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Improving Functionality and Sustainability of Commercial Insulation: Experimental Study, Heat Transfer Modeling, Environmental Assessment

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Improving Functionality and Sustainability of Commercial Insulation: Experimental Study, Heat Transfer Modeling, Environmental Assessment

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Civil Engineering
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DEDICATION

To my family, for their constant encouragement, understanding and unfailing support.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The Department of Energy names executing and integrating high-performance sustainable design and green building best practices a Strategic Sustainability Performance Plan goal under the Executive Order 13514 (U.S DOE, 2009). As sustainability becomes a primary goal for engineers, a decision making framework is needed to guide their choice of materials and processes; and then to carry out the evaluation of their chosen design. Sustainable design process, and the products developed through its application, work concurrently with functionality and sustainability evaluation methodologies to cultivate a continuous loop of design, implementation, assessment and improvement.

In this context, an alternative insulation prototype exploring the use of evacuated packets of pyrogenic silica substituting for conventional insulation for refrigeration applications was developed and assessed. Assessment criteria included experimental comparison of heat transfer characteristics and the energy efficiency of the new insulation as well as its life cycle as it related to environmental sustainability. Results indicate that by utilizing alternativeinsulation design, heat flux decreased by an average of 36%, and energy efficiency improved by 5.1% over a 24 hour period. The new insulation design also resulted in improved environmental sustainability, resulting in a savings of 0.257 metric tons of CO_2e over 20 years for a single unit. Results provide an alternative insulation design for use in commercial insulation applications, and a framework by which to assess the efficiency and environmental performance of similar products.

CHAPTER 1: INTRODUCTION

Since 1950 energy consumption in the United States has far outpaced energy production. Figure 1.1 shows that residential and commercial buildings together use more energy than either the industrial or transportation sector. Accordingly, they also emit more carbon dioxide (DoE, 2011). Buildings are just one part of the many types of societal infrastructure in the United States that accounts for 41% of all energy needs, two thirds of electricity consumption, and one eighth of all water use (DoE, 2010).

The U.S Department of Energy states that increasing energy efficiency in commercial buildings is a U.S. priority. Energy Efficiency improvement is defined by the World Energy Council (2013) as: *"a reduction in the energy used for a given service (heating, lighting, etc.) or level of activity*." The increasing energy demand means that engineers must improve energy metrics across every phase of the societal and industrial infrastructure life cycle, and consider how design choices affect the overall environmental sustainability of the project. Sustainable design , as defined by Mihelcic et al. (2003*): "the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment."*To satisfy the need for both a more environmentally benign industrial product and process, and improved energy metrics, life cycle thinking needs to be employed. Life cycle thinking, a key framework associated with environmental sustainability, employs a holistic approach to determine how each phase of product life cycle: design, use, and eventually disassembly and disposal, affect the overall environmental metrics associated with a project. For the construction of engineering infrastructure, the life cycle phases have been divided into: (1) site development, (2) materials and product delivery (3) infrastructure manufacture (4) infrastructure use (5) end-of-life issues associated with infrastructure refurbishment, recycling and disposal (Mihelcic& Zimmerman, 2014).

As life cycle thinking and energy and material efficiency become primary design goals of engineers, successful products and processes as they relate to engineering infrastructure are those in which key environmental sustainability metrics are considered at every stage of the industrial life cycle and a conscious selection of materials, energy flows and manufacturing and disposal techniques are employed to meet energy and sustainability goals. Comprehensive assessments of the integration of life cycle decisions can be determined through the ability of the basic product design to: (1) meet basic product functionality needs and, (2) align with the *Twelve Principles of Green Engineering for Design* (Anastas& Zimmerman, 2003) (the twelve principles are described later in this chapter in Table 1.1). This research uses a case study related to commercial refrigeration in which the objectives are to engineer a product for use as a component of residential and commercial buildings, which meet basic functional standards, while reducing energy usage and employing a life cycle approach to the material and processes utilized in the design.

1.1 Case Study: Commercial Refrigeration

Commercial refrigeration systems account for approximately 8% of all commercial building energy use (DoE, 2011). Furthermore, Energy Star notes that *"replacing all existing commercial solid door refrigerators and freezers in the U.S. with ENERGY STAR qualified models would result in savings of $410 million per year or more than 35 percent of the energy* *consumed by models currently on the market. These savings would also prevent 6 billion pounds of greenhouse gas emissions, equivalent to the emissions from about 530,000 cars"* (Energy Star, 2013).

Refrigerators are utilized in nearly every home and business in America. The market success of refrigerator manufacturers relies on efficient and innovative unit design. Commercial refrigerators, in particular, are known for their excessive power consumption and energy inefficiency. With increasingly stringent and mandatory efficiency regulations being employed by Energy Star, the California Energy Commission and the Department of Energy, less than 32% of commercial refrigerator units currently meet Energy Star efficiency criteria. Thus, the need for redesign of key refrigerator components in commercial units is important (Energy Star, 2013).

Since the introduction of these mandated energy efficiency standards, the goal of every refrigerator manufacturer- commercial and residential, has been to improve the design and processing of the refrigerator unit to ensure efficiency and environmental sustainability. These energy improvements are typically measured in power savings (in the United States) as expressed in units of KWh/day. The Environmental Protection Agency (EPA) also requires that end-of-life refrigeration units be disposed of safely, and with minimal environmental disruption.

The average refrigerator is comprised of over twelve different types of material, including voluminous amounts of polyurethane foam. Figure 1.2 shows that polyurethane foam comprises 63% of the total volume of the commercial refrigerator redesigned in this study. Polyurethane foam serves a dual purpose in commercial refrigerators. In addition to functioning as the primary insulator of the unit, foam is injected throughout the body of the unit to provide structural support. It has been traditionally used as the insulator of choice due to its relatively high 'R' value. The 'R' value is a measure of the ability of a material to resist heat.The volume of material, as well as variances in material composition, makes efficient recycling difficult. The process of completely recycling a commercial refrigerator is thus both tedious and inefficient. In particular, the disposal of polyurethane foam used for refrigerator insulation presents a significant environmental challenge. And when polyurethane foam is incinerated, it emits carbon monoxide, nitrogen oxides, isocyanine, acrylonitrile, and hydrogen cyanide in levels exceeding those allowed by the EPA (EPA, 2011).

In order to address the key question of energy efficiency optimization, more sustainable operation and end of the life disposal for insulation, one must consider the fundamental design of the product itself. The implementation of stringent Energy Star standards suggests that the time has come for manufacturers to replace outdated and inefficient design with streamlined, innovative solutions that consider the unit from conception to the end of its life. Environmental sustainability and life cycle thinking must become preliminary design objectives for manufacturers.

1.2 Application of This Work to Engineering Infrastructure

It has become increasingly important as engineers seek to develop energy efficient building envelopes for engineering infrastructure that the energy performance of the insulation be considered. As existing buildings are adapted to make them more sustainable, “deep renovation,” or significant changes to traditional building infrastructure for a dramatic energy reduction includes employing materials and systems that are sustainable and highly efficient.

The traditional refrigerator insulation utilized in this study is very similar to that of the insulation system employed in buildings, and developing sustainable alternatives to polyurethane foam insulations have potentially far reaching benefits. Insulation in buildings typically utilizes a structural insulated panel comprised of a foam base. Polyurethane foam is, in the case of a building, typically inserted between two wood particle boards known as OSBs. In the case of the commercial refrigerator, the polyurethane is contained within the plastic walls of the unit.

The mechanisms by which heat moves into the inside space in a building and refrigerator are the same: conduction, convection, and radiation. A key similarity that allows a thermal heat model to be used in both applications to describe energy loss across a wall is a relatively stable external temperature, and the need for a controlled internal ambient temperature.

Additionally, the current version of Leadership for Energy Efficient Design (LEED V. 4) applied to buildings was recently revised to include life cycle thinking into sustainable building design. The standard seeks to reward construction projects that reuse as much material as possible. LEED MR Credit 3, Material Reuse, will thus award points to a building project that utilizes salvaged materials. Polyurethane utilized in buildings presents the same challenges as the foam used in refrigerators; that is, the large volume of material cannot easily be reused or recycled, and thus of disposed of in a landfill, thus presenting a challenge for engineers seeking to salvage any of the insulation material.

1.3 Primary Hypothesis of This Research

To satisfy customers, federal requirements and achieve market success, an engineered product must be designed to match the intended design context(s). It is asserted here that successful products in mature markets have adapted their design to ensure environmental sustainability and efficiency in all stages of the product lifetime.

This research seeks to discover alternative design options for commercial refrigerators and document alternatives to utilizing large quantities of polyurethane foam in commercial grade refrigeration units, while achieving higher energy efficiency and improved environmental sustainability metrics. The results will be presented as actionable design insights. The study begins by documenting and analyzing the product definition information such as customer needs, federal energy efficiency standards and product requirements, for a functional commercial refrigerator. The primary hypothesis is: *When performing an original design for a commercial refrigerator, a more energy efficient, and sustainable product can be achieved through employing the '12 Green Principles of Green Engineering' as a framework for alternative design and insulation solutions.*

1.4 Framework for Analysis

In order to make environmental sustainability and eco-design a primary objective in the redesign of the insulation, a framework for sustainable design is necessary. The *Twelve Principles of Green Engineering* (Anastas and Zimmerman, 2003) is a framework that can be used to guide engineers and designers through the process of eco-friendly product and process development. The work aims to provide performance parameters for designers when considering new materials, processes, and systems, in order to improve the overall eco-friendliness of a system. A set of objectives are proposed by Anastas and Zimmerman (2003) at the molecular, product, process, and system levels to accomplish the goals employed by traditional life cycle thinking: minimizing waste, increasing material recovery, and employing benign manufacturing techniques. The green engineering principles proposed in the work aims to create universal guidelines across designers in every industry to ensure inherency, innovation and to ensure the fundamental goals of sustainability are met through common design objectives.

The principles of green engineering have been applied to many industries. Among them, the textile industry (Allwood, Laursen, de Rodriguez &Bocken, 2006), industrial parks (Lei, Donghui, Jingzhu, Li, & Yi, 2001), the aerospace sector (Zimmerman &Anastas, 2005), as well as green chemistry and engineering (Mulvihill, Beach, Zimmerman &Anastas, 2011). The focus of the commercial refrigeration/freezer redesign will be to employ the considerations suggested by the *Twelve Principles* to develop a more sustainable commercial refrigeration unit, with an emphasis on replacing polyurethane and the primary means of insulation that is more energy efficient than traditional units of the same nature. No known literature was identified by this dissertation's author that applies the *Twelve Principles of Green Engineering* to refrigerator design. Table 1.1 lists the *Twelve Principles of Green Design*, and the green design objective employed by this study for a traditional commercial refrigerator/freezer redesign.

1.5 Outcomes and Objectives

This research did not seek transformative redesign of the refrigerator/freezer, instead it focuses on improving the functional and environmental sustainability metrics of the insulation of a commonly sold commercial refrigerator/freezer. This work examines the design parameters associated with traditional polyurethane foam insulation (referred to as Unit A); and a unit with the exact mechanical and dimensional properties as Unit A, but one that employs an alternative insulation (referred to as Unit B). The type and class of refrigerator unit used in this study represents the most frequently purchased and utilized commercial refrigerator design in the United States. The three factories surveyed in this study accounts for 58% of total unit manufacture and are located in China, Central America and the United States.

In every product, there are tradeoffs among competing design requirements. For the purposes of choosing the best commercial refrigeration unit (Unit A or Unit B) for the desired application, phone interviews were conducted with the primary manufacturers associated with this study. They were asked to identify design criteria and manufacturing constraints based on their knowledge of their consumers and the manufacturing process. The results of this phone survey are summarized in Table 1.2 in order of importance to manufacturers.

The requirements set forth by manufacturers served as guiding design criteria in this research. As a framework for sustainable design, the Principles of Green Engineering are employed. The life-cycle consequences of manufacture, use and end-of-life options are determined through a life cycle assessment.

In addition to life cycle considerations, an analysis of the thermal properties of each type of insulation is considered to determine the overall thermal effectiveness of the traditional model (Unit A) and alternative model (Unit B). Using the framework of the Principles of Green Engineering Design, a comprehensive disassembly process or procedures quantification analysis of the units is also performed to determine issues associated with end of life.

The objectives of this research are to: (1) explore commercial refrigeration design measures that will reduce the volume of polyurethane foam utilized in commercial-grade refrigeration units, while improving or sustaining key metrics (i.e., maximum allowable energy consumption, internal volume, integrated average temperature); (2)evaluate the design alternative in terms of environmental cost, effectiveness of thermal resistance and efficiency of design for disassembly; and, (3) suggest streamlined manufacturing and disassembly to ensure maximum material recovery and reuse.

Insights obtained from the analysis of the data obtained during this research will be made accessible to designers in the form of: (1) alternate design efforts aimed at sustainable unit reconstruction, with an emphasis on reducing the volume of polyurethane foam utilized in commercial refrigeration units, and documentation of their energy efficiency measurements, utilizing ASHRAE 72:2005 standards; (2) providing familiarity with various manufacturing and disposal methods, and their environmental and economic consequences; (3) a theoretical thermal model that allows manufacturers to determine the optimal materials to meet power criteria; (4) a disassembly quantification method to determine the ease of unit disassembly; and (5) recommendations for streamlined manufacturing and recycling processes and suggestions to improve overall environmental sustainability during the manufacturing, use and end-of-life phases.

The results should assist designers, manufacturers, consumers, and policymakers to understand how sustainability can be integrated into the design process and how it can be measured over the life cycle of a component of engineering infrastructure. Additionally the research should also provide insights about economic and environmental implications of utilizing voluminous amount of polyurethane as insulation, and can provide alternatives to this industry-wide problem.

1.6 Summary of Expected Contributions

The expected key contributions from this work include: (1) development of alternate design efforts aimed at reducing the volume of polyurethane foam utilized in commercial refrigeration units, and documentation of energy efficiency measurements, utilizing ASHRAE 72:2005 standards; (2) a comprehensive life cycle inventory and assessment performed on the proposed redesign options; (3) development of a one-dimensional heat transfer model to experimentally determine heat transfer characteristics of both type of insulations ; and (4) suggestions for streamlined manufacturing and recycling processes are proposed for Unit A and Unit B.

- Contributions from Objective 1***:*** *Alternate design efforts aimed at sustainable unit reconstruction, with an emphasis on reducing the volume of polyurethane foam utilized in commercial refrigeration units, and documentation of their energy efficiency measurements, utilizing ASHRAE 72:2005 standards and specifically:*

    - Explore the sustainable design process and research method through comparing performance of different products based on common performance metrics (i.e. - energy efficiency, thermal resistance), presented in Chapter 3.
    - Demonstrate that polyurethane foam is an inefficient and environmentally neglectful insulative product. A key component of this is analysis by life cycle assessment, presented in Chapter 5.
    - Suggest alternative commercial refrigerator design that is more energy efficient and presently feasible industry alternative to injected polyurethane.
- Contributions from Objective 2***:*** *A comprehensive life cycle inventory and assessment of proposed redesign optionsand specifically:*
    - Present unique life cycle inventory data obtained from manufacturers directly involved in the production of this type of insulation, as described in Chapter 5.
    - Develop an integrated decision making process for engineers to systematically estimate the environmental and economic consequences of design changes, and to analyze the exchanges that take place to the environment as related to the examined product.
    - Quantify the emissions into air, water and land that take place in every life cycle phase, and estimate the effects of materials consumption and environmental emissions on human and the eco-system by product production, use and disposal, as shown in Chapter 5.
- Contributions from Objective 3: *A one-dimensional heat transfer model to determine heat transfer characteristics of both types of insulations and specifically:*

- Measure and record quantitative metrics related to thermal characteristics of polyurethane foam, as utilized in Unit A, and investigation of heat transfer through the proposed insulation alternative, utilized in Unit B. An in depth look at these elements are presented in Chapter 4.
- Present a comprehensive look at the contribution of each type of heat transfer mode (conduction, convection, radiation) to the overall thermal resistance of insulation under study conditions, as shown in Chapter 4.
- Develop a theoretical model that manufacturers can utilize to determine the optimal combination of insulation materials and the corresponding thickness of each required to meet energy output targets, described in Section 5, Chapter 4.

- Contributions from Objective: *Suggestions for streamlined manufacturing and recycling processes for Unit A and Unit B and specifically:*
  - Present an exploration of the inefficiencies of current manufacturing and recycling processes for commercial refrigerators, as shown in Chapter 6.
  - Demonstrate an alternate manufacturing schematic that is aimed at ensuring maximum material recovery in order to fulfill the design criteria proposed by the *Twelve Principles of Green Engineering*, as shown in Chapter 5.

Table 1.1 Twelve principles of green engineering and its relationship to this work. The redesigned insulation aims to meet 9 of the 12 principles of green engineering design.

Principle of green engineering	Answering design objective
1. Designers need to strive to ensure that all the material and energy inputs and outputs are as inherently non-hazardous as possible.	Each material that enters the life cycle stage has its own product and process life cycle, and these life cycles must be included in the assessment of the overall non-hazardous inherency. Material and processes will be chosen to reduce the total greenhouse gases expelled in the manufacturing unit process, use less power during the unit life time (thus reducing emissions during the use phase), as well as provide end-of-life options that reduce the need to incinerate or landfill voluminous amount of polyurethane foam.
2. It is better to prevent waste than to treat or clean up waste after it is formed.	The modified design will aim to minimize landfilled materials, and to utilize less injected polyurethane, ensuring the recycling process is less labor-intensive. Utilizing an appropriate insulation alternative will allow material separation for optimum recyclability.
3. Separation and purification operations should be designed to minimize energy consumption and materials use.	Separation and purification operations are not considered in the immediate design of the product. In terms of the product life cycle process, design for disassembly will ensure that separation operations of retired unit maximize material recoverability.
4. Products, processes, and systems should be designed maximize, mass, energy space and time efficiency.	The use of life cycle assessment to guide and evaluate design will aim to ensure a unit alternative that will meet Energy Star criteria.
5. Products, processes and systems should “output pulled” rather than “input pushed” through the use of energy and materials. Le Chatelier’s Principle states: “If a system in equilibrium is subjected to a stress the equilibrium will shift in the direction which tends to relieve that stress.”	Approaching design according to this principle means utilizing less resources and energy to transform the product input to the desired output. By employing a ‘design for disassembly’ approach at the manufacturing level, the recycling and end-of-life will be “output-pulled” to ensure optimum material recovery. Less energy will be used to recovery materials from retired units through ease of access. Additionally, suggested manufacturing operations will also adapt a ‘just in time’ approach, wherein production is based on demand, and waste is eliminated from excessive production. Supply chain monitoring will ensure rapid response to changes in demand.
6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition.	Alternative insulation will increase complexity through the use of silicon dioxide in a vacuum environment in order to ensure a high recoverability rate.

Table 1.1 (Continued)

Principle of green engineering	Answering design objective
7. Targeted durability, not immortality, should be a design goal.	Targeted durability means that products are designed in order to ensure that once past their commercial life they do not deteriorate, causing adverse environmental consequences. Voluminous amounts of polyurethane foam utilized in traditional refrigerator systems are landfilled or incinerated due from refrigerators from expired refrigerators each year. Replacing polyurethane foam with silica packages greatly reduces the end-of-life environmental burden, as the silica can be heated to restore its original properties, or eventually ground to manufacture glass.
8. Design for unnecessary capacity or capability solutions should be considered a design flaw.	The design will aim to meet ISO standards for safety and temperature, but will not consider conditions which are considered abnormal.
9. Material diversity in multicomponent products should be minimized to promote disassembly and value retention.	End of life options are increased though design for disassembly where fewer materials are needed to meet functional requirements. Reducing the amount of polyurethane foam and injected polystyrene will improve disassembly ease and recyclability. Through the use of silica compounds, it will be no longer necessary to manually strip injected foams from unit walls or doors. Instead, when fasteners are removed from the door, the silica packets can be readily removed.
10. Design or products, processes, systems must include integration and interconnectivity with available energy and material flows.	Not addressed within the boundaries of this study's research.
11. Products, processes, and systems should be designed for performance in a commercial "afterlife."	Materials are chosen based on the ability to retain key characteristics after disassembly. Fumed silica can be regenerated to original insulative properties by reheating at a specified temperature over a certain amount of time.
12. Material and energy inputs should be renewable rather than depleting.	A limitation of the design is that material and energy inputs in this case are not renewable. However, the ability of silica to be regenerated means that any damaging processes involved in its mining and extraction are not required as often as it would be for a traditional unit.

Table 1.2 Evaluation criteria and constraints for commercial refrigeration

Criteria	Constraints
- Economical - Energy efficient - Minimum maintenance - Low environmental impact - Minimum waste - Low toxicity - Easy to recycle - Sustainable - Economical	- Requirements for maximum energy usage - Functional temperatures - Traditional Aesthetics

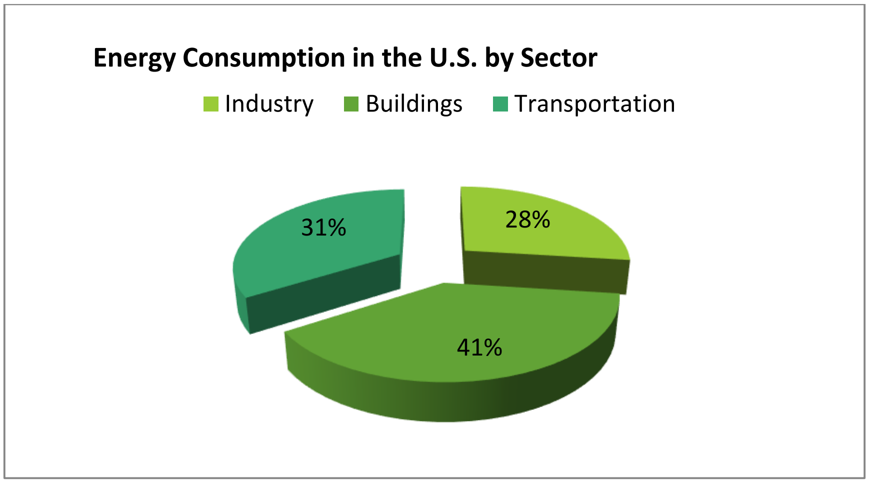


Figure 1.1 Energy consumption in the United States in 2012 totaled 97.461 quadrillion btu. The most significant source of energy consumption is generated from energy use in buildings (DoE, 2011).

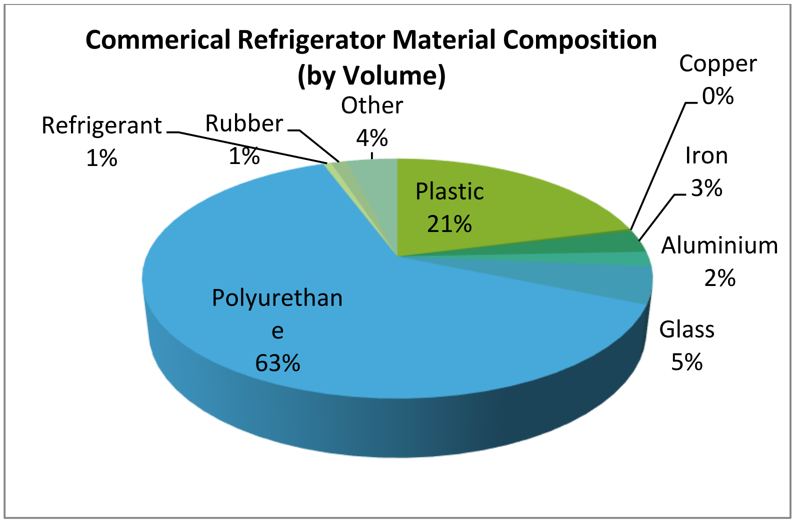


Figure 1.2 Refrigerator material composition. The traditional unit being utilized in this study was disassembled to quantify the composition of materials. Polyurethane foam is identified as the primary insulator in traditional commercial units, occupying 63% of the total volume of the unit.

CHAPTER 2: LITERATURE REVIEW

2.1 Existing Energy Standards

Energy standards set by Energy Star, the U.S Department of Energy, and California Energy have made it necessary for manufacturers to design products that utilize less energy while remaining cost effective. The most stringent of these energy standards is Energy Star. While not yet a required standard, products carrying the Energy Star seal are highly favored by consumers, as it is a recognizable sign of product efficiency. The Energy Star requirements for commercial refrigerators and freezers are summarized in Table 2.1.The energy standards set forth by the Department of Energy are required by law and are described in Table 2.2. California Energy has similar mandatory standards commercial refrigerators and freezers as described in Table 2.3. The energy consumption requirements are a function of the product volume (V), and the product type and configuration.

2.2 Effectiveness of Energy Standards

The majority of studies reviewed for this dissertation suggest that energy efficiency standards are extremely useful in reducing the overall energy demand of commonly used appliances, and are both economical and important for overall energy conservation. Mahlia&Saidur (2010) reviewed requirements and specifications of various international test standards for testing and rating of room air conditioners and refrigerators. The goal of the research was to present a review on the development of the energy efficiency standards and the effectiveness of rating systems in reducing overall energy consumption. The study suggests alternate criteria for energy labels that provide some useful information for identifying energy efficient products.

The economics of appliance efficiency were examined by the American Council for Energy an Efficient Economy (ACEEE, 2009). The article included a review of the energy standards from 17 countries. Waide, Lebot&Hinnells (1997) asserts that based on the available evidence, standards appear to be a very effective energy-saving policy. Policies like Energy Star, and those standards enforced by the California Energy Commission and the U.S. Department of Energy were estimated to reduce energy consumption by 8,216 GWh (cumulative) by the year 2020. The standards that have been implemented to date appear to be cost effective to consumers and have resulted in minimal adverse impacts on manufacturers and conclude that the costs of actually implementing standards are commonly less than estimates made by manufacturers and government agencies during the standard-setting process (Waide et al., 1997).

Similarly Boardman (2004) contended that energy efficiency standards, even those weak in nature, greatly reduce carbon dioxide emissions. That study focused on the U.K, where policy changes for energy efficiency took effect in 1999 for domestic refrigerators. The study estimated that these changes will have a net benefit of millions of dollars to consumers. One of the key differences addressed by Boardman (2004) was between improving energy efficiency and initiatives aimed at energy conservation because the results of energy efficiency typically take more time to reflect real change.

2.3 Improving Energy Efficiency in Refrigerators

There have been great strides made in improving energy efficiency of residential refrigeration, but few in the field of commercial refrigeration. While no literature was identified for this study on efforts to improve energy efficiency in non-residential units, a substantive review of residential unit advances is explored by Bansal, Vineyard &Abdelaziz (2012). A key similarity in many papers evaluating energy efficiency improvements in refrigerators (e.g., Boardman 2004; Mahlia, 2010) is that a fundamental change is needed in the industry. This is because the basic mechanism by which the refrigerator/freezer works, involving the use of a vapor compression system with polyurethane foam as the primary insulation, has been used for decades. With increasingly stringent energy standards, manufacturers must consider non-traditional alternatives.

Many of the options explored by major residential refrigerator manufacturers involve the reduction of the amount of polyurethane foam used in the insulation. Generally, studies focusing on redesign measures in refrigerators can be classified into three categories: 1) alternative insulation techniques, 2) system optimization through mechanical improvement, and, 3) compressor redesign. Figure 2.1 shoes the potential for energy savings in refrigerators by specific system improvements. System optimization, like improved algorithms for the defrost mechanism, have the most potential for energy savings. Compressor and insulation redesign were also identified as areas of high priority for potential energy efficiency improvement in residential refrigerators (Bansal et al., 2011).

2.3.1 Mechanical Improvements

Another approach taken by manufacturers to reduce the energy consumption in refrigerators is to improve the mechanical components utilized in the systems. The main mechanical parts of a commercial and residential refrigerator are the condenser, compressor, evaporator, and PVC gaskets. These gaskets are coated with a magnetic strip to seal the refrigerator from outside air. However, heat losses between the metal door and the gasket cause a degree of thermal leakage and therefore a decrease in thermal efficiency. Due to variances in units, there has been limited research done on gasket improvement. In a study conducted by the Environmental Protection Agency (EPA, 2009), it was noted that 35% of the thermal load on a residential refrigerator was from ambient air seeping in through the gaskets. This is an area that requires greater exploratory studies, as thermal heat leakage through the gaskets has been observed to be a significant contributor to overall heat loss.

Furthermore, Bansal et al. (2011) and Teschler (2008) conclude that electronically commutated motors are much more energy efficient than traditional fans, and may improve efficiency by up to 45%. A variable speed linear compressor and variable capacity compressor were compared for increased energy efficiency by Embarco (2011) and Fisher &Paykel (2010). Oil free compressors were proven to improve energy performance by more than 30%. The developed units were also significantly more lightweight.

Changes in the physical configuration for heat exchangers, defrost mechanisms, and evaporators are also suggested as ways to increase energy efficiency. For example, Lee (1996) examined the feasibility of redesigning the evaporator by equalizing the temperature between the evaporator and cabinet; this resulted in significant improvements in energy efficiency (between 10-14%).

An additional potential mechanical redesign option that can lead to increased energy efficiency is improvement to the algorithm that controls the defroster. Many traditional units still use a timed defroster, where after a set amount of time, the defrost heaters turns on and melts any frost that may have accumulated on the evaporator coils. Common defroster timers turn on in intervals of 6, 8, 12 or 24 hours. At every interval, the timer triggers the unit to start, and the defroster runs between 18-30 minutes, regardless of whether the coils needs to be defrosted, or not. An energy saving method that is being implemented by many manufactures is the adaptive defrost control, whereby the defrost device is programmed to record the power usage of the appliance, and the amount of time it takes for the evaporator coils to frost. At a certain set point, the device will trigger the defrost heater for only as long as it takes for the frost to melt. An example of the use of this type of device in industry is the General Electric “Mother Board,” which almost fully controls the unit, including the DC fan motors. The “mother board” detects the incremental change in the temperature of the evaporator, as the frost melts, and turns off the defrost heater. Energy efficiency can thus be significantly increased by using adaptive defrost sensors. For example, in a study by Samuels (1999) employing adaptive demand defrost using proximity sensors, an improvement in energy efficiency of more than 12% was observed.

2.3.2 System Optimization and Next Generation Technology

Another system improvement that has been studied to increase energy efficiency is vapor-compression system optimization. One of the system improvements considered is a change to the primary refrigerant used in residential and commercial refrigerator units, so that the refrigerant is more environmentally friendly and a more effective coolant. Beyond increasing energy efficiency through the use of more effective refrigerants, another consideration is the environmental effects of current refrigerants. Most residential and commercial refrigerants are hydrofluorocarbon based. Spatz et al. (2010) notes that these chemicals have a global warming potential of 1,430 times that of carbon dioxide; therefore, EPA (2003) requires that end of life disposal centers have a certified technician to remove this refrigerant and dispose of it properly. However, with little to no enforcement, it is unknown how much refrigerant ultimately ends up in the environment. Many manufacturers are currently experimenting with hydrofluoroolefins (HFOs) as a potential alternative, as they have been shown to be as effective of a refrigerant. In addition, HFOs have a global warming potential approximately 300 times less than a conventional refrigerant like R134a (Fleischer, 2009).

Vapor compression systems have been the mechanism by which refrigeration has been achieved since the early 1900s. A complete overhaul of refrigeration technology is suggested by Bansal &Martin (2000). Citing quiet operation, improved reliability, improved scalability, and the ability to utilize solid refrigerants, a case is made for alternative designs like absorption refrigeration, adsorption refrigeration, magnetic refrigeration, Malone cycle refrigeration and thermoelectric refrigeration.

While testing alternatives will be focused on replacing the voluminous polyurethane foam in the commercial refrigerator, a change in the basic mechanism of refrigeration itself could be examined in further works. One of the more promising alternatives to traditional refrigeration is magnetic refrigeration. Magnetic refrigerator occurs at room temperature and utilizes the magneto caloric effect (MCE) found in solid-state refrigerants. The refrigerant replaces Freon, and has no negative environmental consequences regarding global warming. There have been over forty different experimental products developed from this technology. These efforts have been explored in depth by Basso et al. (2006), Bjork et al. (2010), Gschneidner et al. (2008), Hirano (2003), Hirano, Nagaya, Okamura, Kuwanami and Wada (2010), and Russel et al. (2010). These studies focused on magneto-caloric materials such as second-order phase-transition materials, nanostructured materials and multiphase materials and composites. The studies found that in prototypes utilizing this type of next generation technology, energy efficiency improved up to 30%.

These studies reviewed above consider mechanical and insulation redesigns that aim at increasing energy efficiency and lowering cost. However, none consider how the above mentioned redesigns would affect manufacturability, environmental sustainability, and the overall structural integrity of the unit.

2.3.3 Material Selection and Evaluation

The evaluation of insulation utilized in commercial refrigeration can be determined from technical and environmental criteria. For refrigerators, the design can be assessed by considering the unit's energy metrics, including power output per day. A design strategy index was developed by Weaver, Ashby, Burgess and Shibaike(1996) to quantitatively determine the optimal material to use in these types of applications. That study cites the criteria for material selection as divided into three categories. 1) The inefficient use of materials: the best defense against waste and the problems associated with the disposal of the insulation is the decrease in the amount of waste produced through efficient design. 2) The consumption of non-renewable resource- where the life cycle of any engineering product will deplete non-renewable resources. 3) Specific damage to air, water and land by chemical contamination, particulates and solid waste. The design requirements for refrigerator insulation identified by Weaver et al. (1996) are summarized in Table 2.4.

