

According to the graphs, the relationship between the weight of the product and the total cost were not linear. First, when shipping the package only, the total cost by UPS was higher than the total cost by USPS. When the product weight was increased, the total cost by UPS was lower than the total cost by USPS. The difference between the total cost by UPS and USPS tended to be stable when the product weight was increased.

R-values of various insulated packages with different product weights are shown as a function of total cost to compare the insulating ability versus total cost by UPS and USPS for the user to select (Figure 63, 64, 65, 66, 67, and 68). These figures show that R-values of EPS boxes were as high as ISC containers but EPS boxes were much less expensive than the ISC containers.

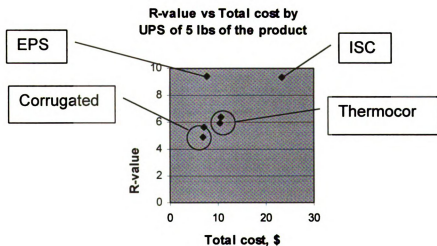


Figure 63. R-values and total costs of tested packages with 5 lbs of product by UPS.

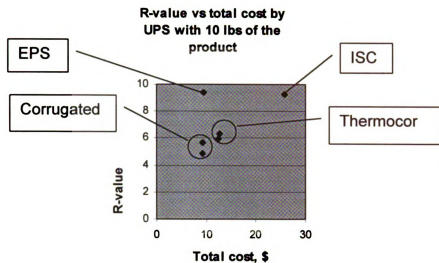


Figure 64. R-values and total costs of tested packages with 10 lbs of product by UPS.

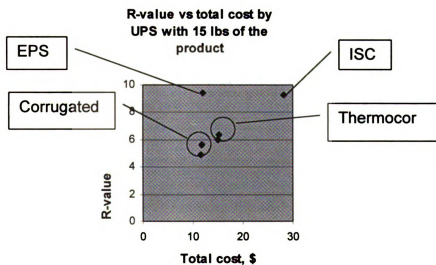


Figure 65. R-values and total costs of tested packages with 15 lbs of product by UPS.

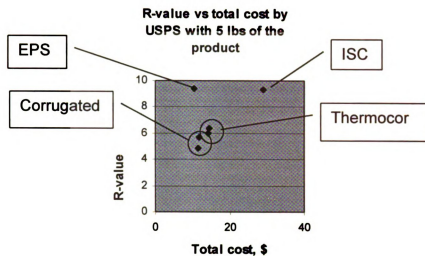


Figure 66. R-values and total costs of tested packages with 5 lbs of product by USPS.

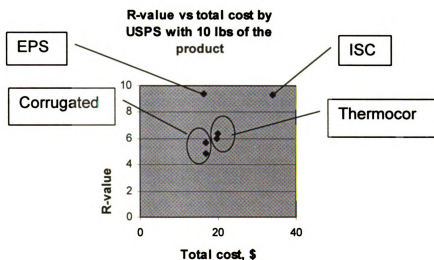


Figure 67. R-values and total costs of tested packages with 10 lbs of product by USPS.

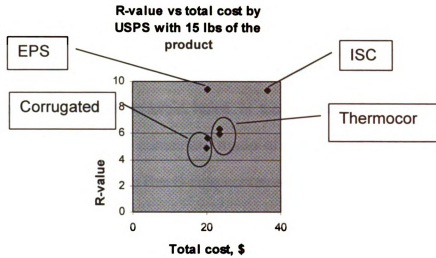


Figure 68. R-values and total costs of tested packages with 15 lbs of product by USPS.

6.0 CONCLUSION

Unlike polymer materials, corrugated board cannot be made by molding or injecting. So it was difficult to avoid holes at the corners of the corrugated shipping containers. Corrugated containers made of S-flute had higher R-value than boxes with lower flute sizes. The S-flute container costs were close to those of EPS containers, but the corrugated board containers had lower R-value. Therefore, it was concluded that S-flute containers are not the optimal choice for insulated containers. However, corrugated containers are friendly to environment and also both corrugated box designs can be knocked down for space saving during distribution.

