MEMORANDUM

TO: Dr. Michael Shafer (Project Client)

FROM: Team 06: Mohammed Alkhaldi, Coy Cody, Donovan Hard, Marissa Munson, and Krysten Whearley

SUBJECT: Final Proposal for Active Roof System Senior Capstone Design

DATE: 12/13/2013

This memo is concerning the final proposal for our team's senior capstone project.

As this semester comes to an end, it is time that we wrap up this project and present our final designs and analysis. So attached to this memo on the following pages is the complete final proposal report for the Active Roof System senior capstone project.

The final proposal combines all of the reports and analysis completed early in the semester into one organized document, and there is also some new material which has been added on the final prototype designs and the project's estimated budget.

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

Thank you for time, and we look forward to continuing to work with you in the spring!

Active Roof System

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Final Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2013

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Nomenclature

Symbol	Variable Name	Units
R (-value)	Insulation Rating Value	$m^2 \cdot K/W$
t	Thickness	in
h_{avg}	Average Convection Coefficient	$W/m^2 \cdot K$
T	Temperature	^oF or K
ε	Emissivity	n/a
Nu_L	Nusselt Number	n/a
Gr_L	Grashof Number	n/a
Pr	Prandtl Number	n/a
k	Thermal Conductivity	$W/m \cdot K$
v	Kinematic Viscosity	m/s^2
T_∞	Temperature of the Ambient Air	^oF or K
T_s	Surface Temperature of the Roof	^oF or K
T_f	Film Temperature	K
g	Gravity	m/s^2
B	Volumetric Thermal Expansion Coefficient	1/K
Δ	Change in	n/a
L	Length of the Roof	ft
$\dot{E}$	Energy Flow	W=J/s
G	Solar Radiation	W/m^2
σ	Stephan-Boltzmann Constant	$W/m^2 \cdot K^4$
α	Fraction of Solar Radiation Reflected	n/a
ρ	Density	kg/m^3
Cp	Specific Heat	$kJ/kg \cdot K$
Bi	Biot Number	n/a
Lc	Characteristic Length	ft
V_{olume}	Volume of Interior of the Prototype	ft^3
$A_{surface}$	Surface Area of the Roof of the Prototype	ft^2
ζ_1	Eigenvalues (Biot Number Constant)	rad
C_1	Biot Number Constant	n/a
Fo	Fourier Number	n/a
$time$	Time	s
Ra_L	Rayleigh Number	n/a
m	Mass	kg
w	Width of Prototype	ft
l	Length of Prototype	ft
h	Height of Prototype	ft

1.0 Problem Formulation and Project Plan

1.1 Project Introduction

The amount of power needed to maintain a constant comfortable temperature inside large warehouse type buildings is too high. To amend this problem our group will design and build prototypes of active and passive roof systems designed to reduce the amount of energy required to maintain a desired temperature.

1.2 Clients

Project clients who will be sponsoring this project are as follows:

- Dr. Michael Shafer – Mechanical Engineer/Professor at Northern Arizona University
- Grant Masters – Graduate Student at Northern Arizona University

Although Dr. Shafer is the faculty member who is sponsoring this project, our main client and the one we will be in most contact with, as instructed by Dr. Shafer, is Grant Masters.

1.3 Need Statement

Every 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 usage to keep the interior of large buildings at a comfortable, cool temperature is too high.

1.4 Project Goal

The goal of this project is to design and build prototypes of active and passive roof systems that will maintain a closed interior structure at constant temperature while withstanding all the extreme weather conditions associated with of all four seasons.

1.5 Brief Description of Prototypes

For this project there will be three basic roof system prototypes constructed: a passive design, an active design, and a control that will be used for comparison purposes to calculate the efficiency of the other two.

The project goal is to design active and passive panel systems that will be placed on the roof of the building to decrease the need of energy to maintain the temperature of the building's interior. An active roof system unit consists of panels that will actively track the sun by use of a solar tracking device. During the summer months the panels will change angles throughout the day so that they will reflect the sun's radiation (or thermal energy) to keep the building's interior cooler (see Figure 1 below) [1]. By continuously changing the angles of the panels throughout the day it will also cause the maximum amount of the roof's surface are to be shaded, which will also help to decrease the amount of heat absorbed by the roof. Then during the winter months, these panels will do the exact opposite: they will change angles throughout the day to allow the sun's radiation to be absorbed by the black roof and help to heat the building's interior (see Figure 2 below) [1].

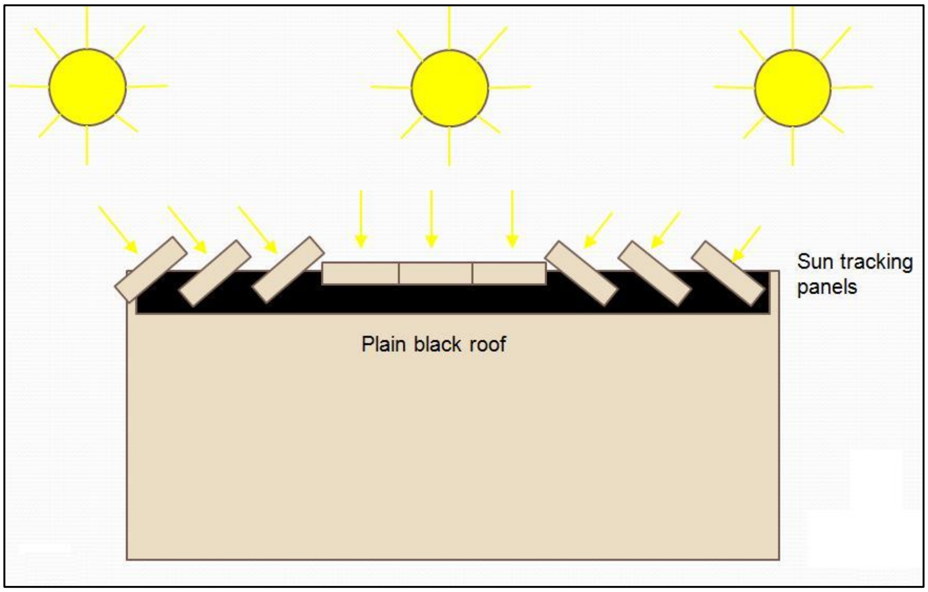


Figure 1: Active Roof System Panel Angle for Summer Months throughout a Day

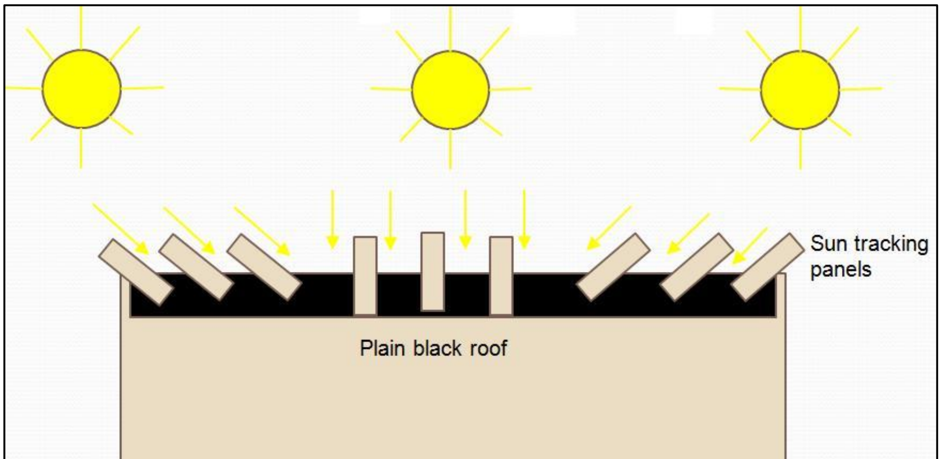


Figure 2: Active Roof System Panel Angle for Winter Months throughout a Day

The passive roof system will be very similar to the active roof system, in that they both will be blocking sun's radiation during the summer months, and then allowing the sun's radiation to be absorbed by the building's black roof during the winter months [1]. The main difference between the passive and active roof system, is that the passive roof system will not track the sun. Instead the passive roof's panels will be stationary and be placed at an optimal angle that will be the most efficient during that time of year at absorbing or reflecting the sun's radiation [1].

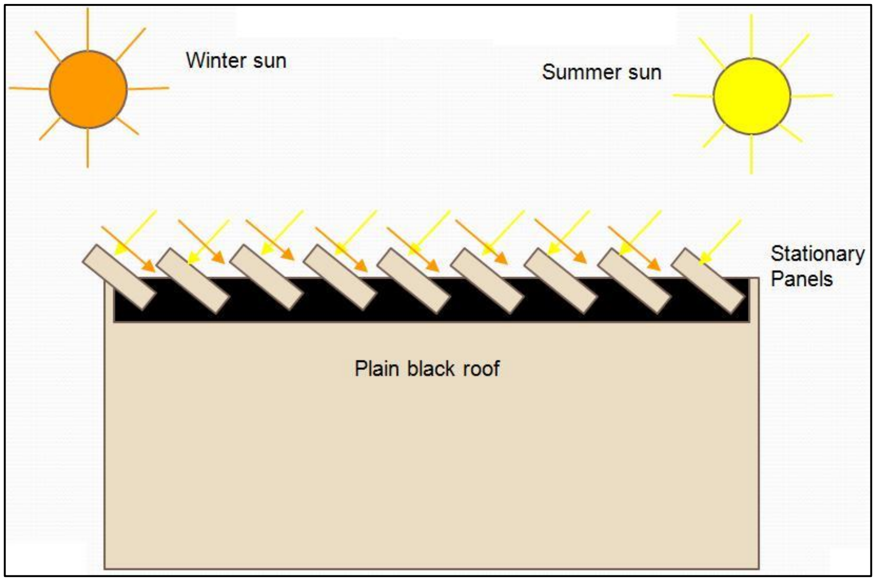


Figure 3: Passive Roof System Panel Angle for Winter and Summer Months

The control roof system will be modeled as a building with a flat, white painted roof to reflect as much of the energy as possible [1]. Many large building have white painted roofs, just for that purpose so having this as the control prototype is valid.

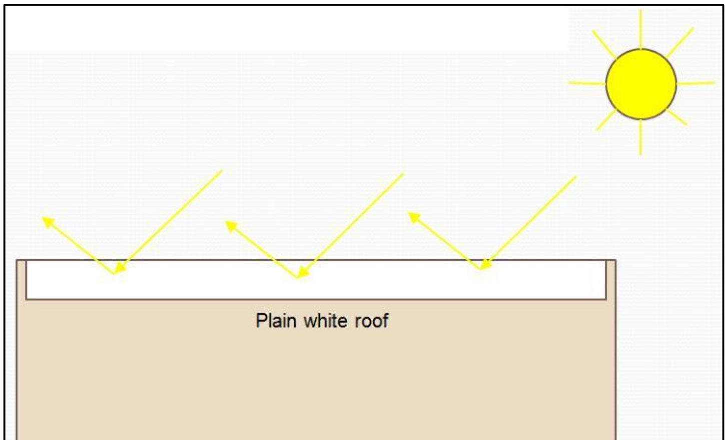


Figure 4: Control Roof System

1.6 Expected Project Outcome

The expected outcome for this project is to design and build improved and inexpensive active and passive roof prototypes that will help maintain interior structure temperature of 70^{o}F. Additionally, the system design will conserve power usage by using solar energy to provide the heat needed to maintain a desired constant temperature.

1.7 Operating Conditions

For this project there are two different operation conditions which will be used for the design and testing of the three prototypes.

The first operating condition will be in a computer lab and conducted mainly by the graduate student, Grant Masters. Mr. Masters will be doing the analytical computer simulations to show an estimate of the effectiveness of each prototype to either transfer heat away from or into the system. However, our team will be making simple heat transfer calculations and concepts to aid us in the selection of our final prototype designs.

The second operation condition comes in when it is finally time to test the prototypes. The prototypes will be tested outdoors where they will be exposed to a variety of weather conditions throughout an entire day. Measurements will also be taken throughout the testing days so that our team can analyze how effective each prototype is at maintaining the required constant internal temperature of 70^{o}F.