Weaver et al. (1996) proposed a modified index-and-chat method based on the functional requirements listed in Table 2.4 and a value function was developed. The selection criteria presented by the authors is useful for quantitative selection of the best material for the purpose. For the purposes of energy efficiency, a key metric to be considered is thermal conductivity. As the thermal conductivity of a material decreases, less heat is allowed to pass through the insulation.

2.3.4 Advanced Insulation Techniques

Thermal conductivity varies by both insulation material and configuration. Polyurethane is the traditional insulation used in refrigeration. Wu and Chu (1998) investigated the heat transfer characteristics of polyurethane foam and showed that evacuating the air from the foam cells can reduce the thermal conductivity of the polyurethanefoam by up to 75%. The authors also showed that radiative heat transfer accounts for about 4% of total heat transfer in across the polyurethane medium.

While the idea of alternative types of insulation have been explored by many companies producing these types of units, advanced insulation technologies to reduce the amount of heat gained by the refrigerator storage cabinet is limited by manufacturers desire to achieve maximum internal volume for product storage. Additional limitations are cost of the insulation material, available manufacturing techniques and labor, and material deterioration over time (DoE, 2010).

Vacuum paneling in buildings and other devices has gradually increased in recent years, and manufacturers have developed more economic panels. A redesigned vacuum panel reduces the volume of air molecules in an evacuated space, thus reducing the amount of heat transfer occurring. There are two main approaches to vacuum technology: vacuum powder and vacuum paneling (VIPs). When vacuum paneling was employed in residential refrigeration units, a 20.4% energy savings was achieved (EPA, 2009). Additional studies by Kudoh, Ohira, Nakamura and Araki (2006) and Eberhardt (2007) suggest that an energy efficiency increase of 25% can be achieved by the successful implementation of VIPs. VIPs can consist of powder- and fiber-filled panels, compact vacuum insulation (with stainless steel walls), or aerogels (Bansal, 2011). Other insulation techniques explored are the use of baffle-type argo-filled panels, proven to substantially decrease thermal conductivity. VIP prototypes were tested by Weaver et al. (1996) and they observed increased energy efficiency of 15% to 25%.

An advanced “version” of polyurethane foam was developed by Parenti, Kramer, Kohn and Patchala (2007) that improved the efficiency of the foam insulation. It combines the idea of the vacuum panel with traditional injection molding. The insulation method employed by the study was found to increase energy efficiency by 35%. Bouquerel, Duforestel, Baillis and Rusaouen, (2012) investigated heat transfer through a VIP in a building through empirical models. While the applications are very different in comparison to refrigerators, the heat transfer can be determined through similar models.

There has been some debate as to the effectiveness of the filling materials used in VIPs. Kwon, Jang, Jung and Song (2009) examined the use of powder, foam, and fibers as filling materials for VIPSs. The results show that that the solid conductivities of the fiber and more solid types of filling for the VIP insulation are lower than those of the powder and foam due to the relatively long thermal path. It can concluded from examination of the literature that the higher density of the filling material of the VIP, the more effective the insulation is for the case of commercial refrigeration.

While vacuum insulation panels are considered one of the foremost technologies for insulation in buildings, the technology is less than ideal for use in refrigerators due to the cost as well as the ability of vacuum insulation panels to be cut to fit specialized models. Another emerging technology in the insulation field is industrial grade silica beads and aerogels. Silica is well known for its thermal resistance. In a study by Fricke, Hummer and Scheuerpflug(1995), vitreous silica was compared to aerogels. The result showed an increase in radiative transfer through aerogels, but a significant decrease in thermal conduction with the use of aerogels.

Vitreous silica was also proven to be an excellent inhibitor to heat transfer. While aerogels are not as yet feasible for use in commercial refrigeration systems due to its high cost, silica in the form of non-porous beads and fibers are still a viable option to consider.

A study by Zhao (2006) investigated the radiative heat transfer properties of a silica aerogel composite. The results show that the effectiveness of this type of material is greatly increased when the inclination, diameter and length are configured based on experimental results. The optimum parameters combined with the fibrous silica utilized in the study produce an effective insulation.

The idea of combining silica as the filling material for a vacuum panel was explored by Fricke et al. (1995). The authors assert that even though VIPs have a thermal resistance ten times that of foam-based insulation of the same thickness, the filling material should contribute to the heat- bearing load , and will then reduce some of the associated draw-backs related to VIPs—i.e.- the loss of vacuum over time. The study suggests fumed silica as a filling material, where the suggested silica material has a thermal conductivity of about 0.004 W m^{-1} K^{-1} at room temperature.

Another material consideration was employed by Yu, Li and Zhu (2009) where thermal performance of insulation was investigated through the walls of a low temperature cold box. The results of their testing indicate that a reflective heat shield significantly reduced heat losses by up to 18%. The study also showed a reduction in heat loss when aluminum foil was used as an alternative to the heat shield.

2.3.5 Insulation Configuration

Aside from the use of the particular material, other studies have been conducted in order to determine the optimal configuration to reduce heat transfer between two encapsulating mediums. The optimal design of the reconfigured insulation for improved energy efficiency was investigated by Jang,Jung, Lee and Song (2013) who investigated heat transfer in vacuum insulation panels. In particular, the heat transfer by radiation was investigated using Monte Carlo analysis. It was found that the radiative heat transfer decreased as the optical thickness of the core of the material increased. It was also asserted in the study that the radiation emissivity of the materials could be reduced through the use of more radiation shields.

Another study by Bond,Clark and Kimber (2013) was conducted on insulation as applied to buildings with various external ambient temperatures. The study investigated heat transfer through thirty-three different wall configurations given specific volume parameters. The heat transfer was modeled using electrical resistance analogy. The temperatures used in the study were the inner and outer temperature exposed to the internal and external environments. The study showed that optimal insulation performance was achieved when the insulation layers were positioned as the first point as transfer through the wall i.e. no reinforcing materials experienced the ambient temperatures before the insulation configuration. The study also noted the need to distribute the insulation material evenly through the wall and that each layer is divided into an increasing number of thinner layers.

2.4 Life Cycle Assessment

The product life stages of raw material extraction, manufacturing, transportation, use and eventually, disposal must be considered holistically when evaluating the environmental sustainability and considering unit improvements. In some cases, changes to material or components of the product would result in a decrease in energy expended by the unit during the use phase, but this decrease would be negligible in comparison to the increase in energy expended in material processing and disposal costs. In order to help designers estimate the holistic environmental consequences associated with their design decisions, Life Cycle Assessment (LCA) is often employed. There are many software offerings that utilize a life cycle assessment framework- SimaPro (Amsterdam, The Netherlands) and Gabi (Leinfelden-Echterdingen, Germany) are the most frequently used.

2.4.1 LCA Applications in Product Design

LCA is an applicable tool in the design of commercial refrigerators and planning for its disassembly and recycling. Disassembly attempts to increase the efficiency and economy of recycling. Huang,Liu, Zhang and Sutherland (2009) defined disassembly as "*the processes of systematic removal of desirable constitute parts from an assembly while ensuring that there is no impairment of the parts due to the process.*" LCA was utilized by Kuo (2010) for recycling planning, including the disassembly and eco-design for a roller blade. Through modularity network and the employment of life cycle assessment and disassembly planning, an economically viable support system to the designer that allow engineers and manufacturers to determine the probably effects of prospective design decisions. LCA was also employed by Turielet al. (1997) in the design of more energy efficiency residential furnaces and boilers. The study considered alternative variety of design options.

Figure 2.2 illustrates various studies identified in this literature review where LCA was employed to various products and processes including PET bottles and biodiesel. There are several types of life cycle assessment that can be employed to meet the goals of the designers. Among them, life cycle cost, 'cradle to gate', social life cycle are common types of LCA employed by manufacturers to determine the environmental consequences of variables in the system.

2.4.2 LCA Applications in Refrigeration

As shown in Figure 2.2, LCA has been applied to a wide variety of products and processes. However, there have been limited studies in which LCA was applied to refrigerators. In one of the studies found in this category, Kim, Keoleian and Horie (2006) developed a dynamic life cycle inventory in order to determine energy consumption through each stage of the life cycle. This data were then utilized to develop an optimal residential refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. The study investigated what the optimal lifetimes of household refrigerators should be in order to maximize energy efficiency. The result of the study showed that depending on model years, energy efficiency in refrigerators decrease after 7 years, due to wear and tear on the mechanical components. The study also concludes that the global warming potential (GWP) for refrigerators is significantly increased after 11 years of use. However, an 18-year refrigerator lifetime was proven by the study to be most economical. The study further concluded that enhancing the energy efficiency of the unit over its lifetime may be increased with more efficient insulation.

Another LCA approach was employed by Huang et al. (2009) who developed a performance index to rank proposed material selection for products. The study applied the performance index to an air conditioner support plate. The performance index integrates into traditional life cycle analyses by quantifying the importance of each stage of the manufacturing and disposal process, and assigns importance to input and output values. This method of assigning values to quantify the importance of variables is useful in analyses of product life cycles as they enable engineers to draw more accurate and need-based conclusions. The study further illustrates that decision-making analysis can provide design guidelines and criterion for materials selection to achieve environmentally conscious designs.

Life Cycle Assessment is also used to both guide and evaluate design and performance. Recent developments of learning algorithms that are incorporated into LCA programs allow designers to analytically evaluate their concept designs. There have been several general models that aimed to create a more specialized approach to the LCA process. An example of an extended LCA model was developed by Sousa (2006) where auxiliary models to create "specialized learning surrogate LCA models" were developed. These auxiliary models created classifications of products that will meet the needs of specific sectors of industry designers. The study groups utilize 'surrogate' LCA models as principle decision making tools, and classify them by various environmental categories. Decision tree algorithms were then developed for each grouping, the results are a learning surrogate model that is a novel approach to decision support for life cycle assessment, specialized for varying classification of products. A similar "decision-tree" approach was employed to provide an auxiliary tool for decisions within a product life cycle. The model considers material and process options within a life cycle, and also evaluates the use of a decision tree and matrix computational structure in the valuation of material and processes as it applies to life cycle inventory. The model aims to find the optimal set of process and material inputs that will best meet the key metrics in the study, while aiming to minimize the burden of data collection (Cooper, Godwin, & Hall, 2008).

Similarly, several other studies have considered decision-tree matrices in order to guide design in specific industries (Azapagic, Millington &Collett, 2006). An example of this model aimed at developing a decision tree matrix as an auxiliary decision-making tool for designers in the chemical industry. In particular, the model focused on material and process selection in the vinyl chloride monomer process. The methodology guides the practitioner through a series of design stages and processes, considering economic, environmental and social metrics. The result is a case study that allows decision makers in this area to account for a more sustainable design based on chosen sustainability criteria.

Another sector utilizing auxiliary LCA models is the remanufacturing industry. Re-manufacturing aims at reducing landfilling and associated pollution by remanufacturing a product to a ‘like-new’ state. This developing pollution-control technique is considered at the fore-front of the waste management industry. An example of this describes a methodology to improve on guidelines for design-for-remanufacturing in the United Kingdom (Ijomah, McMahon, Hammond & Newman, 2007).

A similar decision support for LCA approach was employed in a study by Bhander, Hauschild and McAloone (2003). The goal of that study was to outline potential environmental problems that the product and process designer may face as they proceed with assessing the environmental benignity of a product or process. The model then guides the designer through a set of decisions based on the evaluation of the various unit processes. The authors provide opportunities for designing by unit stage by satisfying metrics set by the user for each stage of the LCA. This systematic analysis of the consequences associated with design at later stages in the processes allows designers to evaluate the environmental consequences of their decisions. The study utilizes a model called the “Environmentally Conscious Design” method, which allows the user to presents design alternatives and their corresponding design solutions. The method is also focused preliminary on the early stages of the design process as applied to product design (Bhander et al., 2003).

An alternative approach in utilizing LCA to guide design is a process named ‘Design for Adaption’ (DFAD) in which it asserted that product life ends because a product is inadaptable to change. In cases when the product is not ‘phased out’ for alternative reasons, DFAD can be utilized, where the products are modeled as dynamic systems with feedback control strategies that will allow it to respond or adapt to changes in product and performance criteria. The DFAD is a design strategy that may be used to guide design when the primary objective is design longevity.

Within this category, there are also studies that aim to “fill in the data gaps” using techniques to allow users to make decisions without a full data set. This was the aim of the model presented by Fitch and Cooper (2005), in order to assess life cycle impacts for a complex systems with many design phases and few product specifications. The model uses probabilistic theories to forecast environmental consequences associated with potential design decisions. In this way, the model combines LCA with statistical probabilities without necessitating additional information. This process is referred to as Life Cycle Modeling for Design and makes model predictions based on past design scenarios, when limited data is known. The model is demonstrated on an automotive case study (Fitch&Cooper, 2005).

Another study considers a similar framework, with a reverse engineering methodology approach to guiding design. The study proposes a general method for use with the convention life cycle assessment. The study utilizes similar products and their design to correlate environmental consequences to design decisions. The framework developed does not necessitate that designs have a data bank, instead the study proposes filling in the “knowledge gaps” with data from similar products. The study considers the case of electric kettles to demonstrate the principle (Telenko, &Seepersad, 2010).

Life Cycle Assessment has also been shown to be particularly useful for the electric and electronic equipment industry. An example of one of these studies was conducted by Kuo, who employed a collaborative design platform to utilize the limited data available to manufacturers from a supplier’s Bill of Lading. This data is able to provide manufacturer’s with enough input data to perform a LCA for disassembly and recycling (Kuo, 2010).

Another approach is to combine several guides to environmental design to develop a modified tool to support environmental goals. A study conducted by Sakao (2007) proposes a methodology that utilizes three tools to guide environmentally friendly design: LCA (life cycle assessment), QFDE (quality function deployment for environment), and TRIZ (theory of inventive problem solving). The study focuses on the design of a hair-dryer to illustrate the concept. Through the use of LCA, the user is able to identify the least-environmentally friendly processes and materials, and define a requirement in QFDE to reduce the impact caused by said process or material, with a high weighting. This framework effectively allowed designers to identify four possible process improvements in the design of the hair dryer. Results indicate that the combination of the three design methodologies has a greater benefit that using them as separate entities (Sakao, 2007).

A multi-criteria approach was also employed by Bovea and Pérez-Belis (2012) and in that study, the author suggests a best tool for life cycle design for a particular or process. Another auxiliary model is presented by Haapla, Rivera and Sutherland (2008) that attempts to consider social, economic and environmental impacts of product and process decisions simultaneously. The study considers the case of a steel component, wherein several alternatives are evaluated using this model in conjunction with LCA. The study then utilizes a sensitivity analysis to identify which materials and processes impact the overall sustainability most. The model addresses metrics in sustainable design that occur mainly in the manufacturing process (Haapala et al. 2008).

A further study by Heijungs,Huppes and Guinée(2010) further attempts to incorporate social and economic factors as it relates sustainability, basing its study on developing a framework from the three pillars of sustainability. Incorporating the ISO-work for life cycle assessment, the study proposes a broader view, focusing on the societal affects that design considerations have, rather than the micro effects typically felt by the manufacturer or designer. The result is not a quantitative model, but a series of predictions on the social and economic impacts on the societal structure.

The research of Robèrtet al. (2002) further supports the idea of combining sustainability models for a more accurate and complete forecast in his study of sustainability tools and approaches. The study shows how these tools can be used in tandem for a more holistic approach to sustainability. The study considers LCA as well as other tools that consider product and process and life cycle inventories (Robèrt et al., 2002).

There is another set of literature for guiding design that utilizes various components of risk/benefit analysis to guide decision making. Examples of this research are Bevilacqua,Ciarapica and Giacchetta (2007), BoveaandWang (2007) and Howarth and Hadfield (2006). A major challenge for product and process designers is balancing stakeholder interests with feasible environmental design. One such study applies life cycle assessment and ‘design for environment’ techniques to the development of products, as well as the redesign of existing products. In particular, the study focuses on the manufacture of a particular class of electrical distribution products. The key to the study is the “environmental break-even point” whereby the additional expenses- environmentally and economically incurred by various material and process options are considered, and iterated, until the overall environmental impact and economic cost of the material and processes are feasible and reasonable to the client (Bevilacqua et al., 2007).

Similarly, another study focuses on establishing a relationship between key metrics: quality function development, life cycle assessment, contingent valuation, life cycle cost, cost requirements, and customer willingness to pay. The study considers products in a market where the customer is willing to pay for more environmentally-friendly products. It aims to compare the increase that alternations in material and processes for environmentally friendly gains to that of the response of customer-willingness to pay for the perceived environmental improvements (Bovea and Wang, 2007).

One study by Howarth and Hadfield (2006) attempts to quantify the variables involved in the process of satisfying the stakeholders associated with the manufacture of a new product. The results are a proposed concept model, as well as practical “Bournemouth University” model. In order to address sometimes-conflicting issues, risk/benefit model is proposed. The major social, economic and environmental metrics are considered and tabulated and presented graphically. The goal of the analysis is to develop a database with social, economic and environmental impacts associated with various design options. The aim of the assessment is to enable decision makers to find the balance that satisfies the various stake-holders involved in the process (Howarth and Hadfield, 2006). A further study suggests a decision matrix “road map,” user-friendly interface for designers to integrate social implications into their sustainable design and manufacturing solutions (Waage, 2007).

Most frequently, life cycle assessment is utilized to compare the environmental consequences of utilizing material or process over another. There are many case studies in which LCA or an LCA-hybrid approach is utilized make evaluate a design. An important consideration is which type of life cycle assessment is most appropriate to evaluate a given design or process. This was the focus of a study conducted to evaluate which LCA method performed best under certain conditions, using the case of a cellular phone and vacuum cleaner system. The methods considered for this study were a simplified LCA specific to Electrical and Electronic Equipment and ERPA, the environmentally responsible product assessment, utilizing a matrix. The usefulness of each method was evaluated against known case studies for the same products. The results were that the SLCA method generated more information on the environmental consequences of the product system, where environmental design was the primary goal; however the ERPA method was able to provide more information on how a present model could be improved. It was found that the most information was gathered by using both of the models, as they complemented each other (Lee,O'Callaghan & Allen,1995).

Another study used LCA to compare the environmental impacts of using one catalyst over another in acrylic acid; the software used in the study was SimaPro (Holman,Shonnard&Holles, 2009). Another study utilizes life cycle assessment to evaluate the environmental performance of vehicular Body-In-White's through the entire life cycle, from raw material processing to end of life considerations (Mayyas, Qattawi, Omar & Shan, 2012). Similarly, investigators have also used both LCA and LCC to assess economic and environmental consequences to photovoltaic module production (Kloepffer, 2008).

2.4.3 Life Cycle Assessment for End of Life Planning

Life Cycle Assessment has also been frequently utilized in comparison of environmental consequences for various end-of- life alternatives. A study by Gamage,Boyle and McDowall (2013) employed life cycle assessment as applied to office furniture to determine environmental hotspots in the life cycle of the two chairs, compare the life cycle impacts of the two chairs and compare alternative potential waste-management scenarios. The study considered the waste management associated with current end of life options, and ultimately suggested that , it was found that a substantial reduction in the global warming potential over 100 years would occur if the chairs are recycled rather than landfilled, assuming an expanding market for aluminum. Thus, recycling the two LIFE chair models at end-of-life was highly recommended (Gamage et al. 2013).

Life cycle assessment has been frequently studied for its application in the disposal of paper and cardboard waste. Villanueva attempted to find a correlation in the recommendation of various life cycle assessments as it relates to end of life recommendations in this industry. Nine LCA studies with 73 various scenarios regarding to the end of life options for paper and cardboard were considered. The study showed that due to different assumptions and system boundaries, there was no trend or consensus in these studies, and that the outcome of various LCA is dependent largely on user inputs (Villanueva and Wenzel, 2007).

A study specific to evaluate end of life options for appliances proposed the use of a new LCC methodology, wherein economic thinking was applied to a conventional LCA (Nakamura, 2006). The method utilized appliances as a case study, to investigate the Design for Disassembly method as a tool in waste management. The study found that life cycle cost is the highest under intensive recycling, and lowest under landfilling. However, if Design for Disassembly thinking was employed, the study showed that the cost of recycling could be greatly reduced. The paper also suggested the introduction of a carbon tax to significantly reduce the cost disadvantages associated with recycling vs. landfilling. This approach utilized a hybrid LCA approach to investigate the effect of the material recovery process on CO_2 emissions during the recovery process. While an increase in energy consumption was noted during the disassembly process, the energy consumption ‘saved’ by the corresponding raw material not being processed, far exceeds that expended by recycling instead of landfilling.

2.5 Disassembly Quantification and DfD (Design for Disassembly)

One of the goals of this research is to design an alternative insulation that can be separated with minimum labor while preserving the material so it can be reused. The most fundamental measure of this change considers the reduction of steps in the disassembly process, the total time spent, and the material recovery. Thus, the adapted method will allow the designer to objectively quantify the ease of disassembly of the commercial refrigerators.

There have been several approaches to quantify disassembly for recycling. In one study, three decision variables are considered during parallel disassembly, with the objective to maximize profit. The quantification tool considers probability reuse, as well as the environmental and energy impacts of the various parts of disassembly. A two-phased algorithm is suggested. The quantification technique is applied to two case studies: an automatic pencil and a telephone (MaJun, Kim & Lee, 2011).

An alternative quantification technique was employed by Kwak and Kim (2011), wherein mixed integer programming was utilized to develop a model in which component interchangeability is assessed as it pertains to smart phones. The “product family design” assessment method is proposed as a strategy to optimize end-of-life recover. This study has been applied to blow dryers, hot irons, television stands, and a myriad of other products.

A similar methodology was also described by Desai and Mital (2012). In their study, they employed the concept of difficulty scoring in order to evaluate the overall effectiveness of the product design for disassembly. The study utilized the analytic design process (ADP) to evaluate the connectors in products according to three concerns: (1) making product disassembly friendly; (2) making product assembly efficient; and, (3) increasing the product performance when it is in-use.

Table 2.1 Maximum daily energy requirements for commercial refrigerator/freezers as allowed by Energy Star (Source: Energy Star, 2005)

Product volume (in cubic feet)	Energy consumption (KW/day)	
Solid Door		
0–15	0.089V+1.411	0.250V+1.250
15–30	.037V+2.200	0.40V–1.00
30–50	.056V+1.635	0.163V+6.125
> 50	0.06V+1.1416	0.158V+6.33
Glass Door		
0–15	0.118V+1.382	0.607V+0.893
15–30	0.140V+1.050	0.733V–1.00
30–50	0.88V+2.625	0.250V+13.50
> 50	0.110V+1.500	0.450V+3.500
Chest Solid/Glass Door	0.125V+0.475	0.270V+0.130

Table 2.2 Maximum daily energy consumption for commercial refrigerators/freezers as allowed by Department of Energy (Source: DOE, 2010)

Category	Energy consumption (KW/day)
Refrigerator- solid door	0.1V+2.04
Refrigerator-transparent door	0.12V+3.34
Freezer-solid door	0.40V+1.38
Freezer-transparent door	0.75V+4.10
Refrigerator/freezer with solid door	0.27AV–0.71

Table 2.3 Maximum daily energy consumption as allowed by the California Energy Commission (Source: CEC, 2012)

Category	Energy consumption (KW/day)
Refrigerator- solid door	0.1V+2.04
Refrigerator-transparent door	0.12V+3.34
Freezer-solid door	0.40V+1.38
Freezer-transparent door	0.75V+4.10
Refrigerator/freezer with solid door	0.27AV–0.71
Self condensing refrigerators	0.126V+3.51

Table 2.4 Functional requirements when choosing refrigeration insulation (from Weaver et al., 1996)

Function	refrigerator insulation
Functional objectives	Minimize the cost of insulation while satisfying constraints.
Environmental safety	Minimize energy consumption over lifetime. Material needs to be fire resistant.
Constraints	Thickness no more than 2 cm, life time must be greater than 10 years, and inner and outer temperature difference must be at least 16^{o}C.

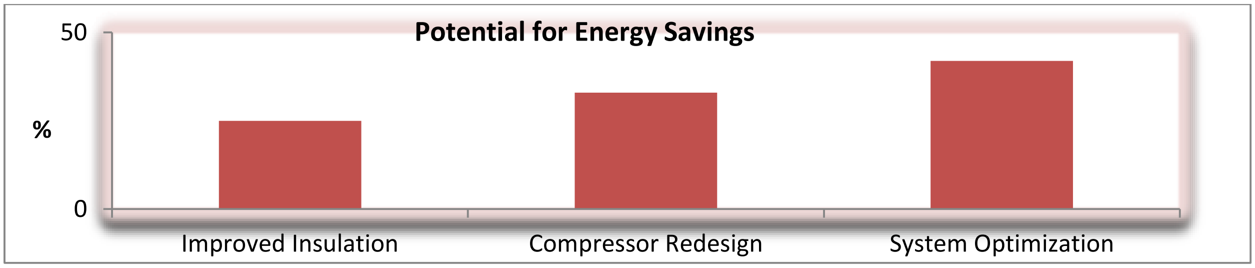
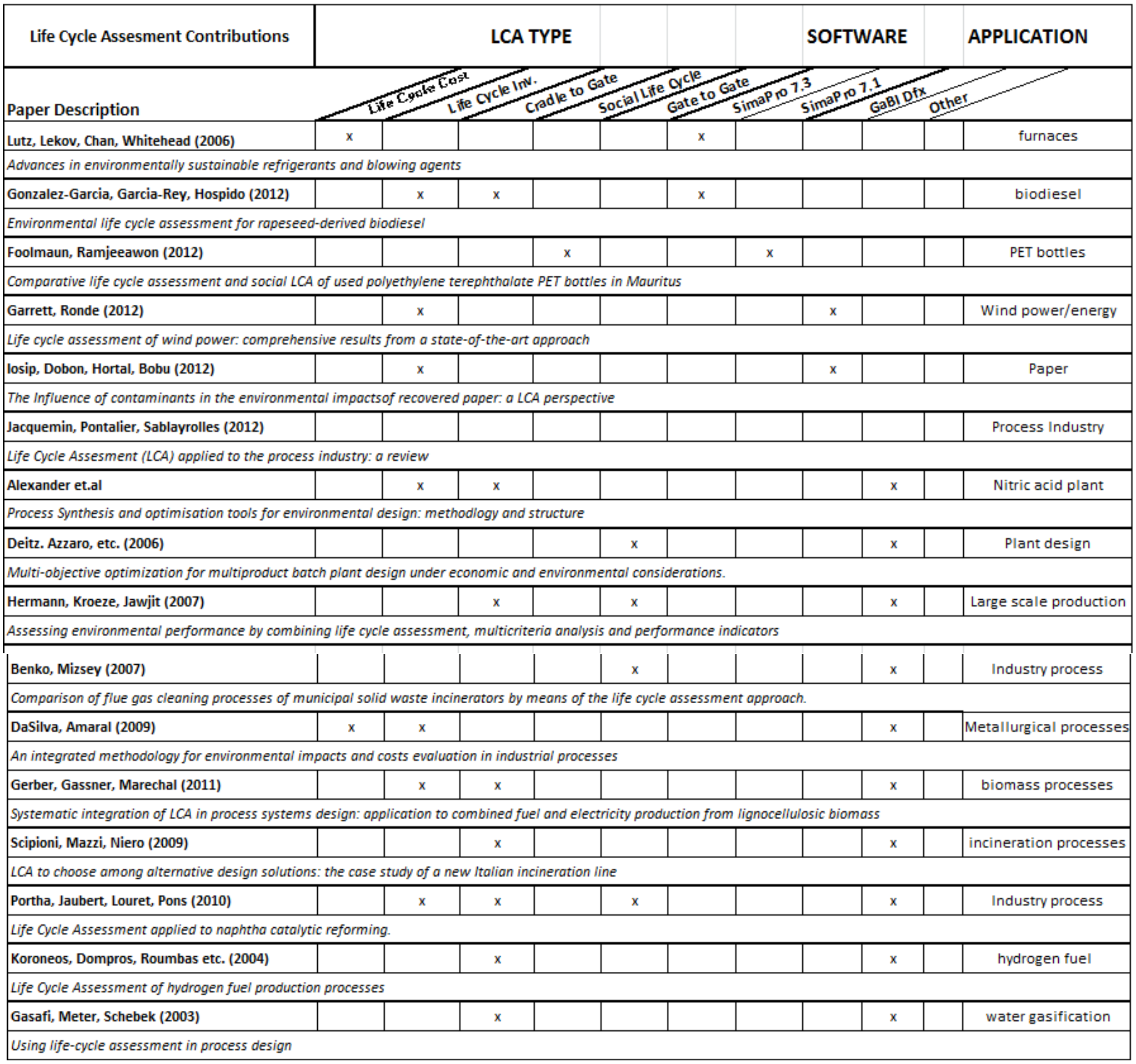


Figure 2.1 Potential for energy savings in refrigerators by employing various redesign measures. (Adapted from Bansal et al., 2011)



Life Cycle Assesment Contributions	LCA TYPE							SOFTWARE			APPLICATION
Paper Description	Life Cycle Cost	Life Cycle Inv.	Cradle to Gate	Social Life Cycle	Gate to Gate	SimaPro 7.3	SimaPro 7.1	GaBI Dfx	Other		
Lutz, Lekov, Chan, Whitehead (2006)	x					x					furnaces
Advances in environmentally sustainable refrigerants and blowing agents											
Gonzalez-Garcia, Garcia-Rey, Hospido (2012)		x	x			x					biodiesel
Environmental life cycle assessment for rapeseed-derived biodiesel											
Foolmaun, Ramjeeawon (2012)				x			x				PET bottles
Comparative life cycle assessment and social LCA of used polyethylene terephthalate PET bottles in Mauritus											
Garrett, Ronde (2012)		x						x			Wind power/energy
Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach											
Iosip, Dobon, Hortal, Bobu (2012)		x						x			Paper
The Influence of contaminants in the environmental impactsof recovered paper: a LCA perspective											
Jacquemin, Pontalier, Sablayrolles (2012)											Process Industry
Life Cycle Assesment (LCA) applied to the process industry: a review											
Alexander et.al		x	x						x		Nitric acid plant
Process Synthesis and optimisation tools for environmental design: methodlogy and structure											
Deitz. Azzaro, etc. (2006)					x				x		Plant design
Multi-objective optimization for multiproduct batch plant design under economic and environmental considerations.											
Hermann, Kroeze, Jawjit (2007)			x		x				x		Large scale production
Assessing environmental performance by combining life cycle assessment, multicriteria analysis and performance indicators											
Benko, Mizsey (2007)					x				x		Industry process
Comparison of flue gas cleaning processes of municipal solid waste incinerators by means of the life cycle assessment approach.											
DaSilva, Amaral (2009)	x	x							x		Metallurgical processes
An integrated methodology for environmental impacts and costs evaluation in industrial processes											
Gerber, Gassner, Marechal (2011)		x	x						x		biomass processes
Systematic integration of LCA in process systems design: application to combined fuel and electricity production from lignocellulosic biomass											
Scipioni, Mazzi, Niero (2009)			x						x		incineration processes
LCA to choose among alternative design solutions: the case study of a new Italian incineration line											
Portha, Jaubert, Louret, Pons (2010)		x	x		x				x		Industry process
Life Cycle Assessment applied to naphtha catalytic reforming.											
Koroneos, Dompros, Roumbas etc. (2004)			x						x		hydrogen fuel
Life Cycle Assessment of hydrogen fuel production processes											
Gasafi, Meter, Schebek (2003)			x						x		water gasification
Using life-cycle assessment in process design											

Figure 2.2 Examples of the many types of LCA studies and their applications.

CHAPTER 3: EXPERIMENTAL DESIGN AND RESULTS

The purpose of the experimental portion of this research is to determine how changing the insulation configuration in the cover of the refrigeration unit (roughly equivalent to 1/3 of the overall surface area of the total insulation used) affects the overall heat transfer for the insulation of the unit and in accordingly, the total energy utilized by the unit.

A commercial 5 ft^3 Whirlpool refrigerator chest (Model EH070FXMM) was outfitted with measurement equipment for testing and evaluation purposes. Heat flux sensors, Omega-HSF-4 (Stamford, Connecticut) and thermocouples, Omega- Type-T (Stamford, Connecticut) were installed in the internal refrigerator/freezer cabinet, as described by Figure 3.8, to measure heat transfer and to monitor internal temperature. A power meter, P3 Kill-A-Watt (New York, New York) was utilized to determine the total energy used by the unit over the testing period.

The refrigerator/freezer was placed, unmodified, in a testing chamber with a controlled ambient temperature of 75°F, relative humidity of 45% and air pressure of 101MPa. The testing methodology was adapted from the ASHRAE 72-2005 testing standard (ASHRAE, 2005). This unchanged, traditionally insulated unit is referred to as ‘Unit A’. Heat flux and power consumption were measured and recorded over a 24 hour period for Unit A. Details of the test are provided later in this chapter.

