Environmental and Economic Assessment of Reclaimed Polyurethane Panels: The Case of Diverting Decommissioned Cold Storage Panels From Landfills and Recycling Into Three Forms of Insulative Building Materials

Environmental and Economic Assessment of Reclaimed Polyurethane Panels: The Case of Diverting Decommissioned Cold Storage Panels from Landfills and Recycling into Three Forms of Insulative Building Materials

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Abstract

This study investigates the long-term thermal performance of polyurethane insulated cold storage panels and the environmental and economic impact of recycling such panels when taken out of service in lieu of discarding them in landfills.

It is estimated, as of 2015, over 180 million square feet of insulated cold storage panels are manufactured annually in the U.S. The panels are most frequently constructed of closed-cell, low density polyurethane insulation utilizing HCF 245fa and HCF 134a blowing agents containing up to 6 million metric tons (CO2e) of greenhouse gases. The expected operating lifetime of the cold storage panels is 15 years after which time they are primarily discarded in landfills. This practice contributes to the build-up of greenhouse gases in the atmosphere, destroys valuable insulating and building materials and requires landfill space for the solid waste.

Three recycling strategies were investigated as ways to repurpose the discarded framed cold storage panels into new forms of polyurethane insulating materials; repurposed cold storage panels, board stock insulation sheets and blown-in/fill insulation. I used three research methods to quantify the environmental and economic impacts. The first examined the initial and long-term thermal performance of the recycled polyurethane insulation through laboratory testing and extrapolative modeling. The second method was comparative life cycle assessments between the business-as-usual-case of discarding the polyurethane insulation with each of the recycled strategies. Finally, an economic

analysis was completed for each recycling strategy to determine the in-use heating & cooling energy savings from the extended life of the recycled insulation.

This research shows recycling of discarded polyurethane cold storage panels provide measurable environmental and economic benefit. First, the productive life of the insulation is extended greatly beyond its initial use period reducing the need for fossil fuels and raw materials to make replacement insulations. Secondly, the high insulating value of the recycled polyurethane maximizes future environmental and economic savings from lower fuel demand in space heating and cooling applications. Thirdly, the majority of the sequestered greenhouse gases continue to be bound in the foam; protecting the environment from the release of global warming gases. Finally, by diverting the cold storage panels from landfills, millions of cubic feet of landfill space are unneeded annually.

Acknowledgements

I wish to express my profound appreciation to Mr. Michael Jackson and the BASF Polyurethanes organization who have given of their time and laboratory resources to support this thesis project. Mr. Jackson has gone above and beyond by performing the role as Thesis Director.

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Chapter I

Introduction

Polyurethane is the highest performing building insulating material available today. It can save 100 times the energy required for its production over a 50 year lifetime (PU Europe, 2013). The Federation of European Rigid Polyurethane Foam Associations found the use of polyurethane insulation in building applications can save 8,000 kWh/Sq. M of energy to heat and cool a building when compared to the same space without insulation (Figure 1).

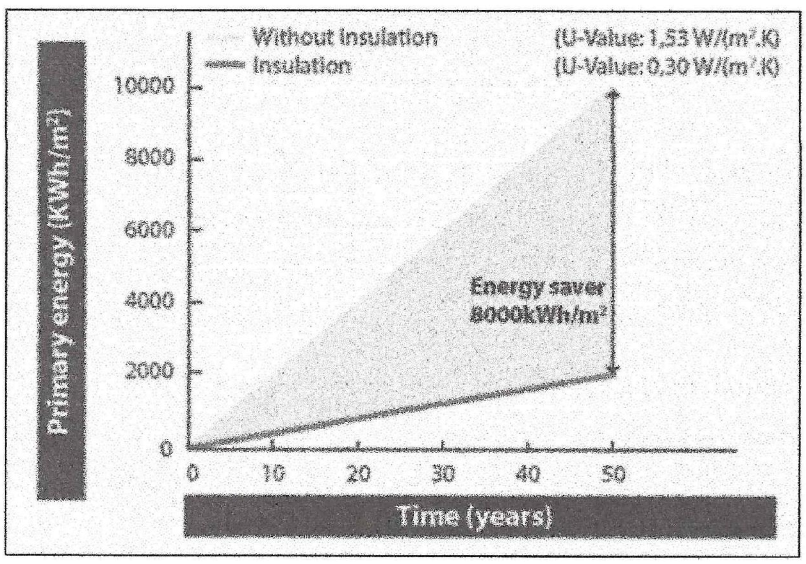

Figure 1. Polyurethane energy savings. This figure presents rigid polyurethane insulation energy savings over a 50 year period (BING, 2006)

Interestingly, that savings value may end up being an understatement especially for building applications, as leading polyurethane trade organizations believe polyurethane insulation will be effective for the life of the building (Federation of European Rigid Polyurethane Foam Associations, 2006).

Open cell spray polyurethane insulation is now used extensively to insulate building structures. The history of the built environment has shown that a building's effective life can be well past 100 years - delivering a much greater energy savings value than currently shown. That may be especially applicable for structures insulated with high efficiency closed-cell polyurethane foam (Kotaji & Loebel, 2010). Buildings not only gain from the high insulating values of the polyurethane (up to R8 per inch thickness) but benefit from the polyurethane's adhesive and structural properties (Al-Homoud & Mohammad, 2005).

Polyurethane Insulation Composition

Closed –cell polyurethane foam insulation is manufactured by combining a polyol-isocyanate mixture with one or more blowing agents. Blowing agents are selected for their low thermal conductivity properties which maximizes the foam's insulating value. During the manufacturing process the blowing agent creates gas-filled cells that are constructed of the polymer mix (Figure 1). Only 3% of the polyurethane foam is solid plastic material - with the balance being the gas filled cells containing the blowing agent (Federation of European Rigid Polyurethane Foam Associations, 2006).

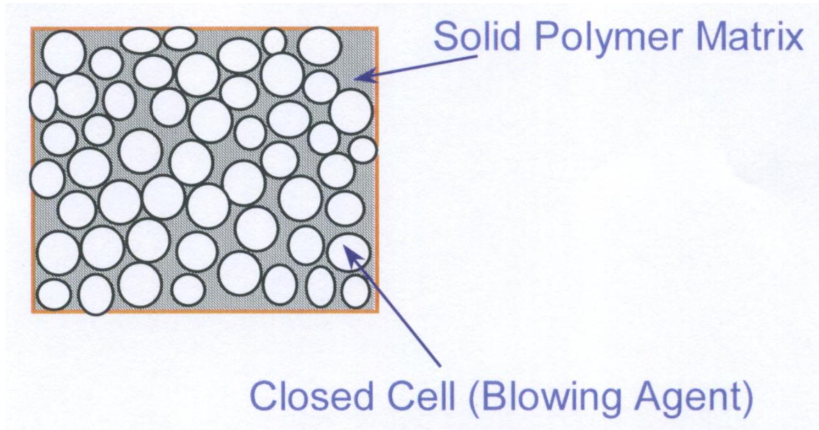

Figure 2. Polyurethane foam composition. This figure presents the polymer structure of closed cell polyurethane insulation (Mukhopadhyaya & Kumaran, 2008).

Use of polyurethane insulating foam in cold storage building applications became the industry-standard in the 1980s (ISOPA, 2014). It provides unique solutions to the cold chain of food production, distribution and storage because of its thermal and structural properties (ISOPA, 2009). This high efficiency insulating system replaced fiberglass and rock wool insulation that had previously been the dominant insulation materials. As polyurethane insulation came into greater use, additional CFC based blowing agents became available including Trichlorofluoromethane; CFC-11 (U.S. EPA, 2014b). The 1980s also brought the use of fire-retardants which began to be blended into the foam chemistry to meet increasingly demanding model fire codes in the U.S. (L. Jewell, personal communication, June 26, 2014).

By the 1980s, a body of research had been compiled which showed the use of chlorine-based blowing agents (chlorofluorocarbons) were having a deleterious effect on the earth's ozone layer. In 1987, the Montreal Protocol treaty prescribed a phase-out of chlorofluorocarbons due to their high ozone depletion potential (U.S. EPA, 2014b). According to Jewell, both CFC-11 and CFC-12 had been the primary blowing agents in the high efficient foam chemistries used in cold storage panel manufacturing and by the mid-1980s, ahead of the Montreal Protocol CFC phase-out requirement, hydrochlorofluorocarbon (HCFC) blowing agents such as HCFC-22 and HCFC 141B were being phased in within the U.S. cold storage panel industry. Their use continued in cold storage panel applications until U.S. mandated phase-out in 2009. They were replaced by hydrofluorocarbon (HFC) blowing agents which had less global warming potential (GWP); primarily HFC 245fa and HFC 134a. They have remained the primary blowing agents used in manufacturing polyurethane cold storage panels in the U.S. (R. Witt, personal communication, July 30, 2014).

Cold Storage Panel Fabrication

Insulated polyurethane panels for cold storage applications, as noted by Mr. Jewell have been substantially made the same way since the 1970s. They are manufactured in either a continuous line or discontinuous method. Each manufacturing approach creates a panel sandwich of metal skins with a polyurethane foam core in a 3" to 6" depth and designed at a foam density of approximately 2 pounds per cubic foot. In the case of both continuous line and discontinuous manufactured panels, the polyurethane foam adheres to all surfaces of the metal faces and frame creating an amalgamated and structural panel.

Cold Storage Panel Use

Cold storage panels create environmental enclosures which are used to refrigerate temperature and environmentally sensitive materials. They can range from fresh and processed foods to pharmaceuticals and chemicals. The majority are used in the refrigerated food industries. The U.S. Department of Energy estimates the average operational life of the cold storage panel in the food industry is 15 years (2014). That is substantially less than the 50 year useful life of the polyurethane insulation noted by the Federation of European Rigid Polyurethane Foam Associations (2006).

Cold Storage Panel Disposal

After this short lifetime, the polyurethane panels are decommissioned and most often discarded (D. Neighbors, personal communication, February 12, 2014). Unlike open cell polyurethane used in applications such as mattresses, furniture, car seats and carpet underlayment which can be recycled or used as a fuel source (waste-to-energy recovery), the amalgamated low density closed cell fire-retardant polyurethane foam used in cold storage applications currently has limited commercially viable recycling options (Zia, Bhatti & Ahmad Bhatti, 2007). Thus as noted by Mr. Neighbors, discarding in landfills is a primary method of managing the disposal needs of decommissioned cold storage panels in the U.S.

Decommissioned walk-in panels are discarded by business operators due to damage or when they change the use of their refrigerated spaces. The most expeditious way for the contractor employed by the business operator to calculate the cost of disposal and manage the process is to discard the panels in a local landfill via roll-off dumpsters. While it is technically feasible to recycle cold storage panel materials into other uses or into raw materials, there has been no commercial markets in the U.S. for the cold storage contractor to use.

Background

The scientific record is substantially void of research concerning the long-term thermal performance and environmental/economic impact of commercial cold storage panels and their disposal or recycling. However, there have been related studies which provide valuable findings for this evaluation. The first are research studies concerning the disposal of other closed cell polyurethane foam insulation in landfills. These studies show the impact of blowing agent release from the shredding of the polyurethane foam insulation. That research is important to this study because one of the recycling options requires the shredding of the polyurethane insulation to create a blown-in/fill insulation. The second key area of research concerns the accurate determination of how the thermal properties of polyurethane insulation change over time. It is key to determining the long-term thermal performance of each recycling method in this study.

Shredded Polyurethane Insulation Blowing Agent Diffusion

One such study (Kjeldsen & Scheutz, 2003) evaluated blowing agent release in polyurethane foam insulation from discarded refrigerators and freezers; trialing four types of blowing agents. The tested blowing agents were CFC-11, HCFC-141B, HCF 134a and HCF 245fa. The polyurethane foam insulation was shredded into various sizes to assess both the immediate and long-term release of the blowing agents into the atmosphere. Their hypothesis was that not all of the polyurethane plastic cells would be destroyed or damaged in the shredding process and not all of the blowing agents would be immediately released from the polyurethane cells. The researchers learned the majority of the cells were not affected by the shredding process and the amount of blowing agent release was proportional to the shredded fragment size (Table 1).

Table 1. Blowing agent releases.

Blowing agent	Size	Main fraction (mm)	% age of total wt. in main fraction (%)	Total content of BA (% w/w)	Total release (%)
CFC-11	small	2-4	65	13.30	39
CFC-11	medium	4-8	77	13.30	34
CFC-11	large	8-16	83	13.30	18
CFC-11	X-large	16-32	84	13.30	9
HCFC-141b	X-large	16-32	74	11.62	9
HCFC-245fa	X-large	16-32	74	11.62	11

This table presents Instantaneous Release during Shredding from Foam Particles of Different Sizes and Different Blowing Agents (Kjeldsen & Scheutz, 2003).