1.8 Objectives

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

Table 1: Project Objectives

Objective	Measurement Basis	Units
Maintain Constant Internal Temperature	Interior Temperature of Structure Throughout a Day	^{o}F
Reflect/Absorb the Sun's Radiation	External Roof Temperature Throughout a Day	^{o}F
Low Power Usage	Power Used by Control, Active and Passive Roof to Maintain	kWh

1.9 Client Needs

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

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.
7. *Ease to Control* - The apparatus will use a thermostat to control the system. If thermostat is complex, we will have less chance to make our design at the top of market.

1.10 Engineering Requirements

In order to come up with effective passive and active roof systems our team will need the following engineering tools and knowledge:

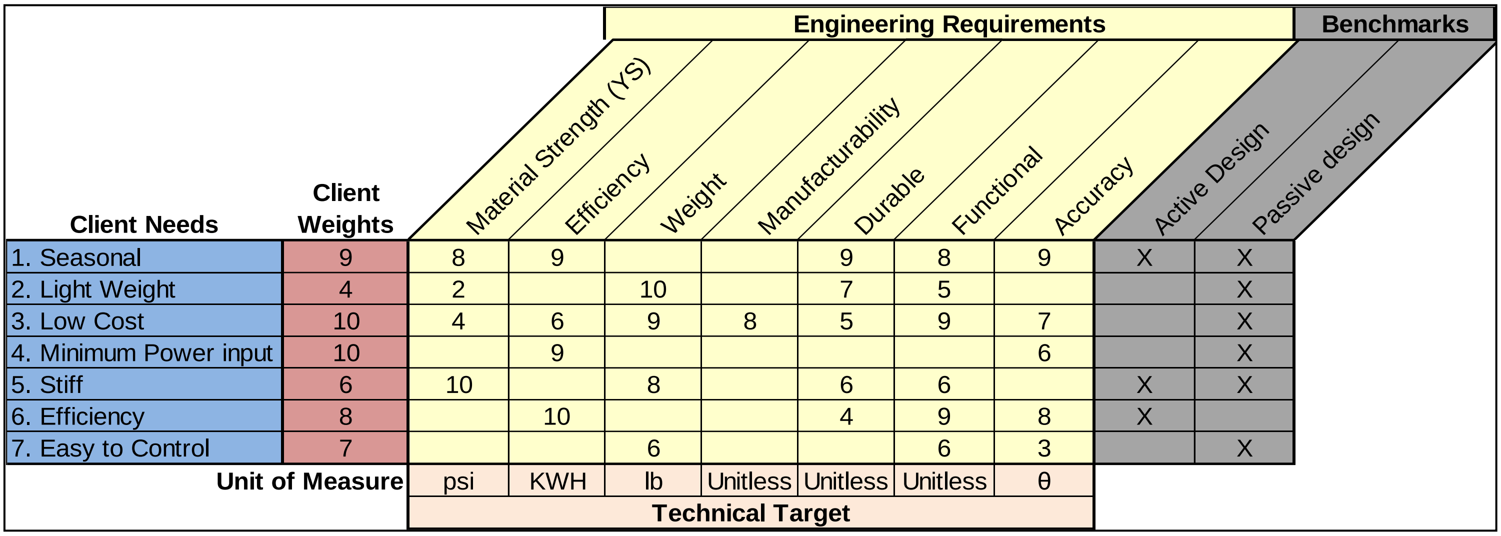
- How to conduct a heat transfer analysis
- Background knowledge of effective Solar Tracking Systems
- Knowledge of in Automated Systems in general.

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

- Material Strength
- Efficiency

- Weight
- Manufacturability
- Durability
- Functional
- Accuracy

The client needs listed within the previous selection are analyzed for which of engineering requirements they correlate to in the Quality Function Deployment Figure 5 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	
7. Easy to Control	7			6			6	3		X
	Unit of Measure	psi	KWH	lb	Unitless	Unitless	Unitless	θ		
		Technical Target								

Figure 5: 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.

1.11 Constraints

The three constraints that are known for this project so far are listed below:

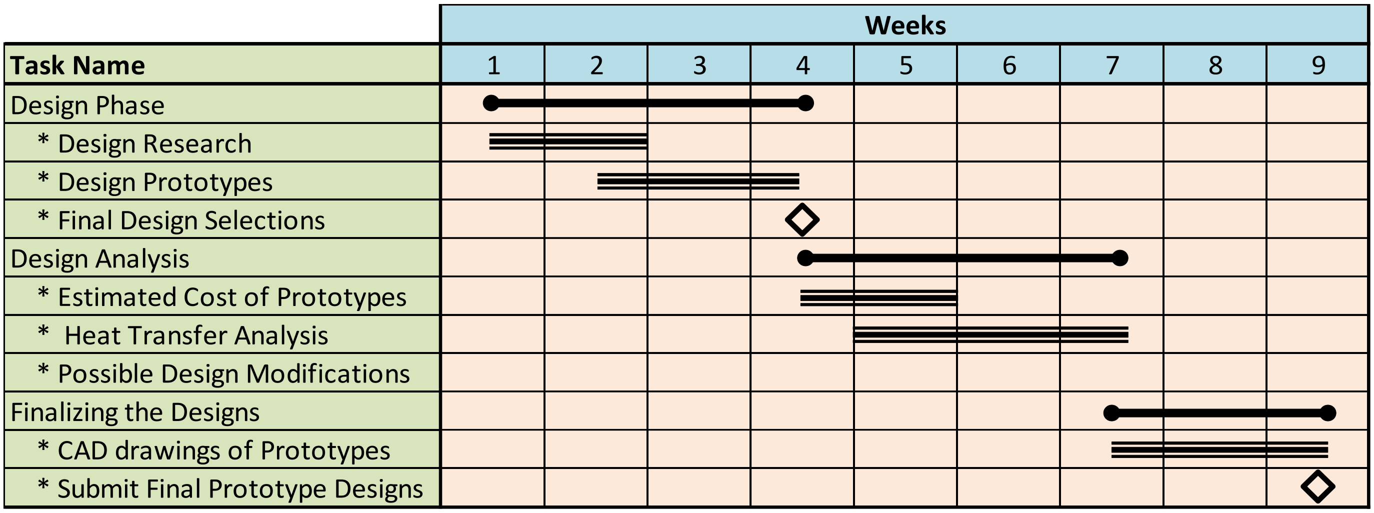
- The interior of the prototype must be able to maintain a constant temperature of 70^{o}F throughout the entire day of all four seasons.
- The prototypes must be able to withstand various extreme weather conditions such as blizzards, ice storms, hail, lightning, dust storms, gusty winds, and extreme dry climates.
- The cost of the construction of the prototypes must be below the (future, client) assigned budget.

These constraints come directly from the initial list of client needs listed in the previous section, and will be added to as more information is gained.

1.12 Project Planning

A basic timeline was made to help us keep on track with the completion of tasks and reminding us the due date of each task. It also gives us an idea of what tasks may be worked on simultaneous so that we are able to work more efficiently.

The Fall 2013 Timeline is shown in Figure 6 below:



	Weeks								
Task Name	1	2	3	4	5	6	7	8	9
Design Phase	●━	━	━	━●					
* Design Research	═	═							
* Design Prototypes		═	═	═					
* Final Design Selections				◇					
Design Analysis				●━	━	━	━●		
* Estimated Cost of Prototypes				═	═				
* Heat Transfer Analysis					═	═	═		
* Possible Design Modifications									
Finalizing the Designs							●━	━	━●
* CAD drawings of Prototypes							═	═	═
* Submit Final Prototype Designs									◇

Figure 6: Fall 2013 Project Planning and Design Phase

The design phase will start at the beginning of the second week of October and end at the last week of October, and the design phase will include the following tasks:

- Design research will take a place during the period 10/09/2013 to 10/18/2013
- Design Prototypes will start at the 16th of October and end at the 31st October.
- Final design selection will be at the 31st of October.

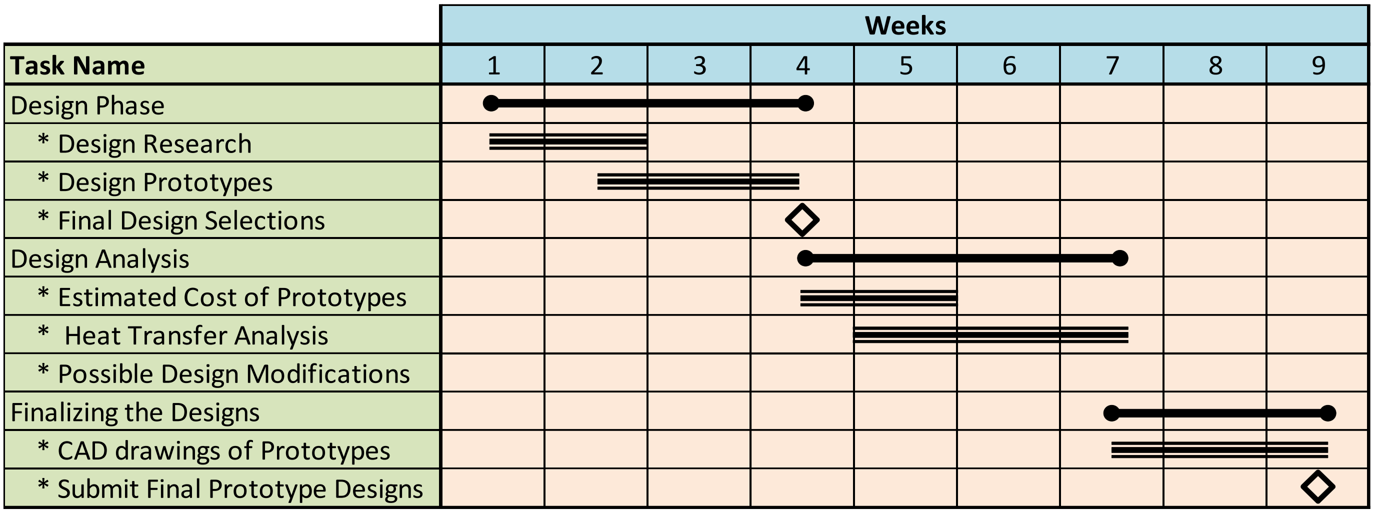
The design analysis can be started after finishing design phase, and this task will happen between the beginning of November and end at third week of November

- Estimated cost of the prototypes will take a place during the period 11/01/2013 to 11/09/2013
- Heat transfer analysis will start at the 3rd of November and end at the 20th of November
- Possible design modification will be made before the 20th of November

Finalizing the design will start right after we finish design analysis and end at the end of the fall semester.

- We will start the CAD drawings of prototypes on November 21st and end on December 7th.
- Submit final prototype design at the December 7th.

Figure 7 below is the estimated timeline of the project for the Spring 2014:



	Weeks								
Task Name	1	2	3	4	5	6	7	8	9
Design Phase	●	━	━	●					
* Design Research	═	═							
* Design Prototypes		═	═	═					
* Final Design Selections				◇					
Design Analysis				●	━	━	●		
* Estimated Cost of Prototypes				═	═				
* Heat Transfer Analysis					═	═	═		
* Possible Design Modifications									
Finalizing the Designs							●	━	●
* CAD drawings of Prototypes							═	═	═
* Submit Final Prototype Designs									◇

Figure 7: Spring 2014 Construction and Testing Phase (Estimate)

We are going to gather materials between 01/08/2014 and 02/05/2014 and that include:

- Budget planning will be placed during the period 01/08/2014 to 01/17/2014.
- Organizing a list of materials for the prototype will take a place between the 01/15/2014 and 01/22/2014
- The estimated date of receiving materials is the 5th of February 2014.

Construction of prototypes will start on the 6th of February 2014 and end at the 5th of March 2014.

We are going to start testing our prototype between the 19th of February 2014 and 20th of March 2014 and that include:

- Gathering data from testing will take a place during the testing time.
- Between 02/27/2014 and 03/20/2014 a modification to prototype will be made.
- Retesting prototypes will take a place during the period 03/13/2014 to 03/20/2014.

The final presentation of the prototypes and their test results should be done and ready by the fourth week of March.