After the testing of Unit A was complete, the cover of the refrigerator/freezer chest was removed; the polyurethane insulation located in the cover was stripped and replaced with an alternative insulation configuration consisting of an insulation cartridge in which packets of evacuated silica are inserted into a honey-comb like recycled plastic structure. A reflective heat shield made of recycled polyester fiber encapsulated the cartridge, and a small amount of polyurethane was applied to seal the structure. This unit is referred to as ‘Unit B’. Unit B was then placed in the testing chamber and underwent the same heat flux and power consumption testing over a 24 hour period as Unit A.

In both the traditional unit (Unit A) and the modified unit (Unit B), the mechanism by which cooling occurs remains the same. A vapor-compression system is utilized, wherein the refrigerant travels along tubing through the compressor. From there, the refrigerant moves through smaller tubes to the evaporator. The movement of the freon from the compressor to the evaporator causes a significant drop in the pressure of the liquid, allowing it to absorb warm air from the internal compartment, the liquid changes state and the heated gas then moves through the coils of the condenser and is released into the cooler ambient air. The cycle then refreshes itself when the freon loses heat and returns to a liquid state.

3.1 Unit A: Traditional Insulation Construction

Figure 3.1 provides the dimensions of the materials utilized in the manufacturing of cover of the traditional refrigerator/freezer, which is comprised of polyurethane insulation. Figure 3.2 illustrates the various materials that comprise the cover and walls of a traditional commercial refrigerator/freezer. Two separate metal trays are coated with polystyrene to form the exterior of the unit. The process by which it is manufactured involves molding steel sheeting to form the inner and outer surfaces of the walls and chest cover. The inner plastic sheeting is molded separately and attached to the metal tray by plastic fasteners. Polyurethane is injected into the outer steel and inner plastic liner. The polyurethane is manufactured in liquid form and is produced by combining poliol, isocyanate, and water or another mixed physical or chemical blowing agent, used to produce flexible polyurethane foam with low densities. The injected polyurethane takes the form of foam and is inserted at a specific pressure. After a prescribed setting time, this foam hardens between the liners and the steel strips and provides insulation and structural support to the unit.

3.2 Unit B: Alternative Insulation Construction

Figure 3.3 shows the dimensions of the materials utilized in the manufacturing of the insulation for the cover of Unit B. Figure 3.4 illustrates the idealized alternative insulation design, employed in Unit B. A specific assembly sequence to optimize energy efficiency as well as material recovery at the end of life was developed. The redesigned insulation proposes two separate production sequences before the final assembly of the refrigerator/freezer chest. The first of these is the production of the insulation cartridge. The insulation system utilizes a honeycomb cartridge; manufactured using vacuum formed recycled plastic obtained from the waste stream of the disassembly and recovery facility to form hexagonal cavities of size 5” with an outside 90 degree flange, 1” wide with predrilled holes. The recycled plastic ‘honeycomb’ mold is used for its ability to provide structural support to the unit.

Cavities within the honeycomb sheet are subsequently sprayed with heat release adhesive and fitted with 3 in.^2 hexagonal plastic packets of industrial grade fumed silica beads. Specialized fumed silica sand is utilized due to its ability to absorb moisture, prevent conductive and convective heat losses, and regenerate after use. The size of the silica sand used in the design was chosen to minimize heat transfer. Thus, silica sand with medium density and higher surface was chosen to reduce heat transfer. The density of the silica was carefully chosen as a sand with higher density would increase conductive heat loss, but a lower density sand would increase heat transfer due to convection and radiation. In the production of the silica packets, each plastic packet is subjected to the generation of a vacuum to a level of 3.4kPa. The generation of a vacuum ensures that heat loss from the cold cabinet to the inside air is minimized. The honeycomb cartridge is manufactured with proportionate dimensions so that it may be inserted into the external and internal refrigerator metal trays, the metal skin is also manufactured with an inside flange with predrilled holes proportionate to the cartridge.

The second part of the production sequence begins with outfitting the external metal skin of both the refrigerator/freezer walls and chest. Heat release adhesive is sprayed into space between the metal tray and a reflective heat shield is inserted into tray for further insulation. The insulation cartridge manufactured in part 1 of the production sequence is fitted into the space between the metal tray and a small amount of polyurethane foam is injected into the area between the cartridge and the external metal through the one way valve. The cartridge is sealed into the metal tray with plastic panel retainer clips.

The walls and the cover of the refrigerator/freezer are assembled through traditional means: e.g., welding at the points of contact. After the assembly is fully complete, the white plastic acrylic is fastened to the outside of the unit to maintain traditional aesthetics.

Following the testing of the traditional polyurethane insulation Unit A, described further in Section 3.4, the cover of the unit was removed and the polyurethane insulation was stripped. It was then replaced with the alternative insulation, as shown in Figure 3.7. Every effort was made to duplicate the conceptual design for testing. However, due to manufacturing constraints, a few changes were made to Unit B. The plastic cartridge in which the packets of evacuated silica were placed was constructed in six parts. This was due to the limitations of the size of the vacuum thermo-former used to cast the cartridge. These parts were then joined using epoxy resin. Accordingly, there was a total additional 6 in.^{2} of thermoformed plastic incorporated into the testing prototype.

3.3 Test Units Description and Environmental Control Chamber Conditions

The refrigerator/freezer unit utilized in the testing is shown in Figure 3.5. It measured 20.7 in. x 23.8 in. x 34.45 in., had a net weight of 117 lbs., and was outfitted with an 115V AC reciprocating hermetically-sealed compressor, automatic electrical defrost heater, and was charged with 140 grams of R134a refrigerant as a working fluid. The compressor was a single fixed-speed type, with thermo-stat based on and off control. The refrigerator unit was installed in a test chamber in the Testing and Development Laboratory in Tampa, FL on March 28-30, 2013. The testing chamber contained the refrigerator unit, laptop computer, and test equipment. All internal metrics were monitored on a hourly basis to ensure they remained constant. The aambient temperature is described my subsequent figires.

The control room was outfitted with a thermostat, humidity gage, and room pressure monitor. The humidity, air pressure, and temperature in the room were brought to steady state conditions as prescribed by the ASHRAE standard 72-2005 which calls for a humidity of 45%, air pressure of 101MPA, and a constant ambient temperature of 75° F.

The heat flux sensors used in testing were an OMEGA HSF-4 sensor (Stamford, Connecticut), used in conjunction with integrated thermocouple and an OMEGA DP41-E digital process indicator (Stamford, Connecticut) connected to a laptop computer. Power consumption on each unit was also measured simultaneously. The temperature and heat flux measurements obtained from the measurements were recorded digitally at the top of every hour of the test. The heat flux sensor and data collection utilized in the study had the ability to record heat flux measurements every five seconds. Table 3.1 further describes the instrumentation utilized in testing.

Once testing for Unit A was completed, the testing apparatus was dismantled and the cover of the unit was removed and replaced with the modified insulation (Unit B). A sequential description of the preparation of the modified insulation is shown in Figures 3.6 and 3.7. Unit B was then placed in the testing chamber and the testing was repeated.

3.4 Experimental Testing of Unit A and Unit B

The testing for Unit A commenced on March 28, 2013. As prescribed by the testing standard, 27 saline packets were placed in the refrigerator. The testing began after the saline packets froze and the internal temperature reached standard operating temperature of -11°F, at hour 7. The testing lasted for 28 hours, during which the heat flux (W/m^2), power consumption (Kwh/day), and internal temperature (°F) were recorded. Figure 3.8 shows the location of the network of monitors used to measure the heat flux and temperature. Thermocouple masses were used to record temperature. Four heat flux sensors (measuring 2 in. x 2 in.) were installed to measure the heat transfer rate across the walls of the refrigerator. Heat sensors were fastened to the inside of the acrylic cover, where it would come in contact with the conditions of the internal refrigerator/freezer cabinet, and the corresponding sensor was placed on the outside of the unit where it would come in contact with the ambient air. Two more heat flux sensors were placed on opposite walls of the unit which served as the control. Figure 3.9 shows the preparation of Unit A for testing. While the focus of this study was to measure the change in heat flux through the cover, since it was the major component that was replaced, heat flux sensors were also placed in the walls of the unit to monitor the heat flux through the walls. Due to manufacturing constraints, polyurethane foam was utilized in the walls for both Unit A and Unit B.

Internal temperature and power consumption in various locations along the walls and cover of the unit were measured every hour. Heat flux sensors were connected to separate data acquisition systems outside of the cabinet and monitored heat flux in five second intervals. At locations where the door seals were displaced with wires from the thermocouple probes, moldable duct sealant was used to block air flow through the gaps, and insulation foam was used to reduce the heat gain made by the presence of the instrumentation.

3.5 Results and Discussion

The ambient temperature for Unit A and Unit B testing is presented in Figure 3.11 where the environmental chamber temperature was monitored to maintain a test standard of 75° F. Following an initial temperature anomaly at the commencement of testing, during hour 2, there was near no fluctuation, with an average deviation of 0.1°F. The consistency of the ambient temperatures ensured the accuracy of the reported data.

The temperature of the internal cabinets of Unit A and Unit B are shown on Figure 3.12. There was a significant decrease in the internal temperatures of the units due to a 7 hour stabilization period where the internal cabinet air went from ambient room temperature to a standard operating temperature of -11°F.

As the initial observations recorded in Figure 3.12 indicated that internal temperature stabilized after 6 hours and 30 minutes, heat flux and power consumption monitoring commenced at hour 7. Figure 3.13 shows the results of the heat flux through Sensor 1, the sensor closest to the west wall of the unit. The heat flux for the polyurethane through this sensor fluctuated from 6.4W/m^2 at hour 15 to 5.3W/m^2 at hour 18. By comparison, the heat flux through this sensor for Unit B varied from a peak of 3.9 W/m^2 at hour 10, to a minimum heat flux of 3.5 W/m^2 at hour 8. This suggests that the insulation utilized in Unit B had a more consistent thermal resistance.

Heat flux as measured by sensor 2 is shown in Figure 3.14. The trend observed by the results of Sensor 1 was also true of sensor 2, where a more significant level of heat flux fluctuation was observed through Unit A. Figure 3.14 shows that the lowest level of heat flux observed by sensor 2 in unit A was 5.5 W/m^2 and occurred at hour 8. The peak heat flux for sensor 2 was 6.7 W/m^2 at hour 19. For Unit B, the lowest heat flux recorded was 3.4 W/m^2 at hour 10. There was a significant increase in heat flux through the insulation of Unit A between hour 18 and 19, where an increase of 1.1 W/m^2 was observed.

Figure 3.15 shows the average heat flux through sensors 1 and 2. It was observed that there was an average decrease in heat flux of approximately 40%, when comparing Unit A to Unit B. Additionally, there is less of a deviation in recorded heat flux in Unit B. This is typically characteristic of a more uniform heat resistance configuration, which may indicate that the honeycomb structure in conjunction with the primary insulator of vacuumed silica packets was an effective pairing for the purposes of thermal efficiency.

Since the ambient conditions and the internal temperature of the refrigerator/freezer remained constant during the testing, the fluctuations in heat flux across each type of tested insulation are indicative of the insulation materials and configuration. This is further supported by the heat flux data collected by the sensors located on the unit walls, as shown on Figures 3.16 and 3.17. The insulation was not replaced in the walls of the unit; polyurethane insulation was utilized as the primary insulator for both Unit A and Unit B. As shown, the heat flux remains relatively constant through Unit A and Unit B, and indicates that the heat flux was heavily dependent on the insulation material utilized in testing.

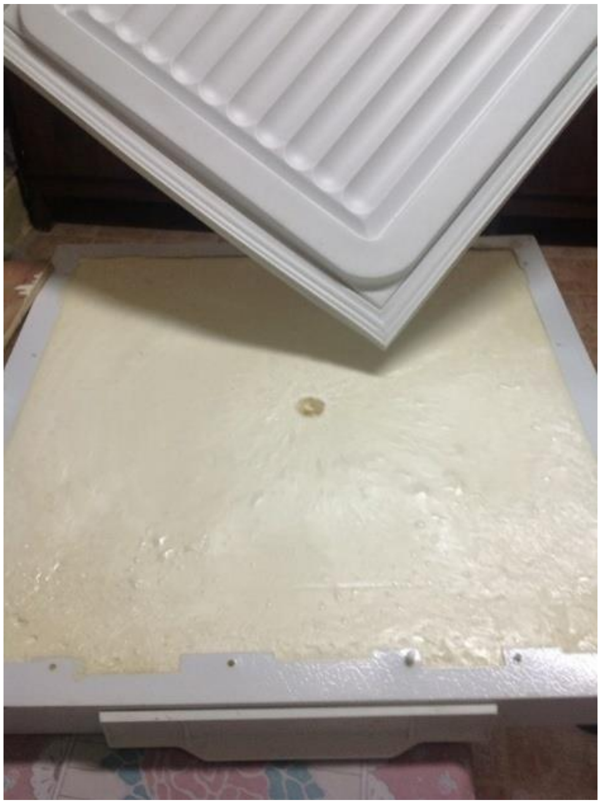
Results of the power consumption measurements are shown on Figure 3.18. The power meter began recording after hour 7, after the internal temperature had normalized.

Figure 3.18 shows the power consumption was consistently higher for Unit A. Cumulative power consumption after 24 hours of testing was recorded to be 0.92 kWh and 0.869 kWh for Unit A and Unit B respectively. It was also noted that the difference in energy consumption was slightly more significant between hours 17 to 20.

While the exact relationship between heat flux and power consumption in this case is indistinguishable from the given data, the results indicate that a clear trend is present, where a marked increase in thermal and energy efficiency is achieved by the use of the modified insulation used in Unit B. On average, the alternative insulation performed 25-40% better with direct heat transfer. In agreement with this trend, there was an observed approximate 5% reduction in overall energy usage per day. This is significant when considering the annual power consumption of a commercial refrigerator/freezer and the power consumption over the life time of the unit.

Table 3.1 The instrumentation used in the testing was selected based on industry standard. Each instrument was calibrated before use.

Sensor	Model	Range	Accuracy	Function
Heat flux sensor	Omega HSF-4	0 - 3.1 x 10^5 W/m^2	2%	Measures the rate of heat transfer between surfaces.
Power meter	P3 Kill-A-Watt	kWh	0.01kWh	Measures cumulative power consumption.
Thermocouple	Omega-Type T	-25 F to 85.5 F	0.5˚	Measures temperature at various points of unit.
Thermostat	Associated Env. Systems FD-200	50 to 95˚C	0.3˚	Measures air temperature in testing chamber.
Atmospheric pressure	Associated Env. Systems FD-200	700 to 800 mm Hg	0.02%	Measures air pressure in room.
Relative humidity	Associated Env. Systems FD-200	0% to 100%	0.50%	Measure relative humidity in testing chamber.



Material	Thickness	Dimensions
Cover	3.08 in.	20.7 in. x 23.8 in.

Figure 3.1 A traditional refrigerator/freezer cover composition. Typically, it is comprised of a plastic skeleton, metal sheet and injected polyurethane foam. The dimensions for the components of the traditional insulation are shown above.

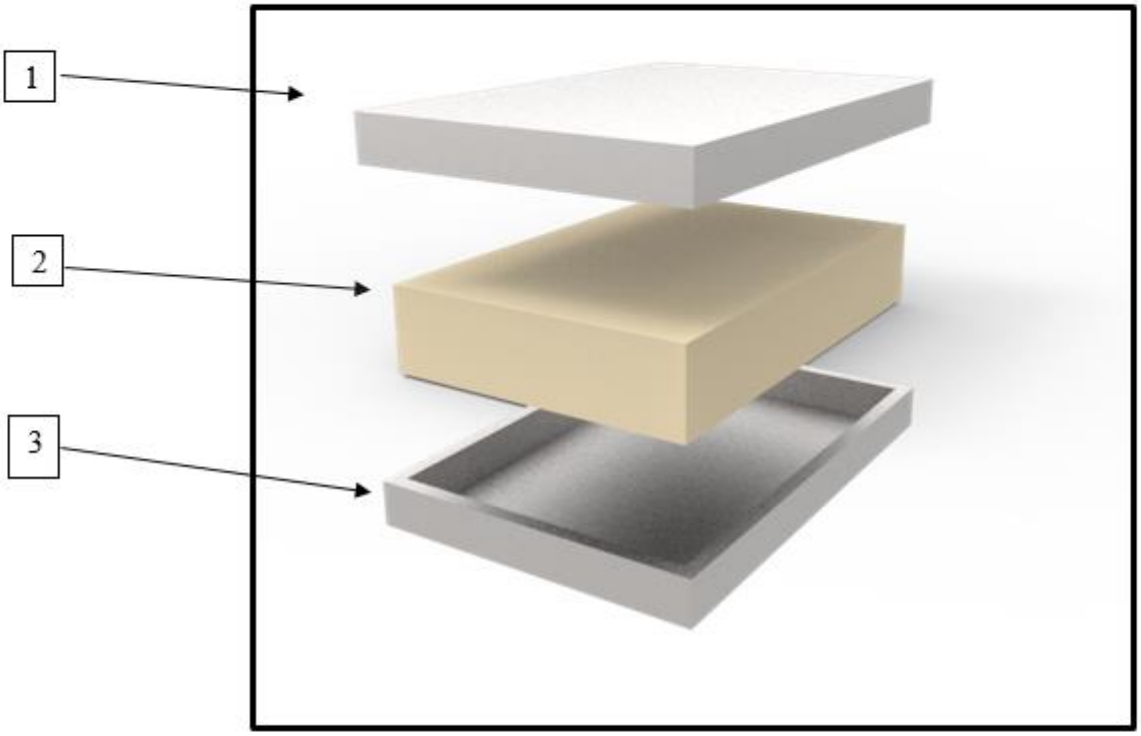


Figure 3.2 Traditional refrigerator/freezer cover composition schematic. Traditional refrigerator cover and walls incorporates insulation that is comprised of liquid polyurethane foam that is injected in between two metal trays and allowed to harden. (1) external metal tray with an acrylic coating; (2) hardened polyurethane, the primary insulator; (3) opposite metal tray also coated with acrylic.

Material	**Thickness**	**Area**
Cover	3.08 in.	20.7 in x 23.8 in.

Figure 3.3 Commercial refrigerator wall cross-section. The insulation redesigns employ the use of recycled silica beads under a partial vacuum to reduce heat transfer between the internal freezer compartment and the ambient air.

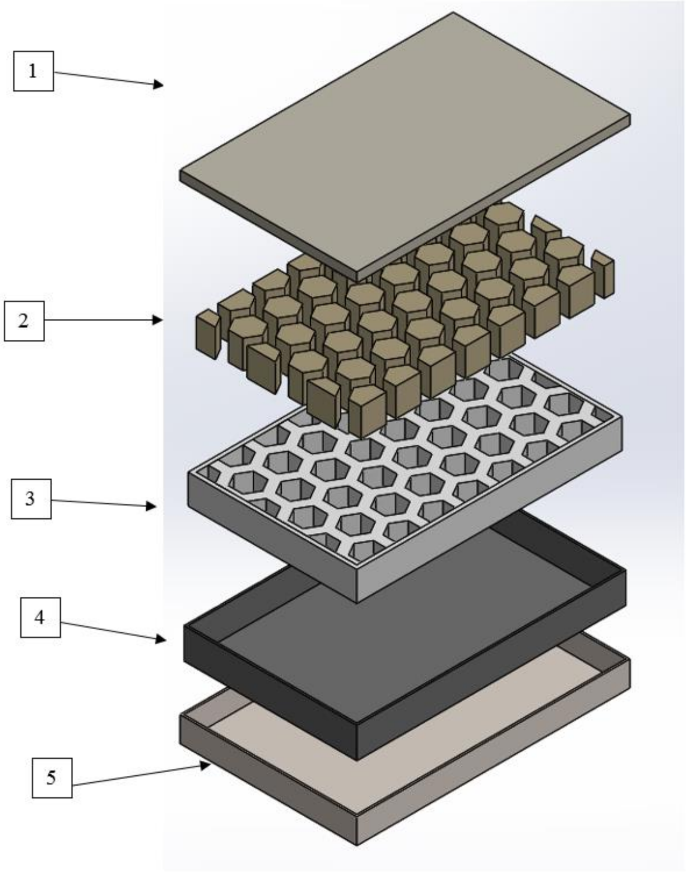
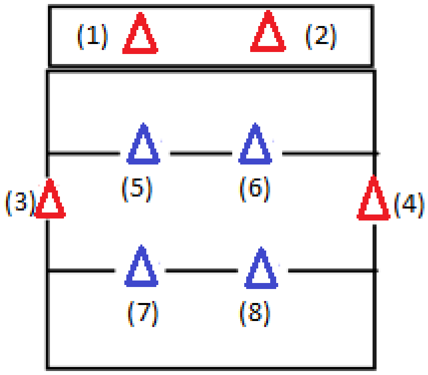


Figure 3.4 Alternative commercial freezer chest cover schematic. It is comprised of (1) external metal cover that is covered with a white acrylic sheet; (2) packets of evacuated silica are inserted into the recycled plastic cartridge (3); (4) reflective heat shield that encompasses the cartridge; (5) external metal tray that is also covered with a sheet of white acrylic for standard aesthetic purposes.

Figure 3.5 The testing unit is a 5 ft^3 Whirlpool refrigerator/freezer. It was placed in a controlled environmental chamber where the ambient temperature, air pressure and humidity were controlled based on ASHRAE testing standards.

Figure 3.6 After the traditional testing was conducted, the cover was removed and the external plastic sheet was removed. The internal metal sheet was pried from between the plastic sheet and the polyurethane manually.

Figure 3.7 The polyurethane insulation from Unit A was manually stripped and the metal sheeting was pried apart from the external plastic sheath. The reflective heat shield was inserted, followed by the thermoformed pastic insulation cartridges contained packets of evacuated silica. The insulation cartridges was split into six parts due to limitations of manufacturing, and then joined using epoxy resin.



Δ: Heat Flux sensor location Δ: Thermocouple location

Figure 3.8 Location of the network of monitors used to measure heat flux and temperature. The blue ‘Δ’s represent the location of the thermocouples, and the red ‘Δ’s represent the locations of the heat flux sensors.

Figure 3.9 Testing of Unit A. Testing protocol (ASHRAE 72-2005) states that test units must be filled with saline packets to simulate real world conditions.

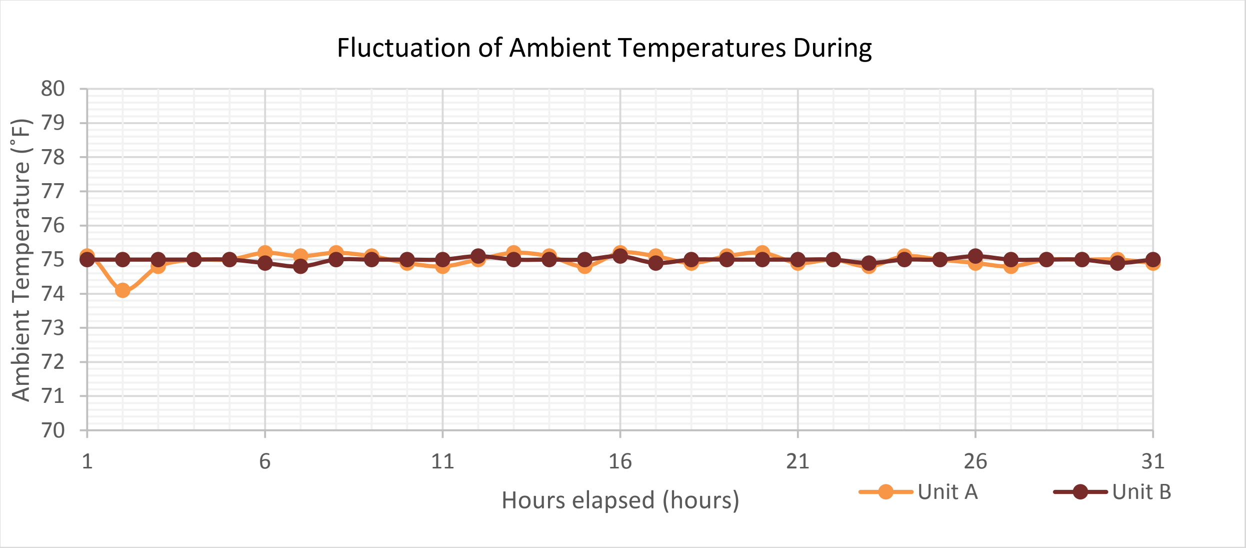


Figure 3.10 Time variation of ambient temperature by hour during testing of Unit A and Unit B. Ambient temperature was kept at a constant of 75°F, as prescribed by ASHRAE methodology.

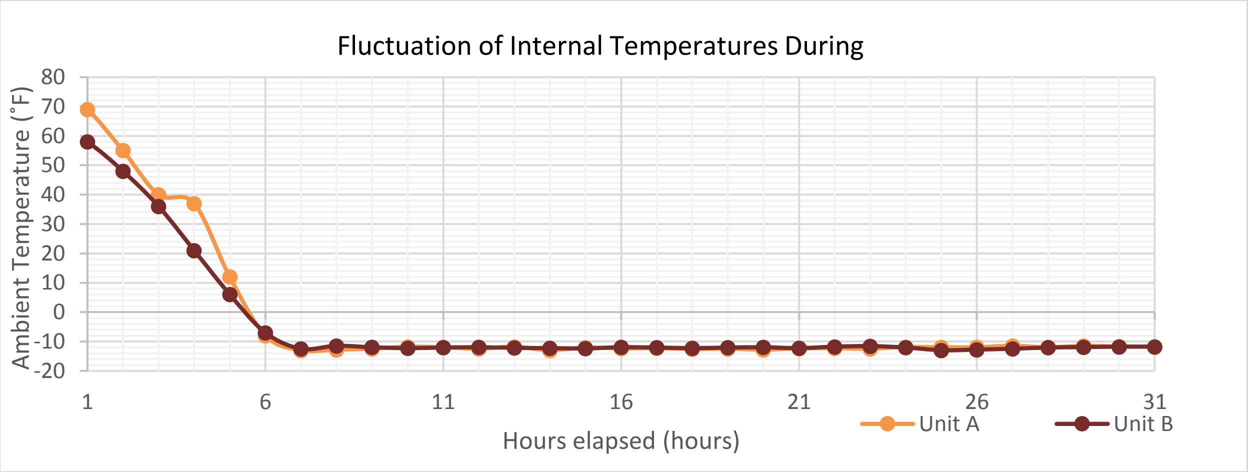


Figure 3.11 Time variation of internal temperature of the refrigerator/freezer was monitored constantly through testing. At (0) hour, the unit was plugged in. At 6.5 hours into the testing, the internal temperature leveled to a consistent operating temperature of -11°F.

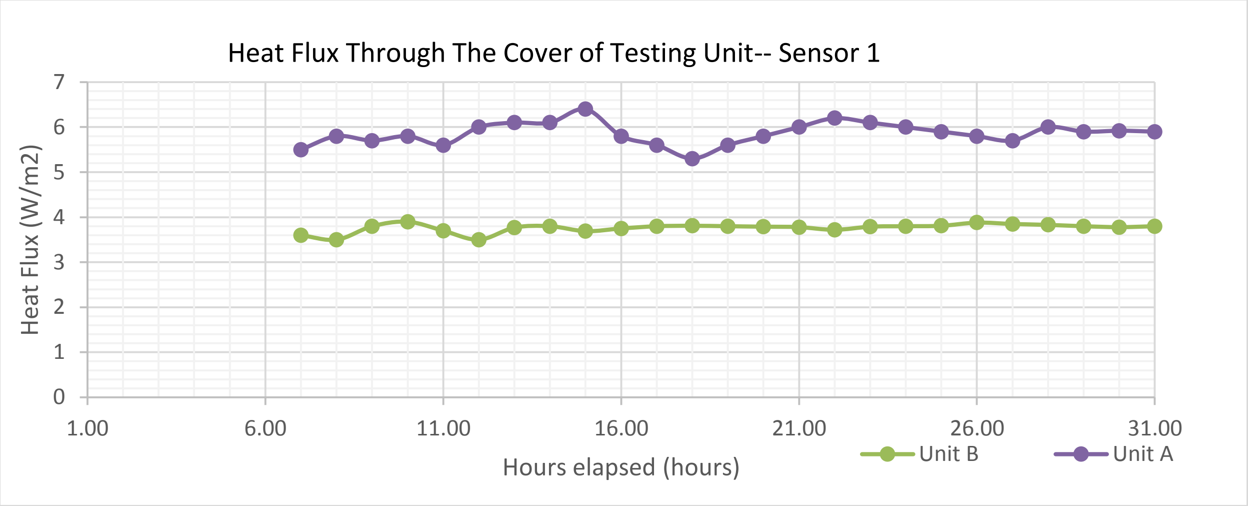


Figure 3.12 Sensor 1 was placed on the west side of the cover. The heat flux of Unit A across this sensor was 20-50% greater than that of the heat flux of Unit B.

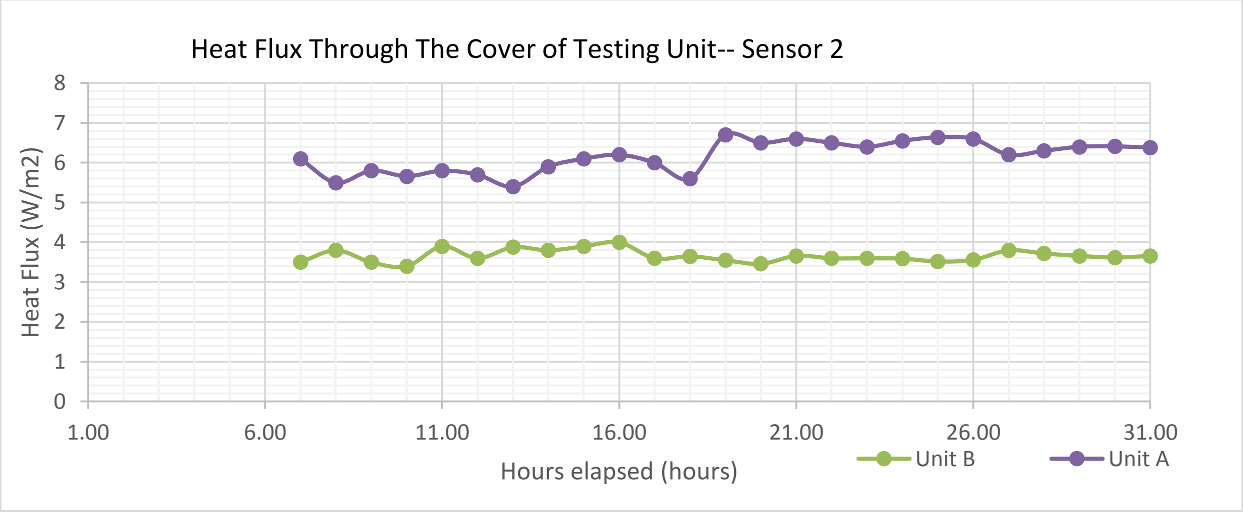


Figure 3.13 Heat flux through the cover the units. Sensor 2 was placed on the east side of the cover. Sensor 2 agreed with the trend observed by Sensor 1: heat flux across the insulation of Unit A was 20-50% greater than the insulation utilized in Unit B.

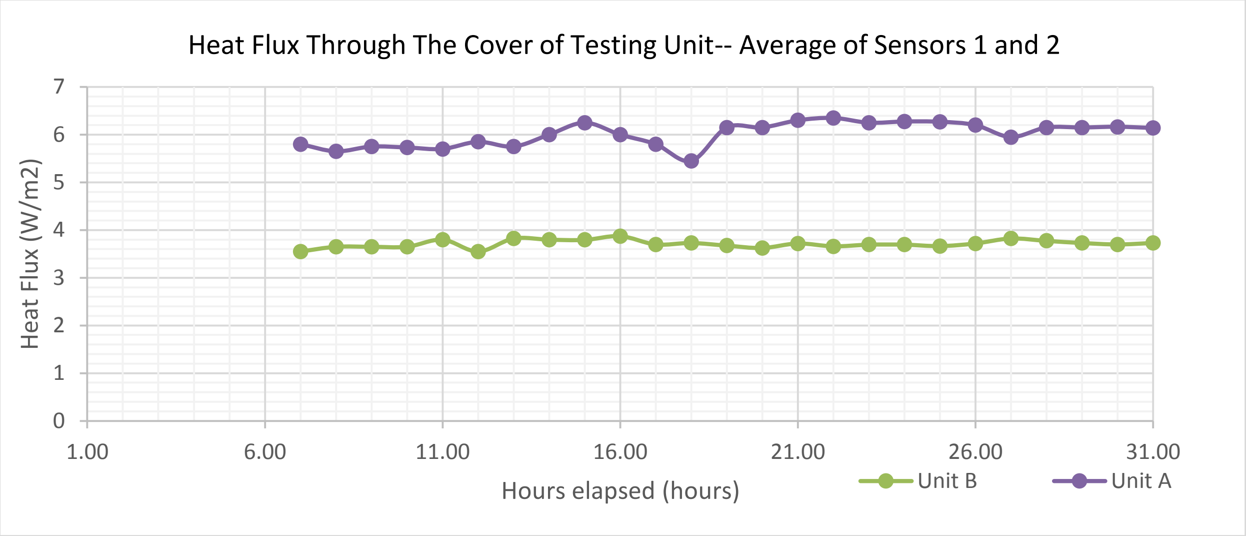


Figure 3.14 The heat flux through the cover of the testing unit was measured and averaged. The heat flux through the modified insulation decreased by 25 to 40% as compared to the polyurethane insulation.