Two structural designs of insulating corrugated containers (i.e., interlocking and folding style) could improve the thermal protection provided by conventional corrugated containers. It was likely that the same concept of double wall with air space could be applied to solve heat loss or heat gain of insulating containers with other materials even though the design details would have to be modified to be compatible with other packaging materials.

The highest R-value was provided by the EPS containers, ISC cooler, Thermocor boxes, corrugated boxes with interlocking design, and corrugated boxes with folding style, respectively. Cost estimation, based on rates by UPS and USPS, showed that the most expensive container to use was the ISC container, even at had different dimensions and weights. In addition, when comparing two structural designs with the same dimensions and flutes, it was

noted that the interlocking style enhanced insulating ability more than the folding style.

Because of limitations, GAMBIT and Fluent 5.0 were unable to predict R-values and temperature distributions for both 2 and 3-D forms. There was no way to identify how heat from outside environment transported into the inside box and how heat transfer was affected by the design structures.

7.0 FUTURE STUDY

The following future are suggested as topics for further study:

1. Designs for insulated shipping containers or bulk containers made of other materials should be created and evaluated by the simple ice requirement method.
2. Investigate new packaging structural designs (such as planes, surface textures, forms, colors, wall constructions) affecting heat transfer modes: conduction, convection and radiation.
3. Change the condition of the simulation for testing such by using bulk containers instead of small packages or by using dry ice instead of normal ice.
4. Create a computer simulation for insulating packages, including a database for alternative materials, package weights, inside dimensions, outside dimensions, distribution costs, material and manufacturing cost to evaluate various insulated containers and to provide help in making a selection.
5. Develop new ingredient paper fibers that can be used with other materials to improve insulating ability.
6. Develop a new process for making boxes with paper fibers such as spraying the fibers into a box mold.

APPENDIX A

APPENDIX A

The results of experiments that were conducted by Smurfit since 1993 were shown in these tables.

Table 32. Evaluation of the combined boards (Smurfit,1993).

Board Comb.	Flute	ETC lbs/in	Flexural Stiffness Composite	Compression Index	Combined Board Weight # / MSF	Board Cost \$ / MSF
KL90-36-KL90	C	80	198	2.04	231	44.05
LX74-36-LX74	C	88	164	2.09	199	39.28
LX56-36-LX56	S	68	326	2.05	169	32.91

Table 33. Analysis of Single/Double wall S-flute laminated bulk bins with 46-1/4x 38-1/4 x 41-1/2 inch dimensions (Smurfit, 1994).

Identification	Value
Compression strength, lbs.	11,125; 12,125; 13,300; 13,025 and 12,500
Average deflection, in.	1.31
Combined board weight, #/MSF	492
SW board combination	69-36-69 S flute
D board combination	69-36-36-69 SC flute
Combining adhesive	Regular
Combined caliper	0.710
SW caliper, in.	0.284
Combined ECT, lbs/in.	169 (expected – 165)
SW board ECT, lbs/in.	64 (expected – 66)

Table 34. C-S flute double wall – compression estimate (Smurfit, 1995).

Identification	Value
Dimension, in.	21 x 21 x 33
Board combination	69 – 36C – 69 –36S - 69
Board Index	4.02
Predicted compression	4,200 lbs ± 10%

**Table 35. Calculations for expected compression strength of 40 x 40 x 41 box
(Smurfit, 1995).**

Identification	Compression Strength, lbs	Flexural stiffness "factor"
400# AA-flute double wall (42-40-69-40-69)	15,800	11,400
AAC-flute triple wall (69-33-42-33-42-33-69)	15,800	11,400
SC-flute (69-33-69-36-69)	15,800	13,400
A tr laminate with 69-36-42 C-flute and 42-36-42-36-42 SC-flute	20,000	35,000

Table 36. Tested results for CL-flute (Smurfit, 1997).

