MEMORANDUM

TO: Dr. Michael Shafer (Project Client)
FROM: Team 06: Mohammed Alkhaldi, Coy Cody, Donovan Hard, Marissa Munson, and Krysten Whearley
SUBJECT: Final Report for Active Roof System Senior Capstone Design
DATE: April 18, 2014

The purpose of this memo is to inform you, Dr. Michael Shafer, of the completion the Active Roof System senior capstone.

Our final designs for the control and passive roof systems have not changed since our final proposal; however, the active roof system has changed significantly. The final design for the active system consisted of the reflective panels being rotated not by a motor but instead by a lever arm system. This lever arm system consisted of aluminum rods connecting all of the panels together then the lever arm as placed into different positions using a peg-board made of an aluminum sheet. A picture of the construction of this final design as well as the final design for the control and passive roof systems can be seen in the following pages of the final project report attached.

The attached final project report includes a complete summary of all of the main concepts, designs and prototype construction which lead up to testing the three different roof systems.

Testing of these three roof prototypes occurred in a controlled environment and the main variable which was being measured was how long the A/C system for the scale model building was on during each test to keep the interior of the building at 70°F. Each of the three prototype roofs were tested twice and the average of the passive and active roof system was then compared to the control roof.

The testing results showed that the active roof system used 72% less power running the A/C system than the control roof, and the passive roof system used 43% less power running the A/C system than the control roof.

If you have any questions, please feel free to contact us.

Thank you for your time, guidance and support throughout the semester!

Active Roof System

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Final Report
Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design II – Fall 2014

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Abstract

Power consumption is a concern for many businesses who invest a large amount of finances into controlling the temperature of their buildings, and for large warehouse like buildings, this task can be very costly. This project investigated two different types of roof designs that reduced this power usage by reflecting away the sun's radiation. One of the roof systems has stationary reflective panels that are set at the optimum, reflection angle, and the other has reflective panels that rotate throughout the day. The efficiency of these two roof designs will be tested using a controlled environment and scaled prototypes. Then, these test results were then compared to a control. The control is a prototype with a plain white roof, which resembles the average roof style of a large warehouse building. The results of this project determined that the active roof system uses up to 72% less power on A/C than the control roof, and the passive roof used 43% less power.

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Nomenclature

Symbol	Variable Name
^oF	Degrees Fahrenheit - Temperature
in	Inches - Measurement of Length
ft	Feet - Measurement of Length
ft^2	Feet - Measurement of Area
$\#^o$	Degrees - Latitude or Angle

Chapter 1. Project Introduction

1.1 Project Introduction

Large warehouse buildings use a significant amount of power to keep the interior cool during the summer. This high power usage is caused by heat being transferred into the interior of the building through the roof, and since warehouse buildings usually have large surface area, that is a large amount of surface area in which the sun's radiation can hit. So if the amount of sun radiation hitting these warehouse's roofs could be reduced, then the amount of power used on air conditioning (A/C) could be reduced as well.

1.2 Client

The client for this project is Dr. Michael Shafer, who is a professor here at Northern Arizona University.

Chapter 2. Problem Formulation

2.1 Project Need and Goal

The very project has a basic need statement that can be used to guide the possible solutions to the problem at hand. For this project, the needs statement is as follows:

The amount of power used to keep the interior of large buildings at a comfortable, cool temperature is too high.

The goal of this project is to design and build roof system prototypes that can maintain the interior at constant temperature of a building model while using minimal power.

2.2 Constraints and Objectives

The two constraints on this project are that a scale model building of a large warehouse building must be built and the interior of that building must be maintained at 70°F (average room temperature).

The measurable objectives and how they will be measured for each prototype are shown in the Table 2.1 below:

Table 2.1: Project Objectives

Objective	Measurement Basis	Units
Maintain Internal Temperature of 70°F	Interior Temperature of Scale Model	°F
Low Power Usage	Amount of Time A/C System is Used Throughout the Day	Seconds

2.3 Operating Environments

The prototypes that were built were tested indoors in a control environment. Also, measurements were periodically recorded throughout the test trials, so that our team could analyze how effective each prototype was at maintaining the required internal temperature of 70^{o}F.

2.4 Quality Function Deployment

Achieving client needs is necessary for the design phase of any product. The following are of the needs expressed by our client:

1. *Seasonal* - Customers need to have an active roof system that work in all seasons. The apparatus need to withstand at a high temperature and at a freezing temperature.
2. *Weight* - The light weight is essential for the apparatus so that it can be maintained easily. The lowest weight it could be, the lowest cost it would be.
3. *Cost* - The cost of the apparatus is important. The cost need to be as low as it could be so it will be affordable for most customers.
4. *Power Input* - The power input to rotate panels need to be low. The purpose of this design is to reduce energy usage.
5. *Stiff* - The apparatus need to be able to withstand harsh climate. The stiffest it could be, the more durable and life it will have and that what most customers are looking for.

Some of the engineering properties/requirements that will be needed for the design of the prototypes are listed below:

- Material Strength
- Manufacturability
- Functional
- Efficiency
- Durability
- Accuracy
- Weight

These client needs listed were then analyzed for which of engineering requirements they correlate to in the Quality Function Deployment (QFD) shown in Figure 2.1 on the following page:

		Engineering Requirements							Benchmarks	
Client Needs	Client Weights	Material Strength (YS)	Efficiency	Weight	Manufacturability	Durable	Functional	Accuracy	Active Design	Passive design
1. Seasonal	9	8	9			9	8	9	X	X
2. Light Weight	4	2		10		7	5			X
3. Low Cost	10	4	6	9	8	5	9	7		X
4. Minimum Power input	10		9					6		X
5. Stiff	6	10		8		6	6		X	X
6. Efficiency	8		10			4	9	8	X	
	Unit of Measure	psi	KWH	lb	Unitless	Unitless	Unitless	θ		
		Technical Target								

Figure 2.1: QFD Table for Project

The yellow columns in the QFD above show how much each engineering requirement correlates to each of the client needs on a scale of 1 to 10. If there is no value represented, then that means that there is no correlation between that particular engineering requirement and client need. The gray columns show which of the client needs are expected to be fully fulfilled by each type of roof system.

It can be seen from this table that the customer needs which are of top priority are to produce low cost of construction prototypes' that use a minimal amount of power to operate. The fact that these two needs hold the most importance to the client makes sense because if the prototype is inexpensive to construct then that will correlate to the full scale models also being relatively inexpensive to manufacture, and of course the prototype has to use a minimal amount of power because the point of these roof systems is to reduce the amount of power used to cool/heat the interior of buildings, so it would be pointless if the roof systems used the same amount of power as the building would normally without it.