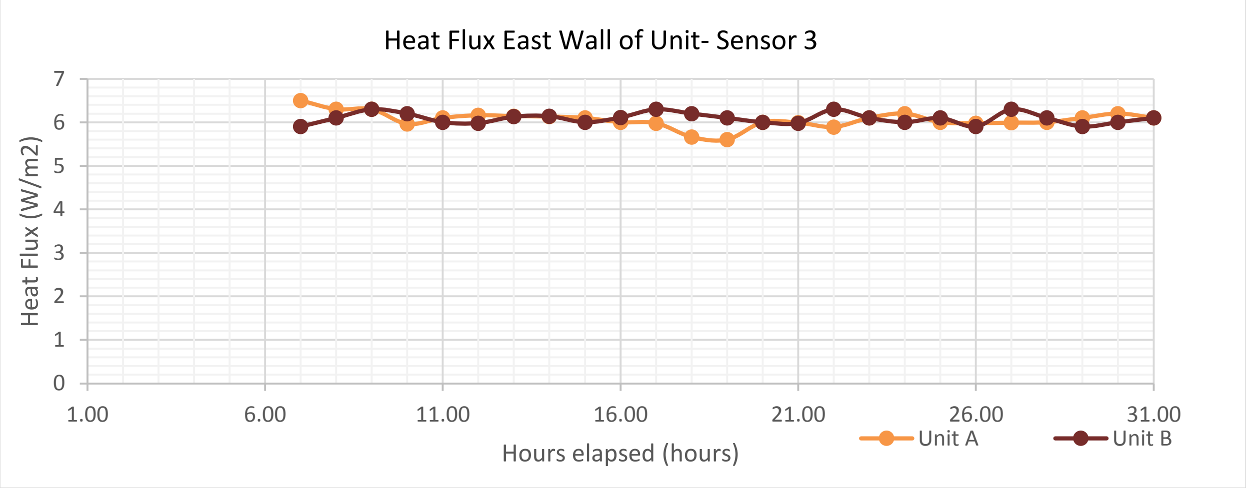


Figure 3.15 Time variation of the heat flux through the east wall (sensor 3) of the refrigerator/freezer unit remained relatively constant for Unit A and Unit B. Both units employed polyurethane insulation as the primary insulator.

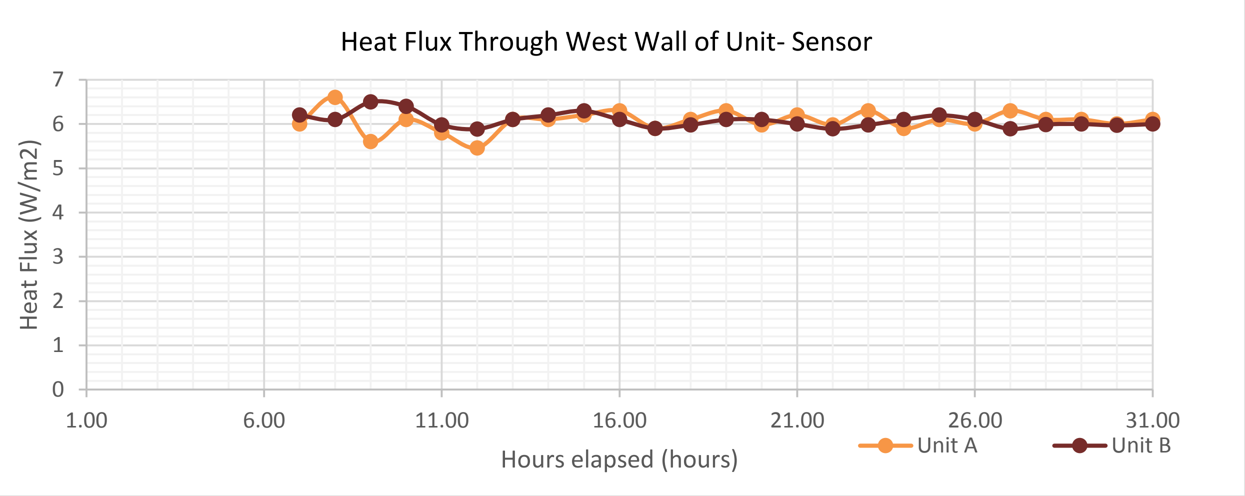


Figure 3.16 Time variation of the heat flux through the west wall (sensor 4) of the refrigerator/freezer unit remained relatively constant for Unit A and Unit B. Both units employed the same polyurethane insulation as the primary insulator.

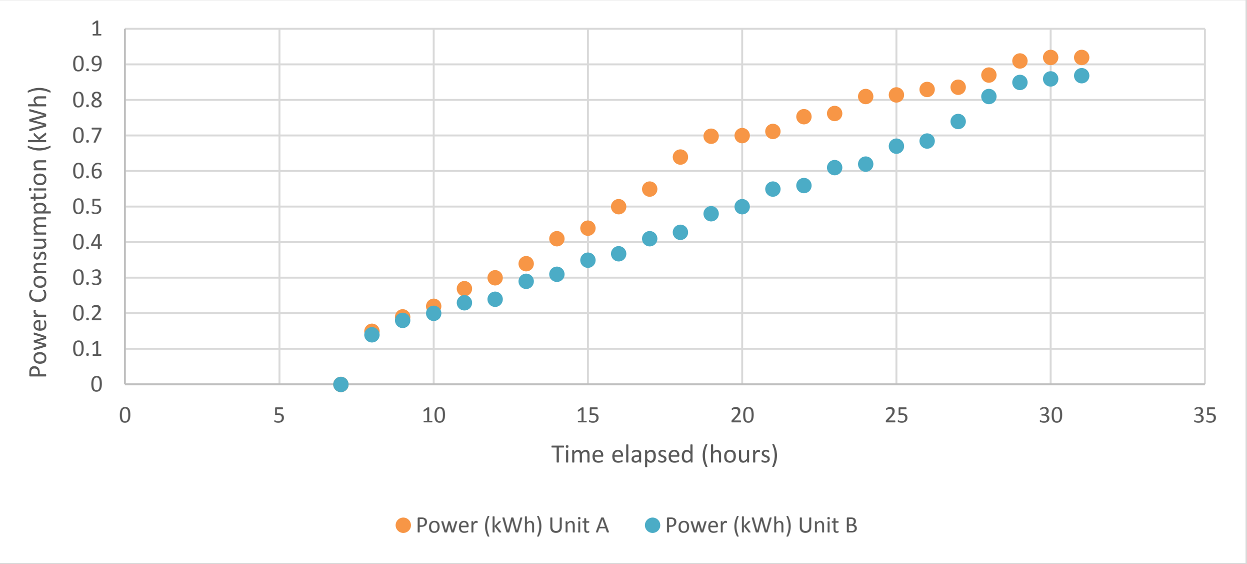


Figure 3.17 Cumulative power usage (kWh) by Unit A and Unit B over 24 hours. Power usage was recorded on an hourly basis as each separate test was conducted.

CHAPTER 4: THERMAL ANALYSIS

4.1 Thermal Analysis Methodology

4.1.1 Analysis of Heat Transfer through Refrigerator/Freezer Cover

The heat flux and power consumption experienced by the polyurethane foam utilized in the traditional unit, Unit A, and the modified insulation utilized in Unit B were investigated experimentally in Chapter 3. This was achieved by recording heat flux and power consumption data through each type of insulation under controlled laboratory conditions. The resulting heat flux and power consumption metrics showed a decrease in heat flux of between 35-50% and a 5.1% in daily power consumption through the modified insulation utilized by Unit B.

To further examine the heat transfer characteristics through each insulation medium, and to calculate the effects of the thermal loads on each component once initial conditions were established a steady-state thermal analysis was conducted. This was achieved using heat transfer principles, and employing the computer program ANSYS (2012) to study the temperature distributions through each type of insulation and determine the most significant sources of heat loss.

The theoretical investigation of the heat transfer utilized an Excel analysis based on the heat transfer principles and the parallel path method to quantify the thermal performance of polyurethane foam as utilized in Unit A, and the alternative insulation, as utilized in Unit B.

4.1.2 Thermal Analysis Model

The theoretical heat transfer through the walls of the refrigerator/freezer unit was studied by considering the insulation in the wall and cover of the refrigerator/freezer unit as a multi-layered structure with each layer contributing its own thermal resistance. The external layers are made of a steel shell, with a thin coating of white acrylic for aesthetic purposes. The internal layer is the core resistance material, polyurethane in the case of Unit A (Figure 4.4), and the insulation cartridge including the recycled plastic cartridge and packets of evacuated fumed silica, in the case of Unit B (Figure 4.11). Heat passing through this multi-layered structure can be modeled and quantified using Fourier's diffusion equation, described in Section 4.4.

In the theoretical component of the study, calculations derived from basic heat transfer principles (described in Section 4.4) were performed to predict the heat transfer through the walls per unit area for each type of insulation. The results of the calculations were compared to the experimental results from Chapter 3 to validate the thermal model.

4.2 Thermal Analysis Assumptions

Under steady state conditions the power utilized by the compressor is used mainly for the removal of hot air that has infiltrated the cold cabinet through the gaskets and walls of the unit, as well as the heat produced by the other mechanical parts of the unit; the defroster and fan. Then, the energy consumption is determined by the exchange of heat between the mechanical parts and can be computed through separate steady state analysis (Hessami, 2012). For the purposes of creating a thermal model to determine heat transfer through the wall of the unit, the following assumptions were made:

1. A steady rate of heat transfer is assumed because the ambient temperature and internal cabinet temperature are at controlled and specific temperatures.
2. Heat flux is one-dimensional.
3. Values of thermal conductivities are constant throughout the materials.
4. Heat transfer coefficients account for any radiation heat transfer incurred.

5. Heat input due to leakage and refrigerator components is equal to the power consumption of the compressor.
6. The heat interface between the contacts of material is negligible.

4.3 Background: Principles of Heat Transfer

The first law of Thermodynamics, the balance of energy, is the fundamental principle by which heat transfer can be expressed, and is the driving principle for the thermal analyses in this research. It can be stated as follows:

Heat transfer occurs in materials in three ways: convection, conduction and radiation, and the total energy flux vector in a material are comprised of these three contributions. Heat transfer occurs by convection as warm air moves; this type of heat transfer is often thought of as moving as air currents do. Conduction occurs when energy is transferred between particles. Radiation heat transfer occurs when electromagnetic waves transmit energy through air.

4.3.1 Mode 1: Conduction

Fourier's Law, the law of heat conduction, states that the transfer of heat through a material *is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient through which the heat flows* (Bailey, 2011).

Fourier's law can thus be expressed differentially (in one-dimension), as in Eqn. 4.1, or in the integral form, Eqn. 4.3. The rate at which heat is supplied by conduction can be expressed as a differential as shown in Eqn. 4.1:

$$\vec{q} = -k\nabla T \qquad \text{[Eqn. 4.1]}$$

where $\vec{q}$ is the local heat flux density, k is a property of the material's conductivity, and the ∇T is the temperature gradient expressed as a vector quantity. More simply, assuming a one-dimensional form in Eqn 4.2:

$$q_x = -k\left(\frac{\partial T}{\partial x}\right)$$ [Eqn. 4.2]

where q_x is the heat flux in the x-direction; or the thermal flux per unit time $\left(\frac{\partial Q}{\partial t}\right)$; and $\left(\frac{\partial T}{\partial x}\right)$ is temperature gradient along the x direction. At room temperatures radiation energy is proven to be negligible. By integrating the differential form of Fourier's law through the surface of the material (S), the integral form of the Fourier's law is expressed as:

$$\left(\frac{\partial Q}{\partial t}\right) = -k\oint_S \nabla T * dA$$ [Eqn. 4.3]

where the term $\left(\frac{\partial Q}{\partial t}\right)$ is the change in heat transfer over time; S is the conductivity surface; T is the vector form of temperature, and A is the area. The final form of Eqn. 4.3 after integration in one dimension (x) is expressed as:

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$ [Eqn. 4.4]

where $\frac{\Delta Q}{\Delta t}$ is the heat transfer rate ($\dot{Q}$), and A is the area of heat transfer. Given there are multiple materials lengths (L) and their associated conductivities (k) across path (x), an alternative form of this equation for heat flux (rate of heat transfer per unit cross-sectional area) is:

$$\dot{Q} / A = \frac{T_1 - T_2}{\left(\frac{L}{k}\right)_1 + \left(\frac{L}{k}\right)_2 + \ldots. + \left(\frac{L}{k}\right)_m}$$ [Eqn. 4.5]

where T_1 and T_2 are the ambient and internal temperatures respectively, and L in is resistance path. Thermal conductivity exhibits a weak dependence on temperature, and a slight dependence on pressure. This thermal behavior is known as Fourier's law of heat conduction. Fourier's law of heat conduction is an analogy of Ohm's law where the current flowing through an element is a function of the voltage across the element proportional to the electrical resistance across the element.

4.3.2 Mode 2: Convection

Convection refers to the movement within gases or liquids though advection or diffusion, where particles move from an area of higher thermal energy to an area of lower thermal energy. The heat transfer per unit area of material described by the convection heat transfer equation is known as Newton's Law of Cooling. Convection does not take place in solids, unless there are air pockets present. The rate at which energy is supplied by convection can be expressed as a differential as:

$$q_z = -h\left(\frac{\partial T}{\partial z}\right) \qquad \text{[Eqn. 4.6]}$$

In Equation 4.6, the new term *h* refers to the convective heat transfer coefficient, a property of the gas. At room temperatures radiation energy is proven to be negligible, and Eqn. 4.5 can be derived as above to obtain an equation for the rate of heat transfer due to convection as:

$$\dot{Q} / A = \frac{T_1 - T_2}{\left(\frac{1}{h}\right)_1 + \left(\frac{1}{h}\right)_2 + \ldots + \left(\frac{1}{h}\right)_\infty} \qquad \text{[Eqn. 4.7]}$$

4.3.3 Mode 3: Radiation

Radiation results from the thermal agitation of the molecules of a material, and can be fined as the energy transport present in the absence of matter through the air by action of photons (Whitaker, 1983). Experimentally, it has been proven that the most significant wave action occurs along wave lengths of range 10^{-2} to 10^{-5}, energy transported on this spectrum is thermal radiation. The thermal radiation emitted from solids between these wave-lengths are described by the Stefan Boltzmann law:

$$q^{R} = \varepsilon\, \sigma\, (T_{h}^{4}) \qquad \text{[Eqn. 4.8]}$$

where $q^R$is the energy that was emitted per unit time per unit area of solid. The temperature term (T) is the absolute temperature of the solid body emitting the radiation. Another property of the material emitting the radiation is (ε), the emissivity coefficient, unique to each type of material. The Stefan-Boltzmann constant (σ) has been found experimentally to be 1.71 x 10^{-9} Btu/hrft^3 -°R^4.

In analyzing the radiation energy exchange, it can be stated that the rate at which radiation energy is emitted from the solid body is equal to the rate at which radiant energy is absorbed by the body. Though theoretically radiative heat transfer is always present, it has been experimentally proven that at moderate temperatures, radiation effects are negligible in higher density materials (more than .0554 g/cm^3) (Pelanne, 1980). Additionally, radiation is typically inconsequential for temperatures lower than 200°F. However, in temperatures greater than 1,000°F, this mode of heat transfer is the most significant of the three types, as radiation is dependent on temperature to the order of four magnitudes (Whitaker, 1983). As all materials utilized in this research have densities higher than that the postulated value, and the ambient and internal temperature are significantly lower than 200°F, radiation effects will be ignored.

4.4 Heat Transfer through Insulation

All modes of heat transfer are present as air passes through insulation. As established above, the ambient conditions and material properties are such that radiation heat transfer is negligible. The steady state heat transfer taking place between the surrounding air and the walls and cover of the commercial refrigerator/ freezer is known as free convection, as the less dense air outside of the unit moves toward an area of more dense air within the unit, the density of the air carries and an intrinsic resistance that must be included in the overall heat transfer calculation.

Conductive resistance occurs as air moves through the insulation material. To quantify the conductive and convective heat transfer occurring between the walls of the unit, the insulation can be considered as a composite structure similar in nature to an electrical circuit. The thermal resistance of the insulation, R_{wall}, varies depending on the type of insulation utilized in the unit. For the traditional unit, the resistance of the insulation will be determined by the thermal conductivity of the polyurethane foam, air pockets and metal reinforcing bars. For the modified unit, the resistance of the insulation relied on a complex network of the reflective heat shield, honeycomb structure and silica beads under a vacuum. The basic mechanism by which the heat transfer can be modeled is shown in Figure 4.2.

T represents the temperature differential between the ambient air ($T_{\infty1}$) and the air inside of the cabinet ($T_{\infty2}$), which is the driving contributor to the convective heat resistance ($R_{conv,1}$) and ($R_{conv,2}$). Also contributing to the overall heat transfer rate ($\dot{Q}$) is the conductive resistance through the wall of the unit (R_{wall}). Utilizing the heat transfer equations described above, and employing the electrical resistor analogy to quantify the total resistance (R_{wall}) occurring air and material properties, the following equation 4.9 for total heat transfer ($\dot{Q}$) is derived:

$$\dot{Q} = \frac{T_{\infty 1} - \mathrm{T}_{\infty 2}}{R_{conv,1} + R_{wall} + R_{conv,2}} \qquad \text{[Eqn. 4.9]}$$

Considering each heat transfer mode to be cumulative, combining the resistances from conduction, shown in *Eqn. 4.5,* and convection, as shown in *Eqn. 4.7,* the total cumulative heat transfer per area (heat flux) can be expressed as:

$$\dot{Q}/A = \frac{T_{\infty 1} - \mathrm{T}_{\infty 2}}{\frac{1}{h_1} + \left(\frac{L}{k}\right) + \frac{1}{h_2}} \qquad \text{[Eqn. 4.10]}$$

4.5 Analysis Inputs

The theoretical thermal model inputs are determined primarily by the material properties as well as the ambient and internal temperatures of the refrigerator/freezer unit.Material properties summarized in Table 4.3.

The traditional unit wall is comprised of injected polyurethane insulation sandwiched between two layers of sheet metal. Within the polyurethane foam there are small pockets of air that allows convection, conduction and radiation to take place through the wall of the unit. The rate at which each type of heat transfer that occurs within the walls and cover of the unit is highly dependent on the size of the air pockets within the foam, as well as the density and configuration of the gaseous pockets relative to the heat flow direction. Past research by Valenzuela & Glickman (1981) and Hessami (2001) shows that the polyurethane foam is made up of 97% blowing agent, of equal parts R_{12} and COB$_2$B, with less than 3% entrapped air. Thus, a simple model can ignore the effects of convection and radiation through any air captured in the polyurethane foam.

In steady-state operation, the rate of heat transfer through the refrigerator wall is constant, and thus heat transfer between the room and the refrigerated space is equal to the heat transfer between the room and the outer surface of the refrigerator. The model ignores the differential at the corners. Using the thermal resistance network, described by Eqn. 4.9, heat transfer due to conduction between the room and the refrigerated space for Unit A can be expressed by Eqn. 4.11:

$$\dot{Q}/A_{UNITA} = \frac{T_{\infty1} - \mathrm{T}_{\infty2}}{\frac{1}{h_1} + 2\left(\frac{L}{k}\right)_{metal} + \left(\frac{L}{k}\right)_{PU-foam} + \frac{1}{h_2}} \qquad \text{[Eqn. 4.11]}$$

The conductive thermal transfer relative to the modified unit is more difficult to model due to the complexity of the heat path. The thermal resistance is more complex for the modified insulation as the heat must travel through a network of materials. Since the silica packets were sealed into the recycled plastic cartridge, at any given point the insulation, heat would be transferred either through the cartridge or through the silica itself. Thus, to obtain an average value and account for the possibility of heat moving through each type of medium, weightings were assigned to each part of the heat transfer path equation depending on the proportion of material used throughout the design. The recycled plastic was assigned a weighting of 0.3, and the silica was assigned a weight of 0.7. The total heat transfer from the ambient air to the refrigerated space within Unit B can be quantified by Eqn. 4.12:

$$\begin{aligned}\dot{Q}/A_{UNITB} = (0.3) * &\frac{T_{\infty1} - \mathrm{T}_{\infty2}}{\frac{1}{h_1} + 2\left(\frac{L}{k}\right)_{metal} + \left(\frac{L}{k}\right)_{cartridge} + \left(\frac{L}{k}\right)_{heat-shield} + \left(\frac{L}{k}\right)_{PU-foam} + \frac{1}{h_2}} + \\ (0.7) * &\frac{T_{\infty1} - \mathrm{T}_{\infty2}}{\frac{1}{h_1} + 2\left(\frac{L}{k}\right)_{metal} + \left(\frac{L}{k}\right)_{silica} + \left(\frac{L}{k}\right)_{heat-shield} + \left(\frac{L}{k}\right)_{PU-foam} + \frac{1}{h_2}}\end{aligned} \qquad \text{[Eqn. 4.12]}$$

4.6 Analytical Investigation: Excel

A simple Excel-based heat transfer analysis was developed for use by engineers and designers to aid in the selection of insulation to improve heat flux metrics. The analysis includes a data inventory of common refrigerator/freezer insulative materials and can be expanded to include materials from developing new technology and their corresponding properties so that designers may explore the best option for their product through employing various networks of materials as primary insulators. Users must enter the ambient temperature as well as the internal temperature of the unit. The thermal analysis consists of a user interface that calculates the heat transfer through the insulation configuration prescribed by the user, utilizing the heat transfer equation described by Eqn.9. This user interface is pictured in Figure 4.3.

Table 4.2 lists the design parameters of the insulation that users may adjust in the Excel thermal analysis, as well as the corresponding effect that change may have on the overall heat flux value. Experimenting with changing the value of these inputs allow users to determine how design decisions regarding material properties and dimensions may ultimately affect the thermal behavior of the insulation.

Part 2 of the Excel model allows the user to employ ‘Goal Seek’ in the ‘Desired Heat Flux’ cell, by varying the lengths of insulation material. This allows the user to determine the effect that varying of certain parameters would have on the overall heat transfer. Limitations to the analysis in Excel are that is a one dimensional model, and it does not account for moisture or dynamic air flow.

Through the use of the Excel model, the value for the overall heat transfer for both units were calculated. The results are depicted in Table 4.3. The analysis also indicates that the total heat transfer due to convection remains constant for both units, and the convection accounted for 37% of the overall heat transfer for the traditional unit, and 62% of the overall heat transfer for the modified unit.

4.7 Analytical Investigation: Using Thermal Modeling Software

4.7.1 Introduction

The computer program ANSYS was also utilized to investigate the overall resistance to heat for both the polyurethane foam, as well as the insulation cartridge configuration. The ANSYS program was utilized in addition to the Excel analysis because of the program’s ability to examine the thermal behavior of the materials utilized in the insulation in a more detailed manner. The renderings for the insulation were imported from Solid Works For the purposes of this study, a steady state analysis was performed, and the initial conditions, internal and ambient temperature was kept constant at -11ºF and 75ºF respectively per experimental conditions. The analysis was steady state in nature as the material properties utilized in this research do not vary depending on temperature. The heat flux of each type of material is applied as surface loads.

4.7.2 Modeling of the Traditional Insulation

The traditional refrigerator/freezer cover was assembled utilizing Solid Works layers and is depicted by Figure 4.4. The first layer was formed of a metal sheet, polyurethane, with another sheet of metal layered on top. Properties were assigned to each layer based on manufacturer specification sheets. The boundary temperatures, 75ºF ambient and -11ºF for the internal cabinet were based on those used in the experimental section of the analysis, Chapter 3, and depicted in Figure 4.5. Figure 4.6 depicts the finite element mesh used in the analysis to ensure computational accuracy.

4.8 Results and Discussion

The total heat flux distribution for the traditional insulation through the cover was then analyzed using a steady state heat transfer analysis. The magnitude of heat flux was maximum at the metal on metal contact at the edges and corners of the refrigerator/freezer cover. At the edges and corners, a maximum heat flux of 29,175 W/m^2 was noted.

In the nodes contained within the metal, a significant decrease in heat flux was estimated with. The minimum heat flux is achieved at the center of the cover, at the point furthest away from the metal sheet, as shown by Figure 4.7. The heat flux through the polyurethane foam is observed to be 6.5 W/m^2.A cross section of the insulation shown in Figure 4.8 and illustrates the distribution of the gradient of the heat flux from the inside of the refrigerator/freezer to the ambient air. The heat transfer gradient is shown to be fairly linear as the heat moves through the polyurethane foam.

Figure 4.9 illustrates the heat flux through a cross section of the insulation. A notable observation from the ANSYS thermal analysis is that the heat conduction associated with the metal-on-metal contact from the metals skins extends approximately 0.05 m from the edge of the metal into the polyurethane insulated area before the heat flux is absorbed completely by the insulativeproperties of the foam. Figure 4.10 indicates the heat transfer vectors. The arrows indicate that the heat flow is perpendicular to the point of contact with the metal. Heat flux is most intense along the edges where the metal makes most contact with the polyurethane. It is also seen from Figure 4.10 that the heat flux intensity decreases as the heat moves through the polyurethane foam insulation.

4.8.1 Modeling of the Alternative Insulation

The alternative insulation was modeled in Solid Works to reflect the layers present in the experimental design. The external metal skins encompassed the alternative insulation design which along with the polyester heat shield, plastic honeycomb cartridge and evacuated silica packets are represented in Figure 4.11.

The SolidWorks rendering for the insulation utilized in Unit B was imported into ANSYS and physical properties were assigned to the layers based on the manufacturer specifications. The internal and external temperatures utilized in the experimental section were also used as the boundary conditions for the ANSYS model.The boundary conditions remained the same as Unit A, as shown on Figure 4.12; and mesh quality was comparable to that used for the analysis of Unit A, as illustrated by Figure 4.13. Figure 4.14 represents the total heat flux distribution through the insulation for Unit B here the maximum and minimum heat flux through this unit's insulation was determined to be 461.23 W/m^2 and be 3.1 W/m^2 respectively.

The heat transfer analysis based on the ANSYS model indicated that the maximum heat flux with the alternative insulation is less than that experienced by the unit with traditional insulation, and the corresponding heat flux extends from the metal only 0.01m, indicating that while the heat is more concentrated along the vertices, the alternative insulation is able to absorb the heat more rapidly.

Is in the case of the traditional insulation, the most significant source of heat flux came from the metal to metal contact at the vertices of the unit. The heat flux gradient is significantly different than that of the polyurethane foam, in that a substantial drop in temperature is experienced as heat moves through the packets of evacuated silica. Also of note is the change in the temperature gradient profile, where the heat is absorbed more swiftly than the polyurethane foam shown in Figure 4.8 as it moves through the insulation medium. When the metal skin layer was removed, as seen in Figure 4.16, it was observed that the packets of evacuated silica provided substantial heat resistance, and was the greatest insulative inhibitor utilized in the design.

Figure 4.17 shows the directional heat transfer through the insulation. The red arrows indicate that the heat flux is most intense. This is attributed to the contact from the metal to the insulation polyurethane. In this case the arrows being present only in the metallic sections of the cover. This supports the idea that while the heat flux is more concentrated along the metal vertices, the alternative insulation is able to absorb the heat much more rapidly than the traditional foam.

The other significant observation made by that the ANSYS analysis is the direction the heat travels when passing through the honeycomb cartridge, where heat is seen to be dissipating into the surrounding medium. This redirection of heat is often referred to as creating of a ‘heat sink’; it is most commonly caused by increased interface resistance.

4.8.2 Discussion

The thermal analyses utilizing Excel and ANSYS were in fair agreement. The experimentally measured heat flux (reported in Chapter 3) was slightly higher than that of the theoretical value found by Excel, but lower than the estimated average heat flux value found by ANSYS through the location where the heat flux sensors were placed. This can be attributed to the sensitivity of the heat flux meters used in the experimental section of the analysis, as well as imperfections in the manufacturing process described in Chapter 3, and the modeling assumptions. While outside the scope of this study, a “theoretical correction factor” may be considered when applying theoretical heat transfer calculations to this type experimental analysis. A limitation of the theoretical models is that the only environmental parameter considered is ambient and internal cabinet temperatures. Humidity, air pressure and other environmental conditions regulated in experimental testing were not considered in the development of the models The theoretical and experimental analyses agree in that the traditional insulation and modified insulation are both effective insulators; the modified insulation proves to be superior in thermal performance. The most significant location of that heat transfer for both the traditional and unit covers was from the external metal skin, currently an industry standard.

Since metal to metal contact was found to be the key source of heat transfer, in order to prevent this from occurring, alternatives like continuous insulation should be considered. While it was outside the scope and objectives of this study, it can be proposed that the insulation cartridge could be made of a flexible mesh like structure, allowing it to be bent around the external skeleton of the structure to reduce heat gains from the vertices.

Table 4.1 Summary of thermal properties of materials utilized in the study

Material	Properties					
	Conductivity (k) (W/m K)	Density (ρ)(g/cm3)	Specific heat (c) (KJ/kgK)	Emissivity (Ɛ)	Resistance path length (l) (m)	Wall roughness (wr) (m 10-3)
Traditional insulation					0.0762	
Polyurethane	0.009	0.4	1.4	0.91	0.074	0.25
Metal skin	47.2	2.7	0.55	0.55	0.002	0.018
Modified insulation					0.0762	
Heat shield	0.3	0.7	1.5	0.02	0.003	0.09
Plastic cartridge	0.5	1.2	1.67	0.91	0.013	0.25
Evacuated silica	0.0041	2.3	0.9	0.88	0.058	0.2
Metal skin	47.2	2.7	0.55	0.55	0.002	0.018

Table 4.2 Design parameters that may be controlled to affect heat flux

Design parameter	Effect on heat flux
Material type	In general, lower density materials will decrease overall heat flux.
Resistance path length	In general, a shorter resistance path will decrease overall heat flux.
Material conductivity	A lower ‘k’ value will result in a decrease in overall heat flux.

