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Design and Construction of a Renewable and HVAC Technologies Testbed "Shack"

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Abstract

In 2012 the university received an ASHRAE Senior Project Grant to design and build a testbed structure (i.e. "Shack") for studying topics related to renewable energy and/or HVAC technologies. The shack design was loosely based on typical ice fishing huts. The shack design incorporates a number of interesting technologies. Its structure includes a unique aluminum frame with aerogel insulation. The roof is partially covered with photovoltaic cells and one wall includes a solar thermal air heater. The collector for this was constructed from recycled aluminum cans. Thermocouples placed on and within different surfaces allow data on temperatures and heat transfer rates to be determined. This paper will describe the basic technical details, the design, and construction of the shack. The design and construction of the shack has taken longer than originally intended. Currently a fourth iteration of student researchers is working to complete the shack. The difficulties students encountered will be discussed in relation to their experience and design approach. Student impacts are included to reinforce this discussion.

I. Introduction

In the spirit of the Solar Decathlon (http://www.solardecathlon.gov/) and the "Tiny Home" (http://www.tinyhouseliving.com/) movement, a project was conceived to design and construct a structure of approximately 24 square feet that could be used to demonstrate renewable and HVAC technologies. This "Shack" was to be designed to accommodate a range of technologies for demonstration and testing, such as solar thermal heating, photovoltaic power generation, and high efficiency insulation options. In 2012 an ASHRAE Senior Project Grant was received to complete this design and construction project.

Given that the university is in the heart of ice fishing territory, the shack design was to be loosely based on typical ice fishing huts or shacks. This was for several purposes. First, the inclusion of "ice fishing" creates an immediate engagement for both students and the public. It is hoped that the Shack will generate interest in energy efficient and sustainable design topics. Second, the ice fishing shack style of design implies it is portable and can be moved to different test sites.

While the initial design has been focused on winter use, the portable and adaptable nature of the structure will allow it to be used for summer applications as well. In this form the structure could demonstrate passive cooling technologies and alternative refrigeration/air-conditioning approaches. For example, other projects have explored the use of thermoelectrics for cooling and refrigeration. This could be adapted to offer shack air-conditioning in the future.

The original design was assigned to a team of four mechanical engineering seniors as part of the senior capstone process (i.e. Senior Design I and II). Unfortunately it was not possible for these students to complete construction of the project. Undergraduate and graduate research assistants were then employed during the following year to work part time on the remaining construction issues. There were still remaining operational issues with the photovoltaic system so another undergraduate research assistant was assigned to solve these problems during the following summer. While he was able to identify a solution it remains to be implemented.

Throughout this project there have been many real-world lessons for students and project planning lessons for faculty. Rather than summarize these all in one place they will be referred to in the relevant sections. To identify the pedagogical lessons from construction/design lessons these items will be indented for emphasis.

II. Structural Design

Initially the structure of the Shack was intended to be modular. It was hoped the design could be folded up or have removable walls to allow interchangeable test sections, such as different windows. However, this caused issues with the structural strength and safety during transportation and a static structure was settled on. The Shack was to be comfortable for two people to sit inside. The limiting constraint on the base dimensions ended up being the size of the lab doors where the Shack was to be constructed. The final base was 7' by 4'. Various roof shapes were initially examined but the only one that provided enough space to mount photovoltaic panels on was a slanted roof. Therefore, the height varied from 5' 4.5" to 6' 10" tall.

At the beginning of the project the student team based their designs on typical construction practices. While steel studs were briefly considered the frame for the Shack was initially specified using wood 2x4 studs. However, after consideration the team decided that since the Shack was intended to demonstrate different technologies and construction methods other approaches should be considered. Aluminum tubing (1.5" x 1.5" 11 gauge) was then selected as the framing material. The design drawback to aluminum is its high cost (on average $2 per lineal foot). It does provide benefits in terms of low density (and hence weight), high strength, and its ability to resist corrosion. The tubing was original taken to a lab on campus where it was measured and cut. It was then laid out, checked for dimensioning, and labeled. The parts were aken to a local piping, HVAC, and roofing company which donated the welding time. Once completed the frame weighed 120 lbs with a material cost of $322 (Figure 1).