The polyurethane insulation which was shredded into smaller fragments released a greater percentage of its blowing agent both in the short and long-term. They further learned there was no direct correlation between the blowing agent type and amount of gas released. Studies for all four blowing agents showed a maximum release of 39% (CHC-11) for particles in the 2-4 mm range and a minimum of 9 percent (HFC-141b) for particles in the 16-32 mm range. Additionally, a batch experiment was conducted with just HCFC-141B to determine how much of the blowing agent is released at various particle sizes. Their research showed the smallest particle (0.8 cm^3) lost 19% of blowing agent over a 1,000 hour test where the largest particle (12.8 cm^3) lost just 3% over the 1000 hour test. The results showed most of the blowing agents were released during the first 200 hours with a much smaller percentage occurring after that. Kjeldsen and Scheutz believed the shredded particles could take more than 10 years to release the initial content of blowing agent and suggest that conditions in a landfill could impact that time assessment.

Finally, the researchers evaluated the amount of blowing agent released based on the duration of time after cell breakage. They evaluated four particle sizes and evaluated blowing agent release over three time frames (Table 2).

Table 2. Blowing agent release distribution.

	Particle size category (mm)				
Release type	<4	4-8	8-16	16-32	>32
instantaneous release (% w/w)	40	34	18	10	5
short-term release (% w/w)	60	40	10	4	2
long-term release (% w/w)	0	26	72	86	93

This table presents a fractional distribution of the instantaneous, short-term and long-term releases as a function of foam particle size (Kjeldsen & Scheutz, 2003).

These test results are useful to understand the potential scale of blowing agent release when shredded from a rigid board stock or block of closed-cell polyurethane. They show the smaller the resultant fragment from crushing and compacting, the greater percentage of blowing agent release.

A second study by Kjeldsen & Jensen (2001) evaluated the release of a blowing agent (CFC-11) from residential refrigerator/freezers. They conducted laboratory experiments to estimate the Total Equivalent Warming Impact (TEWI) of shredding the polyurethane insulation waste. The research method shredded the polyurethane foam insulation to a 2 cm^3 particle size and compared it to a 5 cm thick panel without any facers. The study sought to determine the amount of blowing agent release before landfill burial. Their findings showed the shredded foam, based on a range of diffusion coefficients, was likely to release up to 40% of its CFC-11 blowing agent prior to being buried in the landfill, but could ultimately take upwards of 300 years to release a full 50% of its CFC content. They estimated the un-shredded 5 cm thick slab would have 'insignificant' initial CFC release with the average half-life of the CFC blowing agent remaining in the foam being 800 years - compared to 22 years for the shredded material. They also hypothesized the impact of landfill equipment and the weight of future layers of materials in the landfill could further crush some of the remaining polyurethane foam cells whereby more of the blowing agent would be released.

This study provides additional valuable information for my research concerning the differences between shredded polyurethane foam and rigid polyurethane slab foam on blowing agent release at the point of disposal.

Polyurethane Long-Term Insulating Performance

A key element of recycling cold storage polyurethane insulated panels is to reuse the insulation for other valuable insulating purposes. Knowing the initial thermal conductivity (k-Factor) of the polyurethane is important to determine what purpose(s) the recycled insulation can be best used for and what the long-term performance of the insulation will be. Fortunately, a number of applicable scientific investigations have been done in the past to assess the long-term performance of polyurethane insulations in various configurations.

One of the key studies was performed by The Forschungsinstitut für Wärmeschutz e. V. Münich (1998). It conducted a 15 year analysis of rigid polyurethane insulation to determine changes in thermal conductivity (Figure 2).

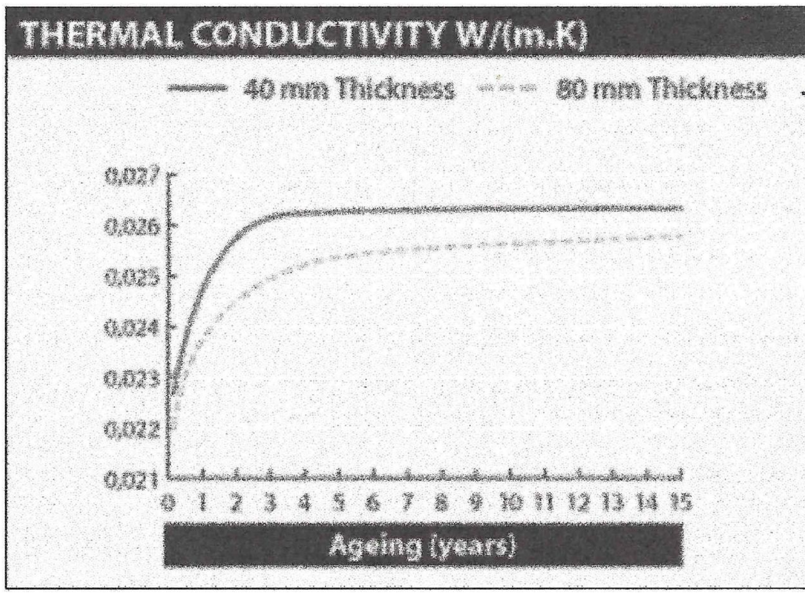

Figure 3. Thermal conductivity study results. This figure presents the thermal conductivity changes in PUR & PIR boards over 15 year study period – Courtesy of Bing. (Prüfbericht, 1998)

The study showed a sharp increase in thermal conductivity during the first 3 years of the study after which the conductivity minimally changed (BING, 2006). The researchers found cell gas diffusion with atmospheric gases was responsible for the rapid conductivity losses.

A subsequent study by Bomberg & Kumaran (1999) evaluated an extrapolative method to determine the performance of insulating foam that had characteristics which didn't permit foam aging estimation using existing methods. Those limiting characteristics include insulating foams with facers (impermeable skins) such as the case of cold storage insulating panels. This extrapolative approach used the distributed parameter continuum (DIPAC) mathematical model. Their study evaluated the thermal performance of eight different chlorofluorocarbon (HCFC) insulation foams, focusing on the blowing agent to air diffusion process. The researchers found lateral gas diffusion of the foam blowing agent was a significant knowledge gap area that required further investigation (Figure 4). This is the process where the blowing agent can diffuse laterally through the foam cells and exit the foam along the exposed edges of an impermeable faced panel (gas barrier). The authors felt a measurable amount of lateral diffusion could occur in the gas cells just under the impermeable skin, thereby affecting the overall performance of the foam insulation.

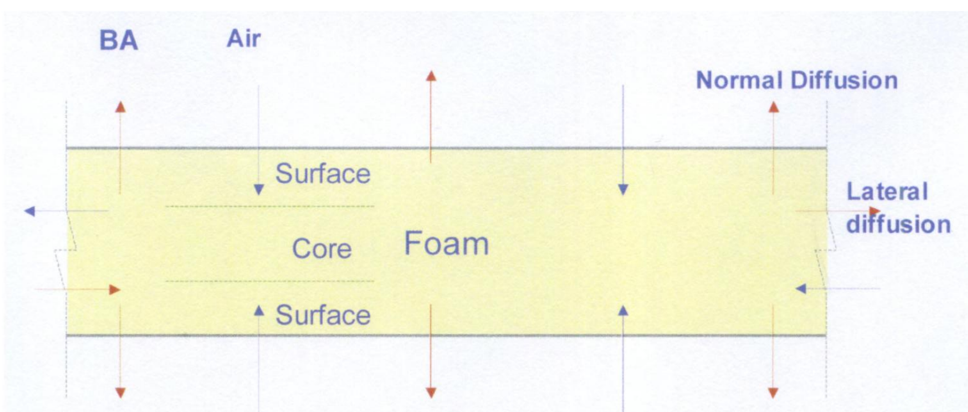

Figure 4. Blowing agent diffusion. This figure represents the blowing agent diffusion processes in polyurethane insulated panel with permeable facings (Mukhopadhyaya & Kumaran, 2008).

A subsequent study of hydrochlorofluorocarbon (HCFC) lateral diffusion by Mukhopadhyaya, et al (2004) confirmed that LTTR estimation using the DIPAC modeling method provided good agreement with performance tests.

A two-year study undertaken by Oakridge National Laboratory studied aging of polyurethane insulation in refrigerator panels comparing full-thickness panel testing with thin slicing predictive modeling in determining long-term thermal performance of refrigerator polyurethane insulations (Wilkes, Gabbard, Weaver & Booth, 2000). Their results showed thin slicing modeling was qualitatively accurate to full-thickness panel testing. Those findings are important for estimating the thermal performance of the recycled cold storage panels over a multi-decade recycled use period.

The tests further showed that thermal performance aging of the polyurethane foam was substantially dependent on temperature of the insulation during the aging period. Reduction in thermal performance at a 40 ^{o}F aging temperature was half as fast than that of insulation aged at 90 ^{o}F, and the insulation aged at -10 ^{o}F was about 1/10th of that aged at 90 ^{o}F. Their study went on to show aging was impacted by the type of blowing agent used with HFC 134a, HCF 245fa and Cyclopentane averaging 18%, 7% and 15%, respectively higher aging rates than with HCFC 141b. Their research also showed having an impermeable surface material encapsulating the polyurethane insulation positively impacted thermal performance. Acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS) sheets were used as sheathing surfaces for the insulation. The refrigerated panels with the ABS and HIPS sheets showed reduced aging at all temperature levels compared to polyurethane refrigeration sheets without a surface sheathing material. The authors believed the reduced aging was due to the gas permeance control from the plastic sheets.

A follow-on Oak Ridge National Laboratory study (Wilkes, Yarbrough, Nelson & Booth, 2003) was conducted through the 4 year aging mark of the refrigerator and freezer polyurethane panels. The study results showed only small insulative performance changes of the polyurethane insulation when aged at -10 ^{o}F, but measurable changes when aged at 40 and 90 ^{o}F. They found the thermal conductivity increases of the ABS and HIPS faced simulated refrigerator panels aged at a lower rate than those predicted for the unenclosed full-thickness polyurethane foam. The polyurethane panels with HIPS facings showed conductivity increases of between 19 and 28 percent at 90 ^{o}F; 12 to 23 percent at 40 ^{o}F; and 3 to 8 percent at -10 ^{o}F. The ABS faced panels showed lower conductivity increases compared to the HIPS. The ABS readings conductivity increases averaged 14 to 21 percent when aged at 90 ^{o}F; 10 to 17 percent when aged at 40 ^{o}F; and 2 to 5 percent when aged at -10 ^{o}F. They once again concluded the difference in aging rates was related to the permeance of the plastic facings and foam temperature.

The Oak Ridge National Laboratory research is relevant to the planned long-term thermal resistivity measurements of this thesis study whereby the polyurethane insulation will have been aged at an average temperature of 35 ^{o}F (freezers) and 50 ^{o}F (cooler) for an average period of approximately 10-15 years. The polyurethane insulation panels have steel facings instead of the plastic facings used in the Oak Ridge study.

A more recent study by the National Research Council of Canada in association with the Canadian Polyisocyanurate Council (Mukhopadhyaya et al., 2014) evaluated the long-term thermal performance of impermeably faced polyisocyanurate (polyiso) insulation. The study tested both full-thickness (24 mm) and thin-sliced (6mm) polyiso board stock blown with HCFC and pentane agents. The six year in-situ study showed an average reduction of thermal performance of approximately 20% across the specimens when tested at 24 ^{o}C (75 ^{o}F); with the HCFC blown polyiso reporting the greatest average performance reduction of approximately 26% and the pentane the smallest average reduction of approximately 7%.

The National Research Council of Canada through the Institute for Research produced the *Long-term thermal resistance of closed cell insulation: research update from Canada* which reviewed the key scientific findings concerning polyurethane insulating foam's long-term thermal resistivity and discussed the implications on the North American construction industry (Mukhopadhyaya & Kumaran, 2008). Their findings confirm while the LTTR measurements and industry-standard predictive models are significantly in alignment, there are still unanswered questions concerning the diffusion of polyurethane insulating foam blowing agents on long-term insulation performance.

Subsequently, diffusion of blowing agents and infiltration of atmospheric gases in recycled cold storage panels could have significant impacts on the long-term insulating performance of any new material created. That could negatively affect their long-term energy savings performance and the environmental and economic value of recycling.

Life Cycle Assessment of Polyurethane Insulation

Conducting life cycle assessments (LCA) is a key element of this research project to assess the environmental impact of diverting polyurethane cold storage panels from landfills. What value will be realized if the panels are re-purposed instead of being discarded in landfills? It is hypothesized the LCA and cost benefit analysis will show a measurable benefit from extending the productive life of the polyurethane insulation.

