Cold Climate Housing Research Center

CCHRC

Passive Refrigeration

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Passive Refrigeration

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Disclaimer: The research conducted or products tested used the methodologies described in this report. CCHRC cautions that different results might be obtained using different test methodologies. CCHRC suggests caution in drawing inferences regarding the research or products beyond the circumstances described in this report.

Overview

Refrigerators and freezers consume about 10% of the electricity (Figure 1) of a typical home in the United States (U.S. Energy Information Administration, 2012). As a general rule, older units consume more electricity than newer units. In the past 20 years refrigerators have gotten 60% more efficient (California, 2012), which reflects stricter energy efficiency standards from the U.S. Department of Energy and Energy Star. Newer Energy Star refrigerators are required to consume 20% less energy than the maximum electricity consumption allowed under the Department of Energy standards (e.g. about 500kWh/yr for a 19 cubic-foot unit).

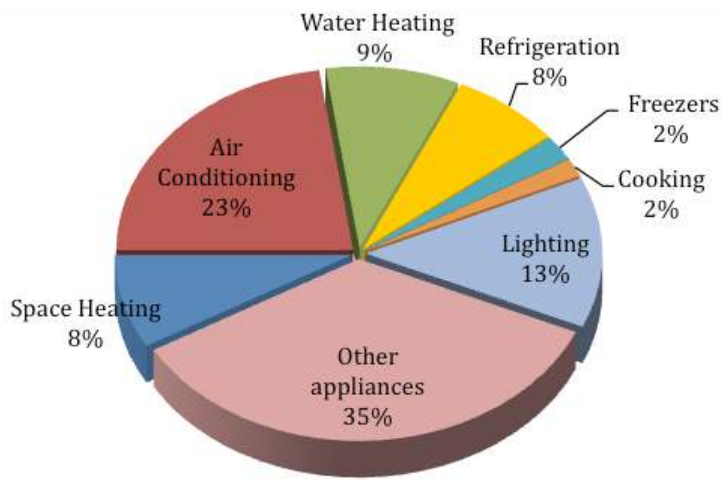

Figure 1. 2010 Home Appliance Use. Refrigeration accounts for about 8% of home energy use; supplemental freezers account for 2%. (U.S. Energy Information Administration, 2012).

One of the most effective ways to reduce the electrical demand of a refrigerator is to replace an older unit with a new Energy Star rated unit (California, 2012). If that is not an option, a few simple steps may lower the electrical demand of an existing refrigerator:

- Store the unit in a cool location, right beside the oven will reduce efficiency;
- Locate the refrigerator so that air can circulate around it;
- Keep the refrigerator between 35°F and 38°F, not any cooler;
- Add extra insulation to the top and sides of the unit (not the back), which can help keep the cold inside (beware that this may cause mold in some installations);
- Try not to open the door too often or for too long;
- Keep the unit as full as possible; more mass will retain the cold better than just air.

In cold climates, one way of lowering electrical refrigeration is to take advantage of the abundant cold outside to keep perishable items cool. Storing frozen items in an animal-proof box outside during the winter is a simple way to avoid running a freezer all winter. Homeowners have installed homemade icebox type refrigerators that rely on a large block of ice in the winter to keep items cool until the ice melts completely. There are also closets that are built into the outside wall of a house and not insulated from the outside; these keep items frozen well in the winter. However, these completely passive methods are largely dependent on the weather for temperature regulation and require some compromise in functionality in comparison to a traditional electric refrigerator and freezer.

A novel approach uses thermosyphons filled with refrigerant to draw heat out of the refrigerator and freezer compartments and release that heat outside while maintaining the electric compressor to use when it is too warm outside for the thermosyphons to function. CCHRC evaluated an existing passive refrigerator design that uses thermosyphons to take advantage of the cold temperatures in the winter. Additionally, CCHRC designed, built, and tested a prototype passive refrigerator by retrofitting a conventional unit. The CCHRC prototype refrigerator was able to passively maintain the appropriate compartment temperatures at exterior temperatures of 0°F and colder. The retrofit unit achieved 16% energy savings over the course of one year.

Objectives

The objectives of this project are:

1. To review pertinent literature on passive refrigeration methods in cold climates;
2. To test a commercially available refrigerator with passive components, in order to study the feasibility of more energy efficient refrigerator and freezer designs for Interior Alaska;
3. To investigate the potential to retrofit conventional, residential-sized refrigerators to make them more efficient in the winter months.

Literature Review

Large refrigeration systems that take advantage of the winter cold in Alaska have been around for centuries. Communities on the northern coast of Alaska have used cellars dug into the permafrost to store food for generations. These cellars were dug into the ground with sod roofs and supported with driftwood and whale bones. They go deep into the permafrost, some a deep as 40 feet (Brubaker et al., 2010). As climate change warms the Arctic, these cellars have been thawing and stored food is spoiling.

Starting in the early 1960s there were several studies into freezing large masses of brine using passive cooling tubes. These brine freezing systems, one in Frobisher Bay, Canada and one in Savoonga, Alaska, had some success but both suffered from brine storage problems due to corrosion of the holding tanks and thawing of permafrost under the tanks (Ringer, 1958; Zarling, 1981).

Figure 2. Ground cooling thermosyphons. Test thermosyphons in front of CCHRC are being monitored to further understand their performance.

Thermosyphons are used all over Alaska to stabilize permafrost under buildings, roads, and pipelines (Figure 2). They are large tubes, partially filled with fluid and vacuum sealed, that operate passively when the ground temperature is greater than the ambient air temperature. A variety of fluids are used in the permafrost thermosyphons: ammonia, carbon dioxide, and synthetic refrigerants. Heat in the ground heats the fluid, causing it to evaporate. The vapor rises to the fins at top of the tube, usually above ground, where it condenses due to the colder temperatures, releasing the absorbed heat to the heat exchanger and then into the air. The condensed fluid then flows back to the bottom of the tube for the cycle of phase change to continue. A thermosyphon needs to be orientated with a downward slope so that the fluid can flow down. (There are newer tubes called heat pipes which can be orientated any direction because capillary mesh directs the flow of the liquid). Thermosyphons move heat passively whenever there is enough of a temperature difference between the ground and the air. When there is no temperature difference or the air is warmer than the ground, they are not active.