Chapter 3. Proposed Design

3.1 Scaled Model Building

The scaled model building will be a representation of a 30,00ft^2 warehouse building with 25ft ceilings. The scale value for this model is $^1/_{40}$, so if the warehouse building was assumed to have interior dimensions of 173.2ft by 173.2ft, then the scale model building would have an interior dimensions of 4.5ft by 4.5ft and 0.65ft tall.

This scaling factor was calculated based on the one component of the scale model building which would be the limiting factor: the thickness of the insulation.

The design for the scaled model building starts with a basic wooden frame constructed of $1in^2$ square dowels with interior space between the constructed walls to be the required 4.5ft x 4.5ft x 0.65ft (see Figure 3.1 below). These dimensions along with the amount of insulation on the prototypes all were base off the thermal conductivity of the possible insulation materials and thickness of those materials. In the end, the chosen insulation for the prototype was $^{3}/_{32}$in thick cork, and since the normal thickness of the insulation used in warehouse buildings is about 3.5in thick, then comparing these two thickness values resulted in the scaling factor of $^{1}/_{40}$. When the thermal resistance values of the cork and real warehouse insulation was compared, the resulting resistance scaling factor was also $^{1}/_{40}$. Therefore, selecting the $^{3}/_{32}$in thick cork for the scale model building insulation is justified because both the thickness and thermal conductivity is scaled the same amount.

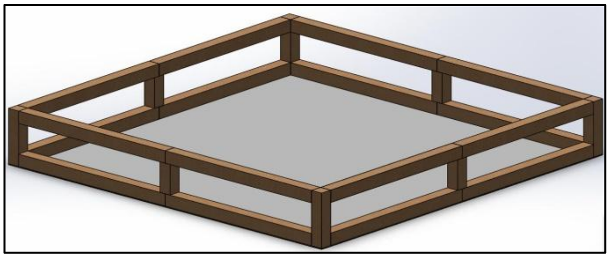

Figure 3.1: Wooden, Interior Frame for All Prototypes

The interior view of the scaled model building can be seen in Figure 3.2 below:

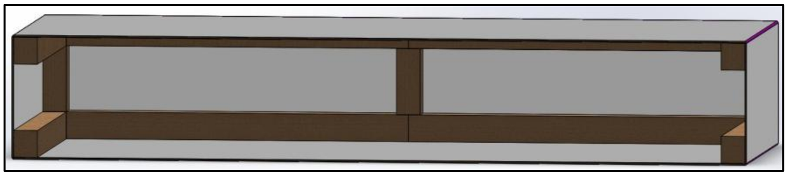

Figure 3.2: View of the Interior of Each Prototype

The walls attached to the outside of the wooden frame consisted of three main components: a poster board layer, the cork insulation layer(s), and then another poster board layer (see Figure 3.3). In order to accurately represent the insulation of the warehouse building, the scale model building has three layers of cork insulation on the roof, two layers on the floor and one layer for the walls.

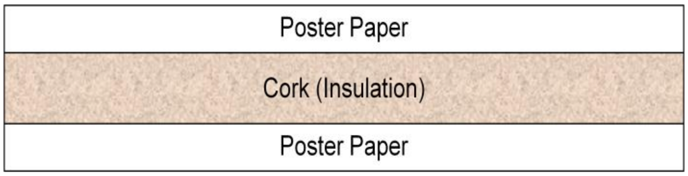

Figure 3.3: The Layers Making Up Each Wall

Where these three layers of each wall meet, a sealant of hot glue was used to connect all the walls together and reduce the amount of heat transferred through these intersections.

3.2 Roof Prototypes

The control roof prototype was designed to match the most common design used in warehouse roofs; it was designed as a plain white roof that would reflect away a fraction of radiation sun with no other aid. The initial design can be seen in Figure 3.4 on the below:

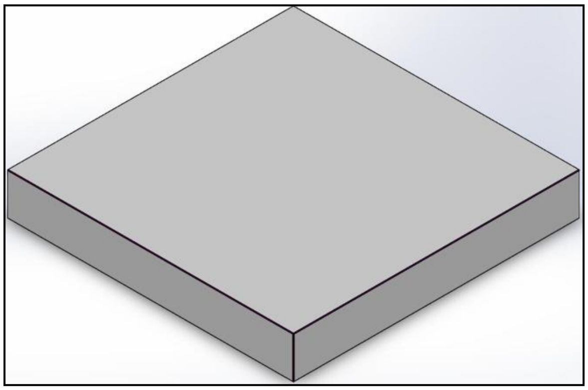

Figure 3.4: Control Roof Design

The passive roof was designed to have stationary, reflective panels set at an optimal angle to block sunlight. The reflective panels for the passive roof were designed to be oriented at a 43° angle. This angle was determined based on the latitude of Flagstaff, which is 35.1992°N. The summer and winter equinox sunlight angles were based on complementary angles. Starting with 90°, the solar angle was found by subtracting the latitude of the city and then adding or subtracting the tilt of the earth, 23.5°, to find the summer and winter equinox angles, respectively. The summer and winter solstice angles were found to be 78.3° and 31.3° respectively. The same equation was used to determine the spring and fall equinoxes, except without using the tilt of the earth. Both equinox angles came out to be 54.8°. The chosen 43° angle was between the lowest winter angle and the spring equinox angle. The passive roof design can be seen in Figure 3.5 below:

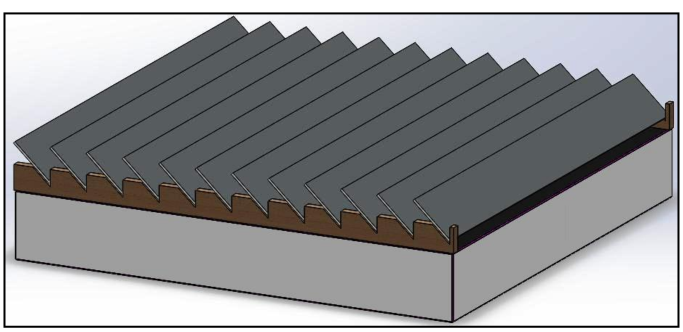

Figure 3.5: Passive Roof Design

The proposed active roof prototype was designed to have rotating panels by using a gear and chain system attached to a motor. The panels reached all the way across the prototype to optimize the amount of sunlight that was blocked. Each panel was reflective on both sides in order to reflect the rising and setting sun. The motor would then rotate the panels continuously as the sun moved across the sky. The panels initially started at a high angle facing the sunrise. At the twelve noon setting, the panels automatically flipped to be completely horizontal. They then rotated to follow the sun throughout the remainder of the day. The active roof design can be seen in Figure 3.6 below:

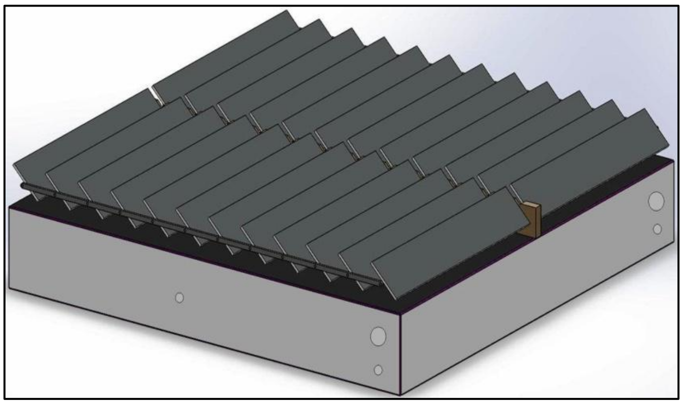

Figure 3.6: Active Roof Design

3.3 Internal Systems

The original design for the A/C system which would be used to cool the interior of the scale model building consisted of mini A/C systems with fans which would be stationed at two of the corners of the building. However, when it came time to buy a system with the specifications needed, it turned out that such a system did not exist. There were no portable A/C systems which could meet the requirements of the temperature of air blown and the size, so the A/C system had to be completely redesigned. This new design is discussed in section 4.4.

The original plan of the temperature system was a fully automatic temperature logger that was available in the market. The device was supposed to measure and record the internal temperature over a period of time, and then the current temperature would have been displayed on LCD screen on the device. The device itself was able to digitally store and send the temperature data to a laptop to be viewed. To access the data, a USB cable would have been needed to connect the device to the laptop. In order for the A/C system to run, the temperature logger device was going to be wired to an Arduino board. The Arduino could have been programmed to read the temperatures and if the temperature reached 75°F, the Arduino would have sent signals to the A/C system to turn on and off when the temperature reaches 70°F. However, due to the high cost of this temperature logger system, the temperature monitoring system design had to be altered. The final design of the temperature monitoring device is discussed in section 4.5.

Chapter 4. Prototype Fabrication

4.1 Scale Model Building

The first step in constructing the scale model building was to build an internal wooden frame, and then the walls and floors were added. The completion of these two steps in the construction process is shown in Figures 4.1 and 4.2 below:

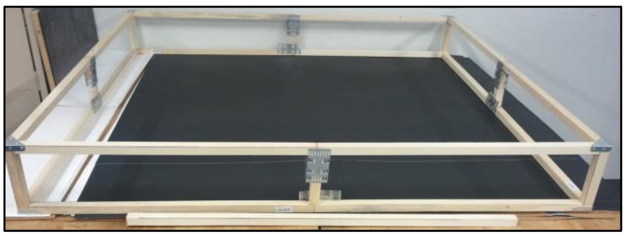

Figure 4.1: Internal Frame of Scale Model Building

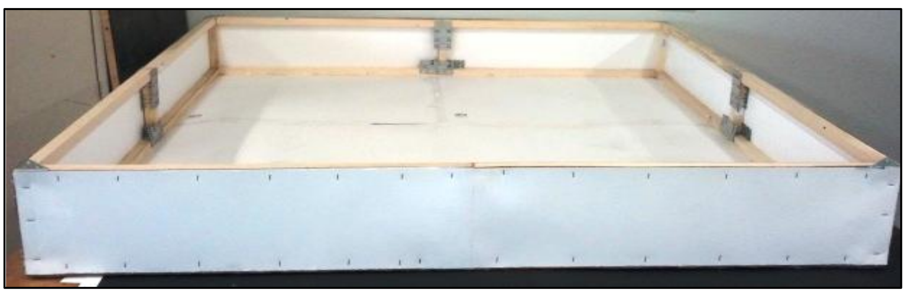

Figure 4.2: Walls Added to the Scale Model Building

However, when the roof was laid on top of this frame it concaved in and the entire frame itself was unstable, so four extra support beams were added to the inside (see Figure 4.3 below).

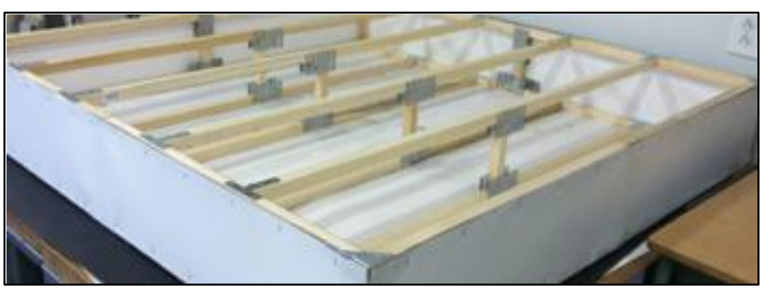

Figure 4.3: Support Beams Added to the Frame of the Scale Model Building

4.2 Roof Prototypes

The first and most basic of the roof prototypes was the control roof. It was made of four white poster boards, two of which were cut down to size. All four pieces were attached together using clear packing tape so as not to cause any color changes on the roof. The glossy side of the poster paper was then laid face up to help reflect away as much light as possible. The control roof had no frame as it was laid directly on top of the building prototype, above the cork insulation. The completed control roof can be seen in Figure 4.4.

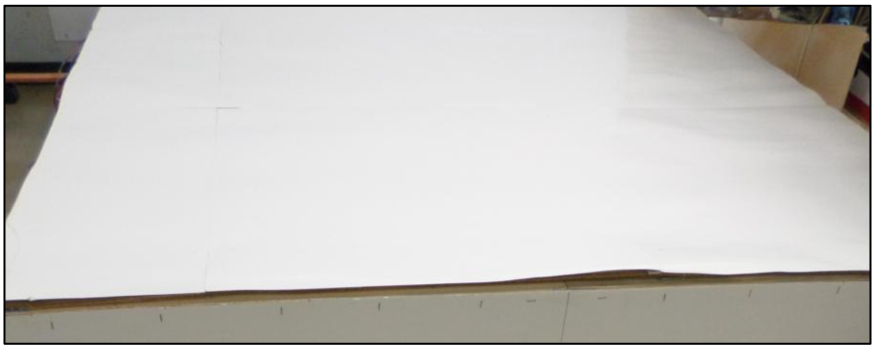

Figure 4.4: Completed Control Roof Prototype

The passive roof prototype was built on a square wooden frame. Wood blocks with 43° angle cuts were then attached to the frame. The reflective panels were made of foam board with Mylar adhered to only one side of the panel. The panels were then set into each cut slot and permanently attached to the frame. The passive roof panels were designed to always remain at the same angle and in the same position. The completed passive roof can be seen in Figure 4.5 below.