I believe the highest uses of the recycled insulation would be for other high efficiency insulating applications. That could include new slab stock for certain cold storage and building applications, new structural insulated panels (SIP) for the building construction industry or blown-in/fill insulation for new or remodel building projects. Modeling the blowing agent diffusion impacts on the LTTR value is an important outcome of this research, and will create one of the critical values to complete the LCA analysis of both the discarded and recycled polyurethane cold storage panels.

While the public record appears absent of LCAs on rigid polyurethane insulation, several LCAs have been performed on polyurethane spray foam insulation by leading trade organizations. The Spray Polyurethane Foam Alliance (SPFA, 2012) published an LCA which examined the environmental performance of both low density open-cell and medium-density closed-cell polyurethane in residential and commercial applications in three U.S. cities (Table 3). The study showed the primary (embodied) energy needed to manufacture the polyurethane could be recovered with one year of use. Their research also determined the polyurethane insulation can save up to 14,000 MJ of energy over its 60 year in-service life.

Table 3. SPFA LCA summary.

Application	SPF Type	Ratio & Payback	Houston		Richmond		Minneapolis	
			Energy	GHG	Energy	GHG	Energy	GHG
Residential Insulation	Low Density Open-Cell	Avoided/Embodied	64	92	128	164	194	248
		Payback (Yr)	0.9	0.7	0.5	0.4	0.3	0.2
	Medium Density Closed-Cell	Avoided/Embodied	32	7.6	64	13.6	98	21
		Payback (Yr)	1.9	7.9	0.9	4.4	0.6	2.9
Commercial Roofing	Roofing R4 --> R20	Avoided/Embodied	55	15	56	15	66	17
		Payback (Yr)	1.1	4	1.1	4.1	0.9	3.6
	Roofing R12 --> R20	Avoided/Embodied	30	8.2	28	7.5	29	7.3
		Payback (Yr)	2	7.3	2.1	8.0	2.1	8.3

This table presents the energy and greenhouse gas (GHG) savings of each polyurethane type in each study city. (SPFA, 2012)

In another study, PU Europe in association with PE International and Institut Bauen und Unwell e.V recently published a LCA results on closed cell, 60 kg per cubic meter polyurethane (2014) evaluating the polyurethane materials manufacturing, construction, end-of-life and recycle/recovery stages. They found in a functional unit of 1 square meter at a 13mm depth, the spray foam consumed a total of 585 MJ of non-renewable energy in the manufacturing through end-of-life stages, with 567 MJ of the energy being consumed in the material sourcing and manufacturing processes. The LCA showed a non-renewable energy savings of 170 MJ in the recycle/recovery stage.

Research Objective and Hypothesis

While research has been accomplished in related products noted above, such as residential refrigerators and freezers, no known research has been completed to determine how cold storage panels thermally age. Although the average life of a polyurethane insulated cold storage panel has been estimated at just 15 years (DOE, 2014), it is not typically because of a failure in the insulation. It is primarily due to surface and panel joint damages along with footprint changes to the layout of the cold storage units. The polyurethane insulation is likely to have substantially retained its high thermal performance through the end of its cold storage panel life. Subsequently, the first key objective of this thesis study was to determine the thermal performance of the aged polyurethane insulation in the extracted cold storage panels.

Knowing this outcome will yield two measurable benefits. First, the results of this research will be beneficial to the cold storage industry whereby long-term thermal performance of the polyurethane insulation will be more fully understood. Secondly and more importantly, knowing the insulative performance of the extracted cold storage panels of this study is critical to understanding the long-term thermal performance of each recycled method investigated. The ending thermal conductivity value (k-Factor) of the decommissioned panels becomes the beginning value for each researched recycling method. The insulation's thermal performance is the basis for understanding the environmental and economic impacts of recycling of the material. It is the key element necessary to support this study's hypothesis that positive environmental and economic impacts can be realized by recycling the cold storage panel polyurethane insulation.

Research Presentation

Chapters II and III of this thesis are presented in the form of discrete journal articles with their own methods, results and summary sections. Chapter II examines the long-term thermal performance of polyurethane insulation within cold storage panels used in U.S. retail grocery stores. Chapter III evaluates the environmental & economic value of recycling decommissioned polyurethane insulated cold storage panels into three forms of recycled insulation. While the articles are inter-related as part of this thesis document, they are intended to be published independently.

Chapter II

Long-Term Thermal Performance of Polyurethane Insulation within Cold Storage Panel Systems used in U.S. Retail Grocery Environments

The long-term thermal performance of polyurethane insulated cold storage panels used in commercial walk-in coolers and freezers is not well known. The U.S. Department of Energy estimates the average life of a cold storage enclosure is 15 years (2014). But as shown in polyurethane insulation long-term thermal performance studies by Prüfbricht (1998), Wilkes, Yarbrough, Nelson & Booth (2003) and Mukhopadhyaya et al. (2014), it does not mean the polyurethane insulation within the cold storage panel is devoid of insulative value. That is far from the case. There are other reasons that are the primary drivers for the replacement of the cold storage panels, such as, damage to the panel surfaces or joints affecting aesthetics and performance or desired changes to the store layout. If the replacement of the cold storage units after such a short lifespan is in fact based on factors other than the insulation's thermal performance, then a key question that needs answering is, "what is the thermal performance remaining in the polyurethane insulation?" This research seeks to determine the thermal properties of the polyurethane insulation in cold storage panels upon their decommissioning, whereby the overall long-term thermal performance of the cold storage panel insulation can be better understood.

Discarded Panel Extraction and Testing

A total of ten U.S. retail chain grocery store sites were semi-randomly selected for the extraction of polyurethane panel specimens from decommissioned cold storage units. The extraction site selection was based on three key criteria. The first was knowing the original date of manufacturer of the cold storage panels. The second was knowing the polyurethane foam chemistry used at the time of original panel manufacture. The third criteria was having access to the discarded cold storage panels via the cold storage remodeling company at the time of the panel decommissioning and discarding. The sample panels were obtained from the ten sites between January and June 2015.

Full-thickness specimens with a target size of approx. 36” (90 cm) wide x 47” (120 cm) long were extracted from a single discarded polyurethane cold storage panel at each extraction site. Each specimen ‘unit’ contained the panel metal facers, perimeter wood frames and the polyurethane insulation configured in the same amalgamated assembly as during the operating period of the walk-in cooler/freezer. A construction-style circular saw or reciprocating saw was used to cut the sample specimen from the extracted cold storage panel. Overall panel size from which the samples were extracted averaged approx. 47” (120 cm) wide and 120” (305 cm) long and was either sourced from wall or ceiling panels of the decommissioned coolers/freezers.

Specimens were extracted from the longitudinal center of the panel to maximize the consistency of the samples. Each walk-in cooler and freezer sample was labeled at the extraction site with the manufacturer's original job number, store number, city and state. The sample was then shipped via truck to the specimen collection site in Fort

Worth, TX. The samples were then inspected for compliance with extraction requirements and either accepted or rejected.

As much as possible, the panel metal faces remained undisturbed on the polyurethane insulation specimens and the cut edges of the polyurethane insulation were sealed with an impermeable tape in order to limit blowing agent diffusion during the period between extraction and testing. Three of the ten sites yielded panel specimens that were unacceptable for testing due to material damage. Subsequently, thermal performance testing was conducted on specimen panels from seven extraction sites.

The seven accepted panel specimens were packaged and then shipped via truck to the rigid polyurethane insulation testing site. The perimeter panel frame and vapor tape remained in place until test preparations were undertaken at the testing facility.

Thermal performance of the cold storage panel specimens was determined by using ASTM C518-10 Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Apparatus test (2010). The test method measures the steady state thermal transmission through flat slab insulation materials. Each C518-10 test for the recycled panel research was accomplished by BASF Corporation at their testing lab in Wyandotte, MI. Testing was conducted between February and July 2015.

Results

Of the seven sites which yielded acceptable polyurethane panel samples for testing, five were extracted from walk-in freezers and two from walk-in coolers (Table 4). The seven acceptable panel specimens had an average age of 11.78 years between the dates of manufacture and extraction yielding an in-service life of approximately 11.5 years.

Table 4. Specimen extraction site details.

Sample	Condition	Extract Date	Age (yrs.)	Type	City	State
1	Acceptable	2/4/15	8.90	Freezer	Clearwater	FL
2	Acceptable	2/9/15	10.39	Cooler	Norman	OK
3	Unacceptable	2/18/15	4.70	Freezer	Burleson	TX
4	Acceptable	2/9/15	15.03	Cooler	N. Richland Hills	TX
5	Acceptable	1/30/15	9.79	Freezer	Huntsville	AL
6	Acceptable	3/4/15	13.61	Freezer	Austin	TX
7	Unacceptable	4/27/15	11.88	Freezer	San Antonio	TX
8	Unacceptable	6/15/15	13.64	Cooler	College Station	TX
9	Acceptable	6/8/15	13.25	Freezer	Metairie	LA
10	Acceptable	6/25/15	11.50	Freezer	Sherman	TX

This table shows the cold storage panel details for each specimen extraction site.

Each extracted panel was labeled by the original manufacturer with material and production details. From those labels, key specimen details including type of product, manufacture date, polyurethane foam chemistry and its thermal properties (k-Factor) were determined (Table 5).

Table 5. Specimen insulation chemistry and thermal properties when manufactured.

Sample	Mfg. Date	Chemistry	Original k-Factor 20 Deg. F	55 Deg. F	75 Deg. F
1	03/15/06	Elastopor® P15820R/P1001	0.129	0.145	0.153
2	09/20/04	Elastopor® P15820R/P1001	0.129	0.145	0.153
3	06/08/10	Elastopor® P1835R/P1230	0.125	0.141	0.151
4	02/01/00	Elastopor® P15820R/P1001	0.129	0.145	0.153
5	04/18/05	Elastopor® P15820R/P1001	0.129	0.145	0.153
6	07/27/01	Elastopor® P15820R/P1001	0.129	0.145	0.153
7	06/13/03	Elastopor® P15820R/P1001	0.129	0.145	0.153
8	10/29/01	Elastopor® P15820R/P1001	0.129	0.145	0.153
9	03/11/02	Elastopor® P15820R/P1001	0.129	0.145	0.153
10	12/29/03	Elastopor ®P15820R/P1001	0.129	0.145	0.153

This table details the thermal properties of the polyurethane insulation within the cold storage panel from each specimen extraction site.

The extracted cooler samples had an approx. panel thickness of 4” (101 mm). The extracted freezer samples had an approx. panel thickness of 5” (127 mm). Each specimen was tested at average foam temperatures of 20, 55 and 75 degrees Fahrenheit and the thermal performance results (k-Factor) measured in Btu-in/h-ft2-^{o}F (Table 6).

Table 6. Thermal test results.

Sample	Test Date	20 Deg. F	55 Deg. F	75 Deg. F
1	03/17/15	0.132	0.151	0.163
2	03/17/15	0.139	0.158	0.169
4	03/27/15	0.137	0.149	0.160
5	05/12/15	0.131	0.151	0.164
6	05/12/15	0.128	0.143	0.155
9	07/07/15	0.130	0.144	0.156
10	07/09/15	0.134	0.152	0.163

This table presents the ASTM C518-10 k-Factor results for the seven specimens at each test temperature.

Test Results Analysis

The test specimen's in-situ age ranged between 8.9 and 15.03 years. The samples when tested at 20 °F had a k-Factor range from a low of .128 to a high of .139 (Table 6). The test results at a 55 °F test temperature ranged from .144 to .158 while the 75 °F test results ranged from a low of .155 to a high of .169. These test results deliver a mean k-Factor of .1414 with a standard deviation of .0042 (Figure 5). Results show an aged thermal performance pattern that is substantially uniform. It is believed the uniformity of the results creates a dataset which can confidently be used to ascertain the long-term thermal performance of polyurethane insulation within this type of cold storage panel construction and use.