Identification	Value
Combined board weight, lbs./MSF	249
Board combination (actual weights), lbs./MSF	60.0-34.1-34.9-43.8-33.8 CL-flute
Combined board caliper, in	0.44
ECT, lbs./in	70.5 (expected 80-90)
Flute height, in	0.2488
Distance between flute tips, in	0.49 (so 24.4 flutes/ft.)

Table 37. K-flute advertising from Montebello Container (Smurfit, 1997).

Identification	200 D/W	200 K-flute	275 D/W	250 K-flute
ECT, Lbs.per inch	42	42	48	49
Bursting	200	230	275	320
Board Combination	33-26-33-26-33	42-33-42	42-25-33-26-42	69-33-42

Table 38. Comparison between BC-flute and K-flute (Smurfit, 1997).

Identification	200 BC-flute	250 K-flute
Dimension	33-26-33-26-33	42-33-42
FCT claimed	42	42
ECT expected	56	45
Index	56/248.4	45/234.2 = 1.38 (-16%)
Identification	275 BC-flute	250 K-flute
Dimension	42-26-33-26-42	69-33-42
FCT claimed	48	49
ECT expected	64	54
Index	64/277.2 = 1.88	54/305 = 1.7 (-10%)

Table 39. Comparison between two-box parameters with the same CS/SC board (Smurfit, 1998).

Dimension	Compression strength, lbs.
51-3/4 x 42 x 41 inch	15,500
51-3/4 x 42 x 28 inch	16,000

Table 40. Evaluation of single wall S-flute (Smurfit, 1998).

Identification	Value
Take-up factor	1.52
Flexural stiffness or bending resistance	2.4 to 2.6 factor
Flat crush, psi	30.5
Mullen and puncture numbers, psi	286
A compression strength index	1.87

**Table 41. Test data for an unprinted regular bulk style with
46-1/4 x 38-1/4 x 41-1/2 inch dimensions (Smurfit, 1998).**

Identification	Value
Compression strength, lbs.	11,125; 12,125; 13,300; 13,025; and 12,500
Average deflection, in.	1.31
Combined board weight, # / MSF	492
SW board combination	69-36-69 for S-flute
DW board combination	69-36-36-36-69 for SC-flute
Combining adhesive	Regular
Combined caliper, in.	0.710
SW caliper, in.	0.284
Combined ECT, lbs./in.	169 (expected 165)
SW board ECT, lbs./in.	64 (expected 66)

Table 42. Evaluation of S-flute (Smurfit, 1998).

Identification		value
Caliper mil		286.80
CD-ECT lbs./in		58.95
MD-ECT lbs./in		28.98
Bending Stiffness	MD inch-lb.	525.00
	CD inch-lb.	217.74
	GEOMEAN inch-lb.	338.10
Flat crush, psi		30.54
Mullen Burst, psi		285.60
Puncture, units		286.00
COMB BD, lbs./MSF		165.68
Liner DB lbs./MSF		68.49
Medium S lbs./MSF		36.52
Liner SF lbs./MSF		42.58

Table 43. Flute profiles and combined board characteristics (Smurfit,1998).

Flute Designation	Flute per foot FpF	Flute per height h,in.	Take up factor, TuF	Flat crush 26-lb fluting	Compression ranking, %
Jumbo K/L	25	0.271	1.59	25	235%
S-flute	24	0.25	1.59	15	131%
A-flute	36	0.185	1.59	28	113%
C-flute	39	0.142	1.42	34	100%
C-flute extra	39	0.156	1.51	32	105%
B-flute	48	0.099	1.35	41	86%
E-flute	90/96	0.049	1.26	86	68%
D-flute	62	0.079	1.3	57	79%
F-flute	126	0.027	1.19	125	59%
N-flute	134	0.02	1.27	134	57%

Table 44. Tested results for S-flute (Smurfit,1998).