A recent UAF study (Peterson and Wendler, 2011) modeled the use of thermosyphons and extra insulation to maintain the thawing ice cellars on the North Slope. They concluded that a combined approach of thermosyphons and insulation could keep the cellars sufficiently cool to maintain frozen food year round. This study is currently on hold pending funding to test a prototype installation.

In addition to the aforementioned large-scale community cold storage systems designed to store and freeze large quantities of subsistence and commercial meats, there have been attempts at selling residential-scale passive refrigeration systems. In the 1980s Sun Frost, a company in California, designed and built hybrid passive residential refrigerators. The DC units ran efficient electric compressors to cool the units in the summer and refrigerant-filled thermosyphons to cool the units in the winter using outdoor air as a heat sink. The company only made 10 due to low demand (Sun Frost, n.d.).

There are a variety of ideas for creating a winter passive refrigerator. The idea of running cold air through the wall into the freezer has been successful in some locations (Freeaire Refrigeration, n.d.). The cold air system has been effective in Fairbanks commercial freezers (B. Grunau, personal communication, November 2011). The system is designed for commercial size freezers and would be hard to scale down for residential freezer use (it would not work for a refrigerator compartment). A University of Alaska Fairbanks project looked at running glycol cooling coils in a residential refrigerator and pumping the glycol outside to cool it (Gustafson, Olson, and Mohrmann, 2009). The prototype system suffered from mechanical problems but the idea worked. It was not completely passive but has potential even in the summer if they route their exterior piping underground.

Method

CCHRC purchased two Frigidaire Energy Star refrigerators (FGHT1846K) and a passive prototype RF–16 refrigerator from Sun Frost. The Frigidaires are rated to use 386 kWh a year, which is more than double the rating for the RF–16 of 183 kWh per year. All three refrigerators were installed in the south lab of the CCHRC Research and Testing Facility (Figure 3). Each unit was set up with power, temperature, and relative humidity sensors (listed in Table 1). Each unit had its own HOBO Energy Logger that recorded data every two minutes. Table 2 presents the timeline for testing and data collection.

Figure 3. The test setup. The Sun Frost is in the front; two Frigidaires are in the back, with the retrofit Fridgidaire farthest back.

Retrofit Comparison Study

The Frigidaire units were set up in the lab in September 2010 with the monitoring equipment. The units were plugged in and run for one week. Energy use and interior condition data were collected from all phases of the testing to compare the performance of the retrofitted refrigerator to the baseline unit. The data were used to ascertain that the two units consumed roughly the same amount of energy. In one week the two units used an average 3.82 kWh, and were within 0.2 kWh of each other for total electricity used.

Following the establishment of the baseline agreement of the units, one unit was retrofitted with two thermosyphons (Figure 4). Holes were drilled into the side of the unit for both the refrigerator and freezer compartments. The hole locations were carefully chosen to

Table 1. Data Collection Sensors		
Sensor	**Purpose**	**Type**
Temperature	Monitor the interior temperature of the freezer and refrigerator compartments	Onset S-THA-M002
Relative Humidity	Monitor the interior humidity of the freezer and refrigerator compartments	
Energy	Monitor the electrical use of the unit for comparison to other units	Wattnode WNB-3Y-208, Onset pulse input adapter S-UCC-M006, and 50 amp current transducer T-MAG-SCT-050

Table 2. Study Timeline	
September 2010	Baseline tests of Frigidaires
Late September 2010	Retrofit installed in one Frigidaire
November 2010-December 2010	Frigidaires run side-by-side with no load
January–April 2011	Sun Frost installed and monitored
January–November 2011	Frigidaires run side-by-side with "typical" load

be in the side of the unit so that the drill did not cut into the refrigerant lines embedded within the refrigerator. Then two holes were cut into the exterior wall of the building. The holes in the building and the refrigerator were drilled so that they aligned for straight refrigerant tubes as shown in Figure 5.

Three-quarter inch copper tubing (0.74 inch inner diameter) was sealed on one end and fed through the holes from the outside of the building (Figure 5). A ball valve was installed between the unit and the wall on each of the pipes. Copper fin tube (with aluminum fins) was attached to the copper tubing on the outside of the wall. The fin tube was braced to the building using unistrut (Figure 6). The fin tube came in 4-foot lengths. For simplicity of installation the full tube was used for the refrigerator fin section and two lengths were used for the freezer section. The fin tube lengths were not the limiting factor in the design and using the shortest length available would have probably been sufficient.

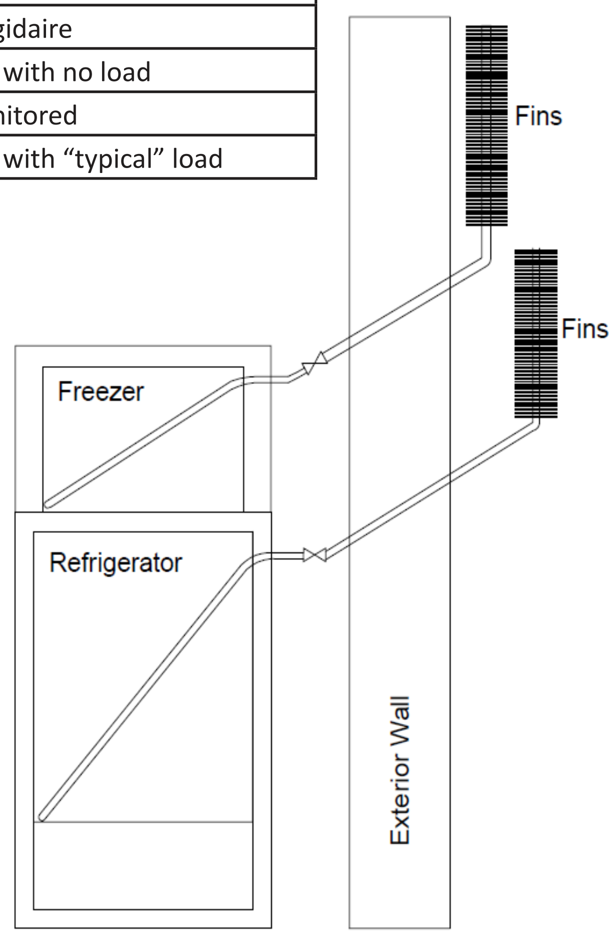

Figure 4. Schematic of passive retrofit refrigerator. In the final version the fin section for the freezer compartment were twice the size of the refrigerator compartment fine section.