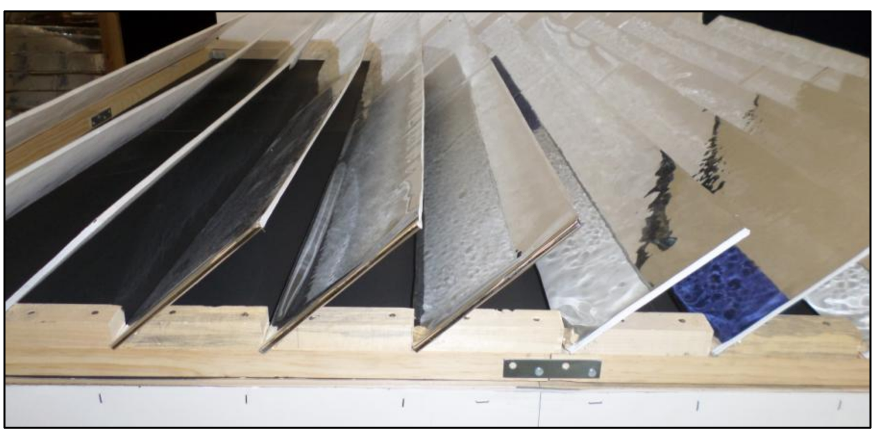

Figure 4.5: Completed Passive Roof Prototype

The original design for the active roof prototype was to use a gear and chain system to rotate the panels; however, due to some complications this design it was altered into a simpler design. These complications include problems resulting from being unable to size a motor with the correct torque required to rotate all the panels and the high cost of purchasing a small gear or sprocket for each of the panels.

The altered active roof design consisted of 14 reflective panels which pivoted on one of their long sides and connected together with metal links. The dimensions for each panel were 4in by 4.5ft and made of foam board with Mylar glued to both sides of the panel. This altered design is shown in Figures 4.6 and 4.7.

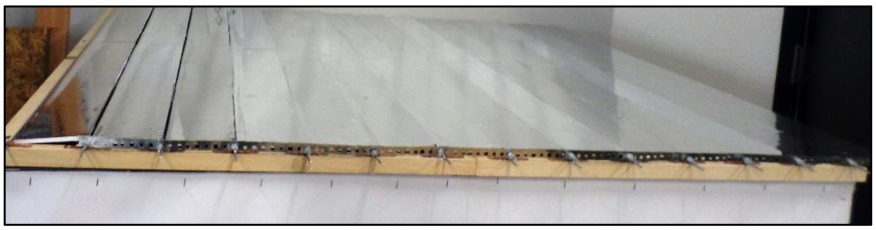

Figure 4.6: Altered Design for the Active Roof Prototype with Panels Laying Flat

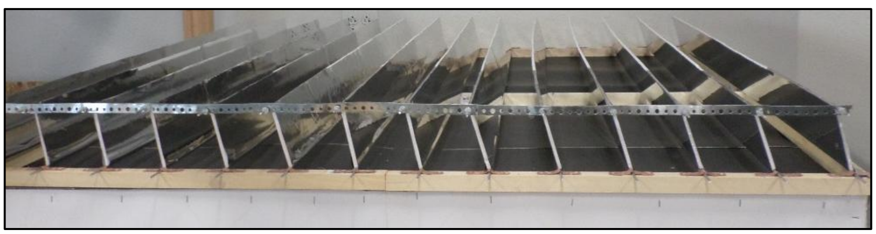

Figure 4.7: Altered Design for the Active Roof Prototype with Panels at an Angle

The flaw with this altered design was that the links used to connect the panels together were not strong enough to hold up the weight of all the panels and the links towards the unsupported end started buckling.

To solve this problem a new linkage system was created which used thin strips of a 1/16 thick plate of aluminum (see Figure 4.8).

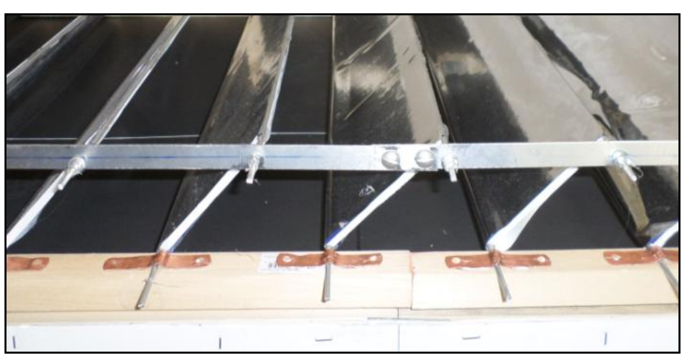

Figure 4.8: Final Design for the Active Roof Prototype with Panels at an Angle

This final design of the active roof system was strong enough to hold up the weight of the panels without buckling and could successfully change the angle of the panels by use of a peg-board rather than a motor. This peg board was made of an aluminum sheet and had holes drilled into it following a circular pattern (see Figure 4.9).

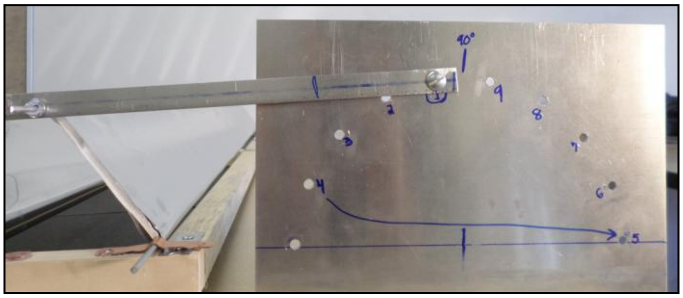

Figure 4.9: Peg-Board used to Control the Final Design for the Active Roof System Prototype

In Figure 4.9, the panels are shown at position 1, which represents the morning where the sun is just starting to rise. As the day (test) continues the panels were rotated to a new angular position by moving the rod connecting all the panels together to a new hole. A hole was drilled every 20° on a semi-circle, and the angular positions were as followings:

- Position 1: 100°
- Position 2: 120°
- Position 3: 140°
- Position 4: 160°
- Position 5: 0°
- Position 6: 20°
- Position 7: 40°
- Position 8: 60°
- Position 9: 80°

As for why there were only 9 different angular positions had to do with the movement of our simulated sun which is explained in the Section 5.2 (Testing Procedure).

However, it should be noted that at position 5 the panels are completely flat against the roof as to reflect way close to all the radiation, and this position represents the position of the panels during 12pm to 2pm when the sun is directly overhead.

4.3 Simulated Sun

Based on the desire for have controlled testing environment in order to neglect environmental conditions such as wind, temperature, and radiation variance, our team decided to design a simulated sun which would provides constant radiation to the prototype building. The basic idea of this simulated sun is that a large panel of lights would move over the prototype roof imitating the varying radiation levels as the sun moves throughout the day (see Figure 4.10).