Identification	Reference Method	Units	Identification
Board Caliper	Tappi T411 Om89	mils	252.06
ECT	Tappi T839 Pm-95	lbs./in.	63.6
Flexural Stiffness MD	Tappi 820 cm-85	lbs. in.	207.07
Flexural Stiffness CD	Tappi 820 cm-85	lbs. in.	156.57
Flexural Stiffness GEO. MEAN	Tappi 820 cm-85	lbs. in.	180.06
Flat crush	Tappi T825 Pm-86	psi	No end point
Comb. BD. Basis weight	Tappi T410 om-93	Lb./MSF	222.1
Basis weight Double Back	Tappi T410 Om-93	Lb./MSF	79.2
Basis weight Medium (S-flute)	Tappi T410 om-93	Lb./MSF	42.3
Basis weight Single Face	Tappi T410 Om-93	Lb./MSF	78.4

Table 45. C-S flute bins with board combination:

69-36C-42-36S-42/69-36S-42-36C-69 (Smurfit, 1998).

Identification	Bulk bin (41-1/2 x 32-1/2 x 35)	Outer double wall
Compression strength, lbs.	12,658	-
Deflection, in.	1.53	-
Caliper, mils	876.4	441.8
ECT, lbs./in.	186.8	90.6
Bending stiffness MD	-	1149.31
Bending stiffness CD	-	579.71

Table 46. Comparison between S/SC and CA/AC combinations for a 40 x 34 x 36 inch bin (Smurfit, 1998).

Identification	69-40-42/42-40-69-40-69 S/SC combination	90-40-42-40-42/42-40-42-40-90 CA/AC combination
Compression strength, lbs.	9450	12,195
Bending resistance, in.lbs.	4550	6230
ECT, lbs./in	174	220
Combined weight, lbs/MSF	471	586
Caliper, inch	0.724	0.744

Table 47. The strength properties of suggested 69-40-69/69-40-69-40-90 S/SC combinations (Smurfit, 1998).

Identification	Value
Compression strength, lbs	11,740
Bending resistance, in.lbs.	7207
ECT, lbs./in	199
Combined weight, lbs/MSF	546
Caliper, inch	0.744

Table 48. Predicted compression strength of a tri-laminate bulk (Smurfit, 1998).

Identification		Value
Box dimension, in.		46 x 38 x 39
Board combination	Outer	69-36S-69
	Middle	69-36S-69-36C-69
	Inner	69-36S-69-36C-69
Predicted compression, lbs.		28,050

APPENDIX B

APPENDIX B

The samples of other alternative designs created were shown in Figure 69 and 70.