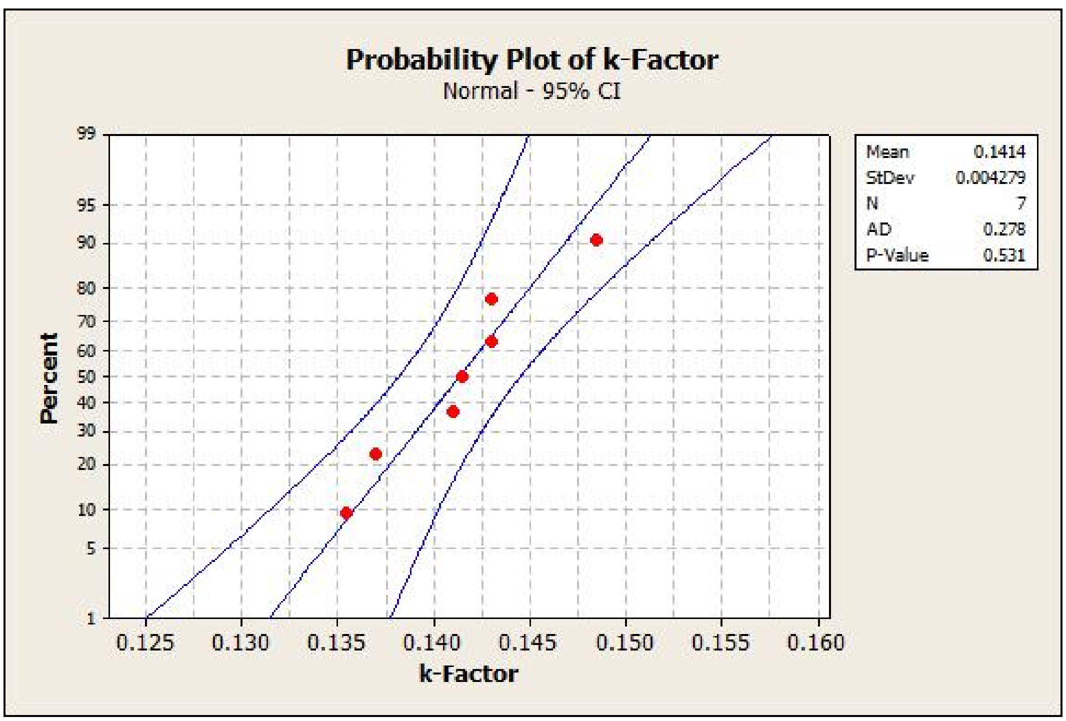

Figure 5. Plot of k-Factor tests results. This figure presents the k-Factor test results shown within a probability plot.

When those ages and k-Factor results were compared and plotted, a clear image emerged which showed there was no apparent correlation between the aging of the polyurethane insulation and its thermal performance. The calculated P-Value was .531 and the R-Squared (adjusted) value was 0%. Interestingly, two out of the three oldest specimens tested had the lowest (best) k-Factors (Figure 6).

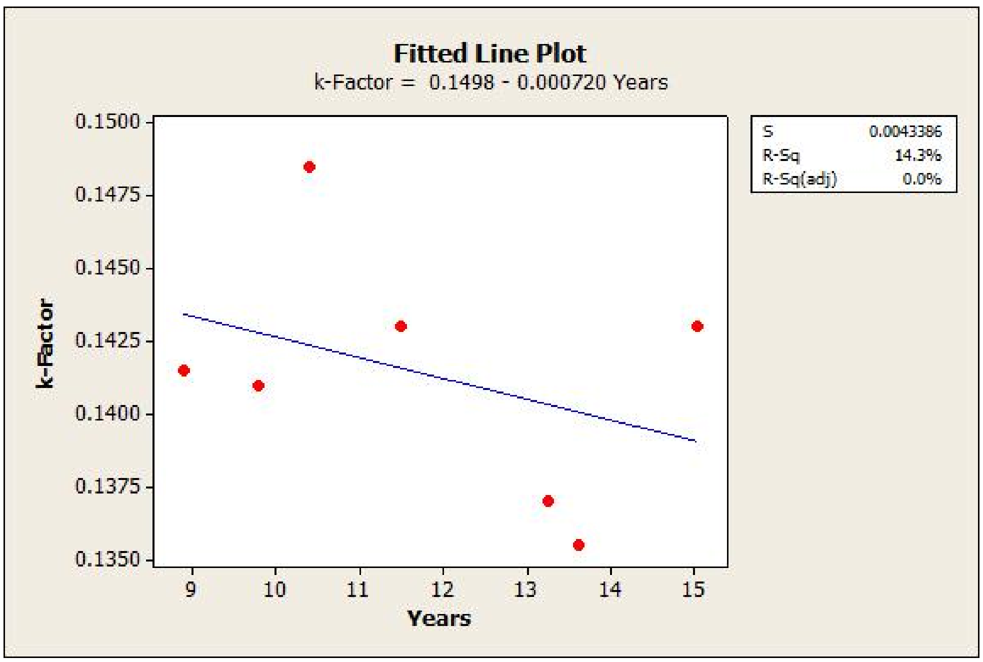

Figure 6. Plot of k-Factor and specimen age. This figure presents the correlation between k-Factor and polyurethane age of the seven tested specimens.

Segregating the results by sample type (cooler vs. freezer) suggests the panels operated in freezer environments (Table 7) yield better thermal performance measurements (lower k-Factor) than those operated in a cooler environment (Table 8), although the sample sizes are too small to test for statistical significance.

Table 7. Freezer specimen test results.

Sample	20 Deg. F	55 Deg. F	75 Deg. F
1	0.132	0.151	0.163
5	0.131	0.151	0.164
6	0.128	0.143	0.155
9	0.130	0.144	0.156
10	0.134	0.152	0.163
Average:	0.131	0.148	0.160

Table presents ASTM C518-10 k-Factor results for extracted freezer specimens.

Table 8. Cooler specimen test results.

Sample	20 Deg. F	55 Deg. F	75 Deg. F
2	0.139	0.158	0.169
4	0.137	0.149	0.160
Average:	0.138	0.154	0.165

Table presents ASTM C518-10 test results for extracted cooler specimens.

The test results of the freezer aged polyurethane insulation showed a 5.07% improvement at 20 ^oF, a 3.45% improvement at 55 ^oF and a 2.61% improvement at 75 ^oF over the cooler environment aged polyurethane.

When compared to the specimen's thermal performance at the time of manufacture, the aged (long-term thermal performance) results were only moderately less (Table 9).

Table 9. Aged k-Factor Differences.

Sample	20 Deg. F	55 Deg. F	75 Deg. F
1	2.33%	4.14%	6.54%
2	7.75%	8.97%	10.46%
4	6.20%	2.76%	4.58%
5	1.55%	4.14%	7.19%
6	-0.78%	-1.38%	1.31%
9	0.78%	-0.69%	1.96%
10	3.88%	4.83%	6.54%
Average:	3.10%	3.25%	5.51%

Table shows percentage difference between initial and aged k-Factors.

The rate of polyurethane thermal efficiency loss in freezers was measurably less than in the coolers when compared to initial k-Factors (Table 10).

Table 10. Freezer and cooler polyurethane specimen k-Factor differences.

Test Temp	Manufactured k-Factor	Avg. Aged Freezer k-Factor	Difference	Avg. Aged Cooler k-Factor	Difference
20 Deg. F	0.129	0.131	1.55%	0.138	6.98%
55 Deg. F	0.145	0.148	2.07%	0.154	5.86%

This table presents k-Factor difference between freezer & cooler specimens compared to k-Factor at time of manufacture.

These results show the closed-cell polyurethane suffered minimal long-term thermal performance losses when operated in a freezer environment and only moderate losses when operated in a cooler environment. The k-Factor results also showed while there was measurable difference between the long-term thermal performance of freezer and the cooler specimens, the cooler polyurethane thermal results averaged just 3.7% less than the freezer (Table 11).

Table 11. Freezer/cooler polyurethane specimen conductivity differences.

Test Temp:	20 Deg. F	55 Deg. F	75 Deg. F
Freezer	0.131	0.148	0.160
Cooler	0.138	0.154	0.165
Difference:	-5.07%	-3.45%	-2.61%

This table presents the average k-Factor differences between the extracted freezer and cooler specimens at each test temperature.

Discussion

This study shows thermal performance of the aged closed-cell polyurethane insulation used in freezer and cooler panels when encapsulated within perimeter frames and metal faces remains remarkably good over the cold storage use period. The results of the ASTM C518-10 specimen tests show that polyurethane insulated cold storage panels operated in a walk-in freezer environment lost an average of 1.55% of its initial thermal performance over an in-use life which averaged 11.4 years. The tests also showed the polyurethane insulated cold storage panels operated in a walk-in cooler environment lost an average of 5.86% of its initial thermal performance over its use life of 12.7 years.

Previous studies had showed performance reduction to a much greater degree when the polyurethane insulation was aged with and without permeable facers. Mukhopadhyaya et al. (2014), showed polyiso board stock with impermeable facers and HCFC blowing agents lost an average of 26% of their insulative performance over a six year period. Wilkes et al. (2003) showed polyurethane with HFC 245fa and 134a blowing agents had an average thermal performance reduction of 28% over 14 years. In addition, Bomberg & Lstiburek (1998) showed an average polyurethane foam resistivity reduction of 29% percent in 1,000 days of aging and the Singh & Coleman predictive LTTR study (2007) showed polyiso board thermal performance reduction of 18 % over 15 years of aging**.**

The results of these previous studies differ measurably from our aged test results. The restriction of gas diffusion afforded by the cold storage metal facers and wood frame appears to be a key factor in maximize the polyurethane's thermal performance over long operating periods as cold storage insulated panels. In addition, the lower mean operating temperature of the polyurethane in cold storage applications likely further reduces the rate of conductivity increases.

The results from this study have implications for the use of closed-cell polyurethane insulation in both the cold storage and general building insulation environments. First, the polyurethane insulation within the cold storage panels can be expected to perform at high thermal efficiency levels for extended use periods which can be multiple times greater than the 15 year average cold storage unit life of today. To take advantage of that benefit, effective ways will likely be needed to remediate panel surface or frame damage that may occur over longer use periods which could impact the visual or operation functions of the cold storage facility.

Secondly, when the time comes to decommission and discard the cold storage facility, the polyurethane insulation within the panels will still possess a high thermal performance. That could create significant insulative benefit if effective ways are found to recycle and convert the polyurethane into new forms of insulation material.

Hopefully, the long-term thermal performance results of this study will create incentive for operators/suppliers to establish effective methods to extract and repurpose the polyurethane insulation from decommissioned cold storage panels into other high-efficiency insulation products. Creating those extraction and conversion solutions would maximize the polyurethane insulation's capacity to perform. By doing so, both significant environmental and economic value can be realized.

Chapter III

Environmental & Economic Assessment of Converting Discarded Polyurethane Insulated Cold Storage Panels into Three Forms of Recycled Insulation

Cold storage polyurethane insulated panels which have been constructed with impermeable metal facers and perimeter framing have shown to retain, on average, more than 95% of initial thermal performance over their cold storage lifetime (Costanza & Jackson, 2015). Such a residual thermal value lends itself well to recycling the decommissioned cold storage panels into other forms of insulation in lieu of discarding. This research evaluates the environmental and economic impact of recycling the polyurethane insulation from used cold storage panels into three forms of building insulation (Figure 7).

The first reuse/recycle Method (A) reconfigures the spent cold storage panel into a redesigned cold storage panel to be used in a similar manner as the decommissioned panel. This recycling approach could be especially beneficial to food aid agencies that need walk-in refrigeration storage but don't require new materials. The second area of research, Method (B), harvests the polyurethane foam from the discarded panel and reshapes it into insulated board stock materials to be used in building insulation applications. The third Method (C) shreds the harvested polyurethane foam from the discarded panel creating blown in/fill insulation especially appropriate for residential attic applications.