An additional consideration with the structural design was transportation of the finished Shack. One option considered was to make the base of the Shack a trailer. This option was considered to be overly expensive and involved additional safety design issues regarding highway safety approval. The more traditional method of placing the Shack on skis (or skids) was settled on.

> Monitoring team interaction and communications can be an important aspect of advising a design project. It is important for students to realize that even though they have been placed in charge of one particular portion of the design their decision will affect the others. Therefore, these decisions should be made by the group. This issue arose when one team member decided to build a road capable trailer for the Shack without consulting the remaining team members.

Figure 1: Completed aluminum structural frame for the Shack.

Figure 2: Partially completed Shack showing roof and back wall construction.

A major design criteria for the project was weight. Designed as an ice fishing shack the structure could not be so heavy that it could not be placed on a frozen lake. The students learned that there are two types of ice; snow ice and lake ice. Based on a final weight of approximately 900 lbs a minimum thickness of 8" of lake ice would be needed to support the shack. Due to its lower strength twice as much snow ice would be required. For comparison, the recommended thickness before driving a small car onto a lake is 8"-12".

> Students made two major presentations as part of the original design project. The first was in December and involved a preliminary design proposal with members of the Industrial Advisory Board in the audience. When asked by an industry member about the weight distribution and how that might affect the required ice thickness the students learnt the wisdom of the cardinal rule "Don't give answers for things you do not know."

III. Insulation

Due to the purpose (i.e. energy education) and application environment (i.e. the middle of a frozen lake) the selection of insulation was a critical decision. Renewable materials were considered (such as bubble wrap and newspapers) as well as commercial insulating materials (such as Aerogel, spray foam, polyurethane foam board, and fiberglass). The Aerogel insulation had the best insulation potential with a thermal conductivity (k) of 0.097 Btu/ft °F hr and a thermal resistance (R) value of 10.3. In comparison, polyurethane foam board has an R value of only 5.3 but a much lower cost. Again, the desire to demonstrate energy efficiency outweighed the cost factor for the student team and the Aerogel insulation was selected. Aspen Spaceloft blankets were used in the walls and Thermablok stud protectors were used to prevent thermal bridging. However, due to the high cost the budget did not allow the full 1 ½" wall gap to be filled with Aerogel. Instead a ½" of Aerogel was partnered with 1" of polyurethane foam giving a total R value for the wall of R-9. The students confirmed with the campus Safety Office that similar safety precautions are recommended for Aerogel as for fiberglass. Therefore the students wore gloves and face masks when cutting and installing the Aerogel (Figure 3).

> One aspect that cannot be underemphasized in engineering instruction is the importance of real world safety. The opportunity to work with the campus Safety Office was a valuable experience for these students.

The majority of structural and insulation construction was completed by the original senior design team. Small tasks such as the interior finish, flashing around the air vents, and completion of the door remained (Figure 4). During the following Fall these tasks were handed off to the second teach of student researchers. A lack of quality control was evident in the existing construction. Seam fits showed large gaps and cut insulation that did not fit properly. The use of the aluminum tubes proved a hindrance in correcting these issues. The original team did not have a well thought-out method of connecting pieces to them. The tubes were too thick to easily drill through. This meant that extra blocks had to be attached to the frame to allow connection points for the insulation.

Figure 3: Students working with Aerogel insulation during installation.