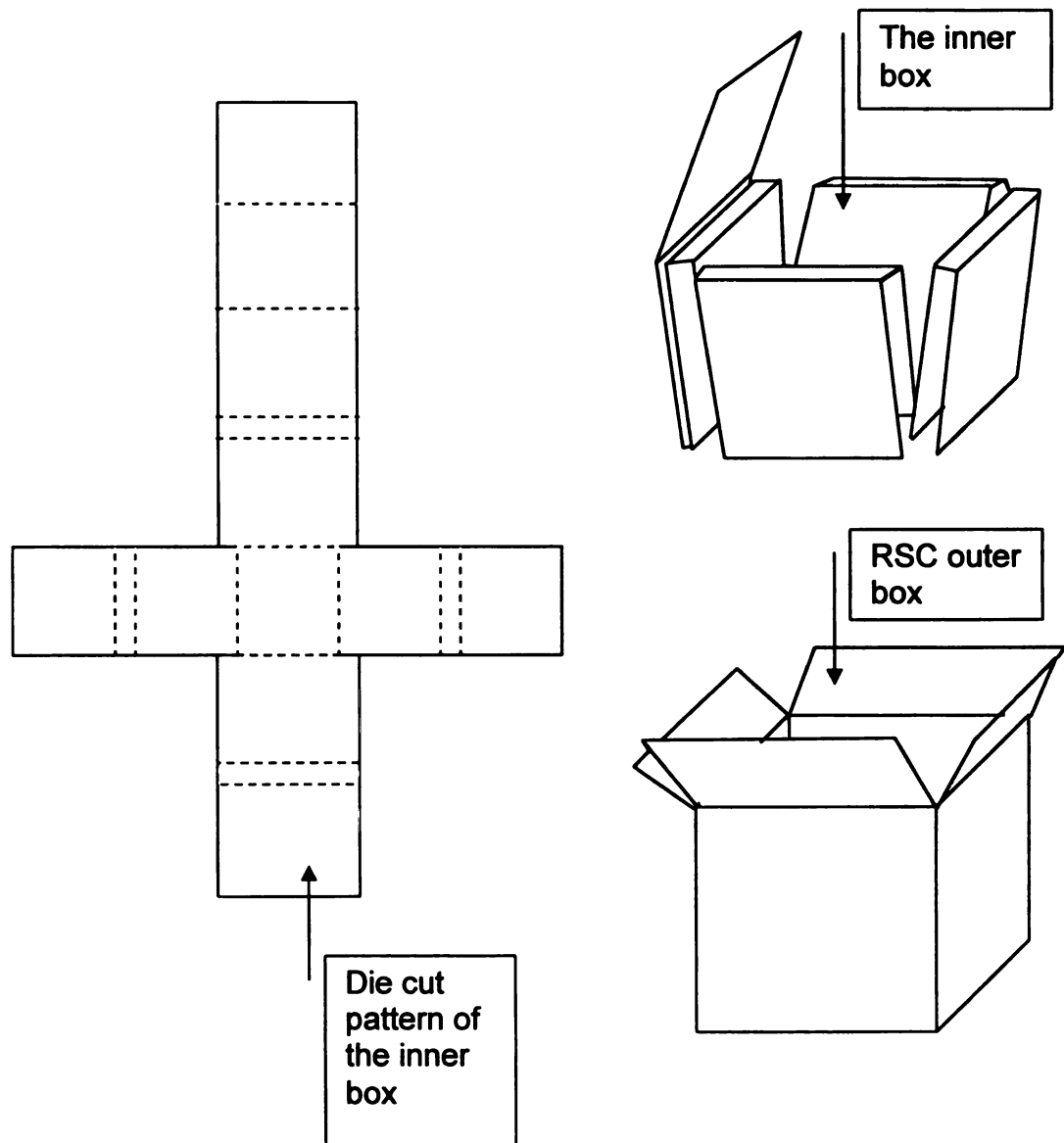


Figure 69. One example of alternative designs.