1.13 Summary

The need that is driving our project is that the amount of power usage to keep the interior of large buildings at a comfortable, cool temperature is too high.

In order to find a way to reduce this power usage, our team will be researching and constructing prototypes different types of roof systems that will help buildings to maintain a constant internal temperature. The two different types of roof system prototypes that will be constructed are the active and passive roof systems. Where the passive roof system has stationary reflective panels and the active panels are moved by a solar tracking device, and then both of these will be compared to the control prototype which just has a white painted roof.

For our project we have two clients and they are Dr. Michael Shafer and Grant Masters, and our team will be working closely with Mr. Masters during the design and construction phase of our three roof system prototypes to ensure that all of the client needs are met. With the top priority of the client needs being to produce low cost prototypes' that use a minimal amount of power to operate.

We expect the design phase for this project to take approximately nine weeks with the first week starting this week, and we expect the construction and testing phase next semester to take approximately thirteen weeks. During the testing phase of this project the prototypes will be tested outdoors to not only test their effectiveness but also to test how well they are able to withstand the environmental elements.

2.0 Concept Generation and Selection

2.1 Design Requirements for All Three Prototypes

There are three main design requirements which all three prototypes must satisfy: 1) Prototypes must be scaled to a real, large building; 2) Prototypes must have an interior heating and cooling system; 3) There has to be a way to measure the internal temperature of the prototypes.

2.1.1 Scaling the Prototypes

For our prototypes, we have decided to construct a scale model of a Wal-Mart store, because these are rather large buildings and there are hundreds of them across the country. Originally, our team wanted to scale our prototypes to a small Wal-Mart Supercenter, but Wal-Mart Supercenters can range in size from 78,000 to 26,000 square feet [2], so naturally the 26,000 square feet building was selected.

In order to properly scale the prototypes it became necessary to know the thermal resistance value (R-value) and thickness of the type of insulation which a large building, such as a Wal-Mart, would use. Insulation's R-value is a measurement of the insulation's ability to reduce the heat flow through an object [3]. The U.S Department of Energy there are different insulation thermal resistance values recommended for different regions of the United State, and this is displayed in Figure 8 to the below:

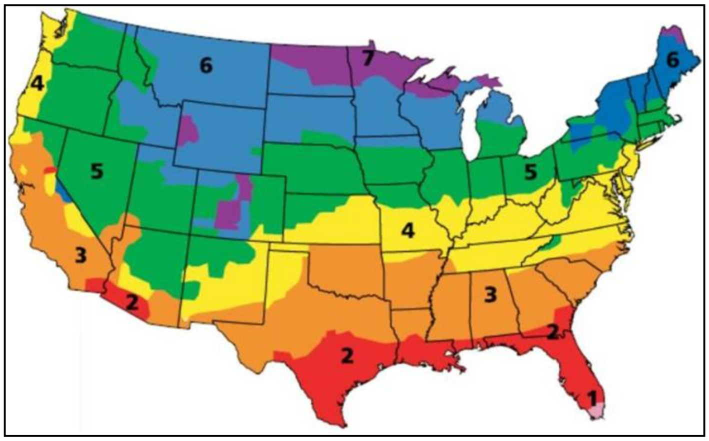
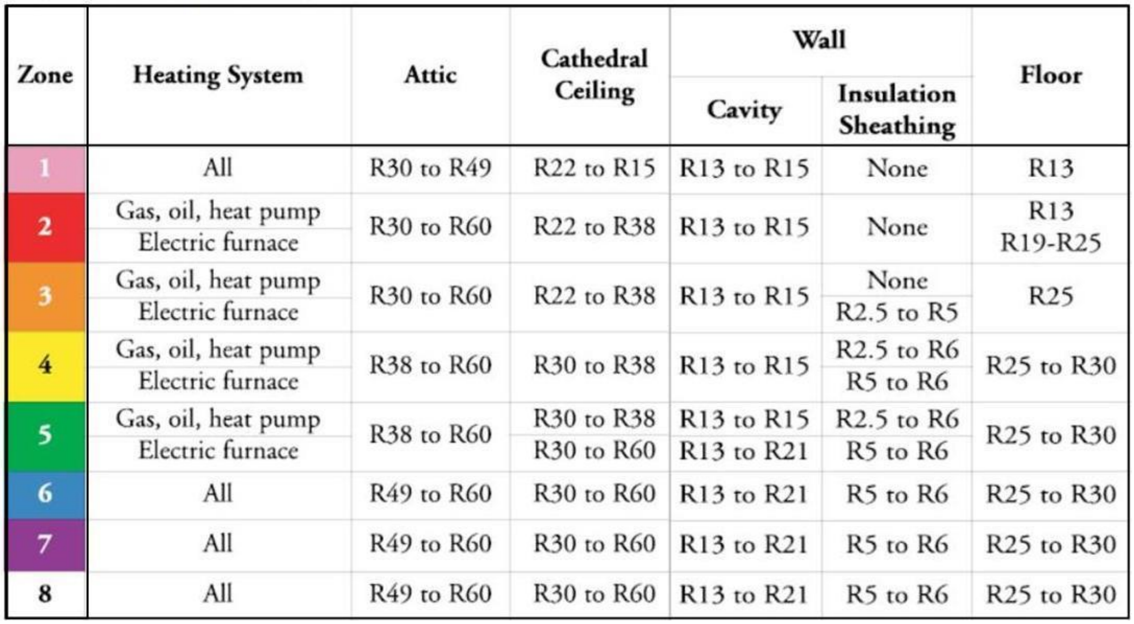


Figure 8: Insulation Type Zone Map [4]

Since our prototype's will be tested in Flagstaff, Arizona and is suppose to represent a real, large building, our team will be using the zone 5 insulation requirements shown in Table 2 on the next page:

Table 2: Insulation Type Based on Zone [4]



Zone	Heating System	Attic	Cathedral Ceiling	Wall		Floor
				Cavity	Insulation Sheathing	
1	All	R30 to R49	R22 to R15	R13 to R15	None	R13
2	Gas, oil, heat pump	R30 to R60	R22 to R38	R13 to R15	None	R13
	Electric furnace					R19-R25
3	Gas, oil, heat pump	R30 to R60	R22 to R38	R13 to R15	None	R25
	Electric furnace				R2.5 to R5	
4	Gas, oil, heat pump	R38 to R60	R30 to R38	R13 to R15	R2.5 to R6	R25 to R30
	Electric furnace				R5 to R6	
5	Gas, oil, heat pump	R38 to R60	R30 to R38	R13 to R15	R2.5 to R6	R25 to R30
	Electric furnace		R30 to R60	R13 to R21	R5 to R6	
6	All	R49 to R60	R30 to R60	R13 to R21	R5 to R6	R25 to R30
7	All	R49 to R60	R30 to R60	R13 to R21	R5 to R6	R25 to R30
8	All	R49 to R60	R30 to R60	R13 to R21	R5 to R6	R25 to R30

Although the table above mainly applied to homes using roll, fiberglass insulation and not large buildings, the thermal resistance values may still be used because they are approximately the same to the R-values of the sprayed polyurethane foam used in large metal buildings [5], such as a Wal-Mart. So based off of Table 1 above and using the values for a "Gas, oil, heat pump" heating system for Zone 5, our team can estimate the insulation used in an average Wal-Mart Building in Flagstaff. For our prototypes our team will use the following R-values: R14 for the walls, R34 for the ceiling and R27 for the floors.

Since R14 is the thinnest of the three different insulation types with an average thickness of only 3.5 inches [6], it will be the main factor used to figure out the scaling factors for the prototypes. How the two different scaling factors were calculated is shown below:

$$\text{Scale Factor}_{\text{R-value}} = (R_{\text{Prototype Insulation}} / R_{\text{Actual Building Insulation}})$$

$$\text{Scale Factor}_{\text{Thickness}} = (t_{\text{Prototype Insulation}} / t_{\text{Actual Builing Insulation}})$$

In the case of the 26,000 square foot Wal-Mart Super center it can be broken down that the building's interior dimensions can be simplified to 426.6 feet by 426.6 feet with a standard ceiling of 25 feet tall. Our team's first, initial guess at what type of insulation to use in the scaled prototypes was the smallest foam insulation boards we could find, and they had an R-value of 3.2 and a thickness of 0.5 inch [7]. Unfortunately, this insulation type proved to be too thick when the scaling factors were calculated as shown below:

Scale Factor $_{\text{R-value}}$ = (3.2/14) = 0.23 & Scale Factor $_{\text{Thickness}}$ = (0.5/3.5)=0.14

The first issue with these scaling values is that they are not close enough to each other and the other issue is that when the Thickness Scale Factor is applied to the 426.6 feet by 426.6 feet building, the prototypes would have to have dimensions of about 59 feet by 59 feet. Building three prototypes that size is unfeasible, and is directly due to the calculated Thickness Scale Factor is simply too high.

The next step was to find a thinner and lower R-value insulation which would produce low scale factors. What our team found was a cork roll with a thickness of 3/32 inch [8], and since cork has an R-value of 3.6 per inch [9] that means that this thickness of cork has an R-value of approximately 0.3375.

The second step was to lower the size of Wal-Mart building we were going to scale, because even the smallest Wal-Mart Supercenter was too large to build a scale model out of under our insulation thickness scale constraint. So instead our team decided to base our scale prototypes off the one of the smallest Wal-Mart stores, which still has an interior of 30,000 square feet [2]. This new store dimension’s can be simplified to a building that is 173.2 feet by 173.2 feet with 25 foot tall ceilings.

Using this newly selected building size and cork insulation the scaling factors were calculated as shown below:

Scale Factor $_{\text{R-value}}$ = (0.3375/14) = 0.024 & Scale Factor $_{\text{Thickness}}$ = ((3/32)/3.5)=0.026

Since both of the scaling factors are reasonably small and relatively close to each other, the 3/32 inch cork was selected as the insulation for the scaled prototypes. The prototype scaled interior dimensions are calculated below:

Wall lengths = 173.2ft * 0.026 = 4.5ft & Ceiling Height = 25ft * 0.026 = 0.65ft

The insulation R-values for the prototype are calculated below:

R_{ceiling} = 34 * 0.024 = 0.816 & R_{floor} = 27 * 0.024 = 0.648

Since R-values of insulation add together if they are stacked together [3], the walls of the prototype will have one layer of the cork insulation while to get approximately the calculated, scaled R-values the ceiling will have 3 layers and the floor will have 2 layers.

2.1.2 Basic Requirements of the Interior Heating/Cooling System

In order to properly model our prototypes after an actual Wal-Mart building, they will each have to include some sort of interior temperature controlling system. This system will be used to maintain a constant interior temperature of 70^{o}F for the prototypes, and this system will have to have a measurable power usage. Having a measurable power usage is crucial for this heating/cooling system because the point of the project is the compare the power usage needed to keep each of the three prototypes, with the different types of roof designs, at this comfortable temperature of 70^{o}F. So by comparing the power usage of each of the three prototypes we can then find out how effective each roof system.

2.1.3 Basic Requirements of the Interior Temperature Measurements

In order for the heating/cooling system to function it will need to have some sort of interior temperature read out. By using periodic measurements of the each of the prototype's interior temperatures the heating/cooling will know when to switch on and off the heating or cooling element. This temperature measurement system should record the temperature of each of the prototypes interiors every ten minutes without opening up the prototype, that way the temperature measurements will be as accurate as possible without the outside ambient air temperature interfering.

2.2 Design Requirements for Only the Passive Roof Prototype

The passive roof prototype will have no mechanical or electrical parts at all, but will instead consist of several stationary panels oriented at an angle to allowing sunlight to be absorbed in during the winter and reflected away during the summer. These panels will be made of a reflective material, such as glass and will be oriented at a 43° angle from horizontal.