Table 4.3 Summary of heat metrics from the Excel-based theoretical heat model

Unit	Average heat flux
Traditional (Unit A)	5.43 W/m^2
Modified (Unit B)	3.36 W/m^2

Table 4.4 Comparison of the experimental and theoretical heat flux values for Unit A and Unit B

	Heat flux (W/m^2)		
Insulation type	Experimental	Theoretical	
		Excel	ANSYS
Unit A: Traditional	6.15	5.43	6.53
Unit B: Modified	3.73	3.36	3.59

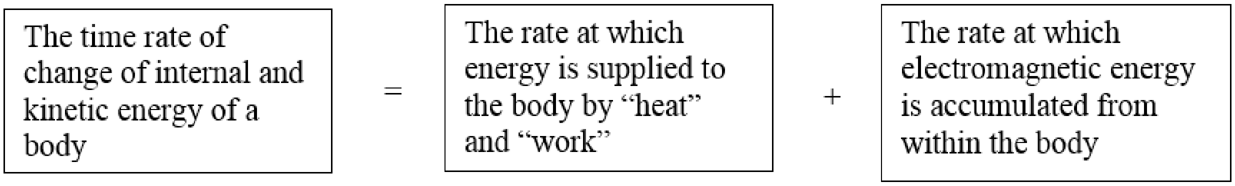


Figure 4.1 Time rate of change of internal and kinetic energy of a body

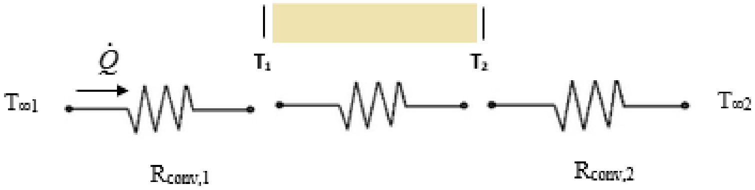
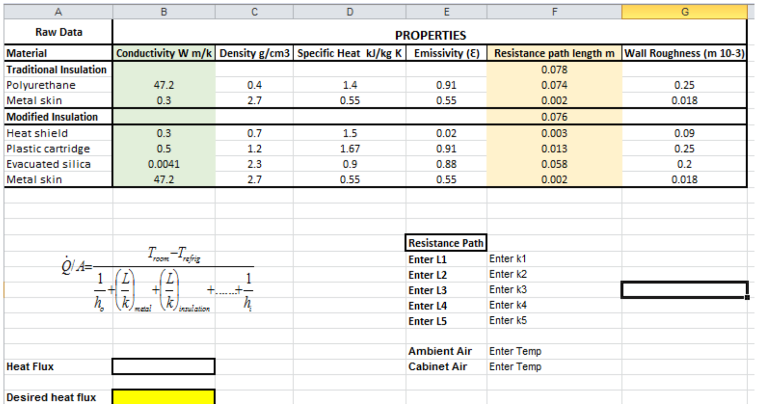


Figure 4.2 Heat moves through insulation similar to the way electricity moves through a circuit



A	B	C	D	E	F	G
Raw Data	PROPERTIES					
Material	Conductivity W m/k	Density g/cm3	Specific Heat kJ/kg K	Emissivity (Ɛ)	Resistance path length m	Wall Roughness (m 10-3)
Traditional Insulation					0.078	
Polyurethane	47.2	0.4	1.4	0.91	0.074	0.25
Metal skin	0.3	2.7	0.55	0.55	0.002	0.018
Modified Insulation					0.076	
Heat shield	0.3	0.7	1.5	0.02	0.003	0.09
Plastic cartridge	0.5	1.2	1.67	0.91	0.013	0.25
Evacuated silica	0.0041	2.3	0.9	0.88	0.058	0.2
Metal skin	47.2	2.7	0.55	0.55	0.002	0.018

$$\dot{Q}/A = \frac{T_{room} - T_{refrig}}{\frac{1}{h_o} + \left(\frac{L}{k}\right)_{metal} + \left(\frac{L}{k}\right)_{insulation} + \ldots\ldots + \frac{1}{h_i}}$$

Resistance Path	
Enter L1	Enter k1
Enter L2	Enter k2
Enter L3	Enter k3
Enter L4	Enter k4
Enter L5	Enter k5
Ambient Air	Enter Temp
Cabinet Air	Enter Temp

Heat Flux

Desired heat flux

Figure 4.3 User interface for the heat transfer model in Microsoft Excel

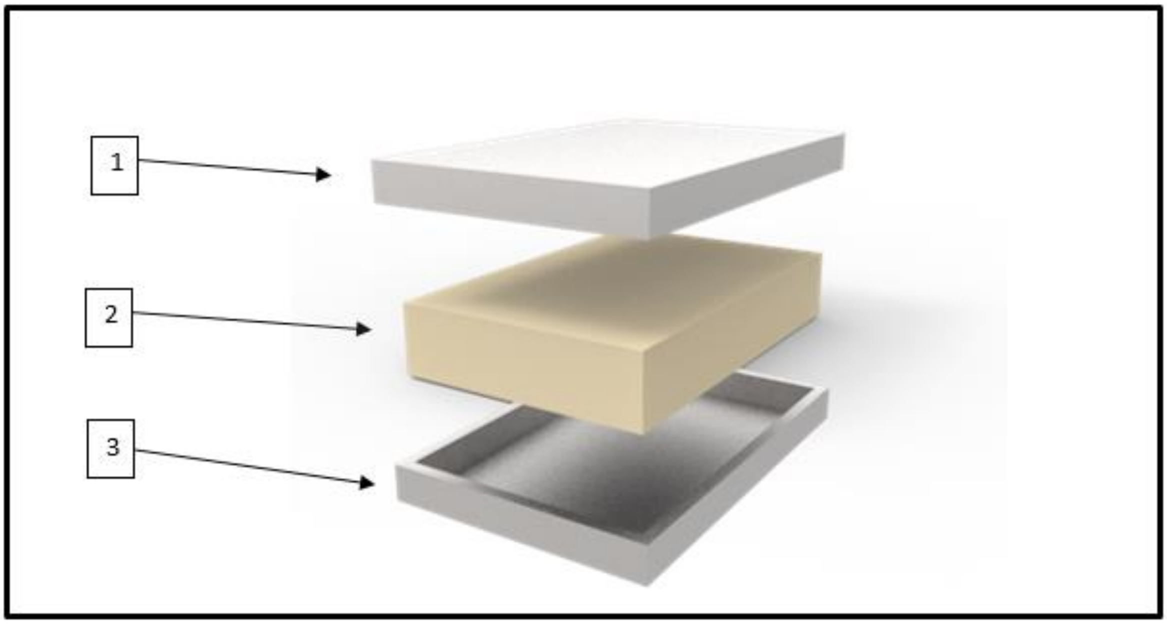
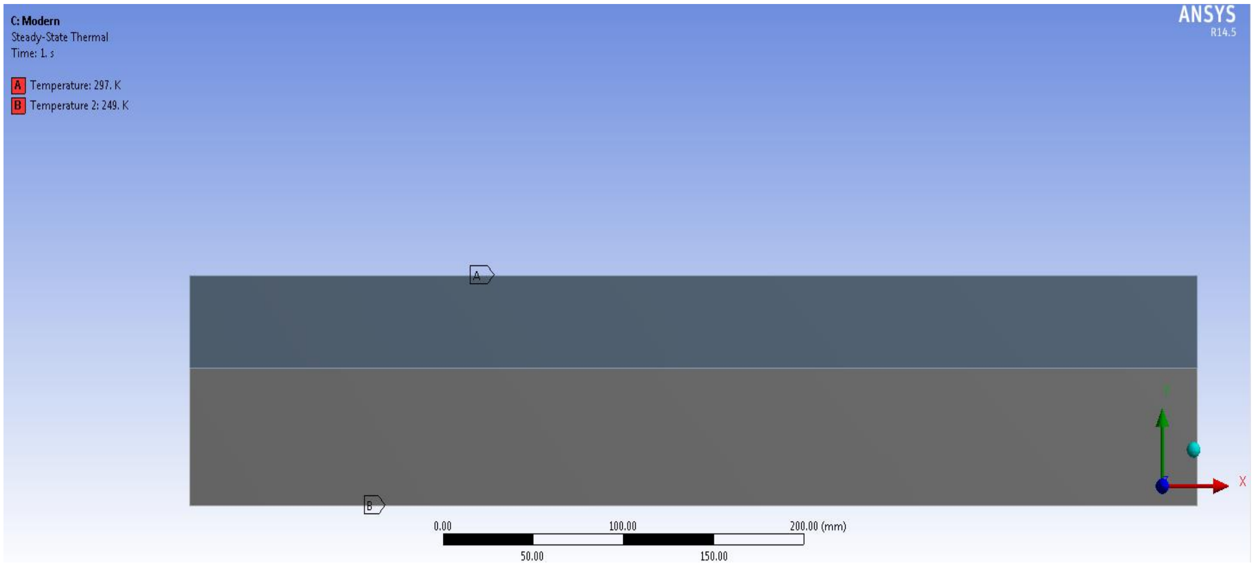


Figure 4.4 Schematic of the assembly of traditional insulation layers assembled utilizing ANSYS



C: Modern
Steady-State Thermal
Time: 1. s

A Temperature: 297. K
B Temperature 2: 249. K

Figure 4.5 ANSYS illustration of boundary conditions

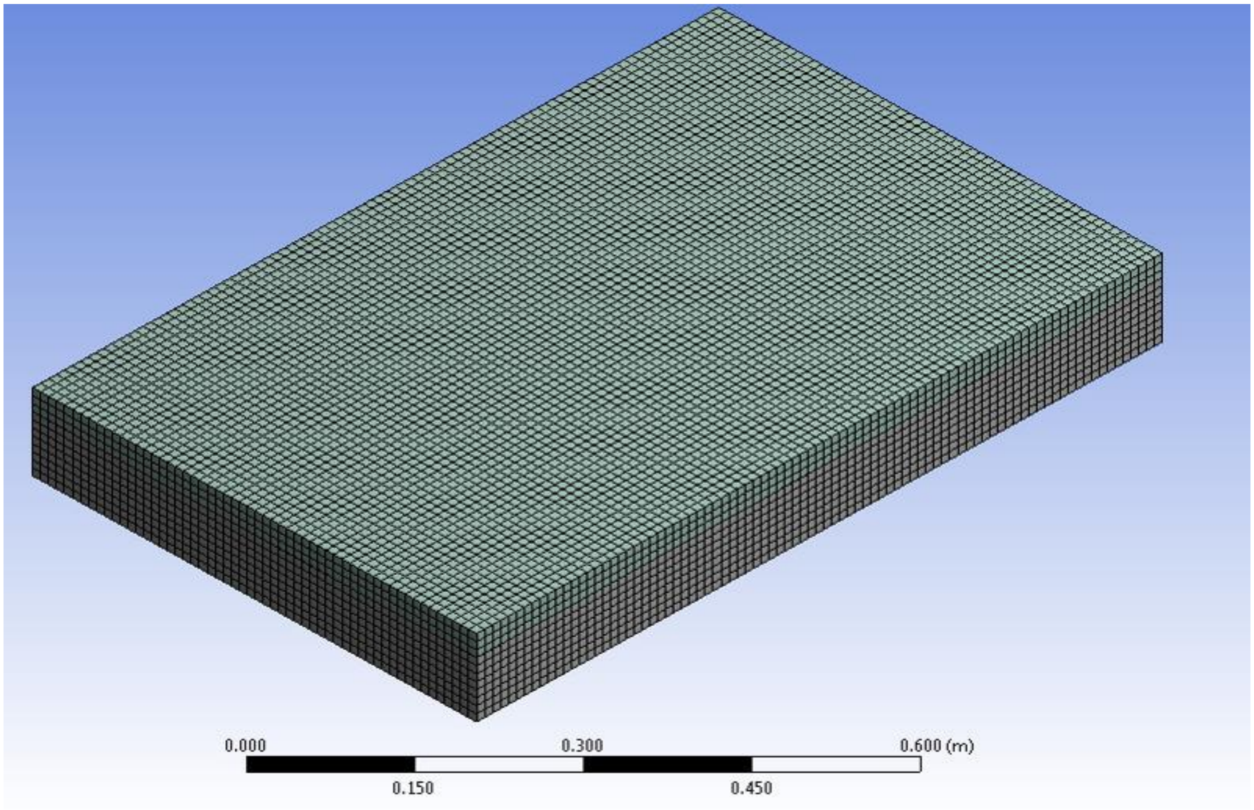


Figure 4.6 Finite element mesh used for the thermal analysis of traditional insulation

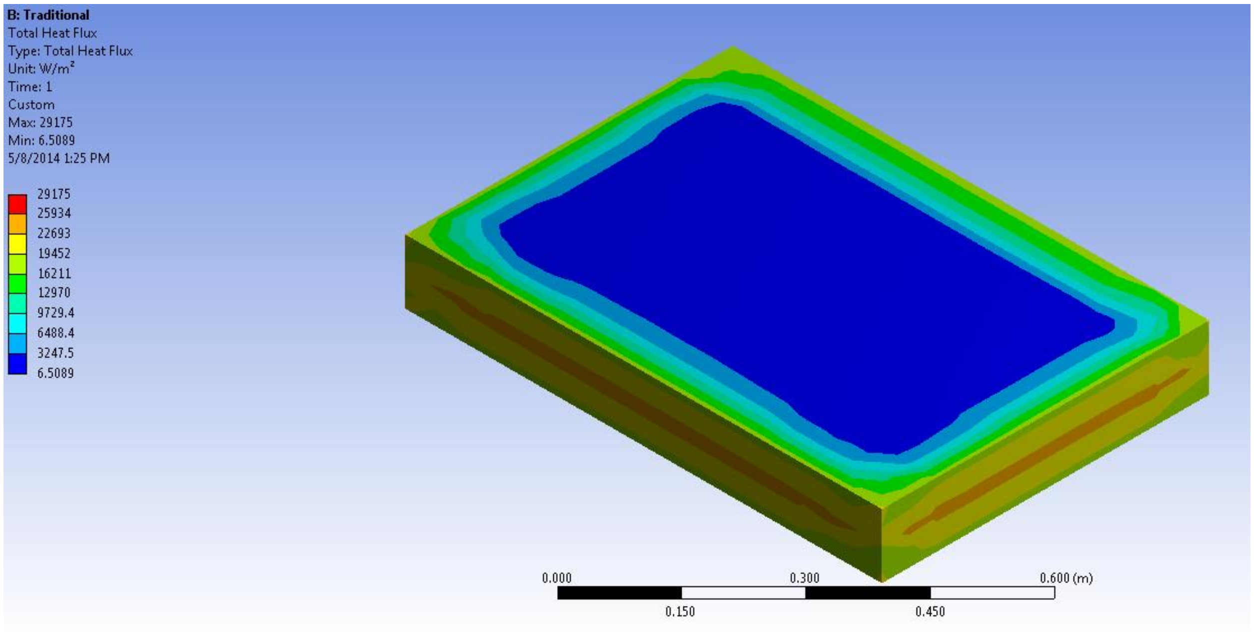


Figure 4.7 Heat flux experienced by the polyurethane

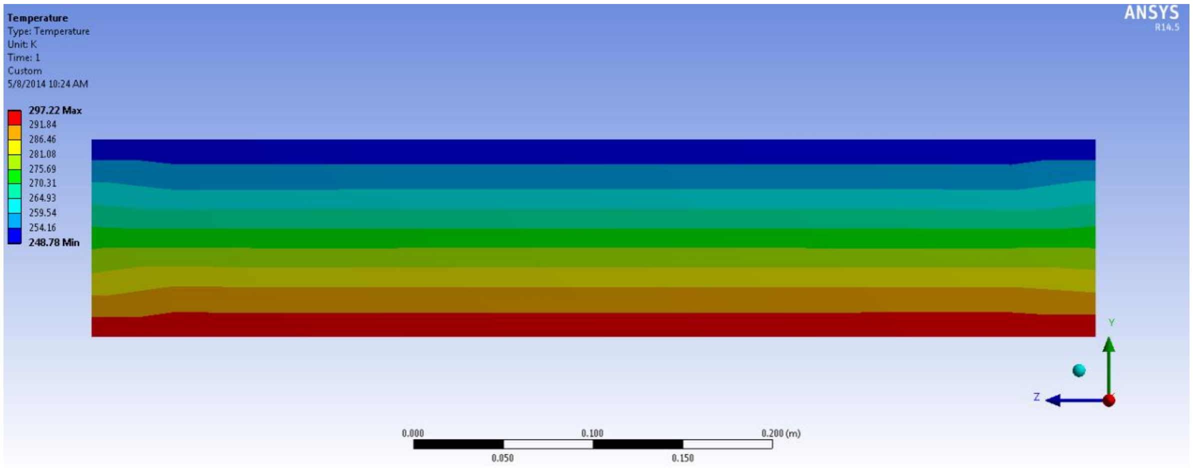


Figure 4.8 Heat flux gradient through cross section of the insulation

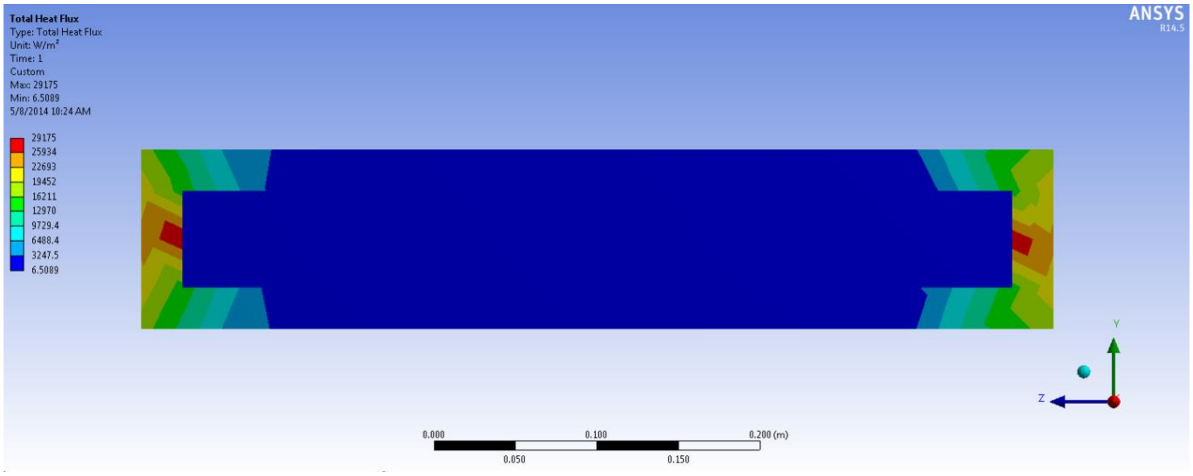


Figure 4.9 Heat flux through cross section of the insulation

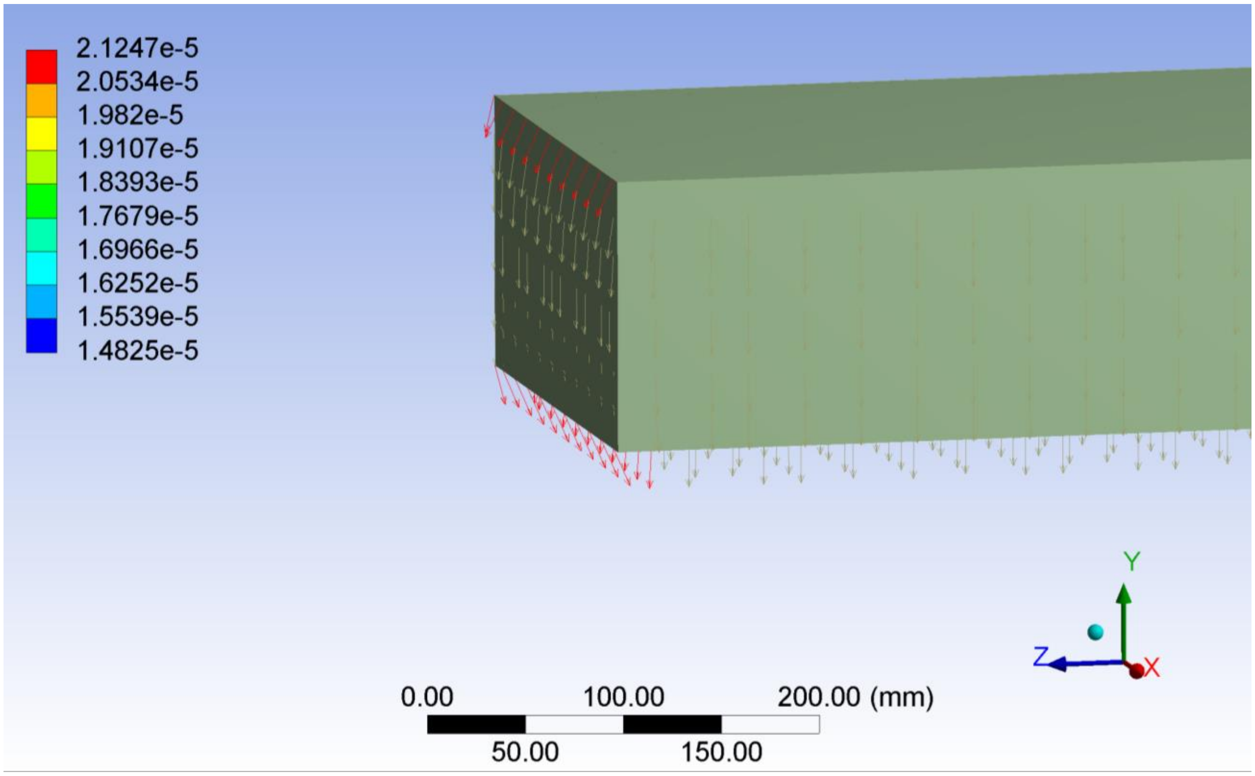


Figure 4.10 Illustration of the heat flux vectors

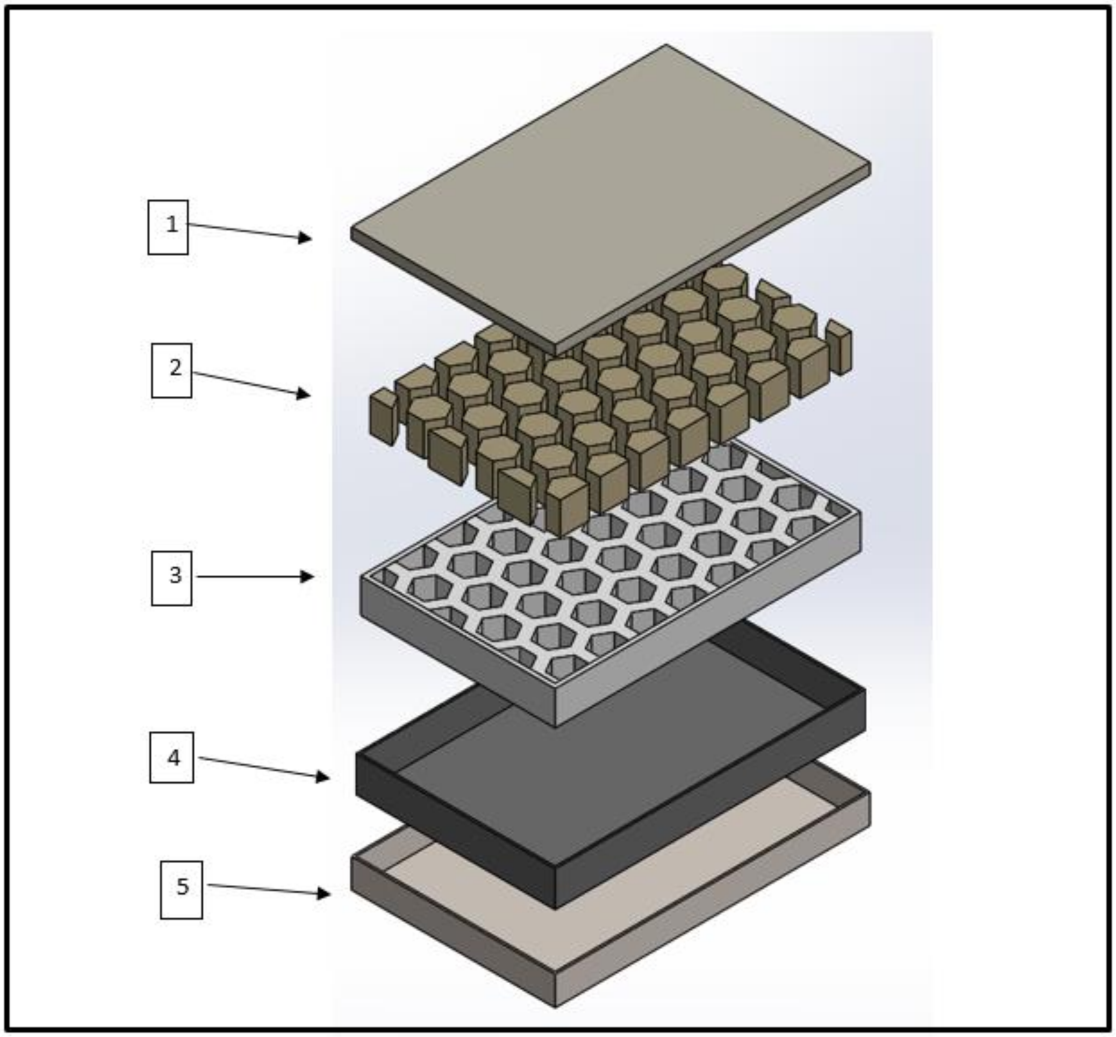


Figure 4.11 The assembly of the alternative insulation in SolidWorks

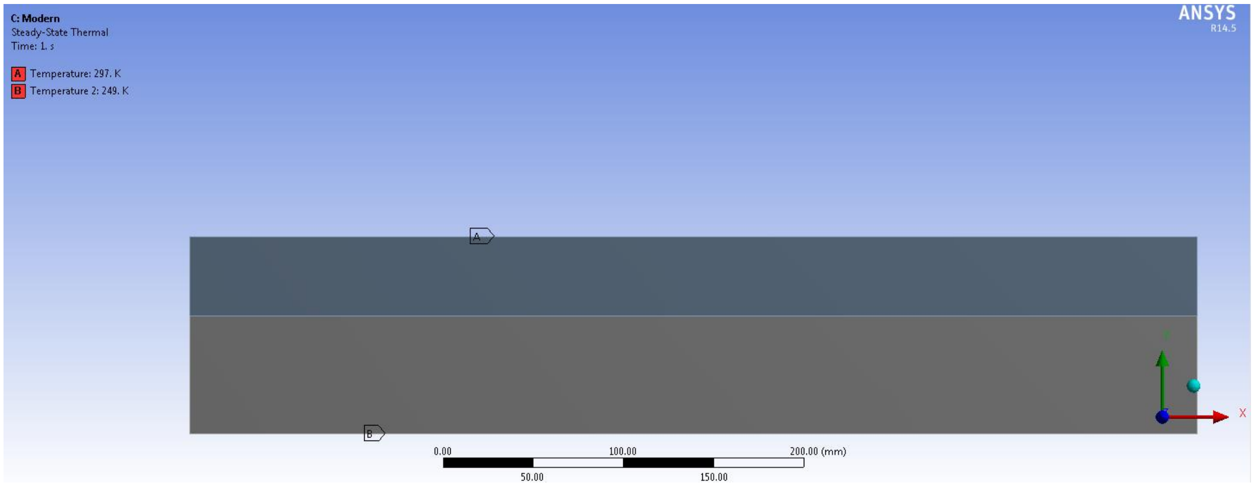


Figure 4.12 ANSYS illustration of the boundary conditions

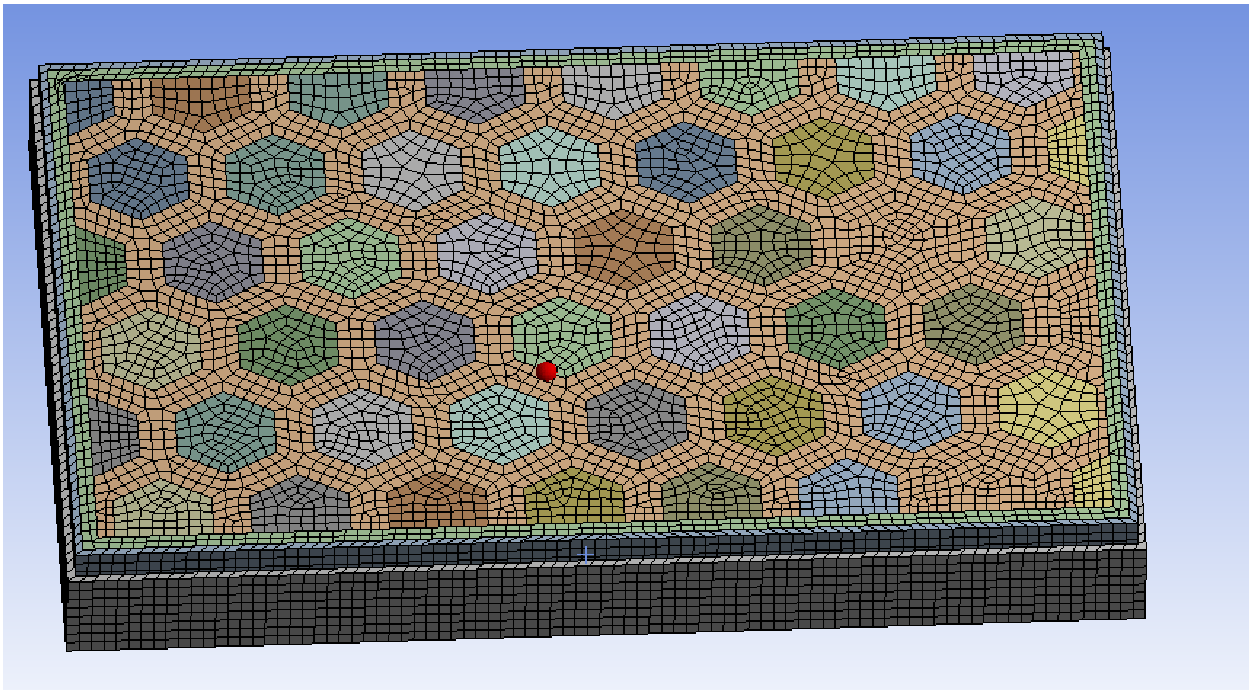


Figure 4.13 Finite element mesh quality for the thermal analysis of the modified insulation

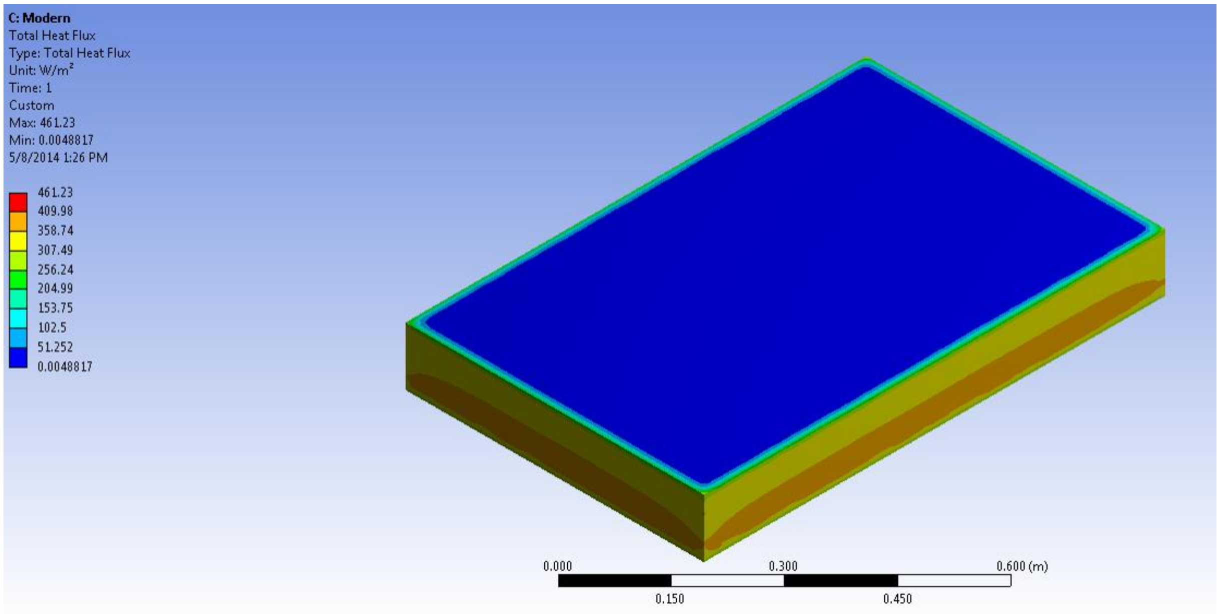


Figure 4.14 Heat flux experienced by the modified insulation

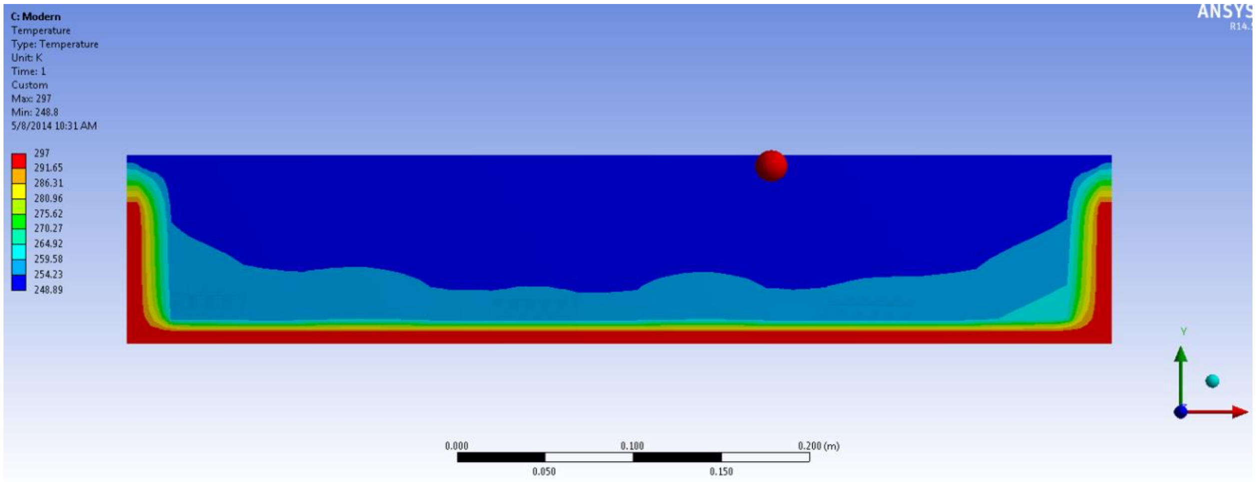


Figure 4.15 Heat flux gradient through cross section of the insulation

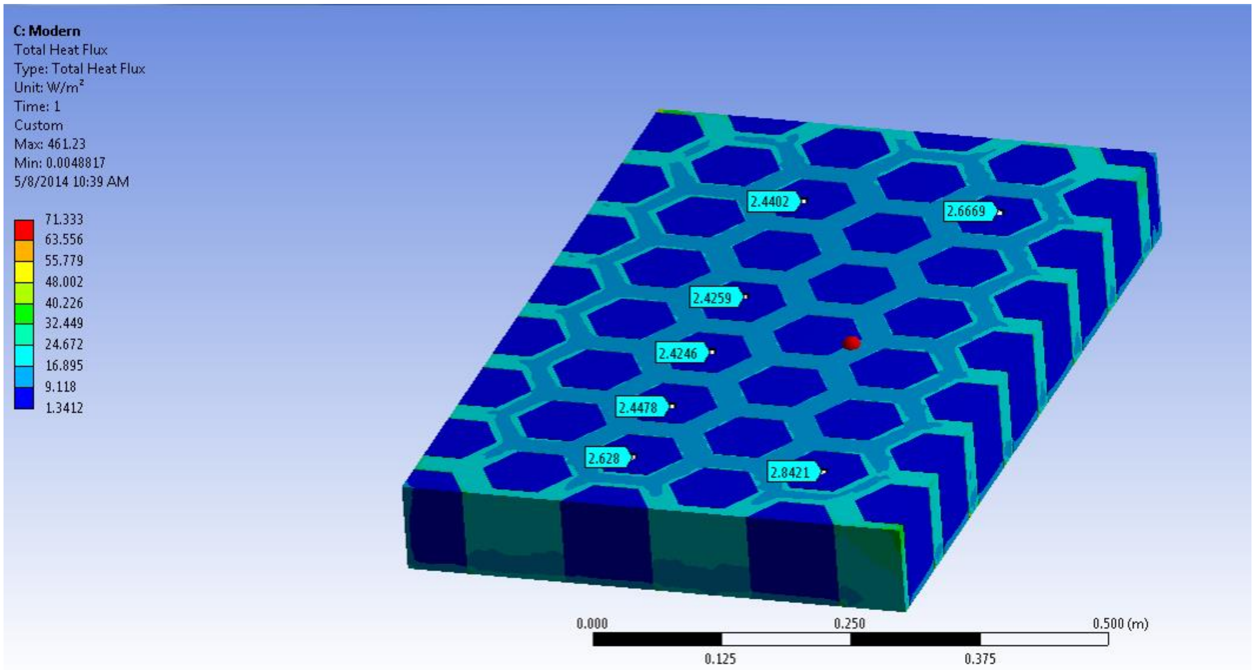


Figure 4.16 The heat flux behavior distribution if the external metal layer is suppressed by ANSYS

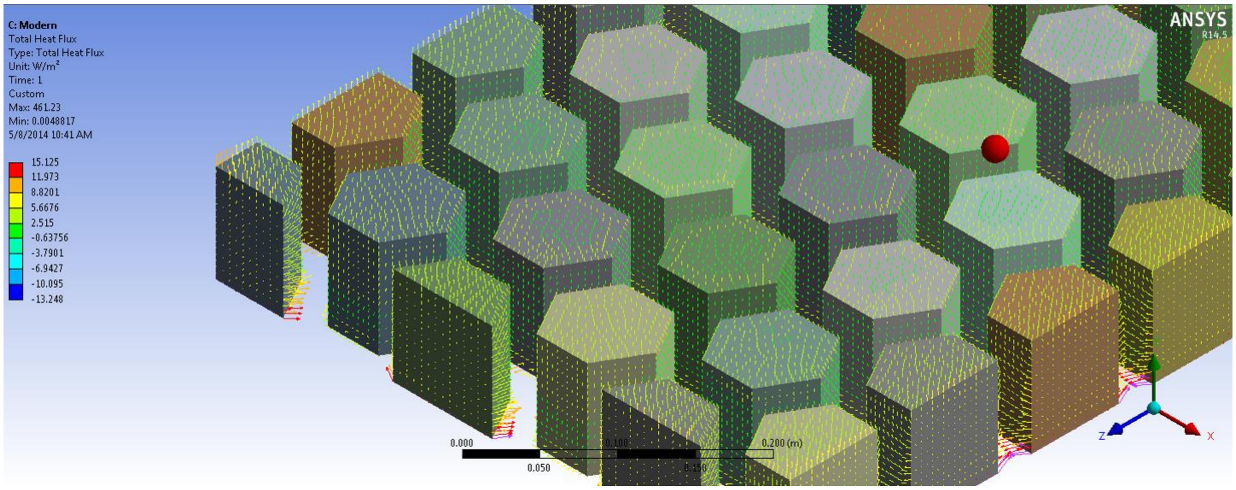


Figure 4.17 Illustration of the heat flux vectors

CHAPTER 5: LIFE CYCLE ASSESSMENT

In this chapter, life cycle assessment (LCA) is employed to quantify the environmental sustainability of the design decisions associated with replacing the insulation of a commercial refrigeration unit that was described in Chapter 3.