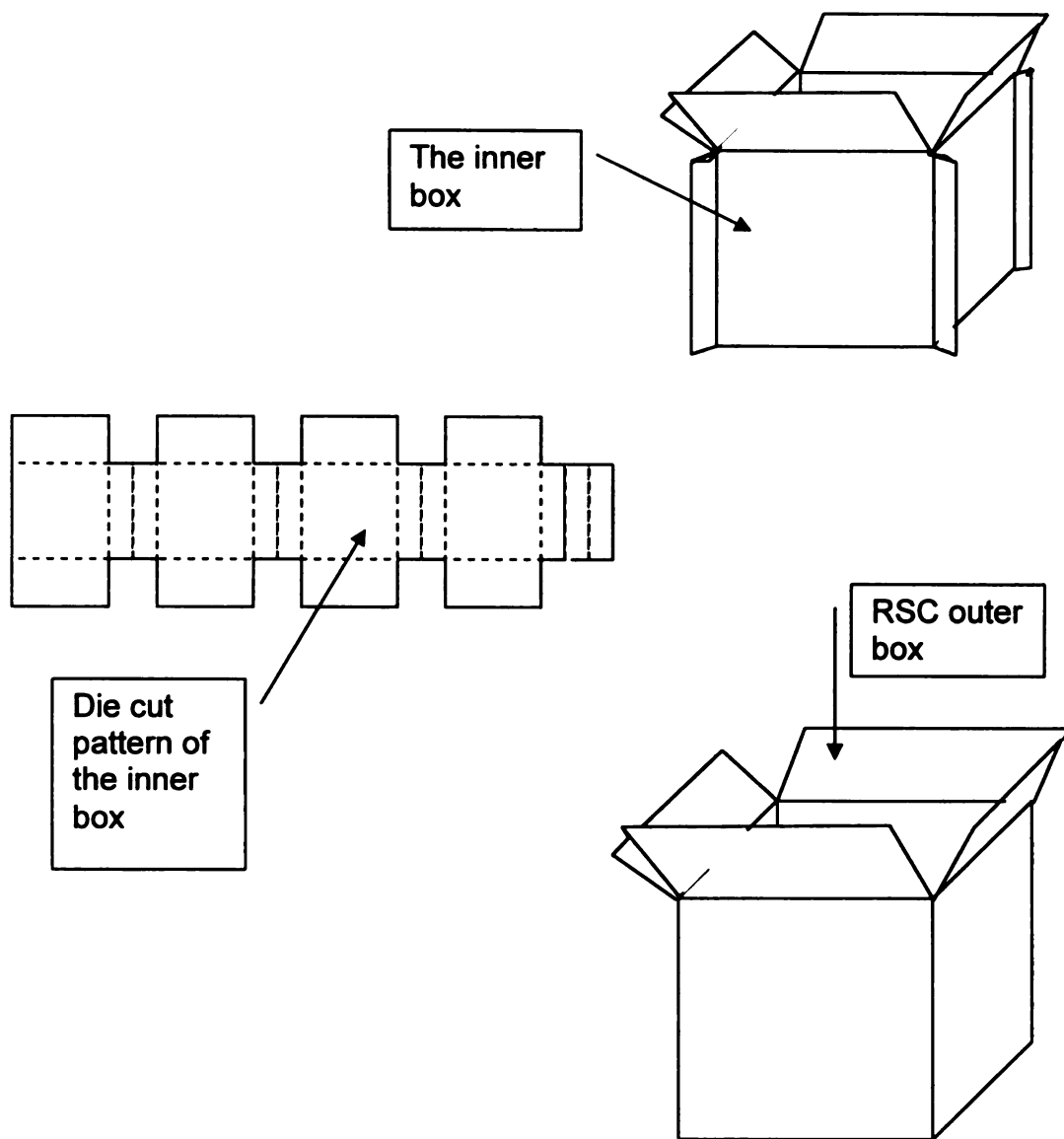


Figure 70. The other example of alternative designs.

APPENDIX C

APPENDIX C

The photographs of the interlocking design and the folding design were shown in Figure 71.

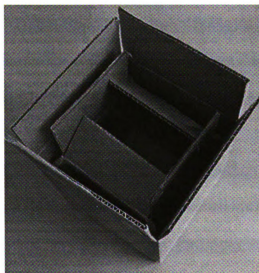
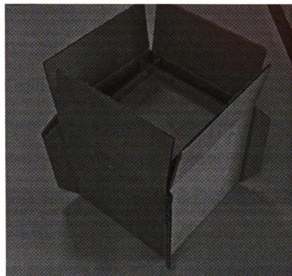


Figure 71. The photographs of the interlocking design and the folding design.