Figure 5. Tubing in the back of the retrofit fridge. The ice build-up on the pipes was not addressed in this study but will probably need to be addressed in future work.

Figure 6. Fins being attached to the building. The freezer section is 8 feet long; the fins were not the limiting heat transfer mechanism of the design and could probably be much smaller.

The tubing was insulated between the unit and wall to prevent condensation on the tubing, as well as limiting short circuiting the heat transfer from the refrigerator compartments. Once the tubing was installed, the thermosyphons were charged with 3 ounces of refrigerant, R-134a. The surface area of the evaporator section of the thermosyphon was very limited by the size of the compartments. Following some initial testing a copper plate (12 in x 20 in) was added to the freezer evaporator section to increase the heat transfer surface area.

For the first four months of the study the two units ran with no load and minimal activity. In January of 2011 a load of water and ice was added to both units. The units ran with the base loads of water and ice for one month and minimal other use. Starting in February, the staff of CCHRC began using the units to store lunches and other foods for short amounts of time. This “typical” use phase was designed to have the two units see similar and “typical” residential use, but CCHRC did not collect detailed data on the refrigerator use pattern.

Sun Frost Prototype Study

The Sun Frost unit was separate from the comparison between the two Frigidaire refrigerators. The Sun Frost RF–16 is designed to use approximately 0.5 kWh per day. The prototype passive RF–16 was set up with one-quarter inch copper tubing for thermosyphons embedded in the roof of the freezer and the back wall of the refrigerator. The passive tubing exited the top of the unit and went through the wall to a flat plate copper fin outside (Figure 7). The refrigerator thermosyphon tubing had a temperature actuated valve to close off the

Figure 7. Passive tubing on Sun Frost refrigerator. The refrigerator tube was set up with a temperature actuated valve to prevent freezing in the refrigeration compartmentt.

thermosyphon if the refrigerator temperature approached freezing. CCHRC charged the tubes with refrigerant R134a to Sun Frost's specifications of 5 oz. for the refrigerator and 3.2 oz. for the freezer.

In addition to monitoring the energy use of the Sun Frost, several infrared photos were taken to help ascertain the contribution of the passive system. Interior temperatures were monitored with and without the unit running.

Results and Discussion

Retrofit Comparison Study

The retrofit refrigerator performed well during the cold winter months. Table 3 and Figure 8 show a comparison between the monthly electrical usage for the retrofit and regular refrigerators. At the height of the winter, in December, January and February, the retrofit unit used 6.3 kWh compared to 36.1 kWh for the regular refrigerator. In the summer the retrofit unit used slightly more electricity than the regular unit, particularly in August. This could be due to heat from the sun conducting from the outside fins along the copper tubing into the refrigerator compartments or to variations in user behavior. Over the year-long monitoring period, the retrofit used almost 16% less electricity than the regular unit.

Table 3. Monthly Electrical Usage (kWh)

	Retro	**Regular**
Monthly Totals		
October 2010	13.53	13.87
November 2010	10.86	14.11
December 2010	0.85	13.24
January 2011	2.72	11.48
February 2011	2.71	11.39
March 2011	9.92	15.33
April 2011	14.71	15.41
May 2011	19.17	19.39
June 2011	20.81	20.53
July 2011	22.28	22.11
August 2011	24.46	20.28
September 2011	16.68	16.22
October 2011	15.90	15.86
Total Energy (kWh)	174.58	209.21

The temperatures inside the retrofit unit were monitored to determine if there was too much cooling of the refrigeration compartment or warming of the freezer compartment. The refrigerator came with a control system based on the temperature in the refrigeration compartment and CCHRC did not alter the controls. When the refrigerator calls for cooling the compressor runs and cools both compartments; however, when the refrigerator compartment is sufficiently cool the compressor does not run so the freezer does not get any cooling irrespective of the temperature in the freezer compartment.

The compartment temperatures for the regular unit averaged 8.9°F for the freezer and 38.6°F for the refrigerator. The retrofit unit had more variable temperatures; Figure 9 demonstrates the fluctuations in the compartment temperatures for a period before a load was added. The refrigerator temperatures were consistent until the end of November. The freezer temperatures were less consistent, covering a wider range and rising toward