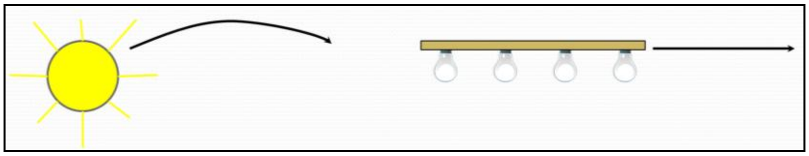

Figure 4.10: Movement of Sun and Lighting System of Simulated Sun

A wooden stand was constructed to hold this lighting system representing the simulated sun so that there would be a constant distance between the light bulbs and the roof of the building model during all testing. The dimensions for the wooden light stand are 12ft long, 6ft high and 4 ft wide. The light stand was also constructed to have slots for the lights to slide on the top of the stand.

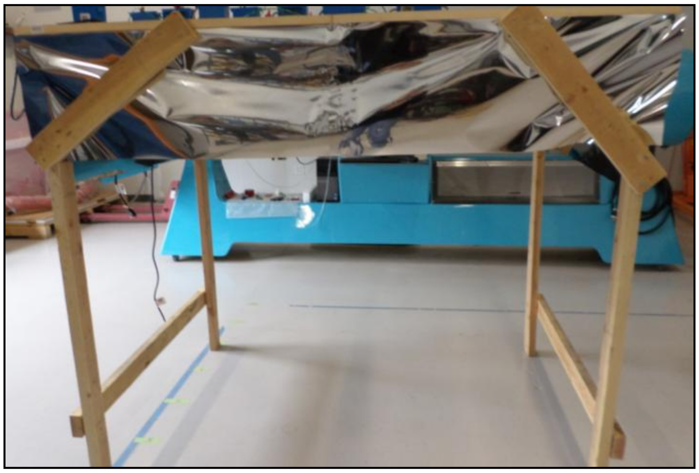

Figure 4.11: Wooden Frame of the Simulated Sun

A light ceiling that slides on top of the stand in the designated slots was constructed out of plywood at 4ft long and 4ft wide. Sixteen $1^{3}/_{8}$in diameter holes were drilled into the plywood for the weatherproof light sockets installation (see Figure 4.12). The plan was to position each light equally spaced from each other in a 4 by 4 grid. The original idea was provide even distribution of radiation and heat to the prototype by the lights. Therefore, our team installed 200Watt incandescent clear lights bulbs to each of the 16 sockets that were previously installed.

Figure 4.12: Original Light Bulb Layout for the Lighting System

The wire connections between each light sockets was connected in parallel series circuit. The wire material was a regular indoor extension cord connected with electrical tape at each connection. This configuration of the wiring for the lighting system can be seen in Figure 4.13.

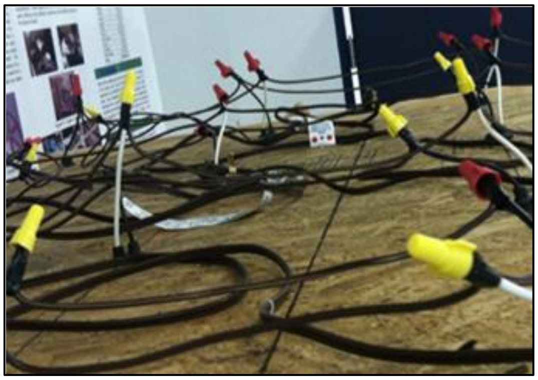

Figure 4.13: First Generation of Wiring for the Lighting System

The next change made to the lighting system of the simulated sun was to add electrical boxes to enclose the wiring connections of each light socket, and this change was made for safety purposes so that it would reduce the possibility of electrocution. The top of the lighting system with the electrical boxes added can be seen in Figure 4.14 below:

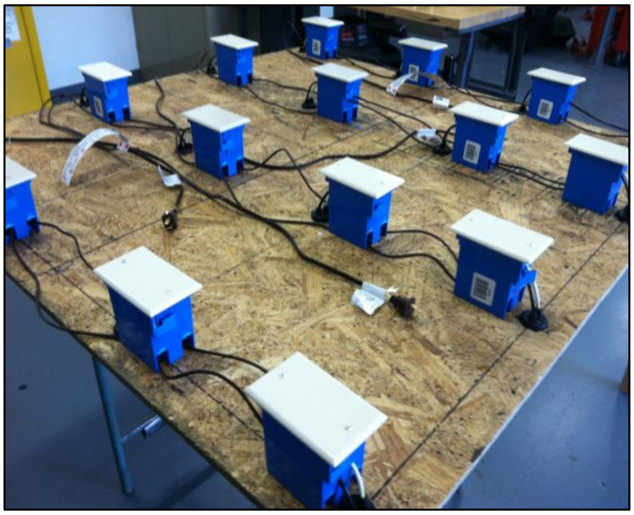

Figure 4.14: First Generation of Wiring with Added Electrical Boxes

Over the course of time of the constructing the lighting system (simulated sun), this section proved to be the most time consuming of any component during the construction phase. The sockets that were used to hold the light bulbs were all-weather sockets in the original design were each rated for 660W which was substantially lower than the necessary wattage. So upon numerous discussions with faculty about the safety of the simulated sun, the lead electrician for Northern Arizona

University was brought in to verify that the simulated sun was wired properly and that the correct components were used. It was after the meeting with the electrician that the majority of changes to the simulated sun occurred. One of these changes was that the overall wattage of the simulated sun was reduced from 3200W to 2500W, and this reduction was done by the addition of nine additional lights but each light was reduced from 200W to 100W (see Figure 4.15 below).

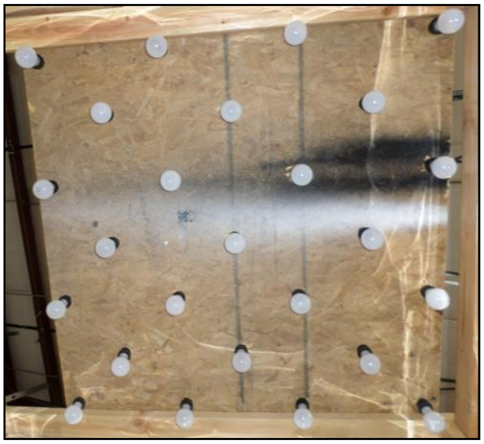

Figure 4.15: Second Generation of Light Bulbs for the Lighting System

The wiring between light bulbs was also changed upon advisement from the electrician, from 16 gauge wire to 12 gauge wire, this insured that the wiring was not being overloaded and causing the failures that were experienced during the trial tests (Figure 4.16 below).