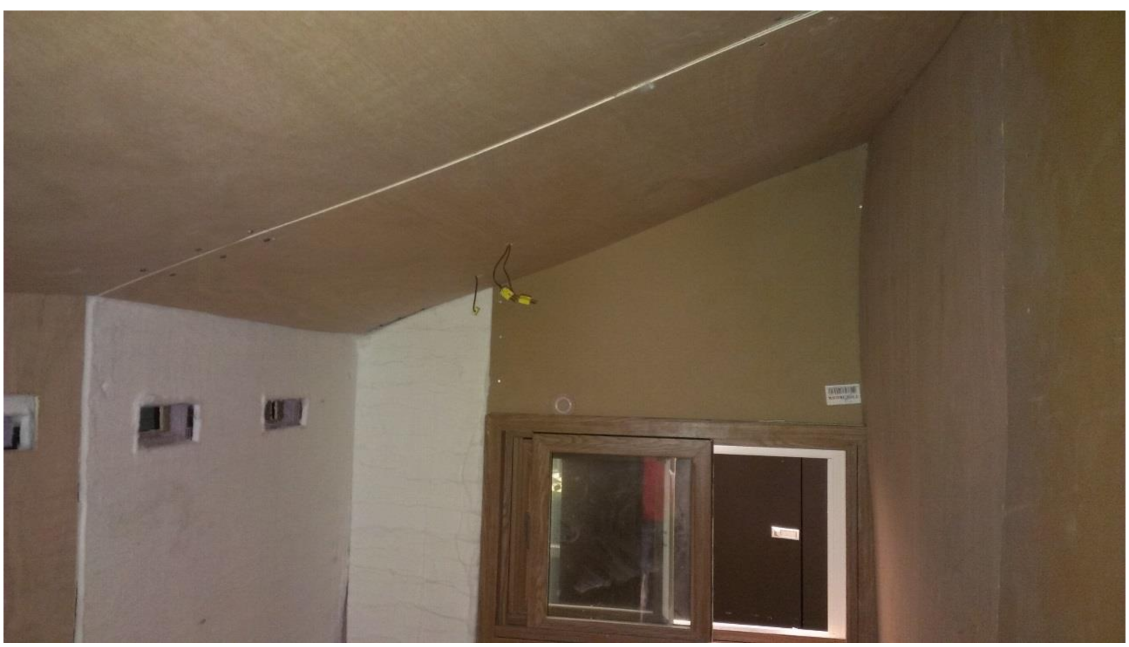

Figure 4: Mostly completed interior. Exposed insulation and air vents can be seen on the left. An installed thermocouple from the roof can be seen at the top.

A recurring theme throughout the project was the difficulty that some students have with actual construction of projects. Having at least one team member or an outside consultant with substantial construction experience is very useful. In the case of this project coordinating the construction tasks was a major undertaking. In retrospect it would have been useful to designate one team member (or recruit an outside member) to serve in the role of Construction Manager.

V. Solar Photovoltaic Collectors

Some form of at least minimal electrical power was needed for the Shack. This would allow interior lighting, space heating, and data acquisition equipment to be powered. While options such as remote or roof mounted wind turbines were considered the final selection was a solar photovoltaic system. The total power required was estimated to be 531W with 128 Ah. Three refurbished solar panels were purchased that were rated at a total output of 540 W.

> Several students from the original design team were able to attend the Winter ASHRAE Conference. During the massive industry Expo they were able to explore numerous products related to their design. It was at the Expo that they made the initial industry contacts for the photovoltaic panels and were exposed to Aerogel insulation.

Battery selection proved more difficult. Besides electrical capacity the project placed constraints on size, weight, price, and performance at low temperatures. Three types of battery were evaluated; a lead acid battery, a lithium ion battery bank, and an absorbed glass matte (AGM) battery. The lithium ion battery performed best with regard to depth of charge and weight; however, the high price of these batteries eliminated them from consideration. While the AGM batteries were more expensive than lead acid they did provide a 75 lb weight savings and were selected.

Researching ASHRAE materials the students determined that the solar panels should face south and be titled at an optimum angle of 15° plus the latitude. For the potential Shack test sites this results in optimum title angles of approximately 60° in winter and 20° in summer. The roof design was then specified to have an angle of 20° with the panels mounted so that they could be tilted up separately during the winter.

There was not sufficient time to complete installation of the photovoltaic collectors during the senior capstone process. This task was handed off to a team of undergraduate and graduate researchers the following Fall. Several roadblocks were then discovered. While the original plan was to mount two of the three collectors on the roof once roof construction was done there was only room for one collector. Also, since the panels were originally designed to be mounted on building roofs in rows there were no manufacturer instructions or mounting brackets for this type of installation. It was decided to add L brackets to the roof that would support the single panel.

The other two panels were relegated to be portable external collectors. Stands were designed to mount each panel on the ground next to the Shack. The stands were designed so that the angle could be adjusted to any value desired. The larger problem this created was developing a suitable system of electrical connections to these panels that were safe, easy to use, and weather proof (Figure 6).