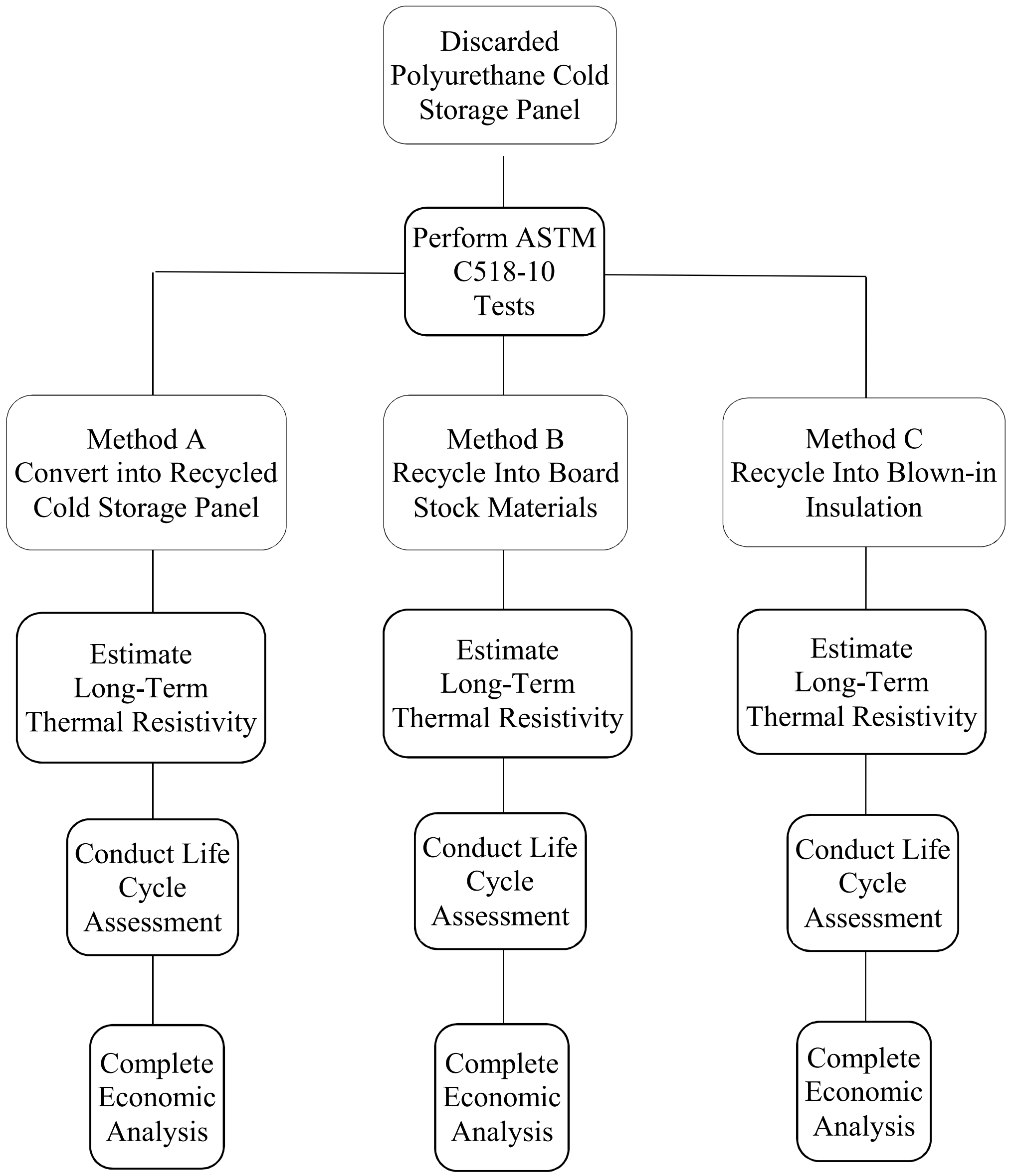

Figure 7. Recycling Method Flowchart. This figure details the three recycle methods examined in this study.

Determining Initial Thermal Performance

A key element needed to determine the environmental and economic impact of recycling the cold storage polyurethane insulation is quantifying the initial thermal resistivity (LTTR) of the new (recycled) insulation. Normally, the LTTR for the rigid polyurethane insulation is determined by employing ASTM C1303-12 Standard Test Method for Predicting Long-Term Thermal Resistance of Closed-Cell Foam Insulation (2012). This method utilizes an accelerated testing approach which simulates the insulation's thermal resistivity up to 15 years of age. The test requires a specific time to complete, and unfortunately the duration of this thesis study does not permit such a time period. Subsequently, other approaches were employed to estimate the LTTR of the recycled insulation options; with each recycling method requiring the use of a different model to estimate LTTR.

Recycling Method A LTTR. The initial thermal performance for Recycling Method A was determined by using the mean thermal resistance aging of polyurethane insulated cold storage panels determined by C518-10 ASTM tests performed on seven panel specimens in the Costanza & Jackson study (2015). The average k-Factor change between the tested aged specimens and when the seven extracted panels were manufactured was used to determine the long-term thermal aging factor.

Recycling Method B LTTR. The approach selected to estimate the polyurethane long-term thermal performance for Recycling Method B was to use the k-Factor average between the highest and lowest performing blowing agent aging curves from the Oak Ridge National Laboratory Aging of Polyurethane Foam Insulation in Simulated Refrigerator Panel Four Year Results with Third-Generation Blowing Agents study co-authored by

Wilkes, Yarbrough, Nelson, & Booth (2003). The averaged HFC 134a and 245fa aging values, when averaged, created a single aging curve used to determine the long-term thermal resistivity aging of the polyurethane insulation recycling Method B (Figure 8).

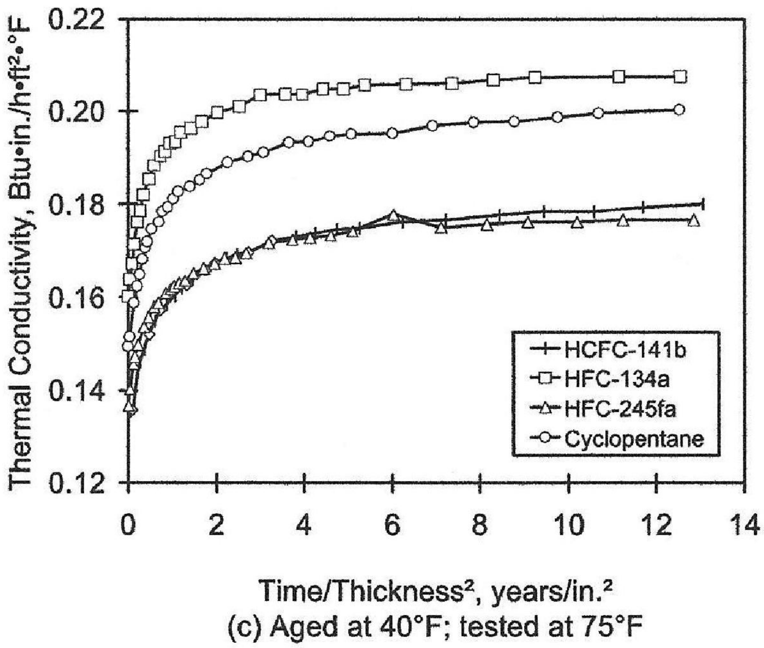

Figure 8. Long-term aging of four blowing agents. This figure represents the aging of thin core-foam specimens blown with third-generation blowing agents by Supplier A. (Wilkes, Yarbrough, Nelson & Booth, 2003)

Recycling Method C LTTR. The initial thermal performance of the polyurethane insulation for Recycling Method C was accomplished by creating a polyurethane insulation rigid panel specimen, converting it into blown-in insulation by shredding to a target size, and then thermally testing to determine k-Factor via the ASTM C518-10 test method.

A 4” (10.1 cm) thick by 47” (119.3 cm) wide x 96” (243.8 cm) long polyurethane insulated cold storage panel was manufactured in January 2014 by Kysor Panel Systems in Fort Worth, TX for the purpose of shredding and testing the resultant polyurethane insulation fragments for thermal conductivity. The panel was constructed using 26g. Electro-galvanized metal facer sheets and dimensional wood perimeter framing. The hollow panel core was injected with BASF Elastopor® P19830R/P1001U rigid urethane foam insulation system containing HCF 245a and 134b blowing agents designed for insulation of discontinuous metal-faced sandwich panels (BASF, 2013). The polyurethane foam was injected to an in-place density of 2.2 lbs. per cubic foot. The Elastopor® chemistry produced nominal k-Factors, as reported by BASF, of .125 (20 ^{o}F/-6.6 ^{o}C) .142 (55 ^{o}F/12.7 ^{o}C) and .153 (75 ^{o}F/24 ^{o}C).

After manufacturing and aging for approx. 30 days, the panel was deconstructed by removing the metal facers and wood perimeter frame from the insulation core. Approximately five cubic feet of the harvested rigid foam insulation was sent to Demand Products in Alpharetta, GA in three panel segments for shredding. The polyurethane insulation was shredded to a target size of .28” (7 mm) in March 2014. See Appendix A for shredded size details.

After shredding, the resultant ‘blown-in/fill polyurethane insulation density was determined to be 1.60 pounds per cubic feet (25.62 kilograms per cubic meter). The shredded insulation was returned via truck to the Fort Worth, TX site and stored at room temperature (approx. 70 ^{o}F/21 ^{o}C) until thermal performance testing was accomplished in 2015. The time delay was used to simulate aging of the shredded insulation; allowing time for measurable gas diffusion of the blowing agents in the polyurethane cells.

The shredded polyurethane was shipped via truck to R&D Services in Cookeville, TN and tested in February 2015 utilizing ASTM C518-10 test methods. The sample was conditioned at the test site for a minimum of 24 hours at 70 ^{o}F (21 ^{o}C) +/- 3 ^{o}F and 50 +/- 5% RH. The test flow meter measured 24” x 24” (61cm x 61cm). The tested specimen dimensions were 6” (15.4 cm) thick, 24” (61 cm) wide and 24” (61 cm) long. The tested density was 1.60 lbs. per cubic foot (25.62 kg/CUM). The tested sample averaged a temperature of 75.03 ^{o}F (24 ^{o}C) with the cold plate temperature averaging 55.02 ^{o}F (12.8 ^{o}C) and the hot plate temperature 95.04 ^{o}F (35.02 ^{o}C). The test duration was 14.8 hours. After initial testing, the sample was on stored onsite at R&D Services facilities for four months at a temperature of 70 ^{o}F (21 ^{o}C) and relative humidity of 50%. The sample was tested a second time using the ASTM C518 test method in June 2015.

The second test was conducted to measure any additional thermal performance changes in the shredded polyurethane insulation in order to create the long-term thermal resistivity aging curve used to estimate the thermal performance of the blown-in fill in-use period. The sample was again conditioned for a minimum of 24 hours at 70 ^{o} F (21 ^{o}C) +/- 3 ^{o}F and 50 +/- 5% RH. The test flow meter measured 24” x 24” (61cm x 61cm). The tested specimen dimensions were 6” (15.4 cm) thick, 24” (61 cm) wide and 24” (61 cm) long. The tested density was 1.60 lbs. per cubic foot (25.62 kg/CUM). The cold plate temperature was 55.04 ^{o} F (12.8 ^{o}C) and the hot plate temperature was 95.04 ^{o}F (35.02 ^{o}C). The tested sample averaged a temperature of 75 ^{o}F. (24 ^{o}C). The test duration was 20.6 hours. The mean results (k-Factor) between the first and second ASTM C518-10 tests were used to determine the initial R-Value of the blown-in fill insulation for Recycling Method C.

Life Cycle Assessment

Comparative life cycle assessments were conducted to determine the environmental impact of recycling cold storage panel's polyurethane insulation. Separate LCA's for each recycling method were conducted to compare the environmental impact of the original polyurethane insulation made for the cold storage panels with the environmental impact of the recycled polyurethane insulation used in each recycling option.

The life cycle assessment measurement consisted of two elements for each recycling method. The first was to determine the environmental impact of new materials (polyol, isocyanate and blowing agents) which could be averted by recycling of the cold storage panel polyurethane insulation. The second element was to determine the net in-use energy saved by using the recycled insulation for the estimated lifetimes of each recycling method.

Harvesting and Conversions Volume Losses

The extracted polyurethane insulation for each recycling method was subject to the reduction of useable material from the recycling and conversion processes. Some amount of deconstruction and conversion losses of the polyurethane was experienced for each recycling method.

Recycling Method A. Net material volume reduction from this recycling method was created by the removal of the perimeter framing system from the foam core. The process required the cutting of the polyurethane to frame connection whereby approximately ¼" of the polyurethane insulation perimeter was lost in deconstruction process. The panel facers were to remain adhered to the foam core in order to maintain the structural properties and resist gas diffusion.

Recycling Method B. The deconstruction processes for Method B involved removing the perimeter frame as noted in Method A along with the removal of the panel facers, yielding a polyurethane foam core block. The polyurethane was then converted into board stock by cutting the foam block into 1” thick layers. It was estimated that the cutting processes destroyed 1/8” of polyurethane foam per 1” layer.

Recycling Method C. Similar polyurethane insulation volume losses were experienced with Recycling Method C during the deconstruction and conversion processes into shredded polyurethane. However, because the resultant converted material was a shredded particle of polyurethane, no measurable volume losses were expected as all particles are anticipated to be useable as blown-in insulation.

In-Use Energy Savings

Energy savings for each recycling method was also used in the environmental impact calculation of recycling the polyurethane insulation from the cold storage panels (in lieu of discarding them in landfills). Most of the fossil fuel savings in the LCA come from the in-use setting. The energy savings for each recycled method was calculated by comparing it to the same use conditions absent an insulation component.

System Boundaries

The embodied phases of this LCA are the upstream processing and manufacture of raw materials, the fossil fuel energy necessary for the production of the polyurethane, the transportation of raw materials to the polyurethane insulation formulation sites, the manufacture of the individual polyurethane insulation material components and the manufacture of the polyurethane insulation. The boundary also includes the transport of the polyurethane to the installation site, the transport of the decommissioned polyurethane panels to the recycling site and from there through distribution to the recycled use site and finally the transport of the polyurethane insulation to the end of life disposal in a landfill. Table 12 provides a detail of the items included and excluded from the embodied phases of the LCA.