This orientation angle was determined based on the latitude of Flagstaff, Arizona, which is 35.1992°N [10]. The summer and winter equinox sunlight angles are based on complimentary angles. Starting with 90°, the summer equinox solar angle can be found by subtracting the latitude of the city and then adding the tilt of the earth (23.5°), and to find the winter equinox angle it is the same process but instead subtracting the tilt of the earth [11]. For Flagstaff the calculated summer and winter solstice angles come out to be 78.3° and 31.3°, respectively. This same equation can be used to determine the spring and fall equinoxes, except the tilt of the earth is not a factor. The calculated spring and fall equinox angles both come out to be 54.8°. The chosen 43° angle is between the lowest winter angle and the spring equinox angle.

During the winter, the sun follows a path closer to the southern horizon [12]. The panels for the passive roof prototype will need to be tilted toward the southeast in order to get as much sunlight in as possible during the morning and evening hours. However, during the summer months, the sun follows a path that up higher, and this will cause the sun rays to point down at a straighter angle onto the building (see Figure 9 below).

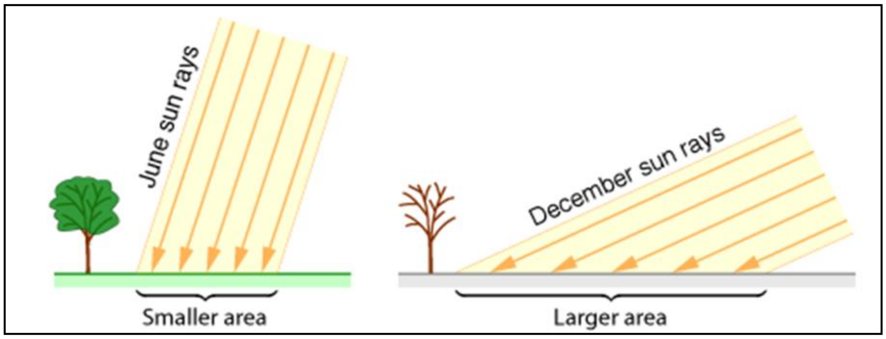


Figure 9: Basic angle of Sun Rays for Summer and Winter [12]

With the chosen angle of 43°, the sun will be blocked during the majority of the day. The morning and evening hours will be the only time of day where sun rays will get through to warm the roof.

2.3 Design Requirements for Only Active Prototype

The active roof prototype will have reflective panels that are all attached to a single shaft or mechanism which can be rotated by a motor. These reflective panels will continually rotate throughout a day to certain angles that will allow sunlight to be absorbed by the roof during winter months and reflect the sunlight away from the roof during the summer months. This motor will be controlled by a computer system that has been programmed to tell the motor when and how much to rotate. As is well known, the sun position continually changes during the day as well during the different seasons.

Writing a thorough program for the real, full scale active roof system would either use a solar tracker or have a program of all the sun angles throughout every day of the year based on the building's location on the globe, but since programming that is simply not possible given the timeline of this project, our team has come up with a simpler model that will be implemented for the prototype of the active roof. This simpler model is based on Flagstaff and consists of the average sunrise and sunset times for the summer, fall, spring and winter, and also the sunrise angle and the sunset angle. The average sunrise and sunset times [13] are shown in Table 3 below:

Table 3: Average Sunrise and Sunset Times for Flagstaff, AZ

Season	Average Sunrise Time	Average Sunset Time
Winter	7:45 AM	5:15 PM
Spring	6:45 AM	6:30 PM
Summer	5:20 AM	7:30 PM
Fall	6:20 AM	6:20 PM

Then, using these sunrise and sunset times our program will rotate the panels by a certain degree every ten minutes, and the angle which it rotates every ten minutes will be based on how long the sun is up and how many degrees the sun rotates throughout the day. Since sunrises and sunsets in Flagstaff are both at approximately 1^o [14] the amount the sun rotates throughout a day is calculated by $180^o-2(1^o)=178^o$ (see Figure 10 below).

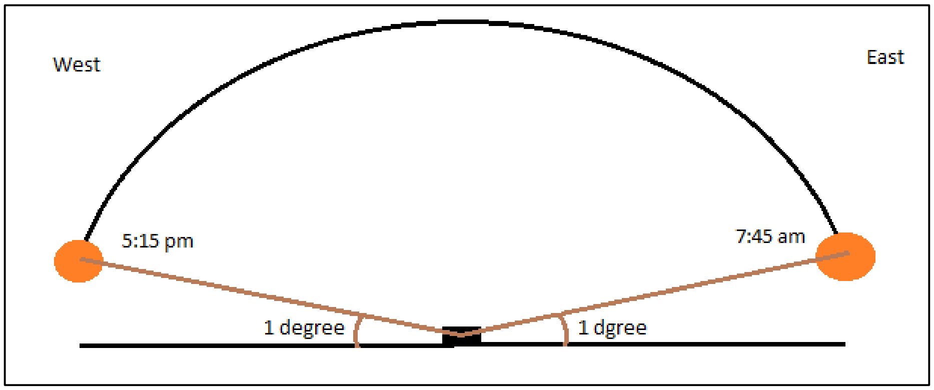


Figure 10: Sun Altitude Angles for Sunset and Sunrise [14]

2.4 Internal Temperature Measurement System

There are three concepts/designs which our team considered for the temperature measurement and recording system. Each one of these designs will be explained individually.

The first design is the “Manual” reading and recording design, and is basically be a thermometer (see Figure 11 on the next page). The thermometer will be placed in the prototype and there will be a sight glass to allow us to read the current temperature. The temperature sampling over a period of time will be manually recorded. To test our designs a temperature sampling will be recording in 10 minutes increments for a long period of time. The advantage of using thermometer is the low cost of the thermometer. The disadvantages of using thermometer are low accuracy and a high time consumption due to manually recording the temperatures.

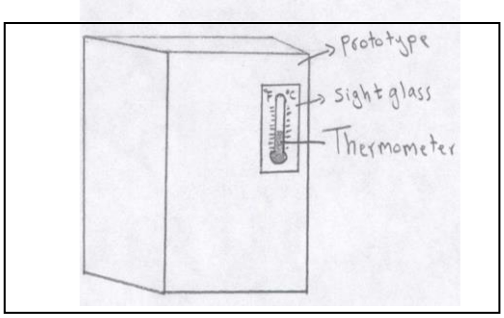


Figure 11: Internal Temperature Measurements ~ Design 1

The second design is the “Semi-Automatic” system (see Figure 12 below). The semi-automatic is an electronic device that will only measure the internal temperature. The device will consist of an internal or external temperature probe. The current temperature will be digitally displayed on LCD screen, and then the temperature would be manually recorded. The advantages of using semi-automatic are accuracy and low cost. While the disadvantages are that this design will have a high time consumption due to manually recording the temperatures.

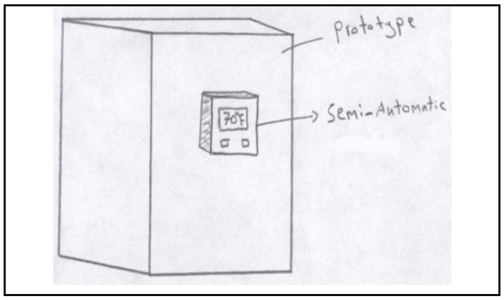


Figure 12: Internal Temperature Measurements ~ Design 2

The third design is the “Fully Automatic” system, and will consist of a measurement device that will measure and record the internal temperature over a period of time (see Figure 13 on the following page). The current temperature will be displayed on LCD screen on the device, but the device itself can digitally store and even send the temperature data. To access the data, a USB cable will be used to connect the device to a laptop. The advantages of using fully-automatic concept are that it is highly accurate and it has the automatic recording feature which will result in saving time during testing. While the disadvantage of this design is that it comes with a high cost.

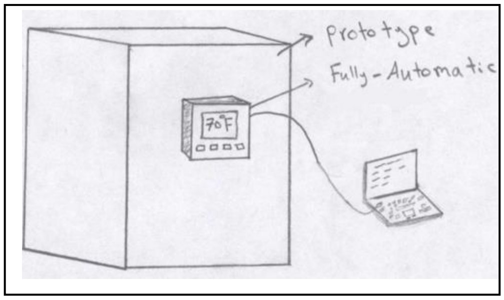


Figure 13: Internal Temperature Measurements ~ Design 3

Each of these three designs have been rated from 1 to 10 for each of the design criteria described below, with 1 meaning that the design demonstrated poorly within that criteria and 10 means the design demonstrates excellently. The decision matrix and descriptions of the design criteria are shown in Figure 14 below:

Internal Temperature Measurement System Decision Matrix

		Designs		
Criteria	**Weight**	**Manual Data**	**Semi-Automatic**	**Fully Automatic**
Accuracy	9	4x9 = 36	9x9 = 81	10x9 = 90
Ease of Construction	7	7x7 = 49	5x7 = 35	7x7 = 49
Response Time	4	5x4 = 20	7x4 = 28	10x4 = 40
Cost	10	9x10 = 90	6x10 = 60	4x10 = 40
Automatic Data Output	8	0x8 = 0	7x8 = 56	10x8 = 80
	TOTAL	195	260	299

Decision Matrix Design Criteria

Accuracy – This is essential to have an accurate set of temperatures over time.

Ease of Construction – The temperature recorder need to be as simple as it could be to avoid having error on our data.

Response Time – The time it takes to read and record temperature.

Cost – The cost of the device need to be low to fit our budget.

Automatic Data Output – The automatic data output is important to have an accurate

Figure 14: Internal Temperature Measurement Decision Matrix and Criteria Descriptions

Based on the decision matrix above the fully-automatic temperature measurement and recorder was selected for our project. The fully-automatic is the one that fulfilled our needs. In our project, the temperature monitor will be used to measure and record sampling temperature over a period of time for three prototypes. The data collected need to be very accurate to realize the effectiveness of the active and passive roof system.

To find the perfect temperature data logger, our team came up with a list of features that are necessary in order for the device to be used in our prototypes. Figure 15 on the following page has a list of the temperature data logger devices being considered and their features as well as cost [15].

Features and Cost of Each Device

Device	Supco SL500XT	HOBO Onset	Lascar – GFX-DTP	Supco DVT4	Lascar EL-GFX-1
Accuracy	± 0.5°C	± 0.21°C	± 0.1°C	± 0.5°C	± 0.1°C
Temperature range	-40°C to 80°C	-20°C to 70°C	-40°C to 125°C	-40°C to 70°C for external -10°C to 65°C for internal	-30°C to 80°C
Response time	1 second to 9 hours	1 second to 18 hours	2 second to 1 hour	1 second to 18 hours	10 second to 12 hours
Memory size	43,344 readings	84,650 readings	252,928 readings	87,000 readings	256,000 readings
Temperature probe	One external	One internal	Two external	One internal Three external	One internal
Cost	$106	$125	$185	$285	$135

Figure 15: Temperature Data Logger Devices and Features

Description of Device Features

Accuracy – The closeness of the temperature measurement to the true temperature is needed to have accurate results.

Temperature Range – The device need to be able to measure and record low and high temperature.

Response Time – The rate of time that the device can take a temperature sampling.

Memory Size – The amount of data that can be stored.

Temperature Probe – Number of internal and external temperature sensor that the device has.

Cost – The cost of the device need to be appropriate with our budget.

2.5 Heating and Cooling System

With the prototypes' interior dimensions being relatively small, there are three designs that we have come up that will work as a heating and cooling system within those small interiors, and they are each described below:

The first design is the "Hand Pump" (see Figure 16 below). This design involves hand pumping hot or cold water through small pipes running through each of the three prototypes. This design seems very inefficient but with the size of the prototypes being relatively small, it could be done. However, this design is dependent upon the fact that someone would have to be standing by to monitor the temperatures and make the heating or cooling system act accordingly.