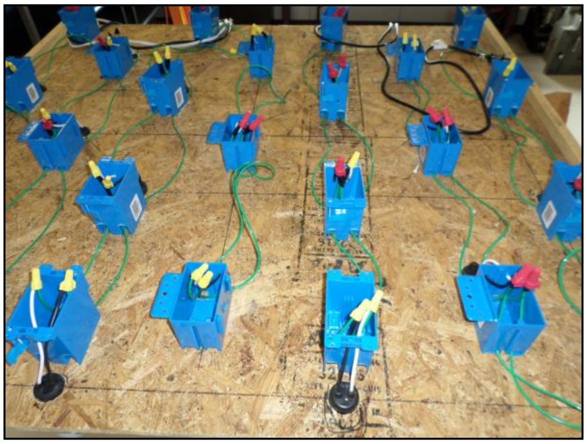

Figure 4.16: Second Generation of Wiring for the Lighting System Boxes

However, even with this addition of nine new light bulbs, all these lights still were wired in which a way that there were only four plugs needed to provide power to the entire system.

The simulated sun was a sensitive piece in the project, due to the constant movement that the simulated sun experienced the wires were beginning to become weak and causing shortages in the sockets themselves, this caused many failures and many flipped breakers. After meetings with the electrician and faculty regarding the unreliability of the simulated sun it was determined that it was necessary to measure the resistance across the individual sockets, it was at this time that the addition of power boxes between the power supply and light strands were determined necessary.

The power boxes added a safety component; they provided an On/Off switch instead of plugging the lights directly into the power supply (see Figure 4.17). After two power boxes were added (two strands for each box) and the resistance was measured prior to each test the light strands proved to be much more reliable. Due to the necessary power being greater than the testing facilities could provide, the NAU SAE Baja team donated a generator to the team to provide sufficient power to the simulated sun (see Figure 4.18).

Figure 4.17: Generator Used to Power Simulated Sun

Figure 4.18: The Power Boxes Used

4.4 A/C System

The final design of the A/C system consisted of water at about 32°F pumped through a serpentine layout of ½ inch type M copper piping, type M was chosen due to the thin wall which would allow for the most radiant cooling. The serpentine layout was chosen because it allowed the group the most area that would be affected by the radiant cooling. The joints that were used to construct the serpentine layout were also a copper piping and were soldered to the straight pipe using a plumbing solder. Two fans were added to this system and were placed in opposite corners of the interior of the model building to help circulate the cold air radiating from the pipes when the ice-cold water was being pumped through. Figure 4.19 shows the serpentine layout and the placement of the fans inside the model building.

Figure 4.19: The Inside Components of the A/C System

The individual components of the A/C system were simple: a reservoir to contain the cold water, a pump to pump the water through the copper piping, hoses for the pumps intake and output as well as the copper piping output for recycling of the cold water, and the copper piping itself. The hoses were used to connect the water pump to the copper piping for pumping, the output of the copper piping also had a hose connection, and this was to recycle the water which allowed the group to recycle the cold water (see Figure 4.20 below).

Figure 4.20: The Outside Components of the A/C System

The A/C system was activated when the temperature monitoring system would register an internal temperature of 75°F, the A/C system would continue to pump cold water until the temperature monitoring system would register a temperature of 70°F and would turn off. This process would be repeated throughout the testing of each roof and then the time the A/C was turned on would be measured. The details of the temperature monitoring system will be discussed in the following section.

4.5 Temperature Monitoring

The original plan for the temperature monitoring was changed due to the high cost of the temperature logger devices. Since both designs used an Arduino, it was less expensive to add thermistors to the Arduino instead of buying a temperature logger device.

The final design uses a TMP36 thermistor and an Arduino board. These two components are the main components of this system. The TMP36 thermistor was chosen because it is accurate, sensitive, and has a high temperature range. It is capable of reading temperature between −40°C to +125°C. The thermistor has three wires as shown in Figure 4.21. The left wire is for the power supply.

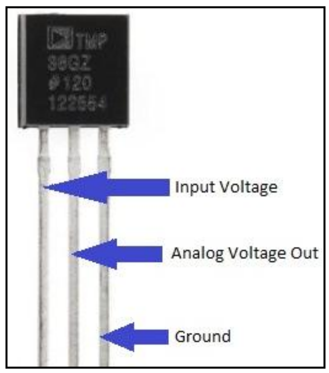

Figure 4.21: TMP36 Thermistor

The required power for this thermistor is between 2.7-5.5Volts (V). Since the Arduino being used can only supply 3.3V or 5V, the thermistor was connected to a power supply with 5V output. The middle wire is for the analog reading. It was connected to the analog pin in the Arduino to read the current temperature. The wire on the right is the ground wire.

Four thermistors are used to monitor the internal temperature of the prototype building, and they were placed in different locations within the prototype. The first thermistor was placed at one of the corners of the prototype. Another was placed at the center of the prototype attached to the roof, and the third thermistor was placed at the center of the prototype at mid height. The last thermistor was placed at the center of the prototype attached to the ground. The locations of the thermistors at the center of the prototype are shown in Figure 4.22 on the following page.

Figure 4.22: Internal Placement of Thermistors Inside the Modeling Building

The type of the Arduino board used is UNO R2. The power supply wire of the thermistor was connected to the 5V pin in the Arduino. The ground wire was connected to the ground pin in the Arduino. Each analog wire of the four thermistors was connected to a different analog pin in the Arduino. The way in which the thermistors were connected to the Arduino board is shown in Figure 4.23 below.

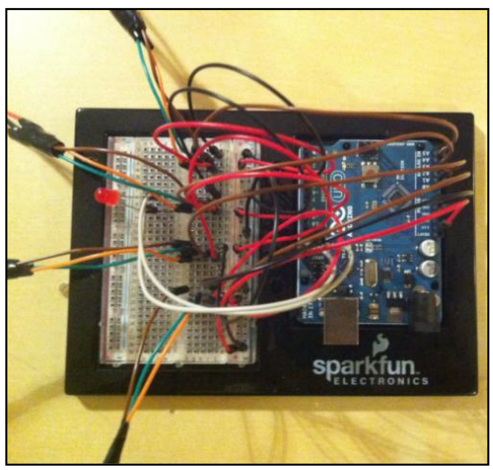

Figure 4.23: Arduino Connection to a Thermistor

The Arduino was programmed to read temperature of the prototype. If the temperature at center of the prototype at mid high was equal or above 75°F, the Arduino sent signal to the cooling system to turn on and turn off when the temperature is less or equal 70°F. The Arduino was also programmed to calculate the total time which A/C system is running during each one hour test, and then this time measurement will be used to calculate the amount of power used by the A/C system.

In order to record data from the Arduino, the Parallax Data Acquisition tool (PLX-DAQ) software was used. The software was able to retrieve the data from the Arduino and save them in an

Excel file. The data from each thermistor were written in a separate column in the Excel file. This provided an easy way to read spreadsheet which can be used for any necessary analysis after testing.