Table 12. System boundaries.

Included	Not Included
Extraction of raw materials	Construction of capital equipment
Production of raw materials for polyurethane	Maintenance of support equipment
Polyurethane foam formulation	Human labor
Polyurethane foam use phase impacts	Polyurethane foam install/de-installation
End of life disposal	Other cold storage and building materials
Transportation between all life cycle stages	

This table presents those items that are included and excluded in the study LCA.

Functional Unit

Net megajoules (MJ) of energy saved per cubic foot of closed-cell polyurethane insulation over a one year period is the functional unit for the polyurethane insulation's comparative life cycle assessment. The impact category is Resource Depletion – fossil fuels.

Polyurethane insulation has a negative environmental impact during its manufacturing, transport and disposal phases, but has measurable positive environmental and economic impacts during its use phase where it reduces the amount of energy needed to heat and cool building spaces. Depending on the climate and the period of time the insulation is used, polyurethane insulation can save more than 100 times its embodied energy (Federation of European Rigid Polyurethane Foam Associations, 2006). Using net MJ of energy saved per board foot of polyurethane insulation provides a functional unit that is common for building materials and is appropriate to calculating the thermal performance of insulation; and thus energy saved. A cubic feet reference flow is used for the polyurethane insulation to determine the life cycle environmental assessment.

Model description

The LCA model was constructed to compare the business as usual case of polyurethane insulation for walk-in cooler/freezer applications with one where the insulation is recycled and repurposed in three distinct forms in order to use a greater portion of the insulation's productive life.

Methods

The life cycle assessment of recycling and reconfiguring the polyurethane insulated cold storage panels into the three forms of insulation (cold storage panel, board stock insulation and blown-in/fill insulation) was calculated through Ecoinvent 2.2 LCA software (GreenDelta GmbH, 2014). Both the embodied and in-use phases of the polyurethane insulation were evaluated. Building energy modeling was used to assess the amount of energy saved from using the recycled polyurethane insulation.

Business as Usual

Inputs for the business as usual case include the polyurethane insulation components, transportation and disposal. The output is polyurethane insulation. The polyurethane inputs are polyols and isocyanate at plant RER and refrigerant 134a at plant RER. The Transport was calculated at 1500 km which included the estimated distance both the inputs materials and the finished goods traveled during their life. All of the environmental impact for the production of polyurethane for this comparative analysis was allocated to the first use walk-in cooler/freezer application.

Economic Assessment

Economic assessments were conducted for each recycling method. Economic values were determined by comparing installation conditions without and then with the recycled polyurethane insulations and measured as megajoules of energy saved per board foot of recycled insulation per year. See Appendix B for calculation details.

Recycling Method A. The economic value from the recycled insulation's energy savings was based on the recycled material being used in a building environment with an average ambient temperature of 70 ^{o}F 21 ^{o}C). The freezer's insulation performance was based on a continual operating temperature of 5 ^{o}F (-15 ^{o}C). The cooler's insulations performance was based on a 40 (4.4C) degree continual operating temperature. The economic value for both the freezer and cooler recycled options was based on a new 15 year useful lifetime. The cold storage panel assembly absent the polyurethane insulation included the following components to determine R & U-values:

- Insulated cavity (dead air space) between panel facers
- Inside of cold storage enclosure air film
- Outside of cold storage enclosure air film

Recycling Method B. The economic value for recycling Method B was based on using the recycled polyurethane board stock insulation as roof deck insulation in Boston, MA. The polyurethane is the insulative component of a roof assembly which included the following components:

- Ceiling air film
- 5/8" drywall sheathing
- Joist area dead air space
- ½" structural wood roof sheathing
- Board stock insulation
- Roof membrane
- Outside air film

The economic value was calculated on both 50 and 100 year productive life for the polyurethane board stock insulation.

Recycling Method C. The economic value for Recycling Method C was based on the polyurethane insulation being used as blown-in insulation within a residential attic application in Boston, MA. The polyurethane is the insulation component in a roof/attic assembly that includes the following components:

- Ceiling air film

- 5/8” drywall sheathing
- Polyurethane blown-in insulation
- Attic air film
- ½” structural wood roof sheathing
- Roof membrane
- Outside air film

The economic value was calculated on 50 and 100 year productive lifetimes for the polyurethane blown-in attic insulation.

Thermal Performance Results

Initial and long-term thermal resistance assessments were conducted for each recycling method to determine the insulative performance over the expected productive life of the recycled insulation. Their results were segregated into rigid and shredded classes.

Rigid Specimens

Recycling Method A & B uses the polyurethane insulation in a rigid, board stock configuration while Recycling Method C uses a shredded polyurethane approach. Because of the different configurations and uses, each recycling method utilizes a different long-term thermal resistance calculation.

Recycling Method A. The long-term thermal resistance value for Recycling Method A was determined by calculating the mean thermal performance (k-Factor) of the seven polyurethane panel specimens of the Costanza & Jackson study (2015), and then applying those aging curves over the recycled in-use life period for each of the Recycling Method A options (Table 13). The LTTR results show an average reduction of polyurethane insulation thermal performance over for the panel's initial life period of 1.55% for freezers and 5.86% for coolers.

Table 13. Thermal test results.

Sample	Test Date	20 Deg. F	55 Deg. F	75 Deg. F
1	03/17/15	0.132	0.151	0.163
2	03/17/15	0.139	0.158	0.169
4	03/27/15	0.137	0.149	0.160
5	05/12/15	0.131	0.151	0.164
6	05/12/15	0.128	0.143	0.155
9	07/07/15	0.130	0.144	0.156
10	07/09/15	0.134	0.152	0.163

This table presents the ASTM C518-10 test results for the seven specimens at each test temperature.

It was assumed the same thermal performance changes in the polyurethane insulation that occurred in the initial use period would be experienced during Method A's new 15 year recycled life (Table 14).

Table 14. Estimated k-Factor changes.

Type	PUR Initial k-Factor	15-Year LTTR Loss in Cold Storage PUR Panels	Estimated PUR Aged k-Factor
Freezer	0.131	1.55%	0.133
Cooler	0.154	5.86%	0.163

This table presents the estimated lifetime k-Factor for the recycled cold storage panels over 15-year recycled life.

Subsequently, the long-term thermal resistance calculation, the life cycle assessment, and the economic value estimate for Recycling Method A reflect these freezer/cooler LTTR reduction values.

Recycling Method B. The long-term thermal resistivity changes for Recycling Method B was derived from the mean polyurethane insulation thermal performance curve between the lowest and highest performing blowing agents (HFC 134a & 245fa) from the 4-year Oakridge Study (Wilkes, Yarbrough, Nelson & Booth, 2003). The model shows an average polyurethane insulation thermal performance reduction of 28% for the two blowing agents over the first 14 years with a near steady-state being achieved after the 10^{th} year (Figure 9). Subsequently, this study used a thermal performance reduction of 29% (.2082 k-Factor) for Recycling Method B's 50 year life option.

Due to the flattening of the thermal conductivity curve after year 10, extending Recycling Method B to a 100 year life only slightly reduces the insulation's estimated performance to 30% (.2102 k-Factor). The long-term thermal resistance calculation, the life cycle assessment and the economic value estimate for Recycling Method B utilizes these performance LTTR reduction values.

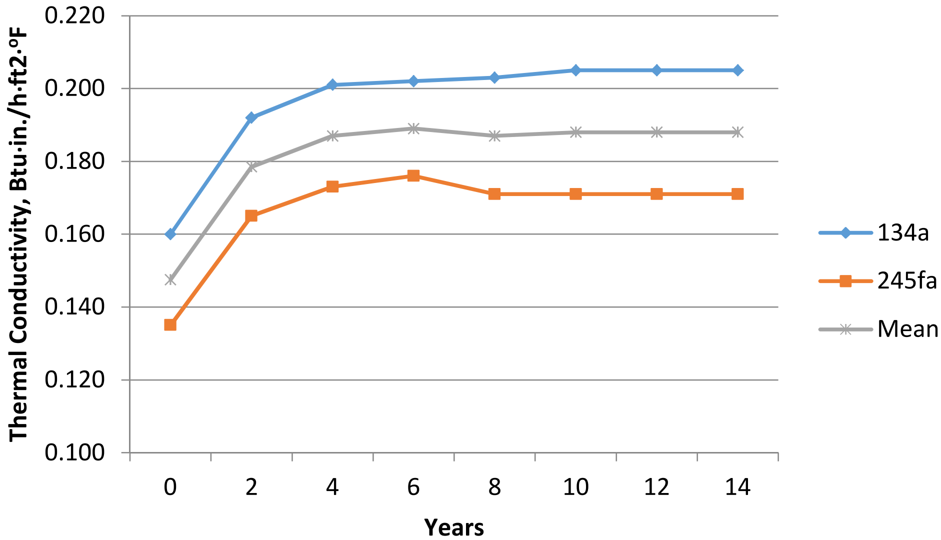

Figure 9. Aging of polyurethane blowing agents. This figure presents individual and mean thermal conductivity of HFC 134a & HFC 245fa blowing agents over 14 years (derived from Wilkes, Yarbrough, Nelson & Booth, 2003)

Shredded Specimen

The shredded polyurethane specimen for Recycling Method C was tested for thermal performance as blown-in fill insulation using the ASTM C518-10 method. The sample was tested on two separate occasions. The first test was conducted in February 2015. The second test was conducted in June 2015. The tests revealed a mean thermal performance of .2827 Btu-in/h-ft2-^{o}F (Table 15). The k-Factor difference between the two tests was .00071% after an additional 116 days aging.

Table 15. Shredded polyurethane k-Factor results.

Mfg. k-Factor @ 75 Deg. F	Shred Date	Aging (days)	Test Date	Test k-Factor @ 75 Deg. F
0.153	3/17/2014	343	2/23/2015	0.2828
0.153	3/17/2014	459	6/19/2015	0.2826

This table shows the thermal performance of each ASTM C518-10 test performed on the shredded polyurethane foam.

The 16 month aging and testing regime used for the shredded polyurethane insulation showed the blowing agents within the the polyurethane cells have either been absorbed into cell walls and/or diffused with atmospheric gases to the state of equalibirum - whereby no significant aging of the shredded polyurethane insulation occured beyond the initial 12 month aging period. Subsequently, this research used a steady-state k-Factor of .2827 as the long-term thermal resistivity value for Recycling Method C's 50 and 100 year life cycle analysis, energy savings impacts and economic value models of this study.

Energy Savings Results

In-use heating and cooling energy savings is a key element that drives both the environmental and economic impact of recycling the cold storage panel polyurethane insulation. The energy savings is based on each recycling method being installed in Boston, MA area with a total of 6,407 heating and cooling degree days (NOAA, 2014). The following is the annual heat loss calculation used.

Annual Energy Loss (Btu) = U-value x Area x Temp Difference x Time

The U-value used in the energy loss formula for the recycled polyurethane was calculated by using the initial R-value (1/ k-Factor) from the aged cold storage panel polyurethane insulation less recycling conversion and LTTR losses.

A comparative analysis of annual energy consumption was determined for each recycling method. It was calculated by analyzing the construction assembly of the recycling method in conditions without insulation and then with the recycled polyurethane insulation (Table 16). See Appendix C for energy use data.

Table 16. Annual energy by recycling method.

Recycling Method	Energy Used-No Insulation	Energy Used-Recycled Polyurethane	Net Annual Energy Savings (Btu)	Net Annual Energy Savings (MJ/BF)
A (freezer)	319,888	78,255	241,632	255
A (cooler)	147,640	40,147	107,494	113
B	45,764	25,517	20,247	21
C	39,428	23,914	15,514	16

This table compares the annual in-use energy consumption with and without insulation, and calculates the net energy savings for each recycling method.

The analysis shows using the recycled polyurethane insulation as a freezer or cooler as shown in recycling Method A provides the greatest annual energy savings.

Environmental Impact – Life Cycle Assessments

This study's Life cycle assessment was used to determine the fossil fuel energy saved by each recycling method. Two areas of fossil fuel consumption were investigated; embodied and in-use. First, the volume of new polyurethane insulation materials (polyol, isocyanate and blowing agents) which could be averted by recycling of the cold storage panel polyurethane insulation was determined. Second, the energy saved during the in-use period(s) for each recycled method was calculated. The net material volume of recycled material as shown in Appendix D was used within the life cycle assessment calculation of each recycling option to estimate the production of new polyurethane materials which could be averted (Table 17).

Table 17. Volume loss calculations for each recycling method.