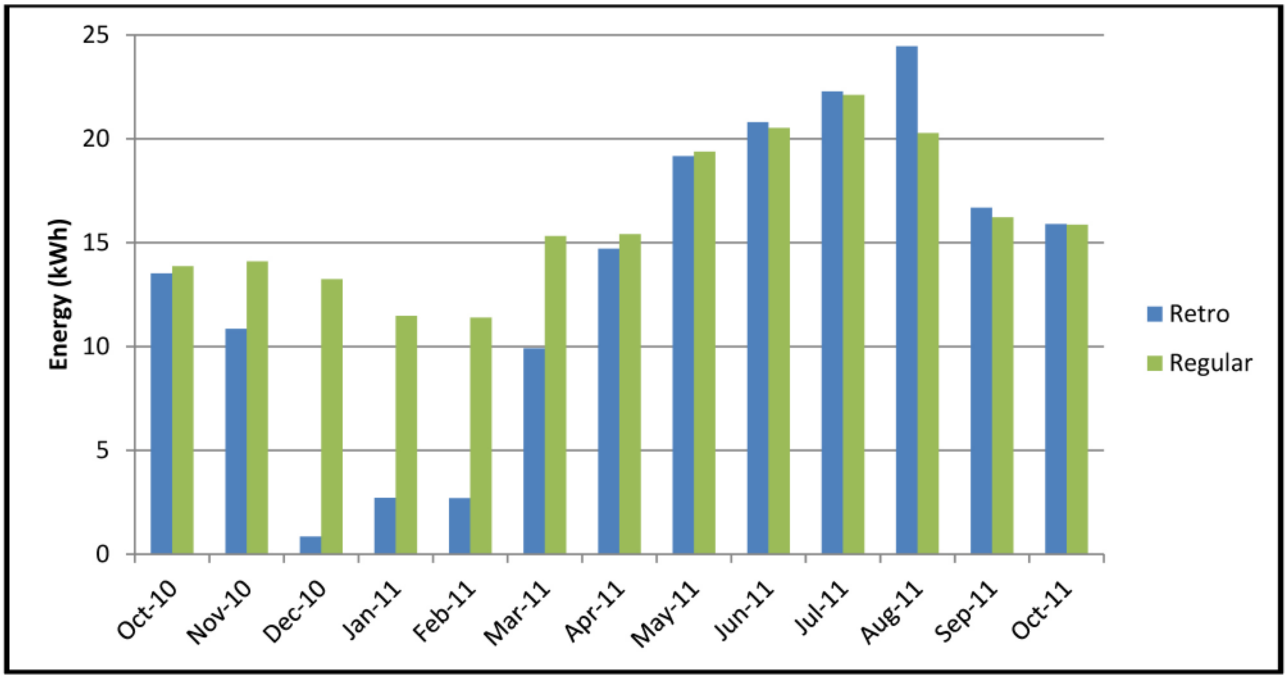

Figure 8. Monthly electrical use by the refrigerators. Both units had low electric usage when compared to older refrigerators.

the end of November. There were also spikes in the temperature every two days, caused by the auto defrost cycle of the original control system (it runs every 48 hours of compressor run time). At the end of November the outside temperature dropped below 0°F and the compressor in the retrofit refrigerator stopped running. It is readily apparent when the compressor ran judging from the interior temperatures of the unit. Exterior temperatures below 0°F were enough to cool the interior of the refrigerator so that the compressor didn't run. The temperature in the refrigerator during these periods was lower than the average of the regular unit, but the temperature in the freezer was higher than the average.

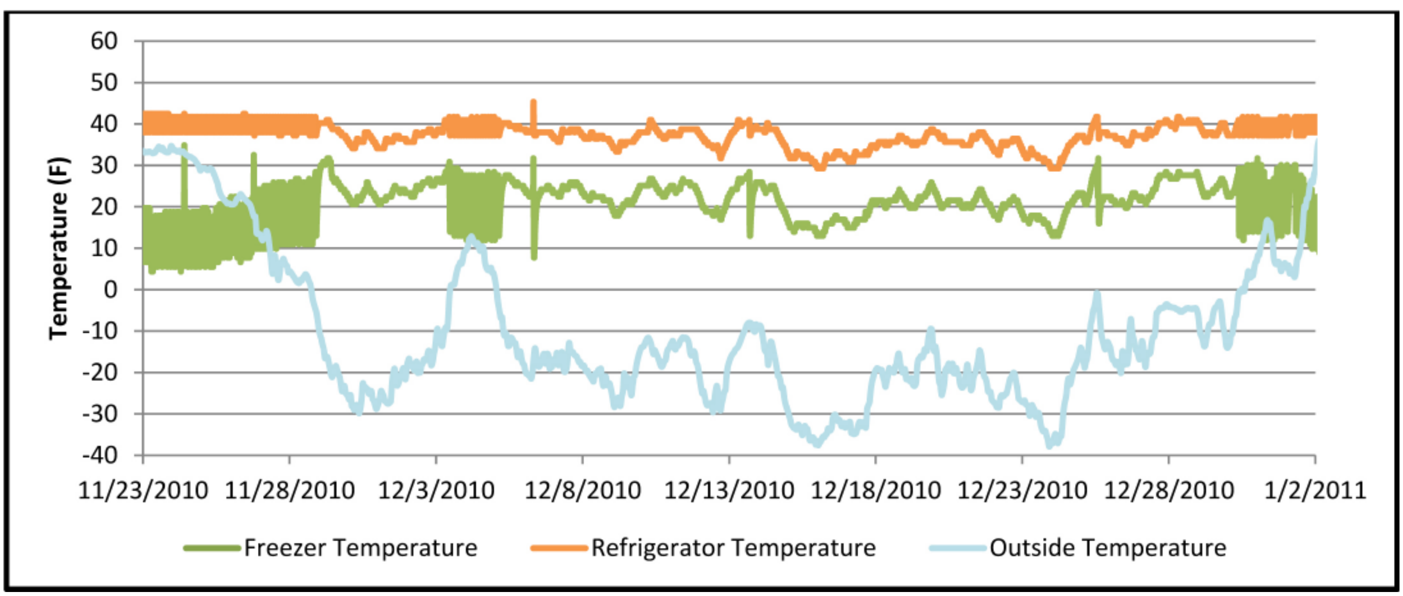

Figure 9. Compartment temperatures for the retrofit refrigerator with exterior temperatures. The compartment temperatures with the least amount of noise indicate that the compressor was not running and the unit was being cooled passively.