Chapter 5. Testing and Results

5.1 Testing Apparatus

The testing apparatus for the three prototype roofs includes the 3 different systems previously described: the simulated sun, temperature monitoring and A/C system. How all of these systems fit together is shown in Figure 5.1 below:

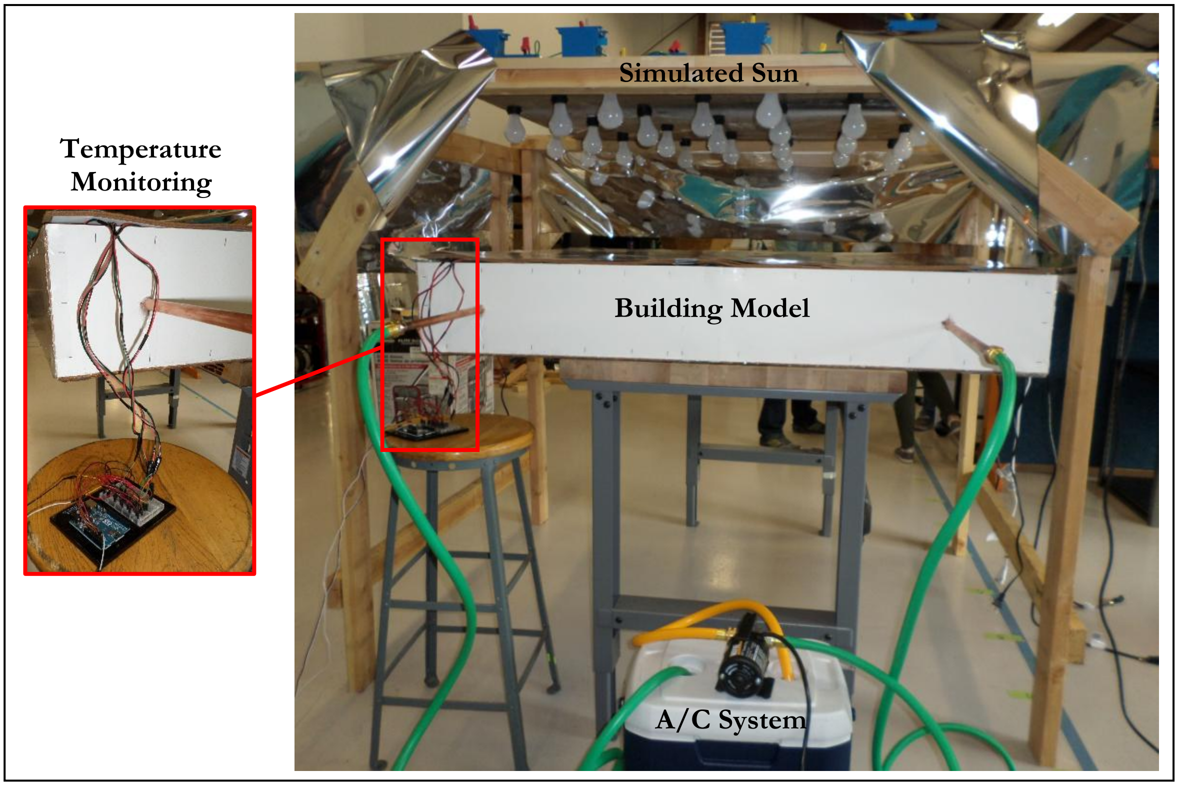

Figure 5.1: Testing Apparatus

The following is a brief summary of how all the systems shown in Figure 5.1 interact with one another during testing:

The scale model building was placed on a table so that the sides and bottom were exposed to the same temperature, and this caused a need to build the large, table-like frame for the simulated sun. The frame for the simulated sun allows for it to emit a constant amount of radiation and heat towards the roof prototypes during all testing. Also, the cords that can be seen hanging down from the right side of the roof of the simulated sun were the four plugs which were plugged into the two breaker boxes, and then extension cords plug those two breaker boxes into the generator which was places outside.

As the heat was transferred through the roof of the building model, the interior temperature steadily increased, and this change of temperature was recorded every ten seconds by the temperature monitoring system. This system consisted of four thermistors connected to an Arduino board and the Arduino board was then connected to a laptop. The Arduino board was placed on a stool next to the model building because the thermistors were only five or seven feet long and the system is delicate so placing it on the ground would be irresponsible.

Once the internal temperature reached 75°F, the temperature monitoring system would send a signal to a toggle switch to turn on the power to the A/C system. The internal portion of the A/C system consisted of copper pipes and two small fans for circulation, and the external portion consisted of two hoses, a small aquarium pump, and a cooler. When the A/C system was activated the ice water from the cooler was pumped into the copper piping on the right, through the serpentine piping inside the building model, and then it exits out the piping on the left to return to the cooler.

Then, once the temperature monitoring read a temperature of 70°F, the power to the A/C system was shut off and the internal temperature of the model building was allowed to increase again.

5.2 Testing Procedure

All testing for each prototype roof was done in a controlled environment. Each test was performed indoors to reduce variable factors such as wind, rain or other weather events that would affect temperature readings. Each prototype roof was tested a total of two times using hour long testing sessions. This came out to be around six hours of testing as well as an extra two hours for refueling the generator and allowing the heat inside the prototype to be let out.

During testing, the simulated sun was moved every six minutes and forty seconds to a new position just over ten inches away. There was a total of nine moves to simulate an expedited day. The reason for an odd amount of moves is due to the center move, which is move five, representing 12pm to 2pm. This is generally the hottest part of the day and therefore it needed to be represented by the simulated sun being directly over the prototypes. The active roof panels were rotated at the same rate as the simulated sun movement. At move five, the panels were completely horizontal to shield the roof from the sunlight.

During testing, as the simulated sun was moved from its starting position to the position representing 12pm to 2pm, the Mylar on the right side was removed so that the radiation could come in at an angle resembling the sun rising. Then, once the simulated sun was directly over the model building at position 5 (12pm to 2pm), the Mylar was added by to the right side so that the entire lighting system was enclosed. This caused a greater amount of radiation to hit the roof of the model building, and that is to simulated 12pm to 2pm which is generally the hottest time of the day. Finally, as the simulated sun is moved to its final position (9) the Mylar is removed from the left side so that the radiation levels could resemble the sun setting.

This movement of the simulated sun during each test is illustrated in Figure 5.2 below:

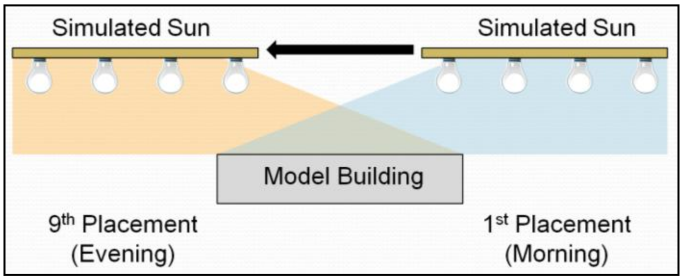

Figure 5.2: Simulated Sun Movement During Testing

5.3 Testing Results

During each test, the temperature monitoring system recorded the internal temperature of the model building every 10 seconds. As a reference, Figures 5.3 and 5.4 below show these temperature readings for trial two for each of the three prototypes.