5.1 Scope

This component of the research examines the life cycle consequences associated with the two separate types of insulation utilized in commercial refrigeration studied in this research: polyurethane for Unit A, and the modified insulation utilizing silica based vacuum paneling for Unit B, as described in Chapter 3.0. The alternative insulation was designed with a primary aim being to enhance material recovery. The alternative insulation is comprised of an insulation ‘cartridge’ employing silica beads under a partial vacuum. The research for this chapter will determine if the environmental benefits of material recovery will offset any additional environmental costs associated with the production and use of the alternative insulation.

5.2 Life Cycle Assessment Goal

The goal of the life cycle assessment is development of a life cycle inventory model for commercial refrigerators. The inventory objectives are to (1) Document the resource input, energy use, and emission outputs including products and co-products as it relates to the manufacture and product life time use of a typical commercial refrigerator with an approximate capacity of 5 cubic feet; and (2) provide a resource to manufacturers and decision makers that will offer opportunities for waste reduction and improved environmental sustainability in the manufacturing process and product design.

The secondary goal is to evaluate how environmental sustainability metrics are affected by changing the insulation to one that has been designed employing a ‘design for disassembly’ approach.

5.3 Methodology

5.3.1 Functional Unit and System Boundaries

The functional unit for this life cycle assessment was defined as a generation of an internal cabinet temperature for a representative 5 ft^3 commercial refrigeration/freezer unit of -11^{o}F for 200,000 hours of operation, under average ambient conditions of 75^{o}F and 40% humidity. This equates to roughly 20 years of operation, the typical life span of a commercial refrigerator/freezer of this type. The system boundary of this research is shown in Figure 5.1. It includes the inputs from raw material acquisition, material processing, manufacturing, use, decommissioning, treatment and disposal and recycling.

5.3.2 Product Manufacturing Process

The manufacture of a commercial refrigerator is accomplished through a series of unit processes. The processes for the manufacture, use, and disposal of the refrigerator are shown in Figure 5.2. The commercial refrigerator production and operation (i.e., use life stage) and end of life inventory were modeled using a single-unit process approach that incorporates the key processes found in the typical manufacturing of this product. The analysis of the product and use and end of life options for these units are critical in determining the overall effectiveness of design and the environmental consequences associated with each phase of the life cycle. The inputs for the production of each separate refrigerator component is also provided in Figure 5.2.

5.3.3 Data Considerations and Assumptions

Between January and July 2012, the primary data for the reporting year 2011 were collected from three representative manufacturers. The manufacturers were surveyed using a self-administered questionnaire based on research objectives, and in accordance with ISO protocol. Three questionnaires (provided in Appendix A) were emailed to the engineering manager at each company. The participating companies were ensured confidentiality, and all three participated in the study. The returned surveys indicated a combined production value of 3.64 million 5-cubic feet units were manufactured in 2011, accounting for 58% of the total production of these types of units internationally. Incomplete data sets were completed by conducting follow-up phone calls and additional interviews with representatives from each manufacturing plant.

Product yields reported by the survey showed how the input materials were manufactured into products, co-products and waste. It was observed by manufacturers that approximately 65% of the input materials were directly utilized in unit production. The other 35% was scrapped and most frequently ended up in landfills. This value was calculated by dividing the weight of the total input materials by the total weight of the unit and multiplying by 100%.

The manufacturer surveys also indicated that all deliveries of raw materials to the manufacturer facility were made by truck. Burdens associated with this transportation are included in the cumulative system boundary assessment. However, transportation data for packaging material are not included within the bounds of this study.

It should be noted that each factory outsourced the manufacturing of some components of the refrigerator/freezer, but were asked to include this data in the data reporting. The factories were also asked to document what data were unavailable when it came to reporting this type of information; incomplete data was assumed based on existing relevant sources from built-in inventory in SimaPro. The data sets available in SimaPro were chosen based on their geographic relevance to this study. The complete list of sources utilized in the study isprovided in Table 5.1. The manufacturer surveys proved to be most useful in determining the manufacturing techniques and processes.

5.4 Inventory Modeling

This study utilized SimaPro life-cycle inventory (LCI) software (Amsterdam, The Netherlands). SimaPro integrates ISO 2006 standards for environmental management and standardized LCI formats to analyze model data. This version has built-in data bases from various sources containing energy and emission data characteristic of those found in the United States and abroad. Aside from manufacturer data discussed in the previous section, these databases were utilized to quantify emissions from unit processes.

5.5 Inventory Normalization

To ensure the highest quality data, the three manufacturers surveyed in the research were from various countries and regions and used similar, but not identical machinery for extraction, manufacturing, and assembling purposes. While many of these processes were unique, several processes for specific unit processes overlapped. Thus, in order to normalize the data for material, energy, and emissions for each unit process, the overlapping data were averaged, and the mean of the data were used as the primary input for the life cycle assessment.

5.6 Impact Assessment

This research utilized two primary impact assessment methodologies to account for the international scope of the study. Since indicators such as land use are heavily dependent on the regional and local field observations, the impact assessment methodologies utilized in this study was EcoIndicator 99 (H). Eco-indicator 99 (H) utilizes a damage-oriented approach to quantify the impact of each system on emissions, land use, and resource depletion. In each of these three categories, there are indicators representative of the key metrics. For example, in the area of emissions some the impact indicators are: carcinogens (carcinogen affects due to emissions of carcinogenic substances to air, water, and soil, expressed in Disability adjusted Life Years (DALY)/kg emission); and ozone layer depletion (ozone layer damage, expressed in DALY/kg emission, due to increased UV radiation as a result of emission of ozone depleting substances to air.). Eco-Indicator 99 utilizes a point system to determine the overall damage impact. The higher the point value, the more damage associated with that impact category.

5.7 Description of Investigated Units

The data collected were used to construct the basic life cycle inventory for the traditional model. “Unit A” employs traditional injected polyurethane as the insulation and “Unit B” utilizes a non-traditional insulation. The other major components of the unit remain unchanged, as described by Table 5.2.

Another key differentiating feature of Unit A and Unit B was the production sequences. Utilizing the framework for a more sustainable design (as described in Chapter 1) yielded a “design for disassembly” approach, by which every effort was made to ensure that the production sequence would eventually lead to increased material recovery at the end of life of the unit. The difference in the production sequence between the two models is provided in Figure 5.3.

The traditional unit assembly calls the external casting of a plastic “skin,” which encompasses the walls and door. The mold casting is held in place by large metal clamps. All additional plastic shelving and mechanical components (i.e. condenser, compressor, and evaporator) are assembled at that time. Subsequently, two 2’’ x 6’’ reinforcing metal strips are placed in each wall. Polyurethane foam is then injected into the gaps between the metal strips and outside plastic skin and allowed to dry. The side-paneling is then sealed into place.

Alternatively, the Unit B insulation assembly encompasses the external casting of the plastic skin by mold casting and the assembly of mechanical components as was the case with Unit A. For the insulation assembly, bags of evacuated silica are sealed into a honeycomb structure made of recycled plastic mesh is placed within the external wall “shell” and sealed using heat release adhesive. After the cartridge is placed into external walls of the unit, a comparatively small amount of polyurethane foam is injected through the value to further insulate and seal the structure.

Disassembly and end-of -life options for the traditional unit were found to be limited. According to the manufacturing survey, none of the insulation material originally utilized in the unit is typically utilized in the remanufacturing process. The specific manufacturing process utilized for Unit B corresponded to an equally specific disassembly sequence to material recovery with the goal of optimal material recovery. Additional energy for the regeneration and disassembly of Unit B is also considered an input to the life cycle assessment. The disassembly sequence for each unit is described in Figure 5.4 and 5.5.

As stated earlier in this chapter, manufacturer and disposal data were collected for companies producing the chest-type freezer referred to in the study which comprises 58% of the total market share for this product. It should be noted that several of the components of the refrigerator/freezer were produced off site by a separate entity or subsidiary of the main company. For the purposes of this study, independent companies that supply components or whole parts to the parent factories were included in the data reported by those respective parent companies.

5.8 Results and Discussion

Figures 5.6 and 5.7 represent a partial network analysis for Unit A and Unit B. Each box in the figure represents a process that contributes to the overall single score environmental impact of the product. The arrows indicate the network flow between processes, and the bars within the box are indicative of the portion of environmental impact generated by the particular process. The bottom network illustrated in Figure 5.6 represents the network analysis of the traditional and modified unit, or Unit B. The inputs to the evaporator, compressor and condenser remain constant. The only input that has been altered is the insulation and subsequent processes associated with its manufacture and disposal. The energy use in the use phase based on experimental results and literature findings indicating that the overall energy consumption would decrease by approximately 15% if the entire unit was replaced with the modified insulation. As shown, for both units, the use phase carried the most environmental load. For Unit A the use phase accounted for the 69.2% of the overall and for Unit B, the use phase accounted for 79% of the total environmental load across the total life cycle. However, the actual energy utilized in by Unit B during the use phase was 15% less. Figure 5.8 isolates two key metrics: energy usage and greenhouse gas emissions, to further compare Unit A and Unit B.

As shown on Figure 5.8, the production of both units was energy intensive, utilizing 27% of the total energy consumption for Unit A, and 38% of the total energy consumption for Unit B. Consequently, the greenhouse gases produced by the use phase for each unit are proportionately higher. In particular, process contribution metrics from SimaPro indicate that the processes involved in the fabrication of the metal frame of the unit, as well as the forming of the plastic sheeting covering the unit expends a large amount of energy and emissions also resulted from the fabrication of the mechanical components of both units, contributing 42 points out of an estimated 55 for the manufacturing of Unit A, and 42 points out of an estimated 73 for Unit B. The production of the insulation of Unit B was more energy intensive due to the energy associated with the production silica, which contributed 24 points. However, a marked decrease in overall energy consumption was observed when an energy analysis was conducted over the life cycle of the unit, where the total points attributed to energy consumption from Unit A was 205 and Unit B carried a point value of 192. This can be attributed to the high recovery and reuse rate expected by the modified insulation.

The use phase of both units was a significant contributor to overall energy usage as well as key environmental impact factors. As previously stated, over the use phase of both units, the energy use from the modified unit was approximately 15% less than that of the traditional unit. Consequently, the greenhouse gas emissions by the unit with the modified insulation were correspondingly less. This life stage thus presents an opportunity for energy efficiency improvement. Studies reviewed in Section 2.0 by Kudoh et al. (2006) and Eberhardt (2007) utilizing similar vacuum technology reported energy savings of up to 25%.

The first unit was found to require 45% more landfilling space (17.6 kg of Unit A was landfilled, compared to 11.3 kg of Unit B). Approximately 60% of the modified unit was salvaged, and 86% of the insulation was recovered for reuse. The inherent complexity of the material used for the insulation allowed for regeneration of the silica, and its reuse. As a result, as shown in Figure 5.8, the overall energy use for disassembly phase was 21% for Unit B, and 12% for Unit A. However, this is offset by the significant amount of material salvaged; and by the energy savings during the use phase due to the increased energy efficiency.

The disassembly phase for each unit contributed against the negative overall environmental impact for both the cases of Unit A and Unit B because of the value of the metal reused in the mechanical components, and in the case of Unit B, reuse of the silica. Reuse of the salvaged metal and insulation material in Unit B was thus a key factor in offsetting many of the environmental costs incurred during the life cycle.

Figure 5.9 shows that the most significant relative decreases were noted in the areas of carcinogens, ozone depletion potential, and mineral usage, which experienced a relative decrease of over 80% when the modified insulation design was utilized in the refrigerator/freezer unit. The overall use of fossil fuels, a key metric in determining overall energy efficiency, showed a relative decrease of 16%, which can be attributed to both the reduction in energy utilized in the use phase, and the energy saved from the production of additional insulation.

Figure 5.10 shows the normalized data from the analysis. For LCA normalization, the data obtained from the impact assessment is divided by the equivalent regional data to provide a better indication of which impact categories contributed the most to overall environmental impact. As shown, the normalized data revealed the most impactful category to be the use of fossil fuels.

5.9 Opportunities Identified for Reducing Environmental Impacts

Some of the significant opportunities to reduce the overall environmental and overall energy impact of the commercial refrigerator unit were found to be during the use phase. This can be achieved by reducing the daily energy consumption used by these units. Unit B, the commercial refrigerator/freezer employing the alternate insulation, is an example of modifications that may be made to existing units in order to increase the energy efficiency of the unit in the use phase. Bansalet al.(2003) has previously discussed the improvements made in residential refrigeration. Generally, studies focusing on redesign measures in refrigerators can be classified into three categories: alternative insulation techniques, system optimization through mechanical improvements and compressor redesign. Figure 5.11 illustrates the potential for additional energy savings in refrigerators by specific system improvements beyond improvement in insulation. These additional improvements have the potential to significantly reduce the environmental impact beyond the impact quantified in this research.

Table 5.1 Data sources used for corresponding LCA unit process

LCA Unit Process	Data Source
Fuel, energy and raw material extraction	
Input materials	Manufacturer survey
Raw material extraction processing	Ecoinvent Database: PRé Consultants and Sylvatica, 2001
Energy/fuel utilized in processing	Ecoinvent Database: PRé Consultants and Sylvatica, 2001
Emissions	Ecoinvent Database: PRé Consultants and Sylvatica, 2001
Refrigerator Component Manufacturing	
Fuel: assembly and processing	Manufacturer survey
Emissions	Ecoinvent Database: PRé Consultants and Sylvatica, 2001
Transportation	
Fuel	Manufacturer survey
Emissions	USLCI database: PRé Consultants and Sylvatica, 2001
Installation	
Operation	
Life span energy use	Manufacturer survey
Energy and material use: reasonable expectation of repairs	Manufacturer survey
Emissions from tooling	USLCI database: PRé Consultants and Sylvatica, 2001
Disassembly and recycling	
Input materials and general process	Manufacturer survey
Energy use for disassembly	USLCI database: PRé Consultants and Sylvatica, 2001
Incineration emissions	USLCI database: PRé Consultants and Sylvatica, 2001
Landfill consequences	USLCI database: PRé Consultants and Sylvatica, 2001
Reuse processing	USLCI database: PRé Consultants and Sylvatica, 2001

Table 5.2 Component description of units. All components remained unchanged, except for the type of insulation utilized

	Unit A: Traditional	Unit B: Modified
Insulation	Injected Polyurethane	Silica and vacuum-panel hybrid
Compressor	Factory Standard	Factory Standard
Evaporator	Factory Standard	Factory Standard
Condenser	Factory Standard	Factory Standard

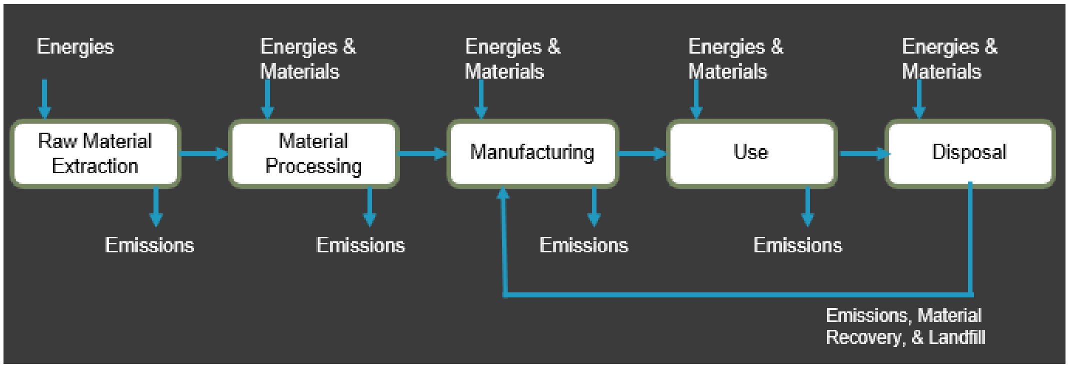


Figure 5.1 LCA system boundary of this research. The LCA encompasses material and energy inputs from raw material acquisition, material processing, manufacturing, use, decommissioning, recycling, remanufacturing, and treatment and disposal.

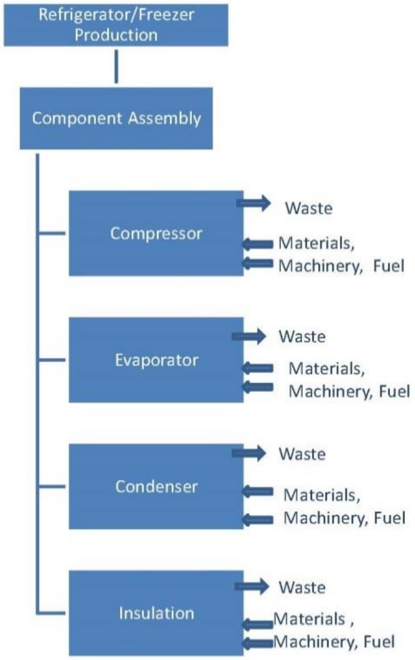


Figure 5.2 Inputs for production of each component of the refrigerator unit. The four major components are the compressor, evaporator, condenser and the insulation. These our components are typically manufactured separately and assembled at the manufacturing plant.

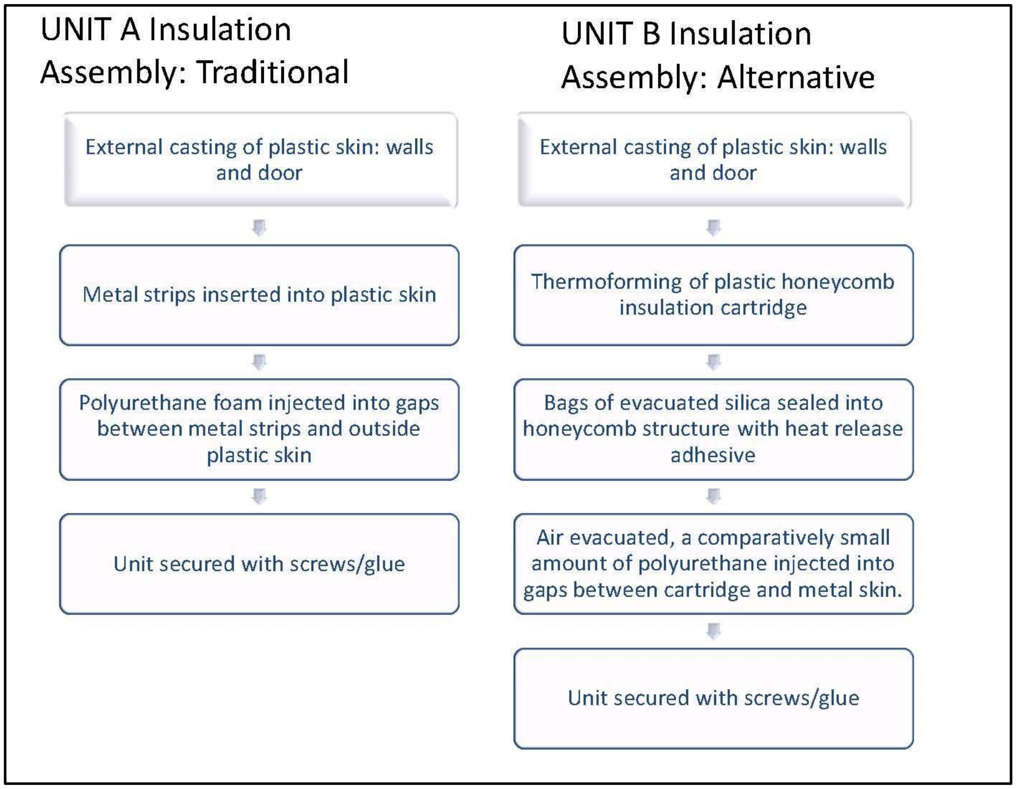


Figure 5.3 Assembly sequences for Unit A and Unit B. The assembly sequence for the modified insulation was prescribed based on a ‘design for disassembly’ approach.

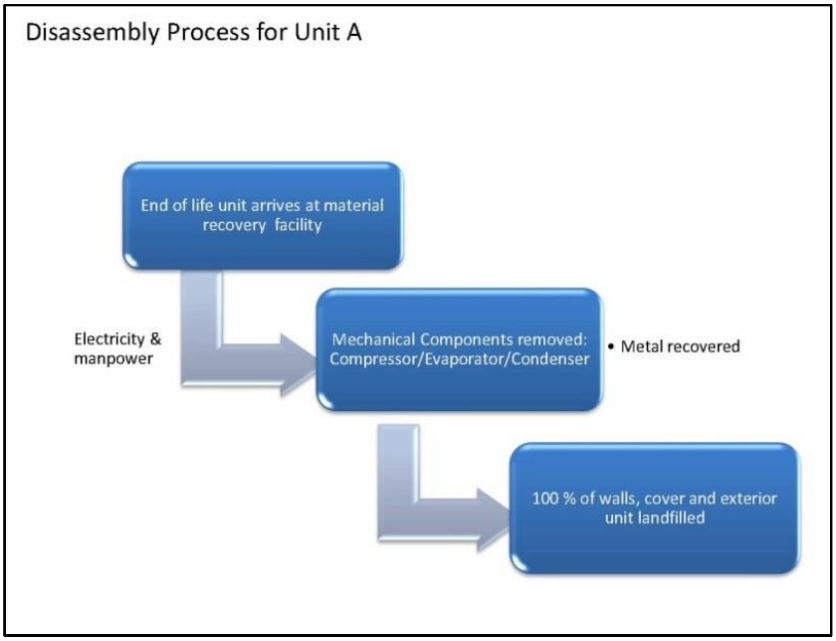


Figure 5.4 The disassembly process for Unit A begins with the removing and salvaging of the mechanical components of the unit. All of the insulation materials utilized in the traditional unit is landfilled.

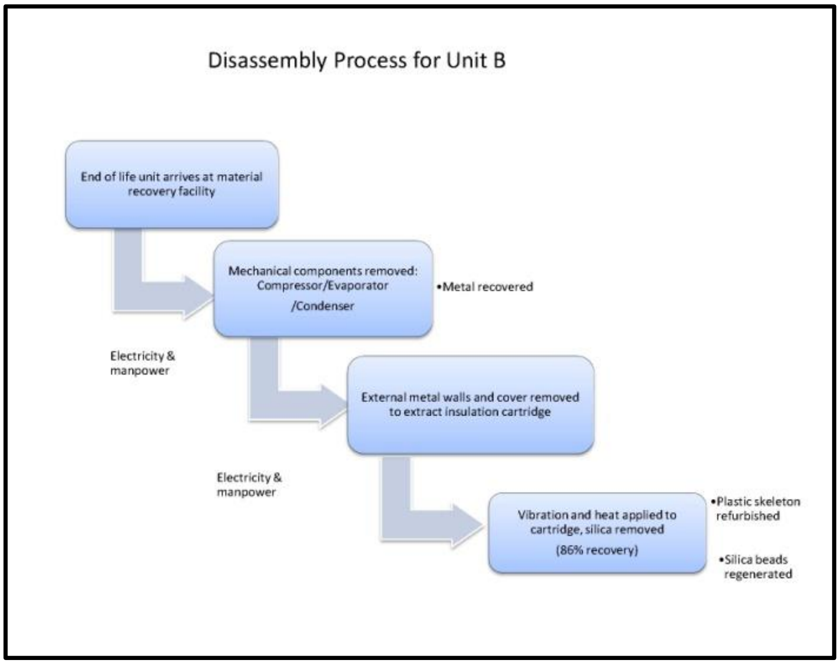


Figure 5.5 The disassembly process for Unit B also begins with the removing and salvaging of the mechanical components of the unit. An estimated 86% of the removed insulation components may be reused in another unit.

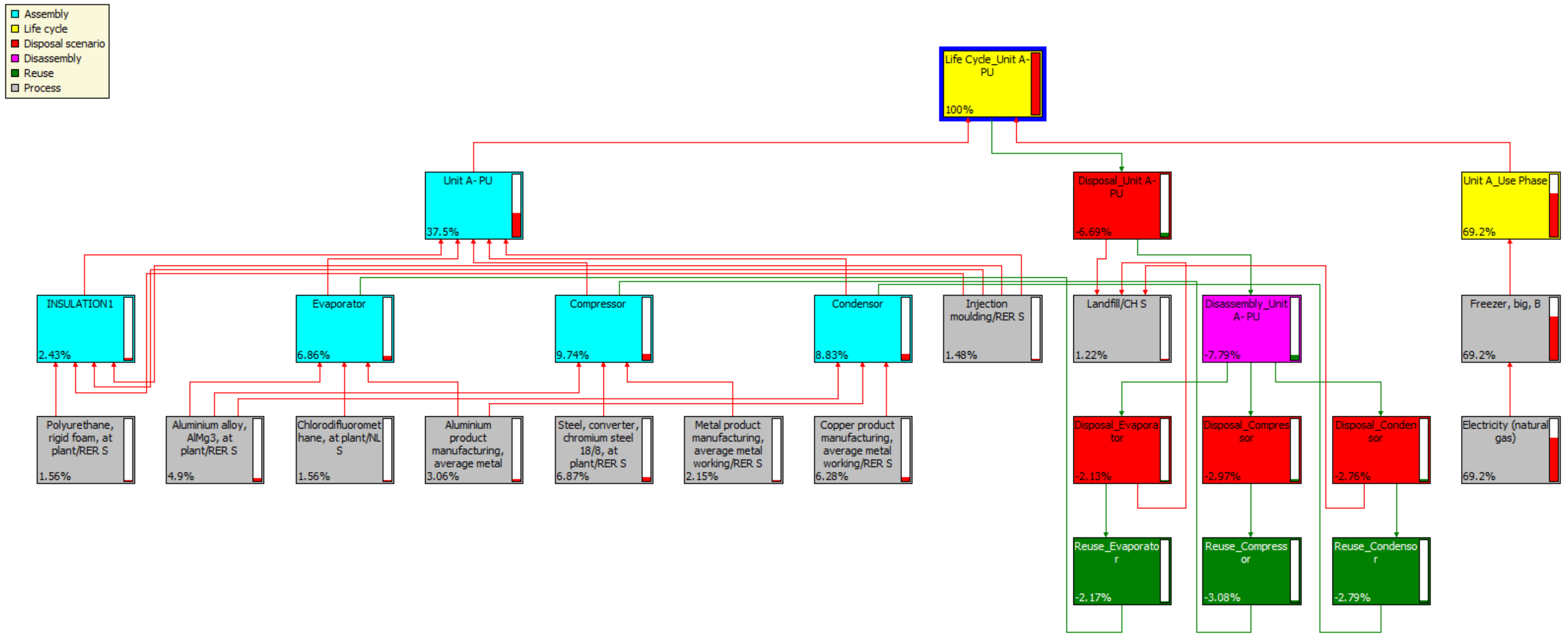


Figure 5.6 A partial view of the life cycle network for Unit A as calculated by SimaPro.

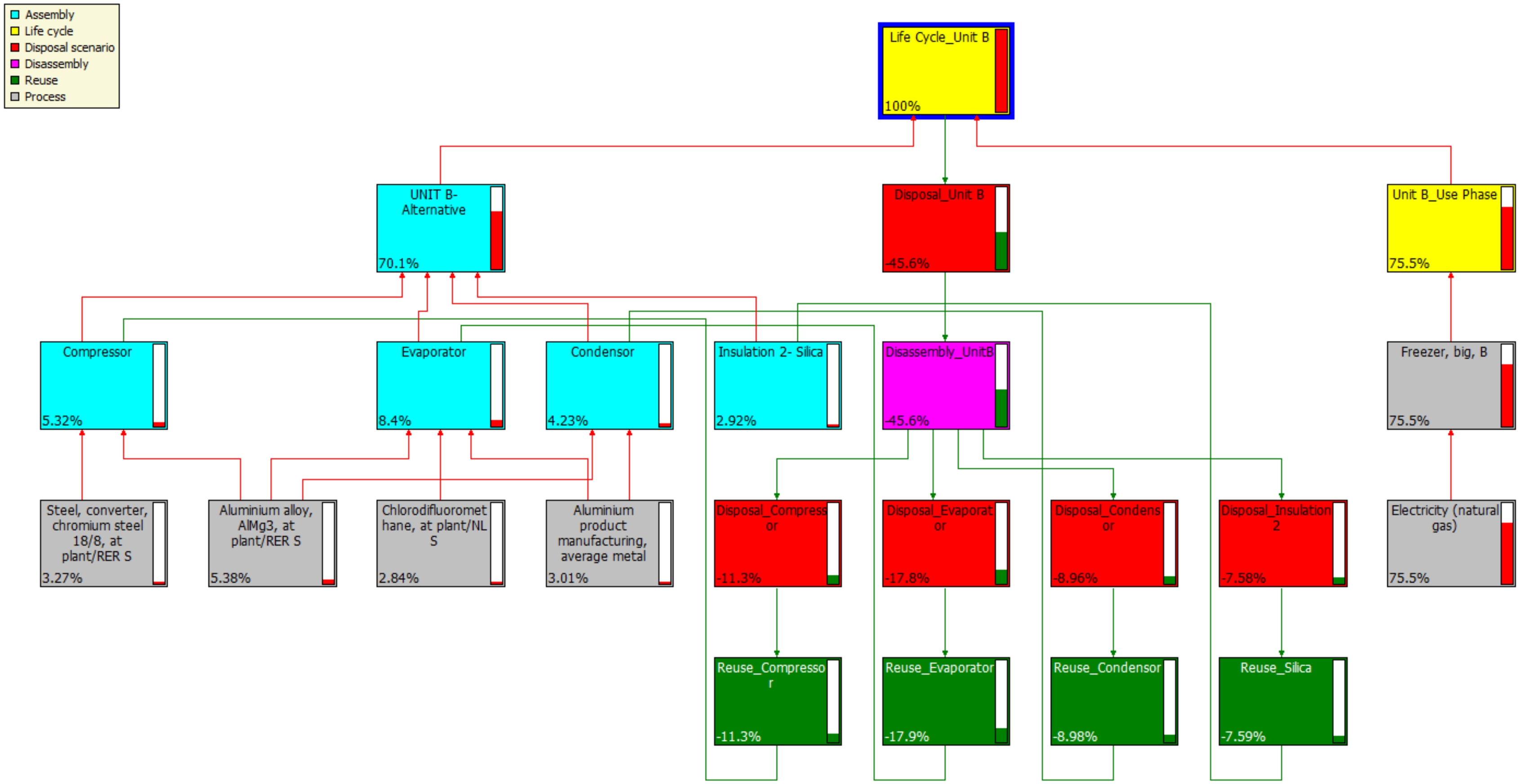


Figure 5.7 A partial view of the life cycle network for Unit B as calculated by SimaPro.