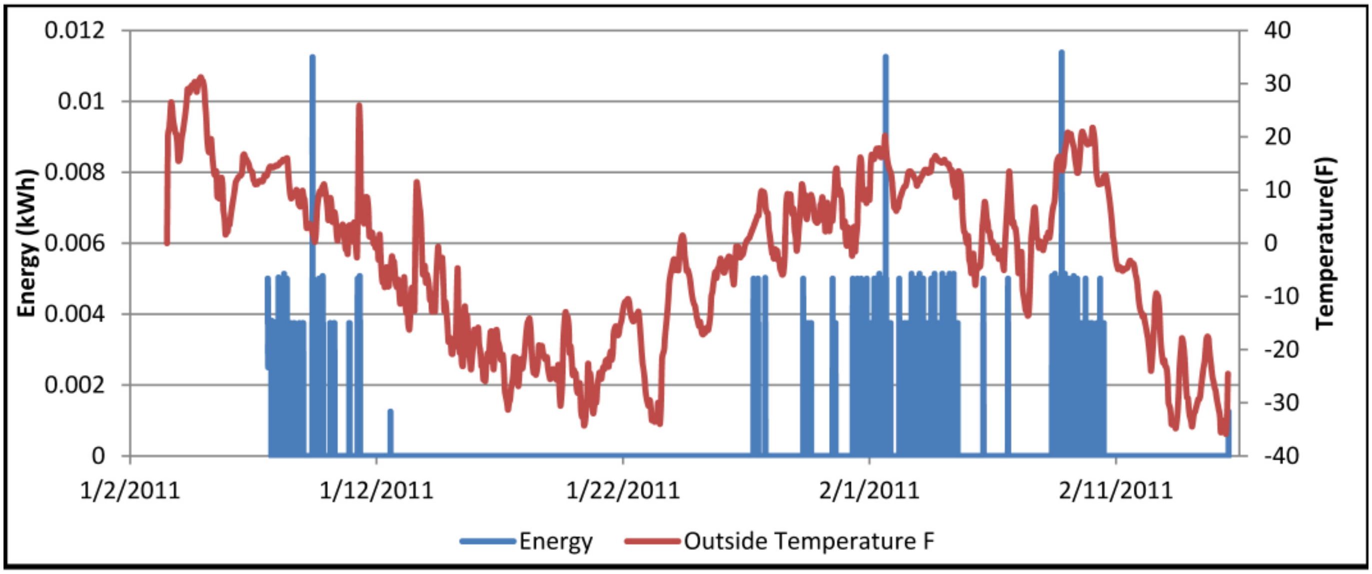

Figure 10. Retrofit refrigerator electricity use vs. outside temperature. The compressor did not run whenever the outside temperature dropped below 0°F.

Figure 10 shows the electrical usage of the retrofit unit and the exterior temperature for a brief period in the winter. This confirms that the compressor did not run if the temperature was below 0°F.

Sun Frost Prototype Study

The testing of the Sun Frost prototype was slightly different than the testing of the retrofit refrigerator. The goal was to see if the passive system made any contribution to cooling within the refrigerator without a second unit to compare with. The Sun Frost already had very low electrical usage, therefore any contribution of the passive system would have been very small.

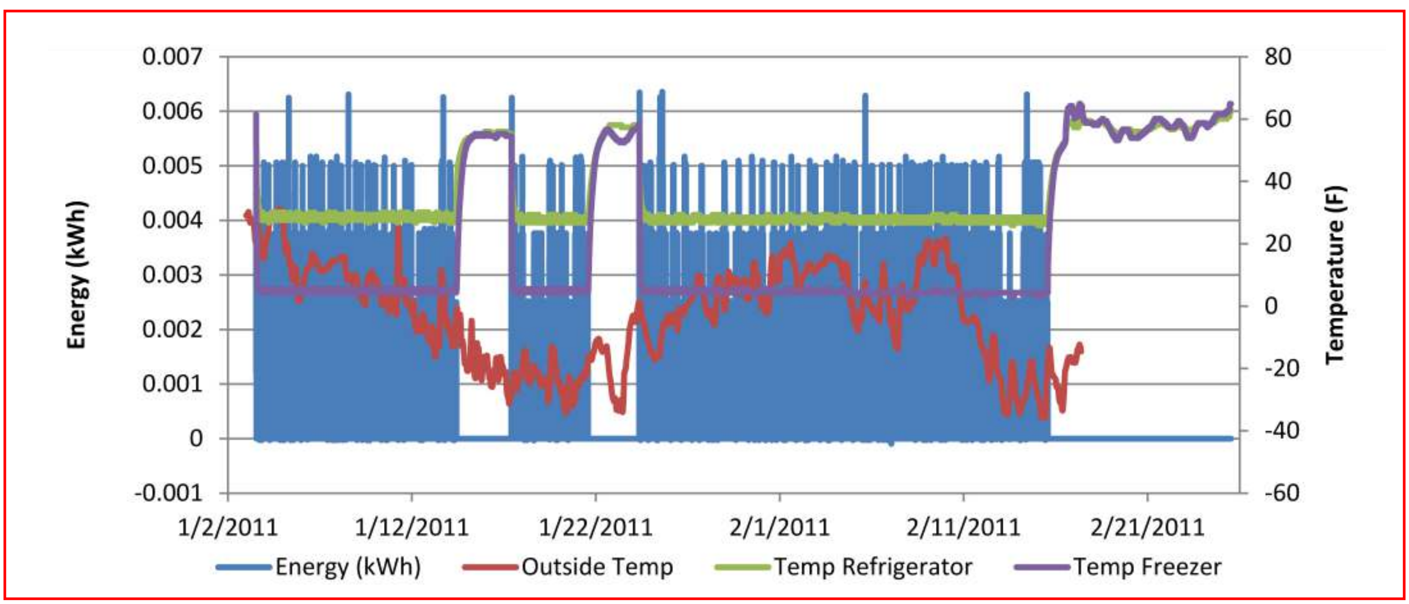

Figure 11. Data from January to mid-February showing the temperatures and power use of the Sun Frost passive prototype. The dip in freezer temperature when the unit was off in late January is the only indication that the thermosyphons were cooling the unit; the outside temperature was -32°F that day.

Figure 11 shows data from early January to mid-February for the Sun Frost. The refrigerator ran every day, using an average of 0.44 kWh per day whenever it was plugged in. The unit was unplugged three separate times over the course of this graph to study the effect of the passive system. Each time the refrigerator was unplugged the interior temperatures rose quickly to room temperature, indicating that the passive component of the system was not transferring heat out of the unit. There is a dip in the freezer temperature on January 23, 2011 that corresponds with the drop in outside temperature to -32°F. The 4°F change in temperature is an indication that the passive tubes were cooling the unit slightly.