Recycling Method	Harvesting Volume Loss	Recycling Conversion Loss	Net Material Loss
A	1.57%	0.00%	1.57%
B	1.57%	25.00%	26.57%
C	1.57%	41.09%	42.66%

This table shows the estimated loss in recycled polyurethane insulation volume during the harvesting and recycling processes.

After the net material volume losses were determined, a long term thermal performance analysis of the polyurethane foam was completed for each recycling method to assess what the overall energy savings capacity of the polyurethane insulation was likely to be over its recycled lifetime. Those reductions in expected thermal performance were added to the volume losses in order to create the expected overall thermal performances to be used in the life cycle assessment calculations. No aging factor was used for Recycling Method C as it was determined to be at a state of equilibrium with atmospheric gases whereby no long-term thermal degradation was expected.

The life cycle assessment for each recycling method showed significant embodied fossil fuel savings when compared to the business-as-usual case of discarding the decommissioned cold storage panels (Table 18).

Table 18. LCA embodied fossil fuel savings by recycling method.

Recycling Method	BAU Case Embodied Energy Consumed	Recycling Case Embodied Energy Consumed	Energy Savings	% Savings
A	23.238	0.372	22.866	98.40
B	23.238	6.081	17.157	73.83
C	23.238	9.897	13.341	57.41

This table compares embodied fossil fuel savings (MJ surplus per cu. ft.) between business-as-usual case and recycling of the polyurethane insulation.

The second element of the life cycle assessment calculation was to determine the amount of heating and cooling energy saved during the productive (in-use) life for each recycling method. This energy consumption/savings calculation was based on the use application of the insulation for each recycling method (Table 19). See Appendix E for energy savings calculation details.

Table 19. Lifetime energy savings.

Recycle Method	Life (yrs.)	Embodied Fossil Fuels Savings (MJ/BF)	Annual PUR In-use Savings (MJ/BF)	Lifetime PUR In-use Energy Savings (MJ/BF)	Lifetime Energy Savings (MJ/BF)
A (freezer)	15	1.91	261	3,413	4,176
A (cooler)	15	1.91	118	1,770	1,890
B	50	1.43	21	1,068	1,091
B	100	1.43	21	2,136	2,159
C	50	1.11	16	818	836
C	100	1.11	16	1637	1,654

This table presents the lifetime fossil fuel savings by recycling method and age.

Recycling Method A produced the greatest overall energy savings. This is due to the recycled insulation being converted into another cold storage refrigeration application whereby the polyurethane retained 98% of its insulative capacity in the recycling process and where the temperatures maintained in the cold storage environment created a significant amount of energy savings demand. The in-use energy savings of the recycled polyurethane insulation provided the majority of the energy savings.

While fossil fuel energy savings (MJ/BF) is the primary life cycle metric used in this study, other significant environmental impact savings are realized through the recycling of the polyurethane insulation versus the business-as-usual case of disposing the decommissioned cold storage panels (Table 20). Those results showed an average environmental impact reduction of 94.54% for Recycling Method A, a 72.47% reduction for Recycling Method B and a 56.34% reduction for Recycling Method C, compared to the business as usual case.

Table 20. LCA environmental impact.

Impact Category	BAU Case	Method A	Method B	Method C	Unit
Acidification	0.1302	0.0042	0.0356	0.0566	kg SO2 eq.
Eco toxicity	34.8974	7.6160	9.2798	14.9724	CTUe.
Eutrophication	0.0325	0.0007	0.0086	0.0139	Kg N eq.
Global Warming	108.655	3.0496	29.3855	46.9857	kg CO2eq
Human Health - Carcinogenics	0.0813	0.0013	0.0213	0.0347	CTUh
Human Health - non-Carcinogenics	0.1335	0.0022	0.0350	0.0569	CTUh
Ozone Depletion	0.0104	0.0002	0.0027	0.0044	kg CFC-11 eq.
Photochemical ozone formation	0.9606	0.0889	0.3046	0.4489	kg O3 eq.
Resource depletion - fossil fuels	23.238	0.3718	6.0814	9.8971	MJ surplus
Respiratory effects	0.0123	0.0011	0.0039	0.0057	kg PM2.5 eq.

Table shows environmental impact of recycling methods vs business-as-usual (BAU) Case per cubic foot of polyurethane.

Economic impact

This study also evaluated the economic value of the recycled polyurethane insulation by calculating the energy savings and its financial impact during its in-use period for each recycling method. The annual economic savings was derived by multiplying the annual energy savings by the utility rate times the estimated productive life (Table 21). The lifetime economic savings were estimated by multiplying the annual savings by the recycled use period options for each recycling method (Table 22). For simplicity, time value of money (TVM) calculations were omitted from the economic assessment. The savings were calculated using local 2015 Boston utility rates of $1.217 per Therm of natural gas and $0.225 per kWh of electricity (U.S. Department of Labor, 2015).

Table 21. Annual economic savings by recycling method.

Recycling Method	Fuel Type	Energy Savings (kWh or (Therms)/BF	Annual Economic Savings ($/BF).
A (freezer)	Electricity	71	$15.93
A (cooler)	Electricity	32	$7.09
B	Natural Gas	0.2025	$0.25
B	Natural Gas	0.2025	$0.25
C	Natural Gas	0.1552	$0.19
C	Natural Gas	0.1552	$0.19

This table presents the estimated in-use economic savings by recycling method.

The freezer and cooler polyurethane insulation of Recycled Method A have a much greater economic savings due to several factors. First is the temperature differences between the cold storage units (cooler/freezer) and the ambient building temperature. The freezer temperature difference is nearly 4X greater than the temperature differential between Boston's average inside/outside residential temperatures (70 ^{o}F vs.18 ^{o}F differential). The second factor is the utility rate. Recycling Method A's savings are based on using electricity where Recycling Methods B & C are based on natural gas. Natural gas is measurably cheaper by unit of energy. Finally, for Recycling Method A's calculation, the polyurethane insulation is the primary insulative component of the structure's assembly, where the polyurethane in Recycling Methods B & C roof assemblies is one of several materials with insulative value.

Table 22. Lifetime in-use economic savings.

Recycle Method	Life	Total Energy Savings (MJ/BF)	Fuel Type	Energy Savings (kWh or (Therms)/BF	Lifetime Economic Savings ($/BF)
A (freezer)	15	4,176	Electricity	1,159.88	260.97
A (cooler)	15	1,890	Electricity	524.99	118.12
B	50	1,091	Natural Gas	10.34	12.59
B	100	2,159	Natural Gas	20.47	24.91
C	50	836	Natural Gas	7.92	9.64
C	100	1,654	Natural Gas	15.68	19.09

This table shows the estimated lifetime in-use economic savings by recycling method.

Results Summary

This study shows recycling the polyurethane insulation within decommissioned cold storage panels have measurable environmental and economic benefits as presented in each recycling method analysis. There are four key areas of savings. First, by recycling the polyurethane into other insulative purposes in lieu of discarding in landfills, the need for manufacture of new insulations can be reduced. As shown in the LCA data, this measurably reduces environmental impact for each recycling method. Secondly, by extending the life of the polyurethane for building heating and cooling applications, significant energy savings can be realized for the 'recycled life' of the insulation – which can extend many decades into the future. Thirdly, by reusing the polyurethane insulation containing blowing agents with significant global warming potential (GWP), the gases can continue to be sequestered in the foam cells, thereby reducing migration into the atmosphere. Finally, by recycling the cold storage panels and the polyurethane insulation they contain, millions of cubic foot of landfill space in the U.S. can be saved annually.

Chapter IV

Discussion

Cold storage panels manufactured with closed-cell polyurethane insulation offer one of the best thermally performing commercial refrigerated enclosure solutions today. The inherent structural and thermal capabilities of the polyurethane insulation make it the primary choice of insulated panel manufacturers for walk-in cooler and freezer facilities in the U.S. When configured in a panel assembly, which includes impermeable facers and perimeter framing, the polyurethane insulation retains nearly all of its initial thermal properties over its cold storage lifetime. However, after its life as a cooler or freezer, the panels are frequently discarded in landfills due primarily to the lack of commercially viable or cost effective recycling approaches or solutions to convert the polyurethane foam within the cold storage panel into other useful insulative products. This study has sought to quantify what the thermal value of the polyurethane insulation is after its cold storage life and how productive it might be if converted into other building insulation products.

Polyurethane Thermal Resistivity Research Summary

This study randomly selected ten U.S. retail supermarket sites to extract and thermally test polyurethane panel specimens from cold storage coolers and freezers which were being decommissioned. Out of the ten extraction sites, specimen panels from seven sites were deemed acceptable for testing. The seven panel specimens had an average in-use age of approximately 11.5 years.

The panels were tested per ASTM C518-10. The results showed the polyurethane insulation within the cold storage panels lost only a small amount of its thermal performance over the initial use period and had significant residual thermal value which might be further utilized as an insulative product in lieu of being discarded in landfills.

Polyurethane Recycling Research Summary

The second element of this research was to environmentally and economically evaluate ways to recycle/convert polyurethane insulation from decommissioned and discarded cold storage panels into other building insulation products. Three recycling forms were evaluated. Recycling Method A sought to convert the cold storage polyurethane panel into a second life within another cold storage application. Recycling Method B evaluated converting the polyurethane into board stock insulation. Finally, Recycling Method C converted the polyurethane insulation into blown-in attic insulation.

Recycling Method A. After the initial use period, there are many opportunities to use polyurethane cold storage panels in other walk-in refrigeration applications. Aid agencies such as food banks that serve the needs of the poor have ongoing demand for used serviceable cold storage products. The thermal value of used cold storage panels are bolstered by this study which shows polyurethane cold storage panels retain the vast majority of their thermal properties through their initial use period. That creates a highly valuable insulation product which can continue to be used far into the future. Recycling

Method A's environmental and economic evaluation showed that reconfiguring spent polyurethane cold storage panels into new freezer applications yield measurable value. Approximately 98% of the fossil fuel energy to manufacture new polyurethane insulation can be avoided and reusing the panels for another 15 year cold life would create annual savings of 261 megajoules of energy per board foot of the cold storage insulation which, when used in Boston, MA translates to approximately $16.30 of economic value per board foot per year. Recycling into a cooler application would save approximately 118 megajoules of energy per board foot and $7.38 of economic value per board foot.

Recycling Method B. Converting the cold storage panel polyurethane insulation into recycled board stock was estimated to reduce the insulating capacity by approximately 24%. The reduction is due to conversion material volume losses during the conversion (cutting) processes and the long-term thermal resistivity (LTTR) performance losses from its future use as roof deck insulation. In spite of those volume and thermal losses, the new board stock materials yields an averted fossil fuel savings of 1.43 megajoules per board foot by not needing to manufacture new materials and an economic savings of $.25 per board foot per year when installed in Boston, MA.

Recycling Method C. The final recycling evaluation was to convert the spent polyurethane insulated cold storage panel into blown-in attic insulation. This method created material and thermal performance losses of approximately 43% compared to the average thermal performance of the seven polyurethane insulation specimens when measured at 75 ^{o}F (24 ^{o}C) using the ASTM C518-10 test procedure.

The losses were nearly all due to the change in thermal performance of the insulation. Before conversion the k-Factor of the rigid polyurethane was estimated at .153 Btu-in/H-Ft2-^{o}F when measured at 75 ^{o}F (24 ^{o}C). After conversion into the blown-in insulation, the mean thermal performance was determined to be .2827 Btu-in/h-FT2-^{o}F when measured at an average material temperature of 75 ^{o}F (24 ^{o}C). This significant reduction is due to the blowing agent loss from the cells; first from the conversion process that breaks and damages the cells when shredded and second, from the diffusion of the blowing agent gases from the foam cells within the shredded particle as the polyurethane rapidly aged after shredding. The second C518-10 test conducted four months after the first strongly suggest a state of equilibrium between the blowing agent gases within the polyurethane foam cells and atmospheric gases was likely reached by the time of the first test (eleven months after shredding); whereby no further changes in thermal resistivity was likely to occur.

This result appears notably different than the Kjeldsen & Jensen (2001) and Kjeldsen & Scheutz (2003) studies which showed a measurable portion of the blowing agents in the 8-12 mm size range remained within the cell for both intermediate and long-term time frames. Our study results appear to show the polyurethane lost its blowing agents and reached a point of balance with atmospheric gases within a year of shredding to a particle size of .019 cu. in (304 cu.mm); with no further diffusion expected to occur.