Figure 5: Photovoltaic panel installed on new external stand. The tilt angle can be adjusted.

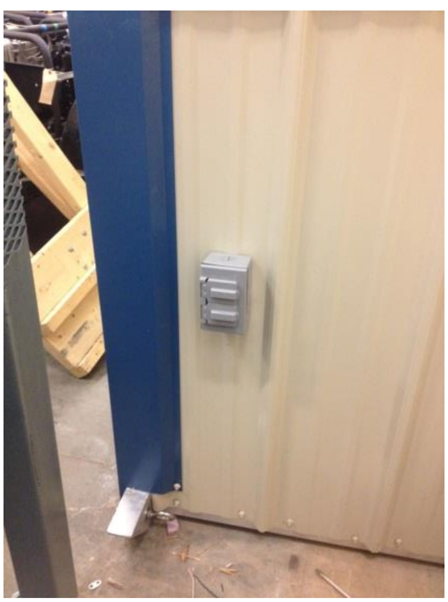

Figure 6: External power connectors added to shack for connection to remotely mounted photovoltaic panels.

The following summer a third rotation began with a new undergraduate researcher assigned to complete the final assembly and electrical hook-ups in the shack. At the time, it appeared that all of the equipment for the system was properly installed with the exception of a few small wiring tasks. Two of the three panels were set outside in a sunny location and were hooked in parallel to a charge controller which was then hooked up to a single 12v battery. According to the research done by the initial student group, the 48v panels would work properly with the charge controller which would down convert the voltage to ~12v in order to charge the battery system. However, it was found during initial testing there was no charging. Indicator lights on the panels as well as the charge controller indicated that the components were working. It was eventually determined that the donated panels were both oversized and too “smart”.

> This proved an important learning experience for the student who took over this part of the project. The student design notebooks from the original group held conflicting or missing information on how the panels should be connected. It was an important lesson is accurately recording design information.

It was determined the panel had embedded smart electronics that controlled current, under and over voltage protection, and when to start and stop current flow. The panels needed to sense a voltage that was within the range of a typical 48v battery bank in order to turn on. Because of both the charge controller and only operating on a 12v system, the panels were not able to operate.

> The students showed great resourcefulness in identifying a donor for the panels. However, the lesson learned was to be wary of gifts. Through no fault of the donor the students did not understand what they were being offered and, while reducing the cost, how this would complicate the overall design. As a consequence the follow-on students gained great experience in working with sales engineers and manufacturer representatives as they tried to solve the problem.

IV. Solar Thermal Collector

It was desired to have some form of supplemental heating to the Shack. While some form of electrical, or perhaps biomass, main heating could be used a solar thermal technology was seen as a good way to reduce the need. ASHRAE standards were first used to determine the 95% winter design temperature as -12°F and estimate the total heat loss from the Shack to be 1741 Btu/h (1434 Btu/h from conduction/convection and 307 Btu/h from infiltration). This value does not include any potential heat gain from occupants.

> Students of the original team were taking the HVAC technical elective course at the same time as this project. The project gave them a real world application for them to apply what they were learning to.

A variety of solar thermal collector designs were evaluated and compared using a design matrix. A forced convection air design that uses recycled aluminum cans as the tubing was selected. 220 12-ounce cans and 20 8.4-ounce cans were collected for the collector. Holes were drilled through the cans and they were sealed together using caulking to make tubes 5’ 4” long. The cans were painted matte black to improve their thermal properties (Figure 7 and 8). Sections of gutter downspout were used to connect these tubes together and serve as air intake and exhaust