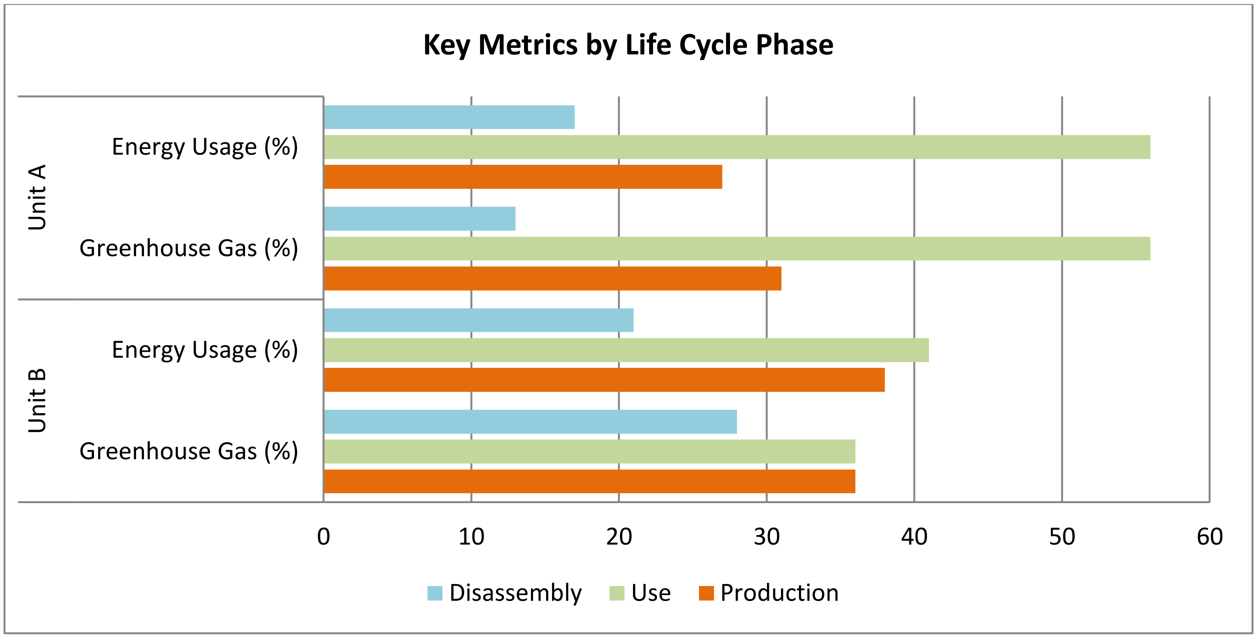


Figure 5.8 Energy usage and green house consumption by phase. For both Unit A and Unit B, the most significant source of energy use as well as greenhouse gases is the use phase.

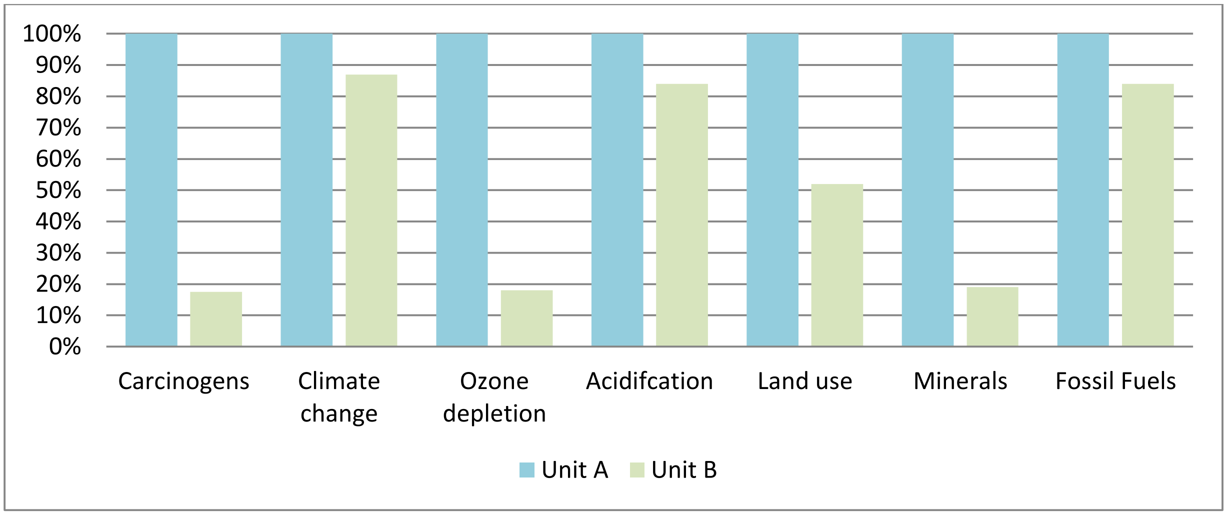


Figure 5.9 Characterization of Unit B relative to Unit A in each key environmental impact category

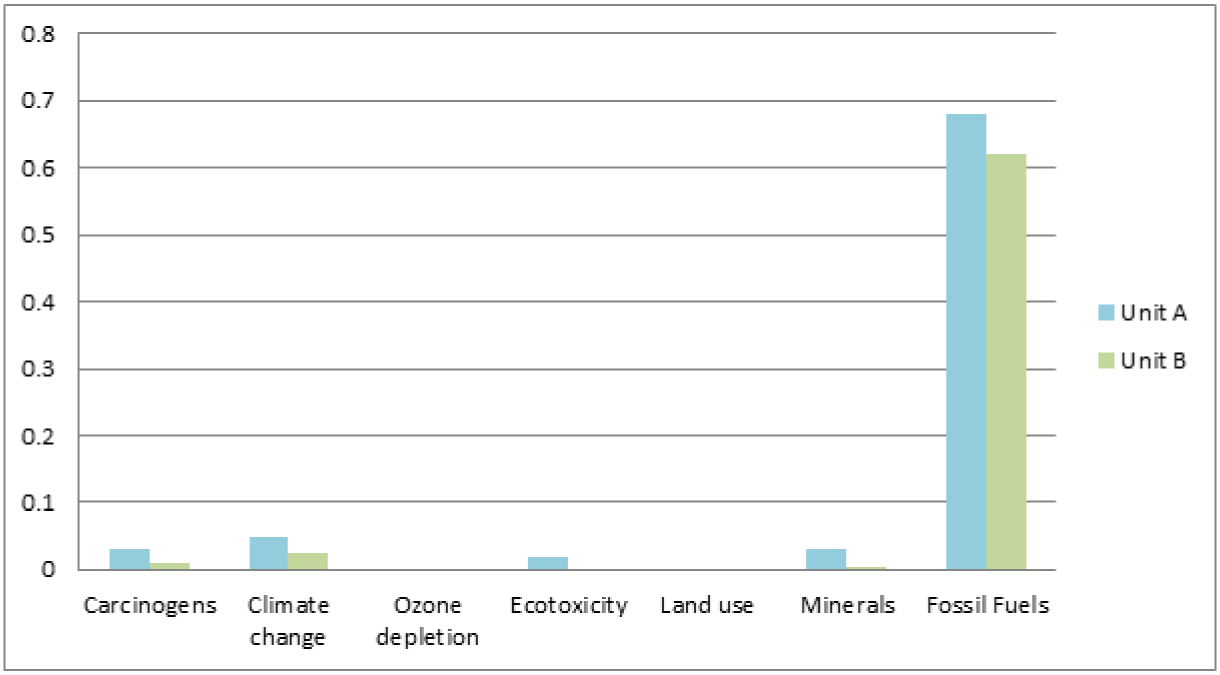


Figure 5.10 Normalization of each type of insulation in key environmental impact category based on equivalent European data. Each impact indicator is shown in terms of its contribution to the overall life cycle impact

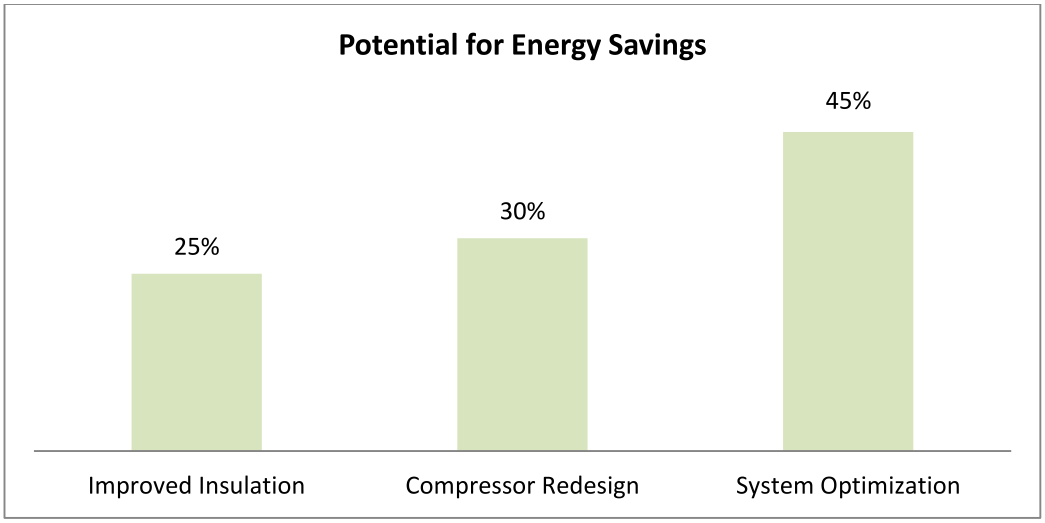


Figure 5.11 Potential for energy savings in residential refrigerators by employing three specific redesign measures (Source: Bansal et. al, 2003).

CHAPTER 6: QUANTIFYING END OF LIFE METRICS

The objective of the research in this chapter is to quantify the efficiency of disassembly and material recovery of the traditionally insulated refrigeration/freezer unit (Unit A), compared with the unit employing modified insulation (Unit B) to evaluate the design in terms of disassembly efficiency, and to determine and examine the flaws in both disassembly processes. This is achieved by employing a disassembly quantification system to determine which refrigerator/freezer unit has a higher disassembly efficiency. The disassembly efficiency is a function of four key factors, described in Section 6.2.

Disassembly is the process by which a product is broken down into its components for material recovery, or to aid in downstream recovery processes to salvage valuable parts or materials from the original product. At the end of life of a commercial refrigerator, the expired units are typically collected by municipal waste management and sent to collection depots specific for white goods. At the collection depots, the refrigerators are separated by type and sent to recovery facilities for refurbishing or material recovery. At the recovery facility, the commercial refrigerator is separated into two distinct categories: 1) the external casing and insulation, and 2) the mechanical components: the condenser, evaporator and compressor. At this point, the disassembly operations take place for mechanical refurbishing and material recovery for reprocessing, or if there is no other viable recovery method, or if the remaining material has no value it is collected for landfilling. This process of disassembly and material recovery is depicted in Figure 6.1.

The manufacturers surveyed in this study (see Chapter 5 for more information on the survey; Appendix A provides the survey) reported that salvaging and refurbishing the mechanical components from the refrigerator/freezer was a priority during disassembly operations, because of the high value associated with the metal: i.e., steel, copper and aluminum all have high scrap values. Typically scrap metal prices in the United States can vary by region and market values, but average 0.20c per pound for steel; 0.70c per pound for aluminum; and $2.59 per pound for copper (Scrap Register, 2014).

Manufacturers reported that salvaging the polyurethane foam utilized in the insulation to be manually tedious and a non-priority, as the foam needed to be manually stripped by workers, and had no value or market for re-sale.

6.1 Profile of Separation Facilities

There are several different type of facilities that sort and separate materials. They range from large and fully automated, to small and completely manual facilities. Of the three facilities surveyed in this research, the sizing and type of facilities were all described as “drop off single stream facilities” where the material separation takes place at the recovery facility, instead of during collection, and most of the separation of the activities taking place were classified as “manual with some tools.” The input stream was surveyed to be an average of 80% commercial and 20% residential. The surveyed facilities each had various types of loaders that transported the waste to a conveyor belt. Sorters in each facility ranged from manual to mechanical.

6.2 The Evaluation Method

This research adapts the evaluation method employed by Das,Yedlarajiah and Narendra(2000). This study has been applied to printers, calculators, and a myriad of other products. For the purposes of this research, a multi-factor approach to compute an overall ‘disassembly factor’ (DF) is presented, allowing an individual to compare scores for competing products. ‘DF’ is then converted to a cost metric by considering the overhead associated with the processes associated with the disassembly, as well as the labor needed for the execution of separation processes. For this research, this cost factor is known as the disassembly cost analysis (DCA), described in Section 6.3. The DCA is then a decision making tool to determine the most efficiently recovered product choice. The method of evaluation entails mapping out the disassembly process of the product and selecting difficulty scores from the database for the tasks involved and logging it on the corresponding spreadsheet. The ideal evaluator has thorough knowledge of the disassembly process, and must assess key aspects of the task performance to assign a difficulty score.

The DCA is based on weighted estimates from four different factors. They are, (1) time needed for disassembly (2) effort needed for disassembly (3) ease of access (4) level of hazard to workers. Each factor has an independent scale that practitioners utilized to rate each factor. A formula for the design factor (DF) metric incorporates the four factors in an overall weighted scheme. Each factor scale was designed to be simply read and interpreted, so it was as easy to utilize as possible. Each factor is weighted based on the level of importance to overall disassembly efficiency. The rationale for the weighting of each factor is described in Section 6.3.

Two main output metrics from this datasheet are considered and compared to evaluated efficiency and ease of disassembly.

Disassembly steps are listed chronologically, and each step is assigned a rating in each of the four factors. The ratings for that particular step in the disassembly process are then added up. This study assumes that (1) the workforce is trained and familiar with the operation of common types of machinery utilized in the disassembly operations; (2) imperfections or corruption to the fasteners, material or overall unit are minor and will not affect the overall disassembly efficiency.

An example of the disassembly evaluation chart is shown in Figure 6.2. The first column ‘Task’ describes the specific step to the disassembly process, recorded sequentially on each row. The column contains data pertaining to the different factors utilized in the analysis. Each factor is defined in a separate database to ensure consistency.

6.2.1 Task Description

Each separation operation is listed chronologically in Column 1. If the task is repeated multiple times during disassembly, it is listed each time it is performed. All tasks should be included in this column once they have been positioned for disassembly. If an answer to one or more of the following questions is “yes,” the disassembly step should be listed on the spreadsheet.

- Does it facilitate the removal or partial removal of a component of the product?
- Does the step facilitate the positioning the product for a disassembly action?

6.2.1.1 Factor 1: Time on Task

The time rating (second column in Figure 6.2) assigns a performance number based on the length of time it takes for a particular disassembly task to be performed by a skilled worker. This is a critical component in determining the overall rating of the disassembly efficiency, as the more time, labor, and power expended toward disassembly, the less economical the process becomes. As such, a ratings and time are directly related in the rating scheme. For this case, in which the disassembly of the insulation for a commercial refrigerator is estimated, manufacturers rated the threshold of “5 mins +” to be the least favorable time for disassembly, and so a value of this amount carries a ‘5’ rating. The survey of manufacturers revealed that at this point, it was unlikely that the material would be salvaged, and would likely be landfilled, unless the material had a very high resale value. The time is inclusive of all time to position, prep, and physically perform the task related to disassembly. Table 6.1 shows the rating allocated to the time taken to perform a given task.

6.2.1.2 Factor 2: Effort

The “effort” factor (third column in Figure 6.2) is a key factor in determining the difficulty associated with disassembly operations, because some tasks require more power to accomplish. For example, prying a glued joint apart is more labor intensive than removing a screw. Similarly, large, heavy machinery with a higher economic cost are associated with more forceful disassembly actions, and would carry a higher effort rating than a simple mechanical tool like a power drill.

Power expended by the disassembly step is a function of energy expended by man or machine. Many plants disassemble products manually; however, lately there has been a conscious movement to mechanical separation. This factor allows for normalization of the mechanization factor, as it rates the different forms of effort that would be expended: human and machinery. Thus, two scales for the ‘effort’ rating are proposed, as shown in Table 6.2. In most disassembly operations, manual methods are employed, as they are considered to a simple solution. This factor ultimately helps an individual determine whether the cost of labor is worth the value gained from material recovery. The following table shows the equivalent rating scheme for Factor 2, force for machinery and the subsequent rating for it.

The following table shows the equivalent rating scheme for Factor 2, force for machinery and the subsequent rating for it.

6.2.1.3 Factor 3: Ease of Access

Ease of access (fourth column in Figure 6.2) to the insulation material is a key factor in determining its recovery rate. If material is not easily accessed, it is more likely to be landfilled due to the time and manpower needed for its removal. Thus, a more sustainable design is achieved if a ‘design for disassembly’ approach is employed, accounting for both ease of access and overall material recovery.

The ease of access rating determines how easily a skilled worker can access the part of disassembly. A difficulty often observed in the disassembly process is the position of a component or fastener. The most common way to access a component’s core material is through the removal of the fastening binding the material to the component. The measure of the ease of access is determined by the ergonomics of the removal to a worker. According to the manufacturers surveyed, visibility of the fastener or component for the removal operation is a critical component to this factor. There are standard types of fasteners typically employed in product assembly; for example, screws, glue, nails. These types of fasteners are the norm and disassembly plants are typically equipped to facilitate their removal.

The other key measurement for this factor is the body position of the worker in order to access the part. The most favorable removal operation is one in which a worker can clearly see the fastener or component for removal, and they are able to access it in a standing position by reaching forward. The manufacturers surveyed indicated that most commonly it was not the fastener themselves that presented the challenge for disassembly, but its placement. Thus, the ‘ease of access’ rating is based on the ergonomics of the disassembly process and the comfort level of the worker performing the task.

6.2.1.4 Factor 4: Risk Level

Separation of materials and disassembly may involve the destruction of parts of a unit in order to salvage recyclable material. The destruction process may expose workers to hazardous conditions and materials that as a part of a product may otherwise be benign. An example of this is the removal of the internal glass and thermometer from residential refrigerators. When the separation procedure is performed incorrectly, the glass may break, or the mercury from the thermometer contained within the unit may spill and become a risk for the workers.

If there is a risk that is routinely encountered by workers during the separation procedure, it is considered an inhibitor to efficiency disassembly operations and so must be considered as a factor when determining disassembly and recoverability. The risk referenced in this scale does not include the common workplace risks that occur at almost all work sites: sharp edges, potential accidents, machinery mishaps, but rather the intrinsic risk of the particular step of disassembly. Table 6.4 lists six levels of common potential risks common experienced at job sites. Any precautions or measures beyond what is listed should be considered ‘specialized’ and carry a ‘5’ rating.

6.2.2 Task Score

The final column on Figure 6.2 is the ‘task score’. As part of the recovery survey, disassembly operation managers were asked to rate the four factors in terms of importance to the overall efficiency. Results indicate that the time factor was the most important, and was so assigned a weighting of 0.4. Effort was the second most influential factor and is assigned a weighting of 0.3; access and risk were rated 3rd and 4th in order of importance to efficiency and were so assigned weightings of 0.2 and 0.1 respectively. Thus, in order to incorporate these factors into the DF rating, each “task score” (TS) was a function of its relative importance, as described by Equation 6.1:

$$\begin{gathered} TS = 0.4(\text{time rating}) + 0.3(\text{effort rating}) \\ + 0.2(\text{ease of access}) + 0.1(\text{risk rating}) \end{gathered} \quad \text{[Eqn. 6.1]}$$

After each step is assigned values from each factor, they are summed in the ‘task score’ column.This allows the practitioner to determine which task has the highest score, and would indicate that the task is more demanding or inefficient than others, allowing decision-makers to isolate the inefficient tasks in the industrial process. The disassembly factor (DF) is the sum of all of the task scores for the disassembly process.

6.3 Analysis

The disassembly factor (DF), as well as the overall time required and the material recovered from the disassembly process is critical in developing a cost-benefit scenario. Material recovery value is estimated by considering the market value of the recovered materials.

The DF is multiplied by a marginalized cost factor (α) that is estimated by the factory. This cost factor is an estimate of the overhead and indirect costs associated with the disassembly. Also included in the cost-benefit calculation is the overall time needed for total disassembly. This value is them multiplied by (β) the cost associated with the labor needed for the prescribed length of time. The cost-benefit analysis is described by Equation 6.2 as:

$$\begin{gathered} \text{Total Cost (DCA)} = \text{Material recovery value} - \\ \alpha\,(\text{Total Disassembly Time}) + \beta\,(DF) \end{gathered} \quad \text{[Eqn. 6.2]}$$

This cost metric quantifies the success of the design as it relates to economic efficiency. This value also serves as a tool to compare alternative designs, as well as alerting the designer to design flaws. The disassembly time for each component allows the design to compare component disassembly and determine to what extent these steps may be condensed and integrated.

For the purposes of this study, the disassembly quantification of Unit A and Unit B did not consider the disassembly of the mechanical components, and only analyzes the section outlined in red in Figure 6.3, which considers the removal of the insulation. This is because it is assumed that the removal of the mechanical components would have little to no impact on the disassembly of the insulation. In the case of Unit A, all manufacturers had worked with the removal of the foam and were able to fill out the manufacturer survey easily. In the case of Unit B, none of the manufacturers had experience with the particular type of insulation before, as the prototype was still in development. Thus, manufacturers were sent a full description and schematic of the proposed design and were asked to base their ratings on their knowledge of the disassembly process.

6.4 Results

Figures 6.4 and 6.5 show the spreadsheet of the analysis of the disassembly of Unit A and Unit B respectively. The disassembly analyses of Unit A and Unit B revealed an overall cost values of $5.78 and ($0.35) respectively, indicating that when material recovery was considered along with the overall design for disassembly rating, recovering the insulation from one refrigerator/freezer unit cost the factory $5.78, after all the recovered material was sold for reuse. Unit B had a cost value of ($0.35) indicating that the value of the recovered material, the sheet metal and the insulation, offset the costs associated with the disassembly. The material recovery value for Unit A came mainly from the resale of the sheet metal recovered, which amounted to $2.71. The overhead costs were estimated to be slightly higher for Unit B, due to the need for heat to active the heat release adhesive utilized in the design.

The total disassembly factor (DF) for each unit is an indication of which unit required more work to separate. For Unit A the rating was 36.5, compared to the 39.3 rating of Unit B. This indicates the complexity and difficulty of the disassembly was slightly greater for the insulation in Unit B. This can be attributed mainly to the increase in added steps in the separation process. Unit A had an estimated 39 steps to the overall disassembly process, whereas Unit B had 54 steps. The overall time taken for both units, the most important factor according to manufacturers, was also very different. The total disassembly time for Unit A, was approximated by factories affiliated to take an average of 46 minutes for one worker to fully separate the components of the walls and cover. For Unit B, the estimated time for one worker to fully disassemble the unit was 11.2 minutes. A closer look at the analysis shows that there were two main contributors to the inefficiencies in the time factor: the removal of the white acrylic top coat from the external metal sheeting; and in the case of Unit A, the manual scraping of the polyurethane foam from the walls and cover of the unit.

One significant inefficiency identified by the analysis for both units was the fasteners used to bind the acrylic to the metal and the metal sheeting to the insulation itself. In both cases, epoxy resin was used to bind the acrylic to the metal and thus, required a large amount of effort to remove it. In the case of Unit A, the polyurethane itself was the key binder for the metal sheeting and the internal insulation. As the polyurethane was injected in liquid form into the unit, it adhered to the metal and eventually hardened. In both the case of the acrylic and the polyurethane bindings, significant effort and time was needed to remove them manually.

Results from the analysis indicated that both the ease of access and risk level were a relative non-issue since in the majority of steps for Unit A and Unit B, the worker had visible and clear access to the part that needed to be separated. In both cases, no specialized equipment was necessary for hazard mitigation.

6.5 Discussion

This analysis assumed a customer for the reusable insulation utilized by Unit B. If no such customer exists, the least costly disassembly process would be chosen. It should also be noted that because the workers surveyed in this study were given a hypothetical disassembly scenario in the case of Unit B, true disassembly times may vary. This model does not provide a highly detailed cost model, but rather evaluates the cost and benefits to each kind of disassembly method in order to aid disassembly plant managers identify inefficiencies in the processes.

The main inefficiencies identified from the analysis of Unit A were the total time for separation, attributed mainly to the manual scraping of the polyurethane foam and its use as a binding agent. Due to the nature of the material itself, it is unlikely that this separation could be fully automated, but a movement toward a more automatic separation process could be achieved by the development of automated scraping apparatus, where one side of the wall or cover is placed on a clamp, and a specialized blade is able to separate large masses from the external refrigerator/freezer skeleton. The inefficiency of separating the acrylic from the metal sheeting is an indication that the traditional white aesthetic should be replaced completely with a fully metal exterior, as many residential refrigerators have done in recent years.

For Unit B, the main inefficiency identified by the analysis was the increase in the separation steps, which increased the overall disassembly factor. This could be mitigated by the use of a continuous insulation cartridge through the box of the unit, where an insulation mesh could bend around the vertices of the unit so fewer steps would be necessary to separate the insulation cartridge from the refrigerator/freezer, as opposed to removing an insulation cartridge per wall.

6.6 Life Cycle Cost Analysis

A life cycle cost analysis was conducted to determine which option was the most cost effective over the life time of a unit. This was done by estimating the initial costs associated with the manufacture of each unit, including materials, overhead associated with tooling, and labor. Unit A utilizing traditional foam was estimated to be approximately $17 less to produce than Unit B. The additional costs were largely associated to the price of fumed silica used in the insulation cartridge. Based on the experimental values obtained in Chapter 3 of this work, it was assumed that Unit B would utilize 15% less electricity over the lifespan of the unit. The operating cost was determined by estimating the average cost of electricity over the 20 year life span, and converting this cost to net present value, using equation 6.1. The salvage value and disassembly costs were also calculated by this method.

$$NPV = \sum_{t=1}^{T} \frac{Ct}{(1+r)^t} - C_0 \qquad \text{[Eqn. 6.3]}$$

The net present value (NPV) was calculated using Eqn. 6.3 where Ct is the net cash inflow during the period, C_0 is the initial cost of production, r is the discount rate (assumed to be 5%) and r is the number of time periods. The disposal and salvage values were based on the disassembly analysis described in Section 6.3. The assumption for this work is that there would be a buyer for the salvaged metal and insulation cartridge. The initial inputs and final results are given in Table 6.5.

This evaluation shows that while Unit B has the higher initial cost, the reduction in power consumption over the use phase of the unit offset any additional costs associated with the fabrication of Unit B.

Table 6.1 Rating scheme for Factor 1, “time on task”

Time on task (seconds)	Rating
240+	5
180–240	4
120–180	3
60–120	2
30–60	1
0–30	0

Table 6.2 Rating scheme for Factor 2, “effort”

Effort	Rating
Force-Human	
High Impact (>50 lbs.)	5
Low Impact (>35 lbs.)	4
Leverage (>24 lbs.)	3
Orthogonal (>15 lbs.)	2
Torsional (>7 lbs.)	1
Axial (>2 lbs.)	0
Force-Machinery	
High Impact (>300 lbs.)	5
Low Impact (>35 lbs.)	4
Leverage (>24 lbs.)	3
Orthogonal (>15 lbs.)	2
Torsional (>7 lbs.)	1
Axial (>2 lbs.)	0

Table 6.3 Rating scheme for Factor 3, “ease of access”

Ease of access	Rating
Difficult to see, out of reach	5
Difficult to see, within reach	4
Partially visible, difficult to reach	3
Partially visible, within reach	2
Visible but requires effort to reach	1
Clearly visible and easy to reach	0

Table 6.4 Rating scheme for Factor 4, “risk level”

Risk level	Rating
Specialized equipment/ room/body suit	5
Air supply	4
Fire protection	3
Face mask	2
Gloves	1
None	0

Table 6.5 Life cycle cost analysis of Unit A and Unit B

Unit type	Production	Use (NPV)	Salvage (NPV)	Disposal (NPV)	Total life cycle cost
Unit A- PU foam	$78.15	$309.37	-$1.09	$3.20	$391.75
Unit B- Modified Ins.	$122.32	$262.97	-$1.42	$1.29	$366.79

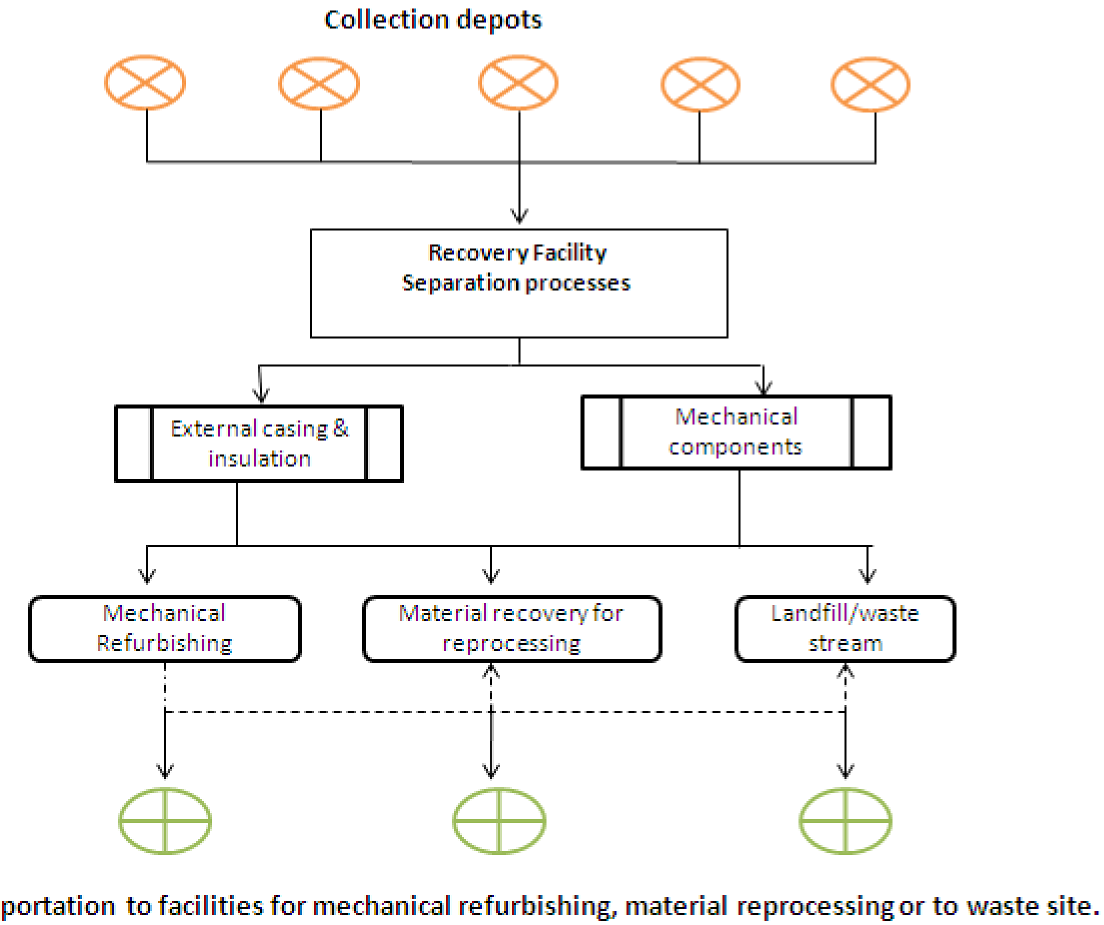


Figure 6.1 Typical disassembly schematic for component separation and material recovery for refrigerator/freezers.

TASK	1. TIME		2. EFFORT		3. EASE OF ACCESS		4. RISK		TASK SCORE
Description	Time (s)	Time rating[1]	Effort (lbs)	Effort rating[2]	Description of Access	Access Rating[3]	Risk	Risk Rating[4]	

Figure 6.2 Example of disassembly evaluation chart. This chart serves as an assessment tool to compare the ease of disassembly of products.