The two shredded polyurethane thermal tests of our study yielded a mean steady-state R-value of 3.53 per inch thickness for the blown-in polyurethane insulation. That value is higher than the long-term R-values of 3.17 for rock wool and 2.4 for fiberglass (Energy.Gov, 2014). It is also higher than blown-in cellulose with an R value of 2.8 net of a 20% settlement factor (North American Insulation Manufacturers Association, 2014). This means that recycled shredded polyurethane insulation obtained from cold storage panels can offer equal or greater long-term thermal performance as blown-in attic insulation when compared to the most commonly used materials today.

This study results showed the blown-in polyurethane insulation when installed within an attic in Boston, MA saved 16 megajoules of fossil fuel energy per board foot per year. The annual economic value of the energy savings totaled $0.19 per board foot of the blown-in polyurethane insulation.

These results create two key questions. First, what would the effective life of a polyurethane insulated cold storage panel be if it continued in service or recycled into another cold storage use? As shown by this research, freezer cold storage panel polyurethane insulation blown with a HCFC 22 blowing agent lost an average of 1.55% of its insulative value over 11.4 years. If it is reused as a cold storage panel with only size and frame alterations, what might the thermal losses be at the end of a 25, 50 or 100 year life? Would it continue to lose thermal performance at a minimal rate as discovered in this study? Conversely, would it lose at a greater rate as shown in the Mukhopadhyaya et al. six year study (2014)? Unfortunately, there is no definitive performance curve or proxy available today which can accurately estimate such changes in thermal performance over such lengthy periods when polyurethane insulation is encapsulated between impermeable facers and a perimeter panel frame. An extension of the rate of thermal performance loss found in this research suggest when used in cold storage panel applications the polyurethane insulation would lose only a small portion of its thermal performance; even over multi-decadal lifetimes.

Second, if the polyurethane is harvested and converted into a new form of insulation how will its thermal performance change over its recycled life? Would the polyurethane insulation have already aged during its initial cold storage use life where it is would not age significantly further? Or would the polyurethane in the recycled application re-age in a similar manner noted in the cited Oak Ridge National Laboratory 2 and 4-year studies (Stovall, 2012) or the Prüfbricht (1998) Studies? These key questions would benefit from long-term aging research of recycled polyurethane insulation to determine the processes that change the polyurethane's long-term thermal performance.

Conclusions

This study showed that polyurethane insulated cold storage panels when configured with impermeable facers and perimeter framing will retain the vast majority of its thermal performance throughout its serviceable life. Because of this stellar insulative performance, the polyurethane could have a much longer serviceable life and be recycled into other insulative products after its cold storage life yielding significant environmental and economic value by averting the manufacture of new polyurethane raw materials and by lessening fossil fuel energy demand for space heating and cooling during the in-use phase.

The challenges which appear most significant to overcome are those associated with the collection and conversion of the decommissioned and discarded cold storage panels. Those impacts are both environmental and economic. Environmental issues can include the energy impact with discarded panel collection, transport and recycling.

Economic impacts can include the cost of demolition, shipping, and recycling-conversion. Further investigation is needed to evaluate approaches to accomplish these tasks environmentally and cost effectively whereby recycling of the decommissioned polyurethane insulation provides a greater benefit than producing new materials.

One approach which may currently be viable is for chain grocery store operators to work with their cold storage equipment supplier/installers to recycle their discarded cold storage panels into insulation products/materials to support the needs of their communities by donating the resultant recycled insulative products to aid agencies that provide food aid, housing or energy improvement programs to the poor. Discarding such valuable insulation materials in landfills offers no value to the store operators, the communities they serve or the environment.

Appendix A

Shredded Polyurethane

Figure 10 Appendix A. Photograph of shredded polyurethane. This figure presents a photograph of the harvested polyurethane insulation shredded into particles for Recycling Method C.

Table 23 Appendix A. Shredded polyurethane particle size distribution.

Sample	X (in)	Y (in)	Z (in)	cu. in	cu. mm
1	0.123	0.247	0.298	0.009	148.361
2	0.180	0.370	0.415	0.028	452.922
3	0.140	0.205	0.430	0.012	202.233
4	0.200	0.220	0.410	0.018	295.623
5	0.130	0.260	0.480	0.016	265.864
6	0.250	0.290	0.400	0.029	475.225
7	0.200	0.340	0.260	0.018	289.723
8	0.370	0.390	0.490	0.071	1158.680
9	0.200	0.350	0.450	0.032	516.192
10	0.130	0.240	0.300	0.009	153.383
Average:					395.820

This table presents the measured sizes of randomly selected polyurethane particles derived from the shredding process of Recycling Method C.

Appendix B

Component Assembly for Each Recycling Option

Table 24 Appendix B. Recycling Method A freezer panel R-value/U-value evaluation.

Freezer Assembly Component	Without Insulation	With 1” PUR Insulation
Insulation	0.0000	7.0771
Dead air space in panel cavity	1.0000	0.0000
Air films	0.7800	0.7800
Total Wall R-value	1.7800	8.4136
U-value (1/R)	0.5618	0.1189

This table shows the walk-in cooler components and their U-values used in the comparative energy calculations for Recycling Method A.

Table 25 Appendix B. Recycling Method A cooler panel R-value/U-value evaluation.

Cooler Assembly Component	Without Insulation	With 1”PUR Insulation
Insulation	0.0000	6.6827
Dead air space	1.0000	0.0000
Air films	0.7800	0.7800
Total Wall R-value	1.7800	7.4627
U value	0.5618	0.1340

This table shows the walk-in cooler components and their U values used in the comparative energy calculations for Recycling Method A.

Table 26 Appendix B. Recycling Method B roof deck R-value/U-value evaluation.

Assembly Component	Without Insulation	With 1" PUR Insulation
Drywall @ Ceiling	0.4500	0.4500
Dead air space @ joist/attic	1.0000	1.0000
Structural sheathing	0.6200	0.6200
Insulation	0.0000	4.8021
Roof shingles	0.4400	0.4400
Air films	0.8500	0.8500
Total Roof R-value	3.3600	7.1621
U-value	0.2976	0.1396

This table shows the roof assembly components and their U values used in the comparative energy calculations for Recycling Method B.

Table 27 Appendix B. Recycling Method C blown-in R-value/U-value evaluation.

Assembly Component	Without Insulation	With PUR Insulation
Drywall @ ceiling	0.4500	0.4500
Dead Air space @ joist/attic	1.0000	0.0000
Insulation	0.0000	3.5300
Roof sheathing	0.6200	0.6200
Shingles	0.4400	0.4400
Air films	1.3900	1.3900
Total Roof R-value	3.900	6.4300
U-value	0.2564	0.1555

This table shows the attic and roof assembly components and their U values used in the comparative energy calculations for Recycling Method C.

Appendix C

In-Use Energy Calculations

Table 28 Appendix C. Recycling Method A differential energy use calculation.

Freezer Panel Assembly	U-value	Temp Diff	Annual Energy Used (Btu/BF.)	Note
Recycle Method A - Freezer	0.1273	65	73,647	Incl. LTTR factor
Hollow Panel – No Insulation	0.5618	65	319,888	
		Delta:	246,240	

This table presents the comparative annual energy use of a walk-in freezer with and without the recycled cold storage panel insulation of Recycling Method A.

Table 29 Appendix C. Recycling Method A cooler differential energy use calculation.

Cooler Panel Assembly	U-value	Temp Diff	Annual Energy Used (Btu/BF)	Note
Recycle Method A- Freezer	0.1340	30	35,788	Incl. LTTR factor
Hollow Panel- No Insulation	0.5618	30	147,640	
		Delta:	111,853	

This table presents the comparative annual energy use of a walk-in cooler with and without the recycled cold storage panel insulation of Recycling Method A.

Table 30 Appendix C. Recycling Method B differential energy use calculation.

Roof Assembly	U-value	Degree Days	Annual Energy Used (Btu/BF	Note
PUR Board Stock	0.1396	6407	29,080	Incl. LTTR factor
No insulation	0.2976	6407	45,764	
		Delta:	16,684	

This table presents the comparative annual energy use of roof deck insulation in Boston, MA with and without the recycled polyurethane board stock insulation of Recycling Method B.

Table 31 Appendix C. Recycling Method C differential annual energy use calculation.

Roof Assembly	U-value	Degree Days	Annual Energy Used (Btu/BF)	Note
Attic with PUR Insulation	0.1555	6407	23,914.15	No LTTR factor
Attic with No Insulation	0.2564	6407	39,427.69	
		Delta:	15,513.54	

This table presents the comparative annual energy use of attic insulation in Boston, MA with and without the recycled polyurethane blown-in insulation of Recycling Method C.

Appendix D

Life Cycle Analysis

Table 32 Appendix D. Environmental impact for each recycling method.

Recycling Method A

Impact Category	BAU Case PUR Insulation	Recycled PUR Insulation	Reference Unit	Environmental Impact Difference
Acidification	0.130	0.004	Kg SO2 eq.	-96.75%
Eco toxicity	34.89	7.616	Ctue.	-78.18%
Eutrophication	0.032	0.000	Kg N eq.	-98.00%
Global Warming	108.65	3.049	Kg CO2	-97.19%
Human Health - Carcinogenics	0.081	0.001	CTUh	-98.38%
Human Health - non-Carcinogenics	0.133	0.002	CTUh	-98.32%
Ozone Depletion	0.010	0.000	kg CFC-11 eq.	-98.27%
Photochemical ozone formation	0.960	0.088	Kg O3 eq.	-90.75%
Resource depletion - fossil fuels	23.238	0.371	MJ surplus	-98.40%
Respiratory effects	0.012	0.001	kg PM2.5 eq.	-91.16%

Recycling Method B

Impact Category	BAU Case PUR Insulation	Recycled PUR Insulation	Reference Unit	Environmental Impact Difference
Acidification	0.1302	0.035	Kg SO2 eq.	-72.63%
Eco toxicity	34.897	9.279	Ctue.	-73.41%
Eutrophication	0.0324	0.008	Kg N eq.	-73.54%
Global Warming	108.655	29.385	Kg CO2	-72.96%
Human Health - Carcinogenics	0.081	0.021	CTUh	-73.81%
Human Health - non-Carcinogenics	0.133	0.035	CTUh	-73.78%
Ozone Depletion	0.010	0.002	kg CFC-11 eq.	-73.72%
Photochemical ozone formation	0.960	0.304	Kg O3 eq.	-68.29%
Resource depletion - fossil fuels	23.238	6.081	MJ surplus	-73.83%
Respiratory effects	0.012	0.003	kg PM2.5 eq.	-68.61%

Table Continued…

Recycling Method C

Impact Category	BAU Case PUR Insulation	Recycled PUR Insulation	Reference Unit	Environmental Impact Difference
Acidification	0.1302	0.0566	Kg SO2 eq.	-56.52%
Eco toxicity	34.897	14.9724	Ctue.	-57.10%
Eutrophication	0.0324	0.0139	Kg N eq.	-57.19%
Global Warming	108.65	46.9857	Kg CO2	-56.76%
Human Health - Carcinogenics	0.0813	3.47E-02	CTUh	-57.39%
Human Health - non-Carcinogenics	0.1335	5.69E-02	CTUh	-57.37%
Ozone Depletion	0.0103	0.0044	kg CFC-11 eq.	-57.36%
Photochemical ozone formation	0.9606	0.4489	Kg O3 eq.	-53.27%
Resource depletion - fossil fuels	23.238	9.8971	MJ surplus	-57.41%
Respiratory effects	0.0123	0.0057	kg PM2.5 eq.	-53.53%

This table shows the environmental impact differences between the business-as-usual cases of discarding decommissioned cold storage panels with each recycling method presented in this study.

Table 33 Appendix D. Fossil Fuel LCI flows.

Fossil depletion Flow	Contribution	Amount	Unit
Gas, natural, in ground	46.14%	0.5446	kg oil eq.
Oil, crude, in ground	36.40%	0.4295	kg oil eq.
Coal, hard, unspecified, in ground	12.26%	0.1446	kg oil eq.
Coal, brown, in ground	5.10%	0.0602	kg oil eq.

This table presents energy elements that create the fossil fuel depletion flow.

Appendix E

Long-Term Thermal Resistivity

Table 34 Appendix E. Recycling & harvesting volume loss calculation.

Method A	%
Net estimated foam remaining after panel deframing:	98.44%
Method B	
PUR foam remaining after panel deframing:	98.44%
Net foam remaining after deskinning & slicing:	75.00%
Net estimated recycled board stock:	73.83%
Method C	
Net foam after deframing and deskinning:	98.44%
Estimated material losses during shredding:	1.00%
Total net foam remaining after shredding:	97.44%
k-Factor retainage @ 75 ^{o}F:	58.91%
Net recycled shredded PUR insulation:	57.40%

This table presents the estimated amount of polyurethane foam remaining for each recycling method after recycling and conversion processes.

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