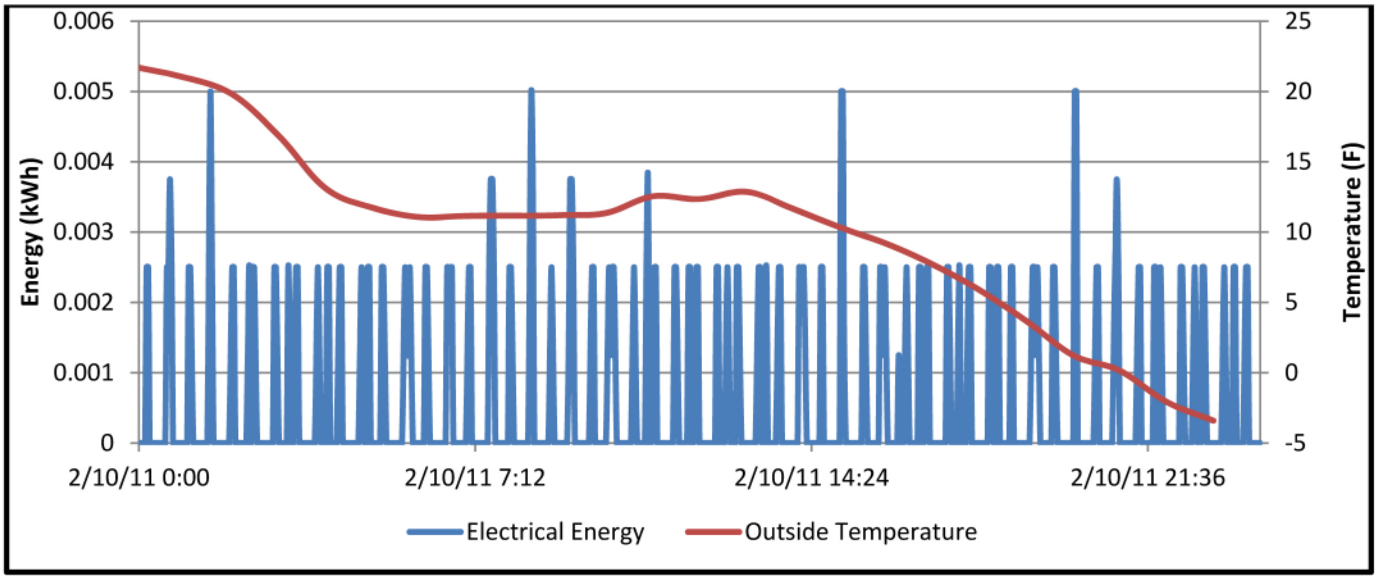

Figure 12. The energy use of the Sun Frost passive prototype on a warmer day. The average outside temperature on Feb. 10, 2011 was 13 °F.

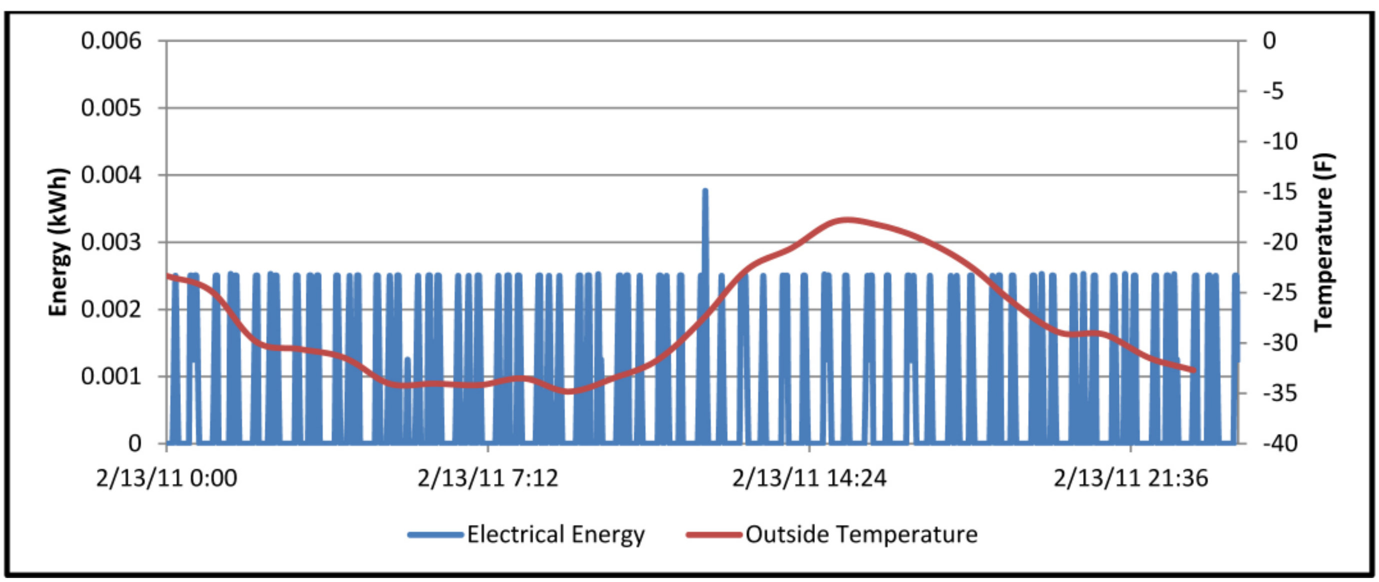

Figure 13. The energy use of the Sun Frost prototype on a cooler day. The average outside temperature on Feb. 13, 2011 was -25°F.