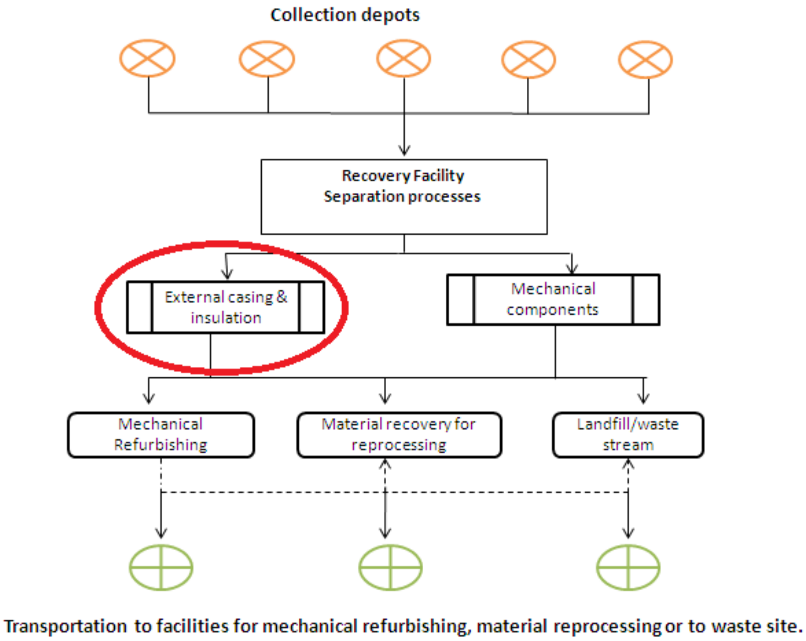
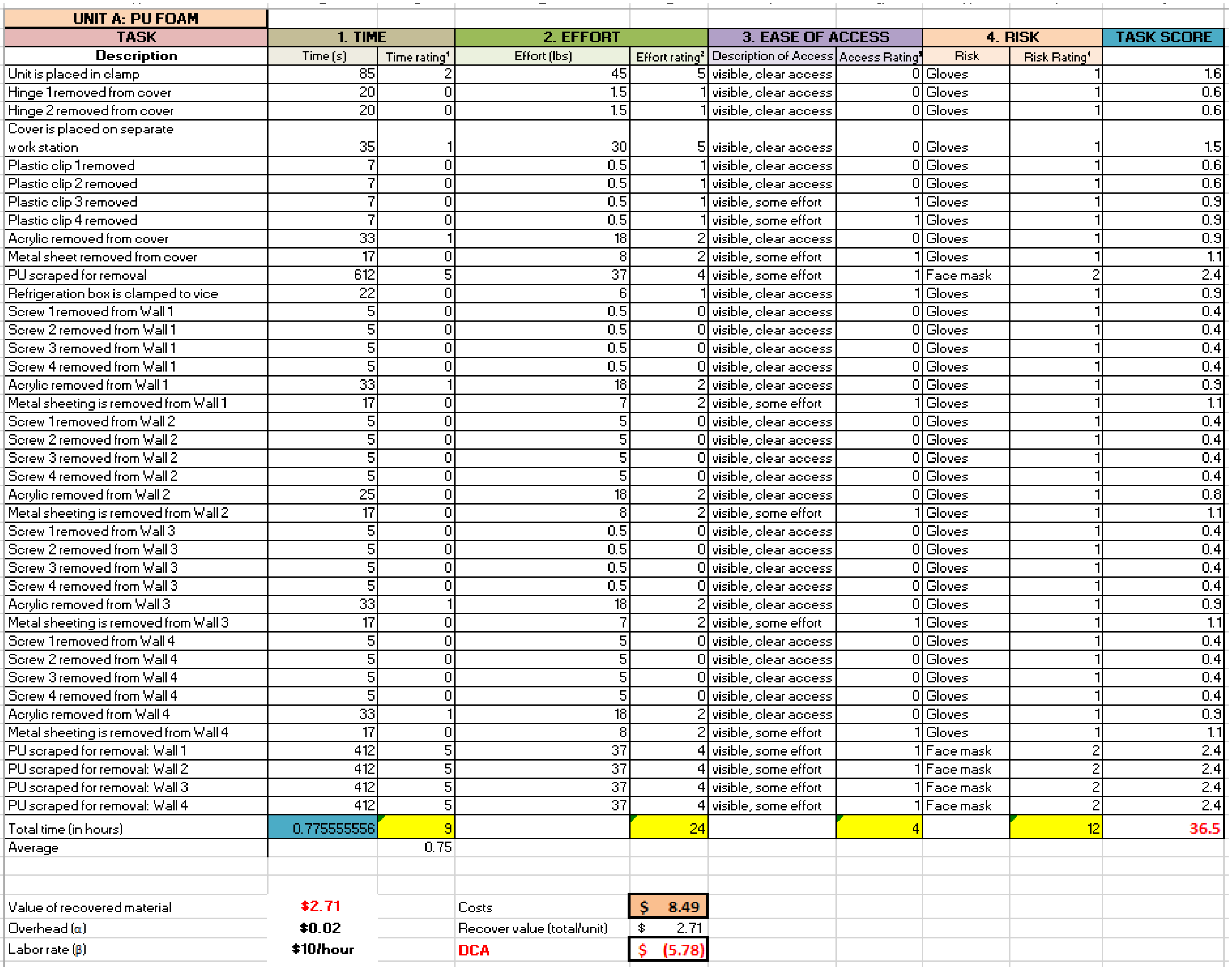
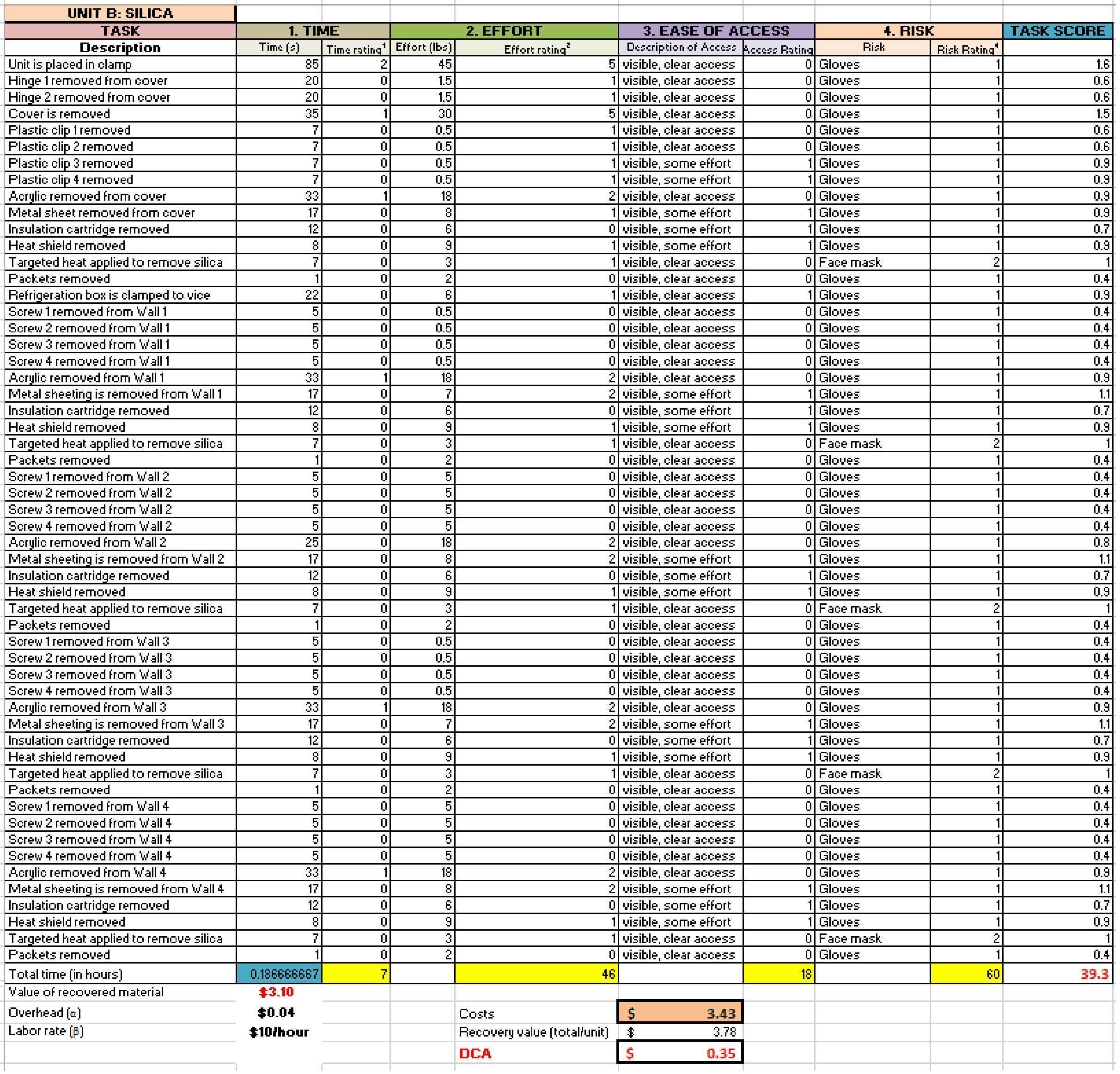


Figure 6.3 Boundaries of the design for disassembly analysis.



UNIT A: PU FOAM									
TASK	**1. TIME**		**2. EFFORT**		**3. EASE OF ACCESS**		**4. RISK**		**TASK SCORE**
Description	Time (s)	Time rating[1]	Effort (lbs)	Effort rating[2]	Description of Access	Access Rating[3]	Risk	Risk Rating[4]	
Unit is placed in clamp	85	2	45	5	visible, clear access	0	Gloves	1	1.6
Hinge 1 removed from cover	20	0	1.5	1	visible, clear access	0	Gloves	1	0.6
Hinge 2 removed from cover	20	0	1.5	1	visible, clear access	0	Gloves	1	0.6
Cover is placed on separate work station	35	1	30	5	visible, clear access	0	Gloves	1	1.5
Plastic clip 1 removed	7	0	0.5	1	visible, clear access	0	Gloves	1	0.6
Plastic clip 2 removed	7	0	0.5	1	visible, clear access	0	Gloves	1	0.6
Plastic clip 3 removed	7	0	0.5	1	visible, some effort	1	Gloves	1	0.9
Plastic clip 4 removed	7	0	0.5	1	visible, some effort	1	Gloves	1	0.9
Acrylic removed from cover	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheet removed from cover	17	0	8	2	visible, some effort	1	Gloves	1	1.1
PU scraped for removal	612	5	37	4	visible, some effort	1	Face mask	2	2.4
Refrigeration box is clamped to vice	22	0	6	1	visible, clear access	1	Gloves	1	0.9
Screw 1 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 1	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheeting is removed from Wall 1	17	0	7	2	visible, some effort	1	Gloves	1	1.1
Screw 1 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 2	25	0	18	2	visible, clear access	0	Gloves	1	0.8
Metal sheeting is removed from Wall 2	17	0	8	2	visible, some effort	1	Gloves	1	1.1
Screw 1 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 3	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheeting is removed from Wall 3	17	0	7	2	visible, some effort	1	Gloves	1	1.1
Screw 1 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 4	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheeting is removed from Wall 4	17	0	8	2	visible, some effort	1	Gloves	1	1.1
PU scraped for removal: Wall 1	412	5	37	4	visible, some effort	1	Face mask	2	2.4
PU scraped for removal: Wall 2	412	5	37	4	visible, some effort	1	Face mask	2	2.4
PU scraped for removal: Wall 3	412	5	37	4	visible, some effort	1	Face mask	2	2.4
PU scraped for removal: Wall 4	412	5	37	4	visible, some effort	1	Face mask	2	2.4
Total time (in hours)	0.775555556	9		24		4		12	36.5
Average		0.75							
Value of recovered material	$2.71		Costs	$ 8.49					
Overhead (α)	$0.02		Recover value (total/unit)	$ 2.71					
Labor rate (β)	$10/hour		DCA	$ (5.78)					

Figure 6.4 Cost/benefit scenario for the disassembly of the insulation utilized in Unit A.



UNIT B: SILICA									
TASK	1. TIME		2. EFFORT		3. EASE OF ACCESS		4. RISK		TASK SCORE
Description	Time (s)	Time rating[1]	Effort (lbs)	Effort rating[2]	Description of Access	Access Rating	Risk	Risk Rating[4]	
Unit is placed in clamp	85	2	45	5	visible, clear access	0	Gloves	1	1.6
Hinge 1 removed from cover	20	0	1.5	1	visible, clear access	0	Gloves	1	0.6
Hinge 2 removed from cover	20	0	1.5	1	visible, clear access	0	Gloves	1	0.6
Cover is removed	35	1	30	5	visible, clear access	0	Gloves	1	1.5
Plastic clip 1 removed	7	0	0.5	1	visible, clear access	0	Gloves	1	0.6
Plastic clip 2 removed	7	0	0.5	1	visible, clear access	0	Gloves	1	0.6
Plastic clip 3 removed	7	0	0.5	1	visible, some effort	1	Gloves	1	0.9
Plastic clip 4 removed	7	0	0.5	1	visible, some effort	1	Gloves	1	0.9
Acrylic removed from cover	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheet removed from cover	17	0	8	1	visible, some effort	1	Gloves	1	0.9
Insulation cartridge removed	12	0	6	0	visible, some effort	1	Gloves	1	0.7
Heat shield removed	8	0	9	1	visible, some effort	1	Gloves	1	0.9
Targeted heat applied to remove silica	7	0	3	1	visible, clear access	0	Face mask	2	1
Packets removed	1	0	2	0	visible, clear access	0	Gloves	1	0.4
Refrigeration box is clamped to vice	22	0	6	1	visible, clear access	1	Gloves	1	0.9
Screw 1 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 1	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 1	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheeting is removed from Wall 1	17	0	7	2	visible, some effort	1	Gloves	1	1.1
Insulation cartridge removed	12	0	6	0	visible, some effort	1	Gloves	1	0.7
Heat shield removed	8	0	9	1	visible, some effort	1	Gloves	1	0.9
Targeted heat applied to remove silica	7	0	3	1	visible, clear access	0	Face mask	2	1
Packets removed	1	0	2	0	visible, clear access	0	Gloves	1	0.4
Screw 1 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 2	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 2	25	0	18	2	visible, clear access	0	Gloves	1	0.8
Metal sheeting is removed from Wall 2	17	0	8	2	visible, some effort	1	Gloves	1	1.1
Insulation cartridge removed	12	0	6	0	visible, some effort	1	Gloves	1	0.7
Heat shield removed	8	0	9	1	visible, some effort	1	Gloves	1	0.9
Targeted heat applied to remove silica	7	0	3	1	visible, clear access	0	Face mask	2	1
Packets removed	1	0	2	0	visible, clear access	0	Gloves	1	0.4
Screw 1 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 3	5	0	0.5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 3	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheeting is removed from Wall 3	17	0	7	2	visible, some effort	1	Gloves	1	1.1
Insulation cartridge removed	12	0	6	0	visible, some effort	1	Gloves	1	0.7
Heat shield removed	8	0	9	1	visible, some effort	1	Gloves	1	0.9
Targeted heat applied to remove silica	7	0	3	1	visible, clear access	0	Face mask	2	1
Packets removed	1	0	2	0	visible, clear access	0	Gloves	1	0.4
Screw 1 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 2 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 3 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Screw 4 removed from Wall 4	5	0	5	0	visible, clear access	0	Gloves	1	0.4
Acrylic removed from Wall 4	33	1	18	2	visible, clear access	0	Gloves	1	0.9
Metal sheeting is removed from Wall 4	17	0	8	2	visible, some effort	1	Gloves	1	1.1
Insulation cartridge removed	12	0	6	0	visible, some effort	1	Gloves	1	0.7
Heat shield removed	8	0	9	1	visible, some effort	1	Gloves	1	0.9
Targeted heat applied to remove silica	7	0	3	1	visible, clear access	0	Face mask	2	1
Packets removed	1	0	2	0	visible, clear access	0	Gloves	1	0.4
Total time (in hours)	0.186666667	7		46		18		60	39.3
Value of recovered material	**$3.10**								
Overhead (α)	**$0.04**			Costs	**$ 3.43**				
Labor rate (β)	**$10/hour**			Recovery value (total/unit)	$ 3.78				
				DCA	**$ 0.35**				

Figure 6.5 Cost/benefit scenario for the disassembly of the insulation utilized in Unit B.

CHAPTER 7: CONCLUSIONS

The primary objective of this study was to explore commercial refrigeration design measures that will reduce the volume of polyurethane foam utilized in commercial-grade refrigeration units, while improving or sustaining key metrics (i.e., maximum allowable energy consumption, internal volume, integrated average temperature). This was achieved through the development and laboratory testing of an alternative insulation prototype, evaluated by measurements of energy consumption and heat flux in a redesigned commercial refrigerator/freezer unit. The research also evaluated the developed design in terms of environmental cost, effectiveness of thermal resistance and efficiency of design for disassembly.

The design was developed by applying the '12 Principles of Green Engineering' (Anastas & Zimmerman, 2003) to the product development process. The insulation design developed for this research was then compared to the traditional polyurethane foam insulation in two contexts: energy efficiency and environmental sustainability using life cycle assessment, and ease of disassembly during end of the product's life. With increasingly stringent and mandatory efficiency regulations being employed by Energy Star, the California Energy Commission, and the United States Department of Energy, the need for redesign of key refrigerator components is thus important. In fact, research shows that if all commercial and residential solid door refrigerators and freezers were just replaced with Energy Star models, greenhouse gas emissions would be reduced by 6 billion pounds (Energy Star, 2011).

The alternative insulation configuration consisted of an insulation cartridge in which packets of evacuated fumed silica are inserted into a honey-comb like recycled plastic structure.

A reflective heat shield made of recycled polyester fiber encapsulated the cartridge, and a small amount of polyurethane was applied to seal the structure. Once the initial prototype of the new insulation design had been developed, the basic function of the insulation was tested by monitoring power consumption and heat flux using experimental methods. Because the primary function of the insulation of a refrigerator/freezer is to insulate the contents contained within from infiltrated heat, a secondary functional analysis was conducted, employing heat transfer principles and ANSYS that developed a thermal analysis model to determine the expected behavior of heat through each type of insulation medium.

The second part of the research, evaluating environmental sustainability, was achieved through the use of life cycle assessment and design for disassembly methodologies that included development and application of a comprehensive disassembly quantification system to identify inefficiencies in the separation and recovery processes for each type of insulation.

Replacing the cover of a commercial 5 ft^3 Whirlpool refrigerator chest (equivalent to 1/3 of the total insulation surface area) with the new insulation design indicated that an increase in thermal and energy efficiency was achieved by the use of the modified insulation. On average, the alternative insulation performed 25-40% better with direct heat transfer. In agreement with this trend, there was an estimated energy consumption improvement of 5.1% employing the modified insulation in the cover of the unit alone, amounting to energy savings of 373kWh over the lifetime of the refrigerator/freezer. This equates to a savings of roughly 0.257 metric tons of CO_2e emissions for a singular unit over its 20 year life span, assuming a national energy mix (EPA, 2014). For a unit fully outfitted with the alternative insulation described by this research, an energy savings of 1,119 kWh and 0.771 metric tons of CO_2e emissions per unit is expected.

The theoretical thermal analysis agreed with the experimental analysis that the traditional insulation and modified insulation were both effective insulators; however the modified unit proved to be superior in thermal performance. The most significant source of heat transfer for both units was from the external metal skin, currently an industry standard. The most substantial mode of heat transfer was conduction, predominantly through the metal. It was found by the thermal analysis that the heat flux extends from the metal only 0.01m in the unit employing the modified insulation, as opposed to 0.05m in the case of the polyurethane insulation, indicating that while the heat is more concentrated along the vertices, the alternative insulation is able to absorb the heat more quickly.

The analysis of the disassembly life cycle phase revealed that the complexity and difficulty of the disassembly was slightly greater for the new insulation design. This can be attributed mainly to the increase in steps in the separation process. However, the total disassembly time for the unit employing the traditional insulation was 46 minutes, and for the unit employing the modified insulation, the disassembly time averaged 11.2 minutes. The disassembly analyses of the conventional and new insulation method revealed an overall cost values of $5.78 and $0.35 respectively, indicating that when material recovery was considered along with the overall design for disassembly rating, recovering the insulation from one refrigerator/freezer unit cost the factory $5.78, after all the recovered material was sold for reuse. The new insulation system had a cost value of $0.35 indicating that the value of the recovered material offset the costs associated with the disassembly. Additionally, a life cycle cost analysis of each unit was conducted. It was determined that the electricity saved in the use phase offset the additional costs associated with the production of the insulation cartridge. It was estimated that the life cycle cost of Unit A would be $391.75, and the life cycle cost of Unit B would be $366.79.

7.1 Unit Selection

In order to select the preferred design for this context, a simple evaluation method was developed. In Chapter 1 of this research, manufacturers ranked the design criteria relative to the importance of the design. A summary of their responses was provided in Table 1.2. Based on their preferred criteria for an alternative design, a weighting system was established. Each unit was then analyzed in an evaluation matrix shown in Figure 7.1. As shown, each unit was assigned scores based on the performance of the design in each category. For simplicity, the rating system in this case consisted only of a score of ‘0’, indicating an inferior design, and a rating of ‘10’ indicating it had performed better relative to the opposing design. If each design performed equally well in a specific category, they were assigned a score of ‘5’. The total score for the design, the last column in evaluation matrix, was calculated using Eqn. 7.1, where the score of each criteria was multiplied by its respective weight.

$$\mathrm{Score_i} = \sum_{j} \mathrm{W_j X_{ij}} \qquad \text{[Eqn. 7.1]}$$

$$\mathrm{Score_{option\,A}} = \left(\mathrm{W_{criteria1}} \times \mathrm{X_{optionA,1}}\right) + \left(\mathrm{W_{criteria2}} \times \mathrm{X_{optionA,2}}\right) \ldots \left(\mathrm{W_{criteria5}} \times \mathrm{X_{optionA,5}}\right) \qquad \text{[Eqn. 7.2]}$$

The life cycle cost revealed that Unit B was more economic overall than Unit A, despite having a higher manufacturing cost, and was so assigned a score of ’10’ for that criteria. Experimental tests in Chapter 3 proved that a unit fully outfitted with the alternative insulation (Unit B) would be approximately 15% more energy efficient than Unit A, so it was assigned a score of ‘10’ in that category. Maintenance needs were assumed to be the same for Unit A and Unit B, so each was assigned a score of ‘5’. The life cycle assessment of each unit (described in

Chapter 5) showed a more environmentally benign designed was achieved by Unit B, and so a score of ‘10’ was assigned in the category of ‘low environmental impact’. The life cycle assessment and end of life quantification (described in Chapter 6) also revealed less waste at the end of life was achieved by Unit Barter each unit had been evaluated based on the weighting system described above, Unit B proved to be the preferable choice in this context.

7.2 Recommendations

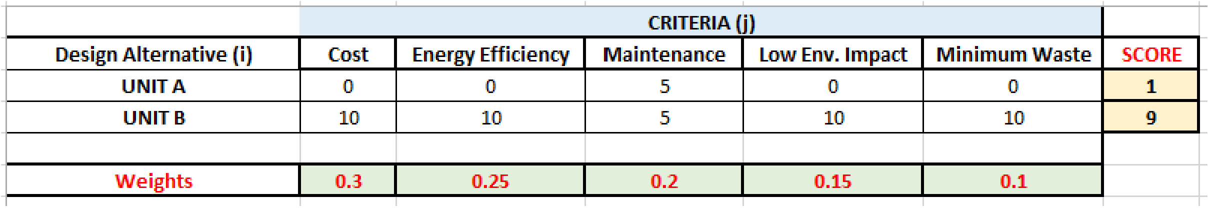
The fumed silica under a partial vacuum environment used in the new insulation design proved to be a superior insulation system to polyurethane in this application under the prescribed conditions. In future works, testing of this insulation cartridge for use in the built environment could result in the development this technology into a panel insulation system for use in residential buildings. However, this form of silica for now remains costly, so improving cost metrics and increasing the efficiency of its production is also necessary before large scale production is feasible.

Experimental and environmental assessment of the refrigerator/freezer unit revealed that significant opportunities exist to reduce the overall environmental and overall energy impact of the commercial refrigerator unit in the use phase, and this can be achieved by reducing the daily energy consumption of these units. The commercial refrigerator/freezer employing the alternate insulation is an example of modifications that may be made to existing units in order to increase the energy efficiency of the unit in the use phase. Modifications like improved defrost algorithms and more efficient mechanical components would further reduce the power consumption on a daily basis.

Also of note is that the metal to metal contact that occurs in the refrigerator/freezer is the key source of heat transfer and additional heat is infiltrated at the vertices of the unit, which in a model considering all vertices of the unit would amount to a significant heat gain. In order to prevent this from occurring, alternatives like continuous insulation through the entire frame of the unit should be considered. While it was outside the boundaries of this study, the insulation cartridge described in this study could be theoretically made of a flexible mesh like structure, allowing for it to be bent around the external skeleton of the structure to reduce heat gains from the vertices. Another benefit from a continuous mesh for insulation purposes would be an increase in disassembly efficiency.

As environmental sustainability becomes a primary goal for engineers, a framework is needed to guide their choice of materials and processes; and then to carry out the evaluation of their chosen design. Of "12 Principles of Green Engineering," nine have been utilized in this research as a framework by which to guide design to achieve both a functionally superior and more sustainable product. However, another critical component of sustainable design is the evaluation of the developed product. Quantitative methods are needed to evaluate the developed design and work in conjunction with an ongoing design process to determine to what extent the developed technology achieved the intended functional and sustainable success.

Evaluation methods should be based on the context of the product, and address the fundamental objectives of improved functionality metrics, and a more sustainable product in terms of its total life cycle; and design for commercial afterlife. It is recommended that the sustainable design process and the product developed through its application work concurrently with functionality and environmental sustainability evaluation methodologies to cultivate a continuous loop of design, implementation, assessment and improvement.



	CRITERIA (j)					
Design Alternative (i)	**Cost**	**Energy Efficiency**	**Maintenance**	**Low Env. Impact**	**Minimum Waste**	**SCORE**
UNIT A	0	0	5	0	0	**1**
UNIT B	10	10	5	10	10	**9**
Weights	**0.3**	**0.25**	**0.2**	**0.15**	**0.1**	

Figure 7.1 Evaluation matrix to select an appropriate insulation design based on the preferred criteria of the manufacturers surveyed in this research.

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APPENDIX A

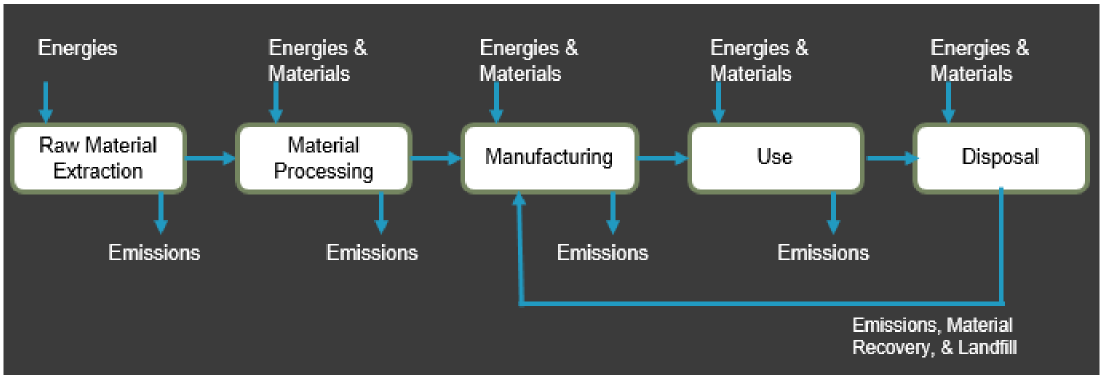
MANUFACTURER SURVEY: REPORTING YEAR 2012

Instructions: Thank you for agreeing to participate in this survey to document the inputs and outputs to the manufacturing, use and disposal of the commercial refrigerator process. Your data will be kept confidential and will not name you or your affiliation. Please answer the below questions to the best of your ability and contact me at cmanoosi@mail.usf.edu should you have any questions or concerns.

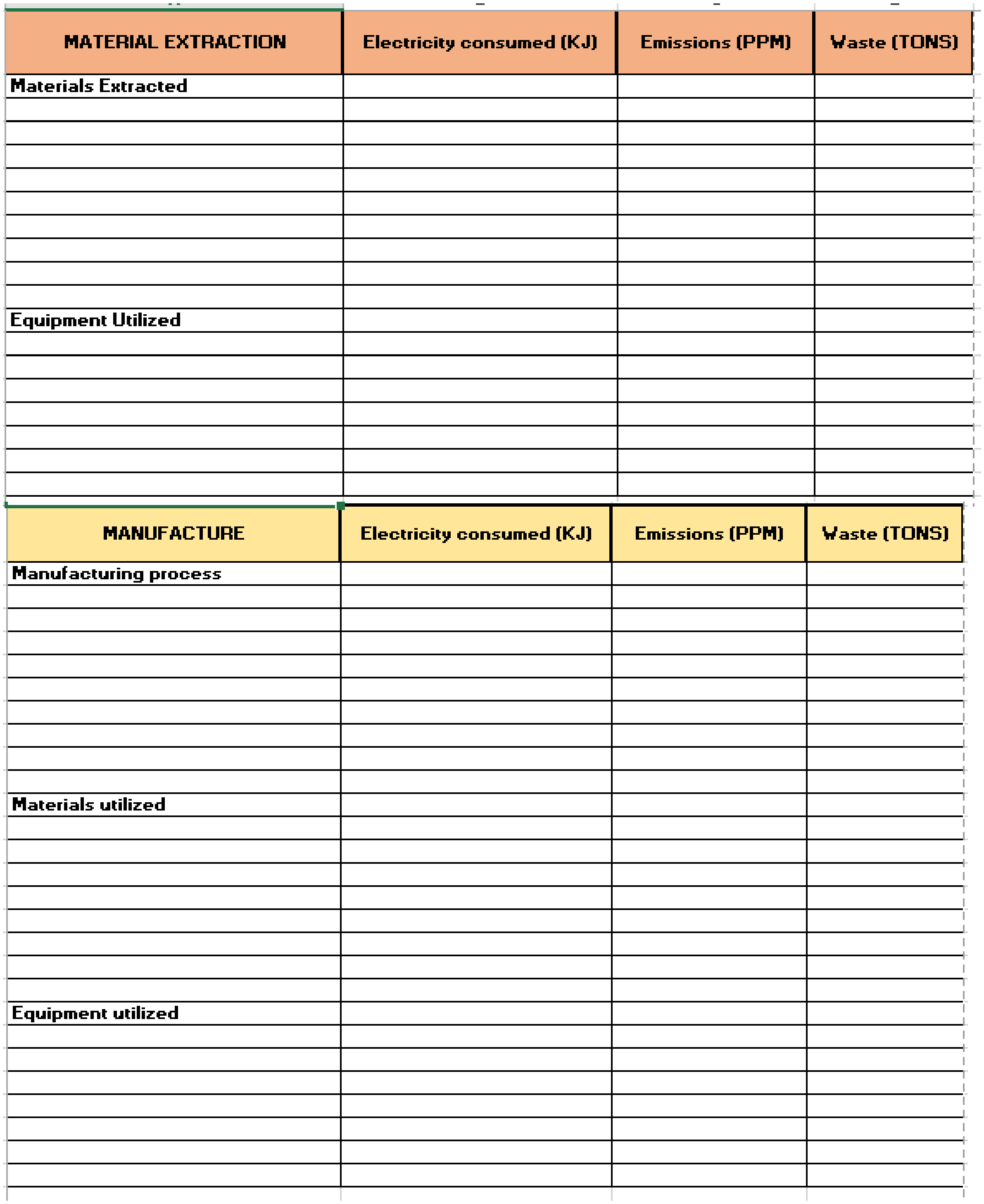
1. How many 5ft^3 commercial refrigerator/freezer units did you produce in the 2012 fiscal year?
   ____.

2. Please describe your primary customer and identify the region in which most of the units you produce are sold.
   ____.

3. Please circle the processes and procedures in which your company participates. You may circle more than one.



4. Please document all inputs, outputs, waste and emissions associated with the activities during each process in the following spreadsheets:



MATERIAL EXTRACTION	Electricity consumed (KJ)	Emissions (PPM)	Waste (TONS)
Materials Extracted			
Equipment Utilized			

MANUFACTURE	Electricity consumed (KJ)	Emissions (PPM)	Waste (TONS)
Manufacturing process			
Materials utilized			
Equipment utilized			

DISPOSAL	Electricity consumed (KJ)	Emissions (PPM)	Waste (TONS)
Disassembly process			
Equipment Utilized			
Material recovery (if any)			

5. Please describe any maintenance that these units would need over its lifetime.

____

____

____

____.

6. Please describe any outsourced manufacturing/disposal procedures that are involved in the production of these units.

____

____

____

____.

7. Please describe any problems you have noticed with the design of these units.

____

____

____

____.

8. Please describe the design criteria that are critical when considering potential redesign to any component of the unit.

____
____
____
____.

9. Please describe what material, if any, would be recovered from the end of life of a unit and what value you would expect this material to have.

____
____
____
____.

Thank you very much for your participation. Please return these surveys via email to cmanoosi@mail.usf.edu.