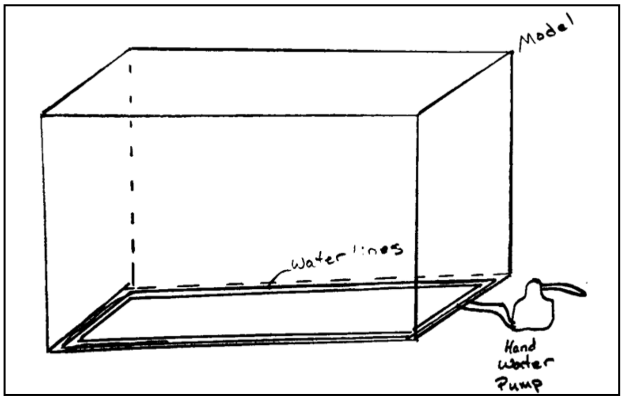


Figure 16: Internal Heating/Cooling System ~ Design 1

The second design is the "Water Pump" (see Figure 17 below). This design still involves using water hot or cold water to cool/heat the prototypes, but instead of a manual pumping system it will consist of an automated pumping system controlled by an electronic device (that will be discussed later in section 8). This electronic device will be programmed to turn on and off the water pump as well as switch between hot and cold water based on the data send from the internal temperature measurement system.

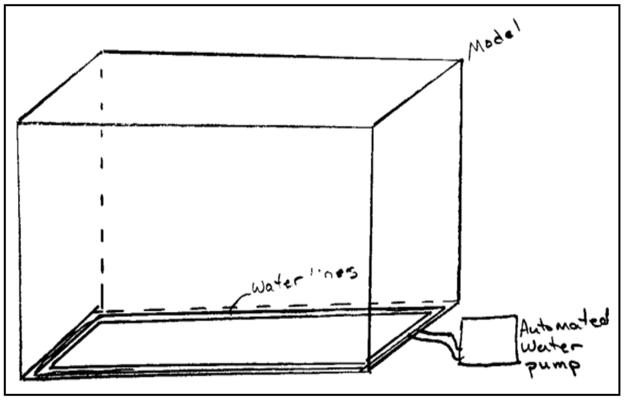


Figure 17: Internal Heating/Cooling System ~ Design 2

The third design is the "Air Flow", and this design will regulate the internal temperature of the prototypes by either blowing hot or cold air into the model (see Figure 18 below). This design will be controlled by an electronic device in the same way as the "Water Pump" design.

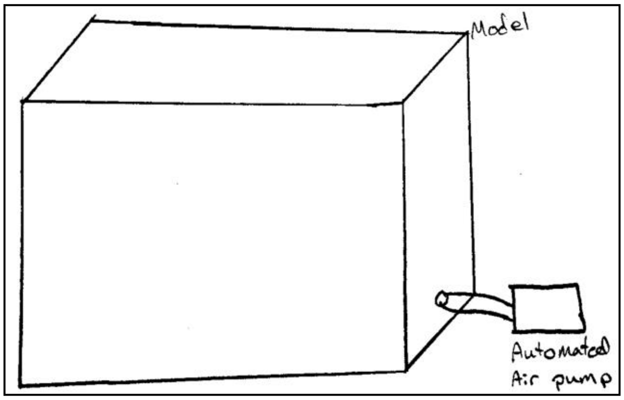


Figure 18: Internal Heating/Cooling System ~ Design 3

Each of these three designs have been rated from 1 to 10 for each of the design criteria described below, with 1 meaning that the design demonstrated poorly within that criteria and 10 means the design demonstrates excellently. The decision matrix and descriptions of the design criteria are shown in Figure 19 below:

Internal Heating/Cooling System Decision Matrix

		Designs		
Criteria	**Weight**	**Hand Pump**	**Water Pump**	**Air Flow**
Accuracy	7	4x7 = 28	9x7 = 63	10x7 = 70
Ease of Use	6	6x6 = 36	8x6 = 48	8x6 = 48
Efficiency	6	3x6 = 18	8x6 = 48	10x6 = 60
Cost	10	3x10 = 30	6x10 = 60	8x10 = 80
Data Collections	8	0x8 = 0	7x8 = 56	9x8 = 72
	TOTAL	112	275	330

Decision Matrix Design Criteria

Accuracy – How close to maintaining 70^{o}F can the system get.

Ease of Use – How easy is the system to use.

Efficiency – An estimate on how well the design will be able to heat/cool.

Cost – The cost of the device need to be low to fit our budget.

Data Collections – How well can the designs take the temperature inputs of the internal temperature measurement system and use them

Figure 19: Heating/Cooling System Decision Matrix and Criteria

Based on the decision matrix above, the way that has been chosen to regulate the internal temperatures of the prototypes is by using the "Air Flow" heating/cooling system. Our team also chose this design because after speaking with our project client, we believe that it will give us a better idea of what the companies are facing when heating and cooling their buildings because most of the large Wal-Mart buildings depend on flowing warm or cold air to regulate their internal temperatures.

2.6 Control Systems

There are two systems within our prototypes which will need to be controlled via an electronic device: the motor controlling the reflective panels on the active roof prototype and the communication between the internal temperature measurement system and the heating and cooling system.

The plan is to incorporate an arduino board electronic device system to operate the motors of the active roof prototype. This arduino board system will operate based on the program that will be developed using the information presented in section 5.

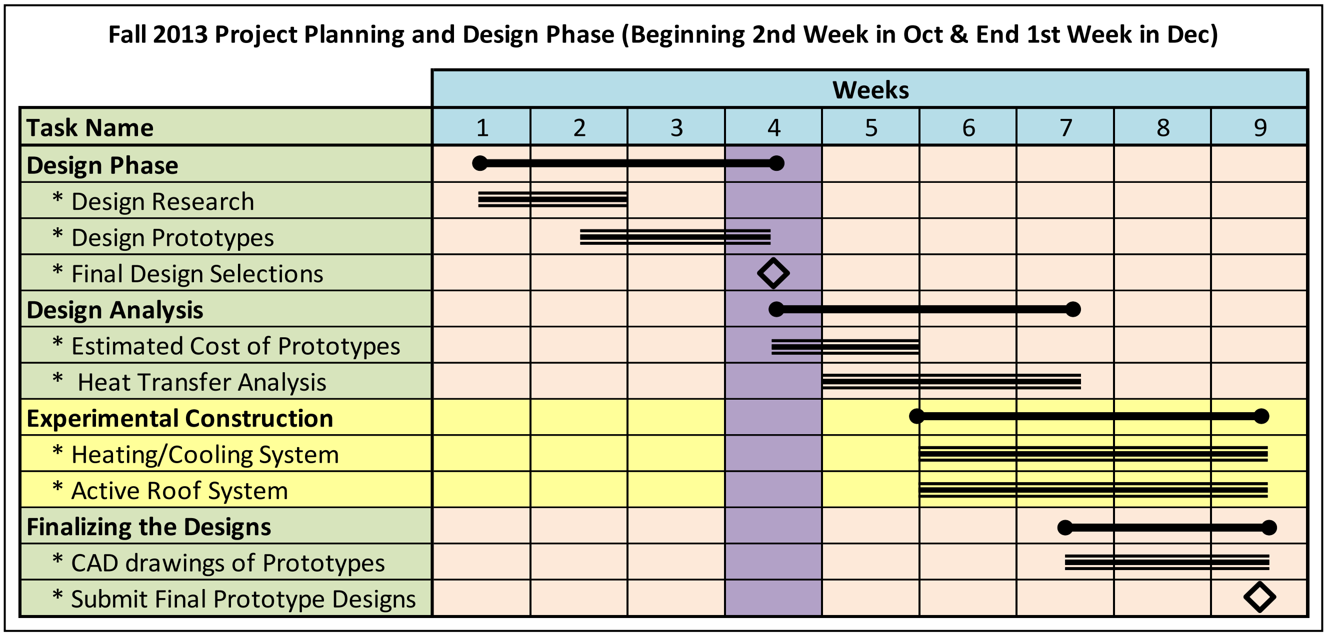
Another arduino board will be in charge of turning on and off the “Air Flow” heating/cooling system as well as switch the system from blowing hot or cold air when on. This arduino board will receive the temperature reading from the “Fully Automated” temperature measurement system every 10 minutes and use its programmed logic act accordingly.

Using these arduino boards will have the following advantages:

1. Inexpensive control devices
    - The arduino boards are relatively inexpensive to purchase [16].
2. Easy to Program
    - The arduino board systems will only require some basic computer programming.
3. Easy to Connect
    - The arduino boards have the ability to connect to all of the systems we need it to control as well as a laptop so the code can be debugged easily.

2.7 Changes to the Previous Project Timeline

The only change that has been made to the entire project timeline is that during the fall semester a task was added. This task is called “Experimental Construction” and is highlighted in yellow in Figure 20 on the following page:



Fall 2013 Project Planning and Design Phase (Beginning 2nd Week in Oct & End 1st Week in Dec)

	Weeks								
Task Name	1	2	3	4	5	6	7	8	9
Design Phase	━	━	━	━					
* Design Research	═	═							
* Design Prototypes		═	═	═					
* Final Design Selections				◇					
Design Analysis				━	━	━	━		
* Estimated Cost of Prototypes				═	═				
* Heat Transfer Analysis					═	═	═		
Experimental Construction						━	━	━	━
* Heating/Cooling System						═	═	═	═
* Active Roof System						═	═	═	═
Finalizing the Designs							━	━	━
* CAD drawings of Prototypes							═	═	═
* Submit Final Prototype Designs									◇

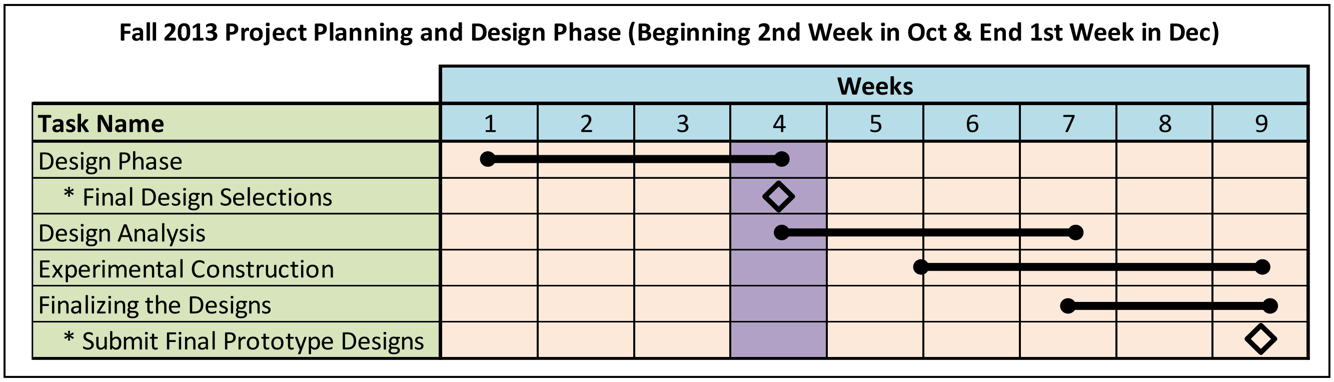
Figure 20: Fully Detailed Fall 2013 Semester Timeline

This new task was added to this semester's (fall) timeline after consulting with our client and he expressed a concern for how complicated actually getting the heating/cooling system and the active roof system operating will be. Since these are our two most complicated systems within our prototypes our goal is to at least start to experiment with how the ardiuno boards controlling these systems can be programmed and start physically constructing the components of these two systems.

2.8 Current Project Timeline

Our project timeline is sub-divided into two semester periods (fall and spring Semester), and each semester's timeline and main tasks are described in the following paragraphs.