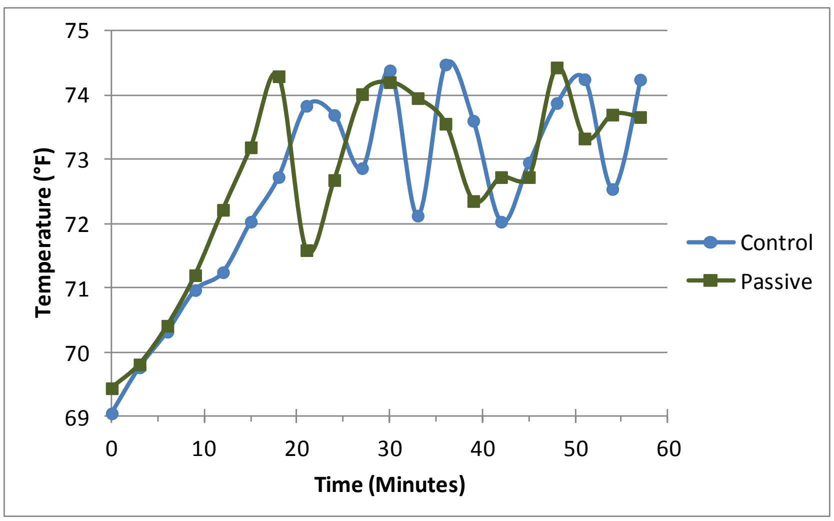

Figure 5.3: Temperature vs. Time for Control and Passive Roofs

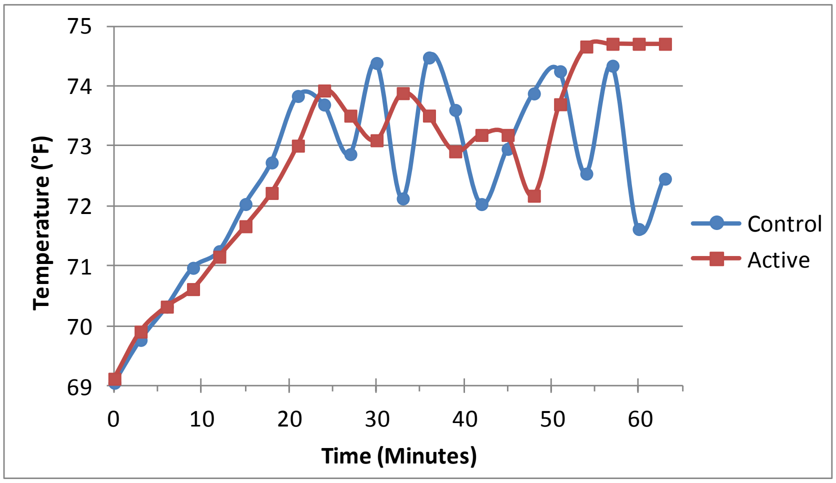

Figure 5.3: Temperature vs. Time for Control and Active Roofs

For Figures 5.2 and 5.3, the average temperature of the interior of the prototype was taken every three minutes and then plotted. The sections where the average temperature drops are sections of time where the A/C system was turned on. Based on that, it can be seen that the control roof prototype turned on the A/C system over twice as much as either the passive or the active roof prototypes.

The power usages of these three prototypes roofs were measured by how long the A/C was one during each test. Then, the passive and active roof prototype results were compared to the control system. Table 5.1 below shows these comparisons:

Table 5.1: Testing Results (Compared to the Control Roof)

Prototype Roof	% Reduction in Power Usage
Passive	43%
Active	72%

Therefore, the passive roof prototype used about 43% less power on A/C than the control roof prototype, and the active roof prototype used 72% less power. It is important to note that the power consumption was determined by using the amount of time the A/C system was on. As a motor was not used in the active roof system, a hypothetical amount of power usage needed to be added to this system.

After reviewing the data, it was determined that the control roof needed the A/C system to be turned on an average of five times over a one hour testing session. The passive system needed the

A/C system to be started an average of three times while the active needed the A/C system an average of two times. However, the active system did not need the A/C system during the hottest part of the simulated day while both the control and passive systems did.

Chapter 6. Cost Analysis

Table 6.1 below is a breakdown of how much was spend on which systems or main supplies and which type of items were included.

Table 6.1: Cost Analysis Breakdown

Category	Supplies	Cost
Wood	1'' Wooden Square Dowels	$233.21
	2' x 4' s	$28.83
Fasteners	Hot Glue & Guns	$45.93
	Brackets & Joining Plates	$74.92
	Screws, Nails, Tape & Staples	$53.70
Cutting Tools	Scissors, Exacto Knife & Drill Bits	$19.75
Prototype Walls	Poster Board	$19.60
	Cork	$249.06
Active Roof	Aluminum Rods &Plate	$81.51
	Foam Board	$10.29
	Metal Ribbon, Arcs & Washers	$10.23
	Spray Adhesive	$7.79
	Mylar	$29.95
Passive Roof	Poster Board	$28.80
Simulated Sun	Light Bulbs	$86.15
	Sockets	$111.18
	Electrical Wiring & Wire Nuts	$231.54
A/C System	Copper Piping & Saudering	$78.14
	Fans, Switches, Hoses	$64.42
	Pump Motor & Cooler	$108.32
Testing	Gas & Ice	$19.97
	TOTAL	$1,593.29

Chapter 7. Conclusions

The amount of power consumption due to cooling the internal temperature of facilities is a concern for many businesses with large warehouse like buildings. This project investigated two different types of roof designs that could reduce this power usage by reflecting away the sun's radiation: the passive and active roof prototypes. The test results from these two roof systems was then compared to the results of the control roof, so that it could be determined how effective these two roof systems were at reflecting away the simulated sun's radiation. Also, since all six trials were tested in a controlled environment the results may be compared to one another without any adjustment due to environmental differences.

From the testing results it can be concluded that the active roof prototype had the lowest power usage combination even with the power of the hypothetical motor added to the power used by the A/C system. However, it should be noted that the passive roof did significantly reduce the power usage as well.

Also, testing showed that the active roof was more efficient at reflecting away radiation during the testing positions representing 12pm-2pm.

Therefore, the active roof system is more efficient on lowering the amount of power used to cool large warehouse buildings than the passive roof. However, in reality, the cost of construction of the active system may be higher than the passive, so in the short run it may be more cost effective to install the passive roof.

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Acknowledgements

Our team would like to thank the following professors for providing guidance during this project:

- Dr. Michael Shafer (Client)
- Dr. Srinivas Kosaraju
- Dr. John Tester
- Perry Wood, PE