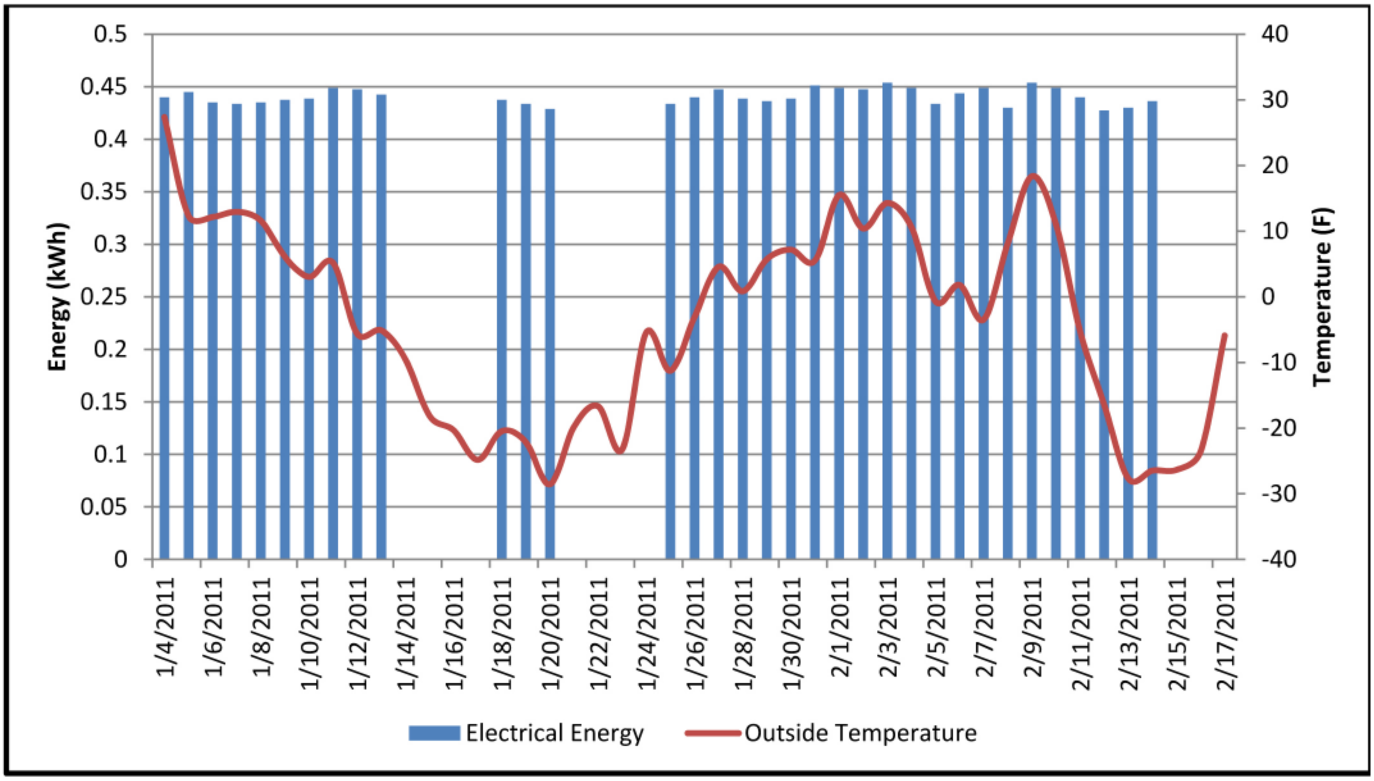

Figure 14. Sum of the daily energy use of the Sun Frost passive prototype overlaid with the outside temperatures. The unit was unplugged three times during the time of this graph.

A closer look at two particular days (Figures 12 and 13) shows a slightly smaller energy draw on the colder day. Looking at the data more closely reveals that it is a very slight difference (0.45 kWh on February 10 vs. 0.43 kWh on February 13). This slight difference between the “warmer” and “cooler” days may be due to the passive system. With such low energy usage to begin with it is difficult to discern the effect of the passive system on the overall refrigerator energy demand. A look at a plot of daily energy draw and outside temperature (Figure 14) shows fluctuations in the daily draw that is only slightly correlated to exterior temperatures. The difference in energy draw is very small, ranging between 0.43 and 0.45 kWh per day.

In an attempt to understand the behavior of the heat pipes, the Sun Frost unit was unplugged and infrared (IR) pictures were taken of the interior looking for indications of the heat pipes functioning in the wall of the refrigerator and the roof of the freezer. Figures 15 and 16 show some of the IR photos taken of the unit shown in false color. The IR images of the unplugged Sun Frost reveal only small variations in surface temperatures (about ±6°F) within the refrigerator compartments that were near the ambient room temperature. The cooler spots in the IR photos could be the result of the thermosyphons, but the temperature difference is so slight that relatively little cooling power can be attributable to the passive system.

Based on the minimal change in energy use and small temperature difference in the IR photographs, CCHRC measured the pressure in the passive cooling tubes to determine the temperature of the refrigerant. At the time of the test the outside temperature was -16°F. The freezer tube was at 17 psi and the refrigerator tube was at 18 psi corresponding to about 19°F. The temperature inside the freezer was room temperature (about 57°F). This testing seems to indicate that there was some cooling from the passive system, but it was not getting transferred to the freezer box.

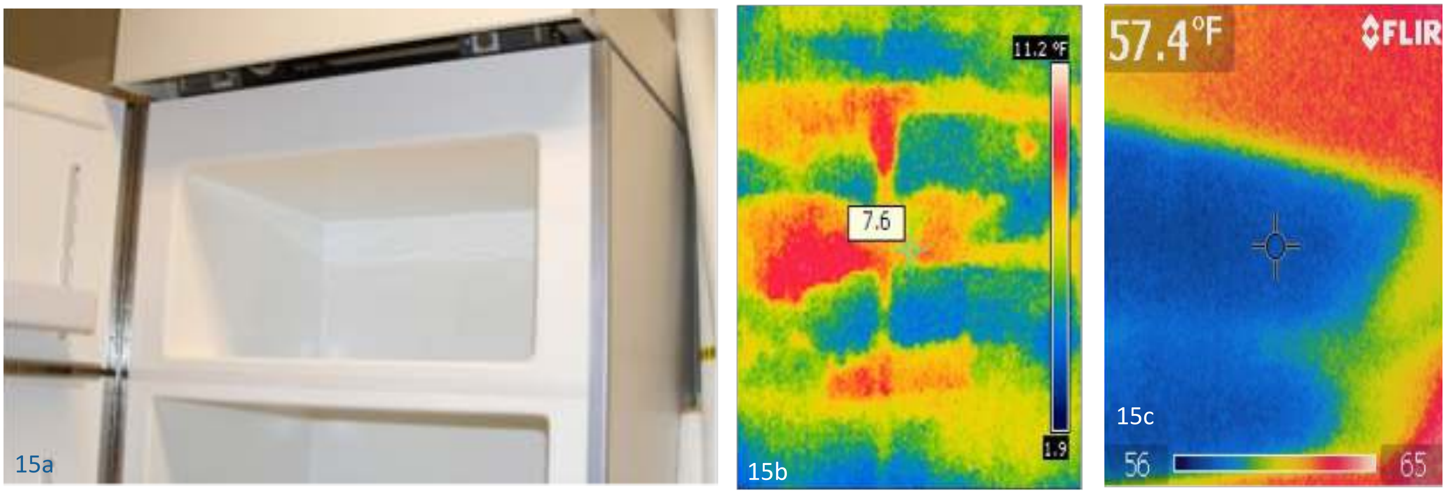

Figure 15a. Freezer compartment in the retrofit refrigerator. Figure 15b. Freezer roof before it was unplugged. Notice the surface temperature scale of the photo; the temperatures were in the range of normal freezer temperatures. The blue lines are most likely the locations of the refrigerant lines. Figure 15c. Freezer after it was unplugged and dried for a day. The outside temperature was -16 °F. There were noticeable "cold" spots, however the temperature difference across the surface was 6°F and the interior compartment was near room temperature.