The general fall timeline is shown in Figure 21 below:



Fall 2013 Project Planning and Design Phase (Beginning 2nd Week in Oct & End 1st Week in Dec)

	Weeks								
Task Name	1	2	3	4	5	6	7	8	9
Design Phase	━	━	━	━					
* Final Design Selections				◇					
Design Analysis				━	━	━	━		
Experimental Construction						━	━	━	━
Finalizing the Designs							━	━	━
* Submit Final Prototype Designs									◇

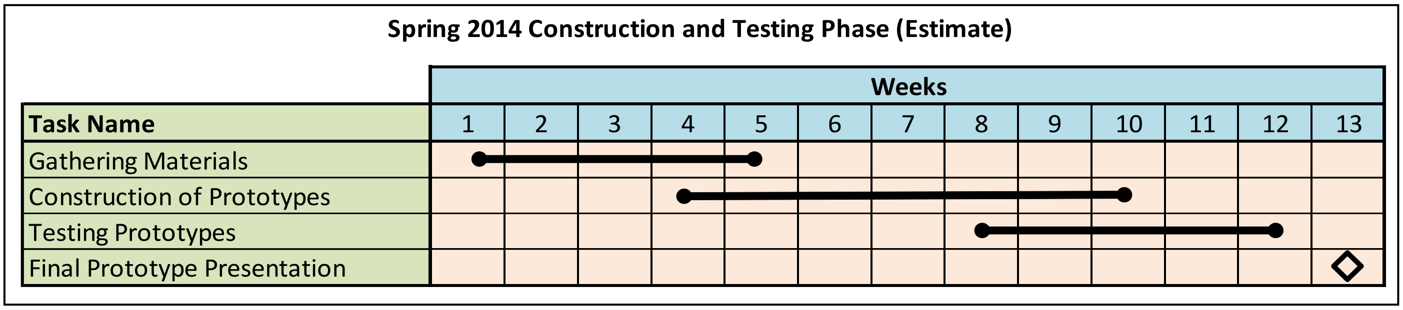
Figure 21: General Fall 2013 Semester Timeline

The 4th week in Figure 21 is highlighted purple because it denotes where we are at in the design phase, and with the completion of this report, we are on schedule with this timeline.

The fall semester will consist specifically on the process of designing and analyzing of the roof prototypes.

- The design phase of the active roof prototypes will take four weeks prior to making a final decision to select what prototype design will best satisfy the projects problem statement.
- Within the fourth week of selecting a prototype design, the design analysis will be initiated unto its completion in the seventh week of the fall semester. This process of analysis will consist of thermal, electrical calculations and then producing 3-D CAD drawings of the three prototype designs.
- Approximately by the end of the fifth week, we hope to start the experimental construction of the Heating/ Cooling System and the Active Roof System
- Once the design analysis is completed, we will begin to finalize the designs of the project unto its final completion for submission for the fall semester.

The general projected spring timeline is shown in Figure 22 below:



Spring 2014 Construction and Testing Phase (Estimate)

	Weeks												
Task Name	1	2	3	4	5	6	7	8	9	10	11	12	13
Gathering Materials	●	━	━	━	●								
Construction of Prototypes				●	━	━	━	━	━	●			
Testing Prototypes								●	━	━	━	●	
Final Prototype Presentation													◇

Figure 22: General Projected Spring 2014 Semester Timeline

The spring semester will consist specifically on the construction of the design prototype and the testing of the prototype under the applications of environmental conditions. This semester will consist of a 13 week process until the final prototype presentation.

- For the beginning of the first five weeks, we will collect the required materials to construct the prototype within the project's budget limits.
- At the fourth week, we will construct the prototypes for the following six weeks until the final completion of the prototypes in the tenth week as expected.
- At the eighth week, we will conduct testing of the prototypes under the applications of the environmental conditions for next following four weeks. Within this process

we will be making improvements and adjustments to the construction of the prototype based on the testing results.

- We expect to be completed with the testing the prototypes at the twelfth week of the spring semester prior to the week of our final project presentation.

2.9 Summary

The amount of power consumption to maintain interior building temperatures at a comfortable temperature is too high. Therefore, this problem situation requires our team to perform engineering quality analysis to design a prototype that will best satisfy the needs and requirements of our client.

This project consists of designing and constructing three prototypes with different roof system: active, passive and control. Each prototype will be a scale model of a small 30,000 square foot Wal-Mart building with 25 foot ceilings. The prototypes will have the interior dimensions of 4.5 feet by 4.5 feet and 0.65 feet tall. These dimensions along with the amount of insulation on the prototypes all were base off the R-value Scale Factor and Thickness Scale Factor which resulted in selecting the 3/32 inch cork to be the prototypes insulation.

Based on the research presented the reflective panels on the roof of the passive prototype will be angled at 43^o, so that it will allow the roof to absorb the sunlight in the winter and reflect the sunlight in the summer.

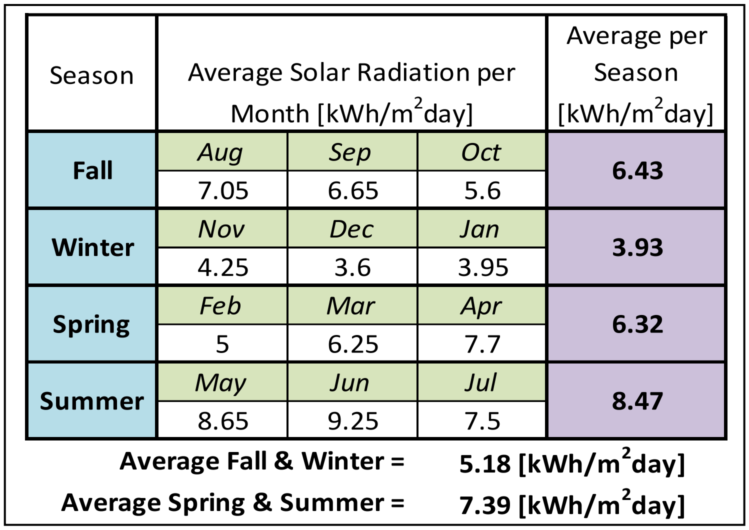
As for the active roof system, the reflective panels will be rotated by a motor which will be controlled by an arduino board. The arduino board will have a program which will control the power to the motor and will rotate the panels according to the time of day and year. The program for this prototype will be based off of the average sunset/sunrise times and angles for Flagstaff.

Each prototype will have two internal systems: one to measure the temperature and one to heat/cool the interior. Since the prototypes are ideally suppose to be keep at an internal temperature of 70^oF, the “Fully Automated” internal temperature measuring system will send data to the attached arduino board every ten minutes, and then based on that reading the arduino board will either turn on or off the “Air Flow” heating/cooling system and switch the system from between blowing hot and cold air.

3.0 Engineering Analysis

3.1 Average Solar Radiation

Before actual calculations could begin, we needed to research the solar radiation found in the Flagstaff area. The average radiation values for each month are shown in Figure 23 below [17]:



Season	Average Solar Radiation per Month [kWh/m^{2}day]			Average per Season [kWh/m^{2}day]
Fall	*Aug*	*Sep*	*Oct*	**6.43**
	7.05	6.65	5.6	
Winter	*Nov*	*Dec*	*Jan*	**3.93**
	4.25	3.6	3.95	
Spring	*Feb*	*Mar*	*Apr*	**6.32**
	5	6.25	7.7	
Summer	*May*	*Jun*	*Jul*	**8.47**
	8.65	9.25	7.5	

Average Fall & Winter = 5.18 [kWh/m^{2}day]

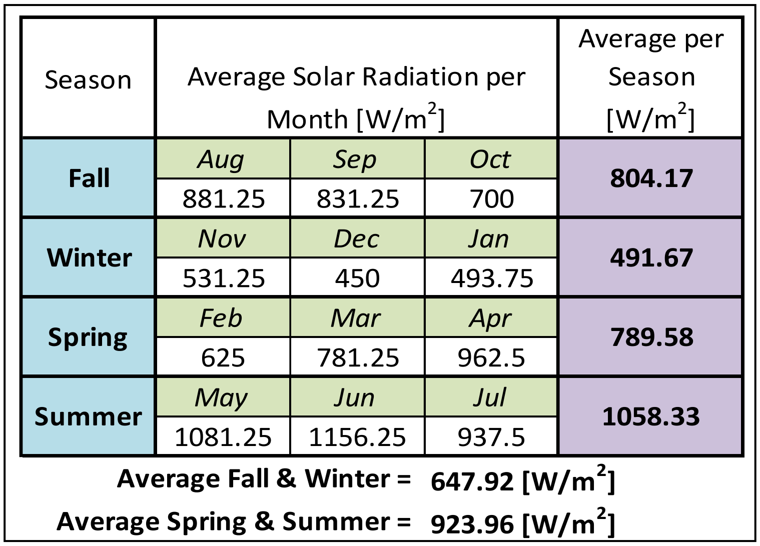
Average Spring & Summer = 7.39 [kWh/m^{2}day]

Figure 23: Average Solar Radiation [kWh/m^{2}day] for Fall/Winter &

However, in order to use the data shown above in any of the following calculations or simulations presented in this report, it had to be converted from $\frac{kWh}{m^2day}$ to $\frac{W}{m^2}$. This was done by using the dimensional analysis shown below:

$$1\frac{kWh}{m^2day}*\frac{1000\ W}{1\ kw}*\frac{1\ day}{8\ hours\ of\ Sun}=1\frac{W}{m^2}$$

The reason why the radiation has been divided by 8 hours in a day rather than 24 hours is because it is more accurate to divide by 8 due to the fact that there is on average approximately 8 hours of sunlight per day. The converted radiation values are shown in Figure 24 below:



Season	Average Solar Radiation per Month [W/m^2]			Average per Season [W/m^2]
Fall	*Aug*	*Sep*	*Oct*	**804.17**
	881.25	831.25	700	
Winter	*Nov*	*Dec*	*Jan*	**491.67**
	531.25	450	493.75	
Spring	*Feb*	*Mar*	*Apr*	**789.58**
	625	781.25	962.5	
Summer	*May*	*Jun*	*Jul*	**1058.33**
	1081.25	1156.25	937.5	

Average Fall & Winter = 647.92 [W/m^2]

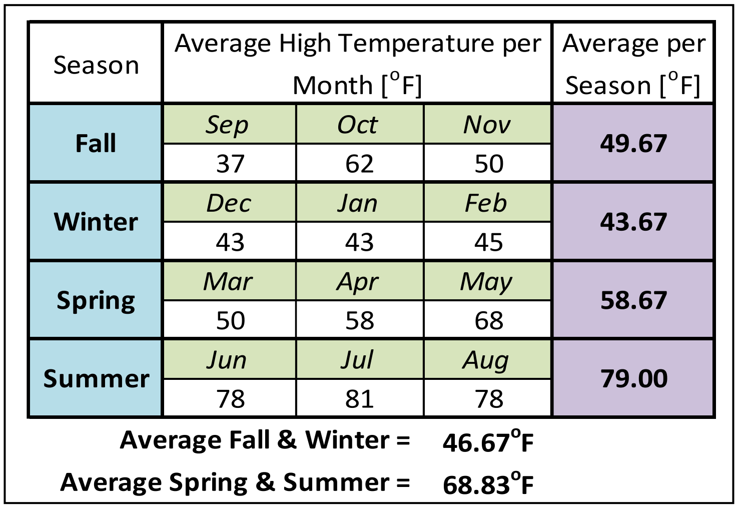
Average Spring & Summer = 923.96 [W/m^2]

Figure 24: Average Solar Radiation [W/m^2] for Fall/Winter & Spring/Summer

So during the fall months of August, September and October, the average solar radiation is 804.17 W/m^2. The winter months of November, December and January have an average solar radiation of 491.67 W/m^2. The spring months of February, March and April have an average solar radiation value of 789.58 W/m^2, which is close to the value for the fall months. The summer months of May, June and July have the highest average solar radiation value at 1058.33 W/m^2. To calculate the irradiation value, the average between the fall and winter months as well as the average between the spring and summer months were used. These were 647.9 W/m^2 and 923.9 W/m^2 respectively.

3.2 Average Outside Temperature

A similar process to the solar radiation calculations were used to find the average outside temperature for the Flagstaff area, and these values are shown in Figure 25 below [18].



Season	Average High Temperature per Month [°F]			Average per Season [°F]
Fall	*Sep*	*Oct*	*Nov*	**49.67**
	37	62	50	
Winter	*Dec*	*Jan*	*Feb*	**43.67**
	43	43	45	
Spring	*Mar*	*Apr*	*May*	**58.67**
	50	58	68	
Summer	*Jun*	*Jul*	*Aug*	**79.00**
	78	81	78	

Average Fall & Winter = 46.67°F

Average Spring & Summer = 68.83°F

Figure 25: Average Temperature for Fall/Winter and

The fall and winter values were fairly close together. Ranging from September to February, the average fall temperature is 49.67°F and the average winter temperature is 43.67°F. The spring and summer values were further apart. Ranging from March to August, the average spring temperature is 58.67°F and the average summer temperature is 79.00°F. For our calculations, the average between the fall and winter months as well as the spring and summer months was determined. These were 46.67°F and 68.83°F respectively

3.3 Average Convection Coefficients

In order to complete the Transient Conduction calculations, which will be discussed in the next section of this report, first the average convection coefficients of the air above the roof of the prototypes must be calculated. A convection coefficient is a value which represents how well heat is able to transfer into that specific fluid at a given temperature.