BIBLIOGRAPHY

- ASTM. (1994). Selected ASTM Standards on Packaging. PA: ASTM.
- ASHRAE, (1997). 1997 ASHRAE Handbook Fundamentals. GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE, (1994). 1994 ASHRAE Handbook: Refrigeration Systems and Applications. GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- BARCO Artios. (1999). Artios CAD: User's Guide. CA: Barco Artios.
- Burgess, G. (1999, March-April). Practical Thermal Resistance and Ice Requirement Calculations for Insulating Packages. Packaging Technology and Science, 75-80.
- Camus, P. and Veaux, M. (1984, September 19-21 th). Feasibility Study of a Testing Method for Isothermics Bags and Boxes used for Transport of Frozen Foods from the Shop to Households/Restaurants. Vienna: EURO FOOD PACK International Conference on Food Packaging.
- Cambridge Refrigeration Technology. (2001). Thermal Testing. Cambridge: www.crtech.co.uk/crtinfo/datain2.asp.
- Cengel, Y. A. (1998). Heat Transfer: a Practical Approach. NJ: McGraw-Hill, Inc.
- Cleland, A. C. and Earle, R. L. (1976). A New Method for Prediction of Surface Heat Transfer Coefficients in Freezing. Refrigeration Science and Technology, 361-368.

- Curley, J. (1993, March). Developing New Products that the Customer Wants Means \$\$\$\$\$. Board Converting News: The White Sheet, 9-20.
- Fava, P., Piergiovanni, L. and Pagliarini E. (1999, vol 12). Design of a Functional Box for Take-away Pizza. Packaging Technology and Science, 57-65.
- FedEx. (2001). www.FedEx.com.
- FedEx. (2001). www.fedex.com/us/services/PkgPrshblShpmntsLvvhUS.pdf.
- Fibre Box Association (1994). Fibre Box Handbook. Chicago: Fibre Box Association.
- Hughes, H. A. (2002). Personal communication. East Lansing, MI.
- International Safe Transit Association. (1999). ISTA 1998-1999 Resource Book. MI: ISTA.
- Ievans, U. (2000). Personal Interview. Illinois.
- Jefferson Smurfit World Research Center. (1993-1997). Interoffice Document. Illinois.
- Krebs, Paul H. (1993-1994, December-January). The Insulative Effect of Packaging on Products in Trailers. Packaging Technology & Engineering, 26-28.
- Krieth, F. (1973). Principles of Heat Transfer. NY: Intext Educational Publishers.
- Musgrave, Dwight S. (2001). Design-The Key to Vacuum Insulation Value. OH: www.dow.com/install/iac%20pdf.
- Muldoon, T. J. (1984, vol 29). Industrial and Shipping Supplies. The Packaging Encyclopedia, 183-186.

Official Board Market. (2001, October). Transected Containerboard Prices. The Yellow Sheet, 1.

Ogawa, H. (1971). The Art of Papercraft. London: B.T. Bastsford Ltd.

Ramaker, T.J. (1974, June 4-6 th). Thermal Resistance of Corrugated Fiberboard. Louisiana: Spring Corrugated Containers Conference.

Sasaki, H. and Kato, E. (1999,vol 12) Heat Insulating Cardboard Composed of Corrugated Foamed Polystyrene Layer, Packaging Technology and Science, 151-157.

Soroka, W. (1995). Fundamentals of Packaging Technology. Virginia: Institute of Packaging Professionals.

Thompson, Bilge F., Roberson Tom R. and Cleland Andrew C. (1998). Modeling the Heat Transfer Resistance of Corrugated Paperboard. New Zealand: Original copy from Smurfit Research.

Thompson, Bilge F., Roberson Tom R. and Cleland Andrew C. (1998, August). Measuring Thermal Resistance of Corrugated Made. Packaging Technology & Engineering. 48-50.

United Parcel Service. (2002). www.ups.com.

United State Postal Service. (2002). www.usps.gov.

Wright, P.G., McKinlay, P.R. and Shaw, E.Y.N. (1991). Corrugated Fibre Board Boxes. Vic:Amcor Fibre Packaging.

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