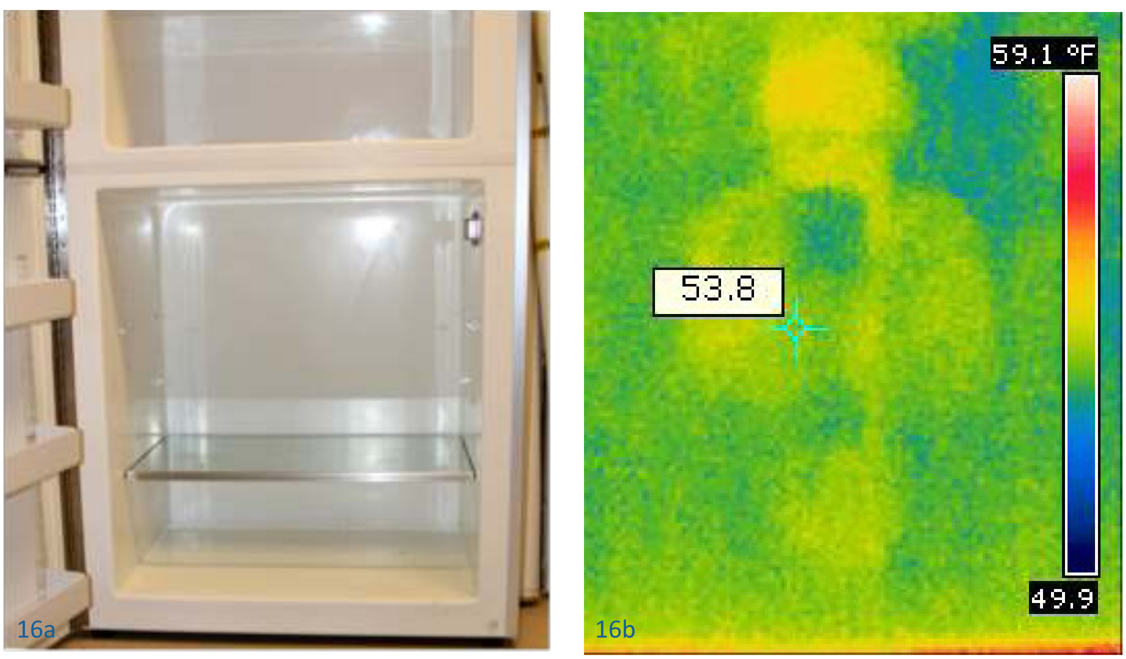

Figure 16a. Back wall of the retrofit refrigerator. Figure 16b. The back wall of the refrigerator after it had been unplugged for a day. The outside temperature was -16°F. The temperature change across the surface was 10°F and the compartment was near room temperature. The camera measures infrared temperature which is why the reflection of the photographer is seen in the back of the refrigerator.

After examining the internal workings of the passive system (Figure 17), there are a few theories as to why there is not sufficient heat transfer. It is possible that there is a refrigerant distribution problem with the way the piping is laid out (lots of loops and very little pitch to the freezer pipes, which is required for fluid return). The tubing itself is very narrow and there may be problems with the fluid and vapor passing each other in such small tubes.

Figure 17. The Sun Frost prototype showing the interior tubing. This picture shows the backside of the freezer compartment in the foreground and a portion of the refrigerator compartment toward the back.

Analysis and Conclusions

For one full year of use the retrofit refrigerator used 175 kWh compared to the 209 kWh of the regular refrigerator. That is a 16% reduction in energy use for an Energy Star appliance. A 16% reduction in energy use for a high-efficiency appliance is not that significant in absolute terms (i.e. 34 kWh per year). If electricity costs $0.20 per kWh, the energy use reduction translates to $6.80 in savings. Sixteen percent may not be big savings for an already super-efficient fridge, but an older inefficient fridge could see much greater savings. Additionally, the design and installation of the passive system was a first approximation and not necessarily the optimal design. Further refinements to the design could increase this energy use reduction even more.

Table 4. Prototype Cost Estimate

	Price	Cost for 2
3’ 3/4” fin tube	$30	$60
6’3/4” copper tubing	$18	$36
Refrigerant	$15	$30
Valve	$10	$20
Supply Total	$73	$146
Labor		$500
Total		$646

The prototype passive system at CCHRC was made of donated and scrap parts, but an estimate of the cost of two passive cooling tubes and their installation is presented in Table 4. Labor costs included a certified refrigeration expert to charge the tube since R-134a is an Environmental Protection Agency regulated refrigerant.

The CCHRC system was custom built on site as a test system, but an alternative method with a more simple installation process could include a portable thermosyphon built out of soft copper and friction fit fins. A portable system could be shipped in a relatively small box with the fins separate from the tubing and the tubing precharged and rolled up. The on-site installation would involve assessing the refrigerator, drilling holes in the refrigerator and the building envelope, inserting the tubes and attaching the fins. The fabrication and installation of the portable system would cost less than the prototype. The estimated prototype material cost is $73, which could go down with more refinement. The labor costs would be much lower on a portable system with the majority of labor for the installation, which could take less than an hour per unit and may not need a refrigeration expert.

This project was a proof of concept for free cooling of refrigerators during the winter. Based on the results, passive refrigeration as a retrofit measure to reduce energy use in a residential setting is feasible. To advance this concept to a commercially available product for Alaskans would require more refinement of the design and a more thorough study of potential applications.

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