In the case of our prototype the type of convection which we are concerned with is the nature convection in the air about the roof. The roof of the prototypes can be modeled as a horizontal plate with an upper hot surface, as soon in Figure 26 below [19]:

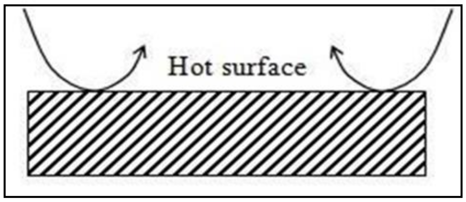


Figure 26: Diagram of Natural Convection of a Horizontal Plate with Upper Hot Surface

The issue that arose while trying to find the average convection coefficient (h_{avg}) for each prototype during each season group was that in a value for the roof surface temperature (T_s) was needed to determine the properties needed to calculate h_{avg}. So then “h” had to be calculated using an iterated process with the following steps:

1st: Guess a roof surface temperature (T_s)
2nd: Calculate h_{avg} using guessed T_s
3rd: Calculate the T_s using h_{avg}
4th: If needed run the program again with a new guessed T_s value

For the 4th step in the process above the newly guessed T_s value was estimated based on how close the calculated value of T_s is to the guessed value.

In order to make this iterative calculation process easier and more time efficient than calculating each step by hand, a Matlab program was written and used. This program used to calculate the h_{avg} and T_s values has been included in this report as Appendix A.

To calculate the T_s values using the h_{avg} values the following emissivity values were used: for $\varepsilon_{\text{black paint}} = 0.92$ [20], $\varepsilon_{\text{white paint}} = 0.99$ [20], and $\varepsilon_{\text{Polished Aluminum}} = 0.92$ [21] (for reflective roof panels). Another set of values which were needed in order to calculate the T_s values were the percent of solar radiation which is estimated to be reflected away from the roof by the reflective roof panels on the passive and active prototype. It should be noted that since the control roof will have no reflected panels, 0% of the solar radiation will be reflected during both season groups. Figure 5 on the next page shows the idealized percent of solar radiation reflection of the active prototype for each seasonal group and the estimated percent of solar radiation reflection of the passive prototype:

Table 4: Percent of Solar Radiation Reflected by Panels for Each Season Group

Prototype	Fall/Winter	Spring/Summer	
Active	0	100	*Ideal*
Passive	35	65	*Estimated*

3.3.1 Equations to Calculate the Average Convection Coefficients

The first step in calculating the $\mathrm{h_{avg}}$ value is to calculate (the dimensionless) Nusselt Number (Nu_L) for a horizontal plate with an upper hot surface, and in order to do that the following variable corresponding to the approximated average temperature (discussed in the next paragraph) need to be found: the Grashof Number (Gr_L), the Prandtl Number (Pr), the thermal conductivity (k), and the kinematic viscosity (v). All these values but Gr_Lcan be found in Table A.4 in Appendix A of the textbook Fundamentals of Heat Transfer and Mass Transfer [19]. An equation will be needed to calculate Gr_Lwhich will be discussed later.

After guessing a $\mathrm{T_s}$ value the next step is to calculate the film temperature ($T_f = \frac{T_s+T_\infty}{2}$ [19]), where T_∞ is the value of the average outside temperatures for each season calculated in section 2. Using this T_f values for the properties Pr, k, and v can be found by linear interpolation from the table previously discussed.

From there the Gr_Lnumber may be calculated by using the following equation: $Gr_L = \frac{1}{v^2}[gB(T_s - T_\infty)L^3]$ [19] where $g = 9.81\frac{m}{s^2}$ (gravity), $B = \frac{1}{T_f}$ [19] (since we are dealing with air), and $L = 4.5$ft (which is the smallest length of the roof based on the interior dimensions of the Prototype).

The Rayleigh Number ($Ra_L = Gr_L * Pr$ [19]) can now be calculated and then it will be needed to find the Nu_L value. For the configuration of a horizontal plate with an upper hot surface, $Nu_L = 0.54{Ra_L}^{1/4}$[19]. It is now that the $\mathrm{h_{avg}}$ value may be calculated by setting $Nu_L = \frac{\mathrm{havg*L}}{k}$ [19] and then solving for $\mathrm{h_{avg}}$.

It now in the iterative process that the initially guessed T_s value has to be checked by calculating the T_s that would result by using the $\mathrm{h_{avg}}$ value the guessed T_s was used to calculate.

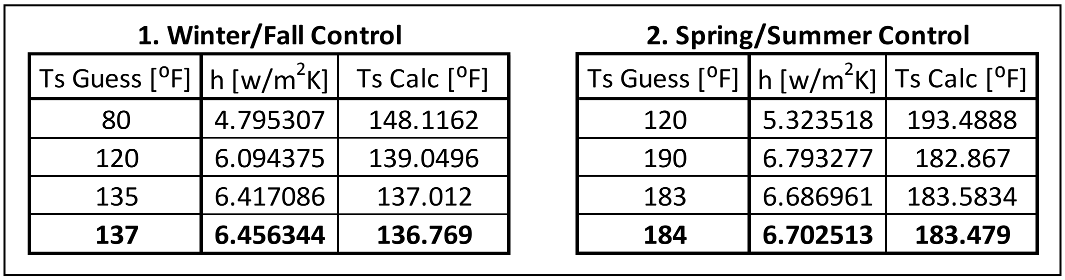
To do this, a simple energy rate balance can be applied for the roof: $\Delta\dot{E}_{in} - \Delta\dot{E}_{out} = 0$. From there, for the case of any of the roof systems the energy rate balance expands to the following equation:

$\alpha G - h_{avg}(T_s - T_\infty) - \varepsilon\sigma\left(T_s{}^4 - T_\infty{}^4\right) = 0$ [19]. In this equation α = the fraction of solar radiation reflected, G = the amount of solar radiation (presented in section 1), ε = emissivity of the roof surface, and σ = the Stephan-Boltzmann constant = $5.67 * 10^{-8}\frac{W}{m^2 \cdot K^4}$ [19].

The energy rate balance above can then be solved for the positive T_s value, and if this T_s value is not within a few tenths of the guessed value of T_s used to calculate h_{avg} then the calculation process must be ran again with a guessed T_s value closer to the T_s value which was calculated in the previous iteration. Examples of the calculated outcome values of this iteration are shown in the table of the next section.

3.3.2 Calculated Average Convection Coefficients

The calculations from the iteration of h_{avg} calculations for the ***control*** prototype during the fall/winter and spring/summer season groups are shown in Figure 27 below, and the row of values which is bolded is the value of h_{avg} which was selected to be used in future calculations.



1. Winter/Fall Control

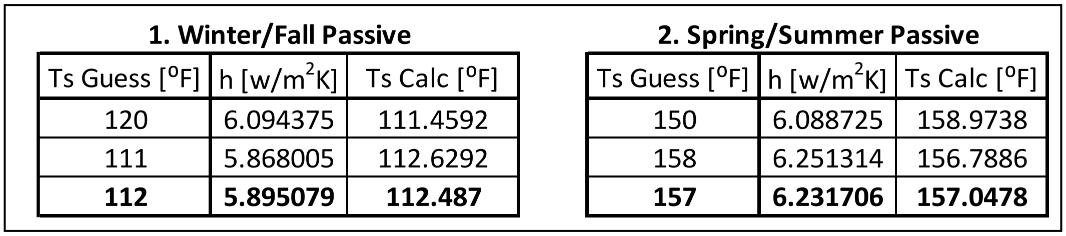
Ts Guess [^{o}F]	h [w/m^{2}K]	Ts Calc [^{o}F]
80	4.795307	148.1162
120	6.094375	139.0496
135	6.417086	137.012
137	**6.456344**	**136.769**

2. Spring/Summer Control

Ts Guess [^{o}F]	h [w/m^{2}K]	Ts Calc [^{o}F]
120	5.323518	193.4888
190	6.793277	182.867
183	6.686961	183.5834
184	**6.702513**	**183.479**

Figure 27: T_s Guesses, Resulting h Values and Calculated T_s Values for Control Prototype

The calculations from the iteration of h_{avg} calculations for the ***passive*** prototype during the fall/winter and spring/summer season groups are shown in Figure 28 below:



1. Winter/Fall Passive

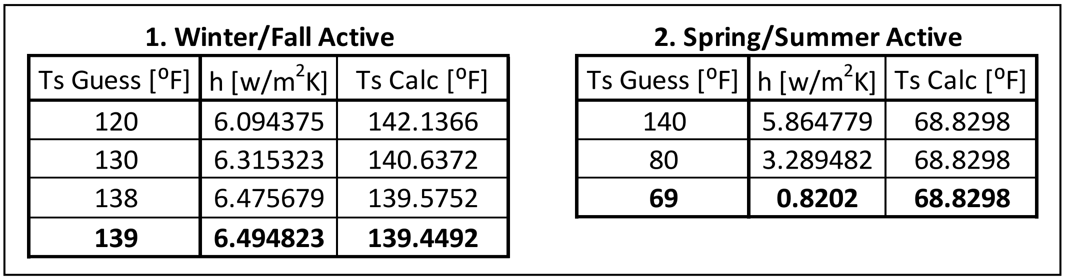
Ts Guess [^{o}F]	h [w/m^{2}K]	Ts Calc [^{o}F]
120	6.094375	111.4592
111	5.868005	112.6292
112	**5.895079**	**112.487**

2. Spring/Summer Passive

Ts Guess [^{o}F]	h [w/m^{2}K]	Ts Calc [^{o}F]
150	6.088725	158.9738
158	6.251314	156.7886
157	**6.231706**	**157.0478**

Figure 28: T_s Guesses, Resulting h Values and Calculated T_s Values for Passive Prototype

The calculations from the iteration of h_{avg} calculations for the ***active*** prototype during the fall/winter and spring/summer season groups are shown in Figure 29 below:



1. Winter/Fall Active

Ts Guess [^{o}F]	h [w/m^{2}K]	Ts Calc [^{o}F]
120	6.094375	142.1366
130	6.315323	140.6372
138	6.475679	139.5752
139	**6.494823**	**139.4492**

2. Spring/Summer Active

Ts Guess [^{o}F]	h [w/m^{2}K]	Ts Calc [^{o}F]
140	5.864779	68.8298
80	3.289482	68.8298
69	**0.8202**	**68.8298**

Figure 29: T_s Guesses, Resulting h Values and Calculated T_s Values for Active Prototype

Table 5 summarizing all the h_{avg} values which have been selected to be used in the next section's calculations and the T_s values which lead to calculating the h_{avg} value is shown below:

Table 5: Summary of T_s Guesses, Resulting h Values and Calculated T_s Values

Prototype	Seasons	Ts Guess [^{o}F]	Ts Calc [^{o}F]	h [w/m^{2}K]
Control	Winter/Fall	137.00	136.77	6.46
	Spring/Summer	184.00	183.48	6.70
Passive	Winter/Fall	112.00	112.49	5.90
	Spring/Summer	157.00	157.05	6.23
Active	Winter/Fall	139.00	139.45	6.49
	Spring/Summer	69.00	68.83	0.82

It is worth pointing out here that the T_s of the active prototype during the spring/summer season group is the same temperature which we calculated to be the average outside/ambient temperature during this season group. This makes sense because if, ideally, 100% of the solar radiation during the spring/summer is reflected away from the reflected panels on the roof of the active roof, then the T_s should be equal to the outside temperature.

3.4 Transient Conduction

In transient conduction, a solid object is changing temperature as time a function of time, so in order to use this type of heat transfer model we had to make a very important assumption. The assumption are that due to the small ceiling height of the inside of our prototypes (0.65ft) that there will be no internal circulation (advection) and that means that it can be assumed that the main mode of heat transfer through the air within the prototype will be by conduction rather than convection. This is an important assumption because the interior and roof (cork insulation) of the prototype need to be modeled as one solid object in order to apply this type of heat transfer analysis, and since we assumed that heat will only be transferred by conduction we are able to model the interior and the cork insulation as one solid object.