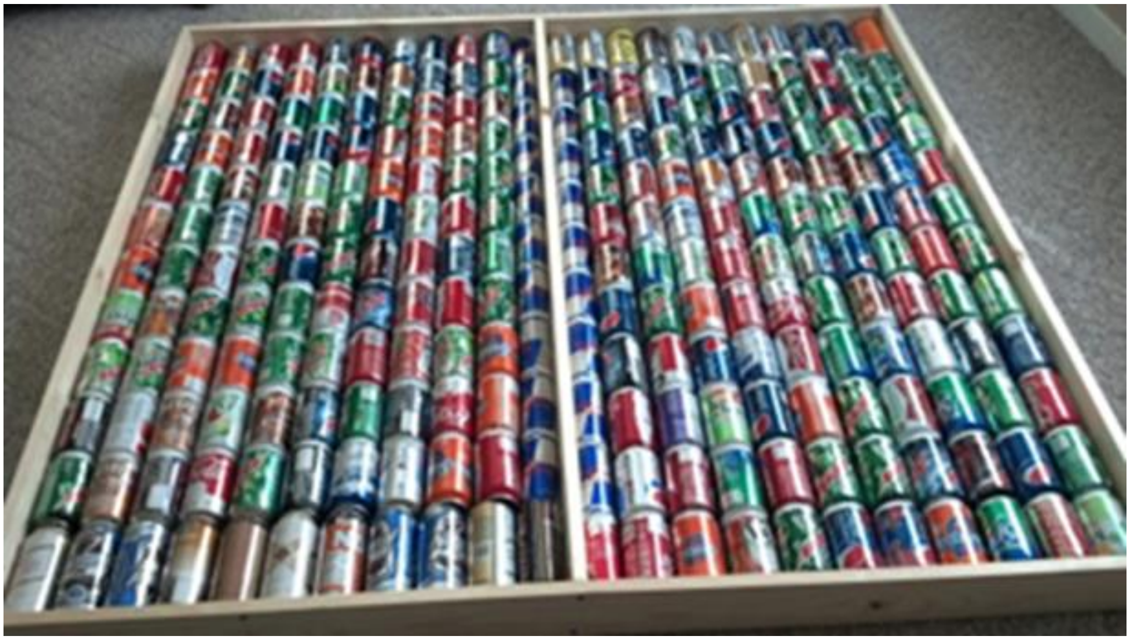

Figure 7: Solar thermal collector constructed from recycled aluminum cans during construction.

Figure 8: Completed solar thermal collector before mounting on the Shack.

points. For the convection source several computer fans were selected. During construction thermocouples were also embedded in the construction to allow performance to be measured.

As mentioned in the previous section, the ideal tilt angle for the solar collector was determined to be 15° plus latitude. However, the tilted roof was already occupied by the photovoltaic panels. However, for the high latitudes of Minnesota it was found from NREL data that a south facing vertical wall receives almost as much solar radiation as one at a tilt. The solar thermal collector was mounted vertically on the 5' high side wall. While this reduced the total area available it allowed both the photovoltaic and thermal solar collectors to be faced South.

The collector was completed and installed during the original team's work. However, the intake and exhaust air vents were not completed on the inside of the Shack. While esthetics were important a larger safety concern was the possibility of pulling Aerogel fibers into the air. A method to cover and seal the edges was developed by a new student researcher. While the material costs for this were low the technical challenge was amplified by the fact the original holes (which were already cut) did not match any standard duct size.

> The primary issue with the original group was a lack of construction experience and recognizing there is a difference between making something and making it well. The main lesson for the follow-on students was that quality matters and takes time.

VII. Conclusions and On-going Work

This project has been a frustrating but worthwhile learning experience. While the original design did not meet all expectations and was not completed it has provided valuable experience for teams of students who have followed. The lessons they have learned by taking over the project cannot be taught in the classroom but must be experienced.

Final construction of the Shack continues. The one large remaining issue is the photovoltaic panels. The current options are to either convert the system to a 12v system or entirely to a 48v system. Because the system was initially intended to be a 12v system, most of the existing electronics are set up for that. This includes the charge controller, battery bank, fans for solar wall, and inverter for powering larger electronics. To finish setting up this system to run as a 12v system would only require new photovoltaic panel to be purchased that are rated to supply 12v. The conversion to 48v would require additional batteries to create a 48v battery bank, removal of the charge controller, an inverter to go from 48v to 120v, and a power supply to power the fans for the solar wall. Since the majority of the original design funds have been spent this decision will likely come down to cost and potential donations.

When the Shack is finally complete students from multiple courses will be able to use it. Students will be able to take data concerning heat transfer, solar thermal collectors, and photovoltaic power. There is also the option for future redesigns based on collected data and new student projects.

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