How we model the roof as one solid object as one solid object is by evaluating the properties of each of the material types (air and cork) at room temperature which approximately equals 300K, and then taking a weighted average of these values based on the thickness of each material. The following property values for air and cork were taken from Table A.3 and Table A.4 [19], respectively: $\rho_{cork} = 120\frac{kg}{m^3}$, $k_{cork} = 0.039\frac{W}{m{\cdot}K}$, $Cp_{cork} = 1800\frac{kJ}{kg{\cdot}K}$, $\rho_{air} = 1.1614\frac{kg}{m^3}$, $k_{air} = 0.0263\frac{W}{m{\cdot}K}$, and $Cp_{air} = 1.007\frac{kJ}{kg{\cdot}K}$. Where in this context ρ is the density and Cp is the specific heat of the material at that given temperature. So for example, the weighted average for k was found by using the following equation: Weighted Avg $= \frac{t_{cork}k_{cork}+t_{air}k_{air}}{t_{cork}+t_{air}}$, where $t_{cork} = 3\left(\frac{3}{32}in\right)\left(\frac{1\,ft}{12\,in}\right) = 0.0234ft$ (because 3 layers of $\frac{3}{32}$in cork used for ceiling) and $t_{air} = \text{height of interior} = 0.65ft$. The same type of calculation was used to find the weighted average of ρ and Cp. Table 6 below shows the values of these weighted average properties:

Table 6: Calculated Values of Needed Properties using a Weighted Average

Property	Symbol	Average	Units
Density	ρ	37.05	kg/m^3
Thermal Conductivity	k	0.03	W/m·K
Specific Heat	Cp	1246.5	J/kg·K

Now the Biot Number (Bi) can be calculate using the formula $Bi = \frac{h_{avg}L_c}{k}$ [19] where h_{avg} is the values shown in the previous section and L_c is the characteristic length of the roof which is $L_c = \frac{V_{olume}}{A_{surface}} = \frac{(4.5*4.5*0.65)ft}{(4.5*4.5)ft} = 0.65ft$. From here the Bi number is used to pull two particular constant values off of Table 5.1 [19]: ζ_1 and C_1.

For this case the approximate solution is found for the mid-plane of the modeled solid object and the equation used was $\frac{T_o-T_\infty}{T_i-T_\infty} = C_1\cos\left(-\zeta_1{}^2F_o\right)$, where T_∞ is the outside/ambient air presented in section 3.2, $T_i = 70^oF$ which is the initial temperature of the inside of the prototype, $T_o = 75^oF$ which is the temperature which our team has decided is the temperature which interior of buildings become uncomfortable, and $F_o$is the Fourier Number and is equal to $\frac{\alpha_{Fo}*time}{L_c{}^2}$

where $\alpha_{Fo} = \frac{k}{\rho * Cp}$ (using the weighted values calculated) and $time$ is the time (in seconds) it takes the modeled solid to reach the T_o temperature if starting at the T_i temperature.

Needless to say this calculation, if done by hand, is rather labor intensive so our team created a Matlab program that would calculate the time variable based on the input values of h_{avg}, ζ_1 and C_1 input by the user. This program is included in this report as Appendix B.

These calculated time values for each prototype during each season group is shown in Table 7 below:

Table 7: Time for the Lumped Solid of the Prototype to Reach 75^{o}F from 70^{o}F

	Time to Reach 75^{o}F from 70^{o}F (min)	
Prototype	**Winter/Fall**	**Spring/Summer**
Control	2.657	80.392
Passive	2.660	80.672
Active	2.656	105.747

The values in the table above prove that this calculation process was done correctly and valid because the time it takes the active roof system to reach $T_o = 75^oF$ in the spring/summer season group is larger than the other two prototypes, and that is accurate because the active roof system has reflective panels which would, ideally, block all the solar radiation from reaching the roof surface. The same kind of thing can be seen with the winter/fall season group for the active roof system, but this time the interior of the prototype will reach $T_o = 75^oF$ the fastest because the panels are now reflecting 0% of the solar radiation and therefore all of it is being absorbed by the black roof below.

The important thing to note about the time values calculated in the Table 7 above is that they were based on our assumption that heat will be transferred by conduction rather than convection, and air has a much lower rate of heat transfer by conduction than it does by convection. So as will be proved in the following section, there is air circulation with the inside of the prototypes, so the heat will be transferred through the air by convection. However, these time values were necessary to calculate because they give us an idea of how fast the inside of the box will heat up during winter/fall compared to spring/summer, and since the calculated time values for winter/fall are all around 2.5 minutes our team has concluded that a heating system is not necessary as part of the air conditioning component of these prototypes. This decision was based off of the fact that since the heat is being transferred by convection rather than conduction than the interior of the box is going to heat up to $T_o = 75^oF$ much faster than in 2.5 minutes as was calculated under the assumption that the heat transfer was by conduction, so even during the winter/fall months, the prototypes will on, average, during testing only need an air conditioning unit to cool down the interior.

3.5 Checking for Internal Circulation

In order to check for circulation within the interior of the prototypes, first the model must be identified as an enclosure with natural convection occurring from within. From there the $\bar{T} = \frac{T_1+T_2}{2}$ value can be calculated using $T_1 = T_{hot} = T_{celing}$ which we chose to be varying temperature from 70^oF to 90^oF because these are the highest ceiling temperatures we expect to have inside the prototypes during testing and $T_2 = T_{cold} = T_{floor}$ which we chose to be either 70^oF or 75^oF because 70^oF is our ideal internal temperature and 75^oF is the temperature at which our air conditioning unit will turn on.

From here the following values are evaluated for air at the $\bar{T}$ temperature where the properties are listed in Table A.3 [19]: Pr and v. From there the following is calculated: $Gr_L = \frac{1}{v^2}[gB(T_s - T_\infty)L^3]$ [19] where just like before, $= 9.81\frac{m}{s^2}$, $B = \frac{1}{T_f}$ [19], and $L = 4.5$ft. From there the Rayleigh Number can be calculated just like before: $Ra_L = Gr_L * Pr$ [19].

In order to efficiently complete this calculation of multiple T_1 and T_2 values a Matlab program was created and has been included in this report as Appendix C. The calculated Ra_L values for various T_1 and T_2 values are shown in Table 8 below:

Table 8: Ra_L Values for Varying Ceiling Temperatures

	Ra_L Number ($*10^9$)for Different $T_{ceiling}$ (^oF)				
T_{floor} (^oF)	70	75	80	85	90
70	0	0.702	1.375	2.020	2.638
75	-	0	0.673	1.319	1.935

For an enclosure, if the Ra_L value is less than 1708 than the buoyancy forces of the air are unable to overcome the resistance of the viscosity of the fluid in the enclosure (in this case air), and therefore there is no natural circulation (natural convection) of the fluid within the enclosure. However, as can be seen in Table 4 above, all of the calculated Ra_L values for every expected T_1 and T_2 values is well above 1708 so therefore there will always be some kind of natural circulation of the air within the prototypes if the ceiling and floor are not at the same temperature (which in testing is highly unlikely).

3.6 Estimating the Temperature of the A/C Air

So in order to keep the interior of our prototype at the desired, constant temperature of 70^oF, our team needs to know at approximately what temperature would the air blown in from the air conditioning unit have to be in order for the interior of the prototype to be cooled from 75^oF (our chosen uncomfortable temperature) to 70^oF.

To begin, the density of air (ρ_{air}) at room temperature is $1.1614\frac{kg}{m^3}$ (as shown in section 4 above). Therefore the mass of the air that would normally be contained in the interior of our prototype is found by $m_{air} = wlh\rho_{air} = (4.5 * 4.5 * 0.65)ft^3\left(\frac{0.0283168\,m^3}{ft^3}\right)\left(1.1614\frac{kg}{m^3}\right) = 0.4329kg$. For the sake of calculation we are assuming that half of the hot air naturally goes out the vents build into the prototype walls, so the $m_{1hot} = m_{1cold} = m_1 = 0.21644kg$, where m_{1hot} is the mass of the hot air (air already inside the prototype) and m_{1cold} is the mass of the air conditioned air been blown into the prototype. Also, $m_2 = 2m_1 = m_{air} = 0.4329kg$, which is the total mass of the resulting ideal gas mixtures.

So to start the analysis a basis energy balance of a closed system is performed: $\Delta U + \Delta KE + \Delta PE = Q_{in} - W_{out}$, which then leads to $U_1 - U_2 = m_1(u_{1hot} + u_{1cold}) - m_2u_2$. This equation can be then solved for u_{1cold}: $u_{1cold} = \frac{m_2u_2 - m_1u_{1hot}}{m_1} = 2(u_2) - u_{1hot}$.

Where u_{1hot} and u_2 can be found by linearly interpolating the values of the internal energy of air at the corresponding $T_1 = 75^oF = 297.039K$ and $T_2 = 70^oF = 294.261K$ from Table A- 22 in the textbook Fundamentals of Engineering Thermodynamics [22]. The needed internal energy values for interpolation are as follows:

- At $T = 290K$: $u = 206.91\frac{kJ}{kg}$
- At $T = 295K$: $u = 210.49\frac{kJ}{kg}$
- At $T = 300K$: $u = 214.07\frac{kJ}{kg}$

So then $u_{1hot} = \frac{(297.039-295)K}{(300-295)K}(214.07 - 210.49)\frac{kJ}{kg} + 210.49\frac{kJ}{kg} = 211.9499\frac{kJ}{kg}$, and then $u_2 = \frac{(294.261-290)K}{(295-290)K}(210.49 - 206.91)\frac{kJ}{kg} + 206.91\frac{kJ}{kg} = 209.9609\frac{kJ}{kg}$.

Entering these values into the u_{1cold} equation created leads to the following:

$$u_{1cold} = 2\left(209.9609\,\frac{kJ}{kg}\right) - 211.9499\,\frac{kJ}{kg} = 207.9719\,\frac{kJ}{kg}$$

However, we want the temperature value of T_{1cold} so we can do this by finding the corresponding temperature to this u_{1cold} value by using Table A-22 [22] again, and as a matter of fact the internal energy and temperatures which are needed for this linear interpolation have actually already been cited above. So to get T_{1cold} , the following formula is used:

$$T_{1cold} = \frac{(207.919-206.91)\frac{kJ}{kg}}{(210.49-206.91)\frac{kJ}{kg}}(295-290)K + 290K = 291.4831K = 64.999^{o}F$$

Therefore, in order to cool down the air within the inside of the prototype from $75^{o}F$ to $70^{o}F$ with half of the hotter air naturally escaping through the vents built into the prototype, the cold air blown from the air conditioning unit would have to be approximately equal to or les than $65^{o}F$.

3.7 Computer Simulated Fluid Modeling

For the computer simulation we used the 4.5ft x 4.5ft x 0.65ft dimensions that we calculated previously for the interior dimensions to represent the air inside the model. The average airspeed of industrial duct systems is 10m/s [23]. The calculated value for inlet temperature is about $65^{o}F$, we chose to use $62^{o}F$ in the simulations because we simulated the worst-case scenario and did not adjust values for the use of panels, which will lower the radiation, thus reducing the interior temperature of the building. With the two simulations, one for the fall/winter and one for spring/summer, each run with 50 iterations. We found that with the cooling system that we plan on using we will be able to keep the model at a temperature of about $77^{o}F$ in the summer and $71^{o}F$ in the winter. These temperatures simulation can be seen in Figures 30 and 31 on the next page. Using the panels will result in being able to reach temperatures closer to the target temperature of $70^{o}F$.

After researching various fans for the inlets we found that placing small individual fans will supply the necessary amount of air so we will not be required to use larger fans [24]. We have found fans that would supply ample airflow which will be supplied to each inlet to cool the building to the desired temperature. These mini fans have an airflow of 2 ft/m^2 which is approximately 10 m/s which is the desire airflow.

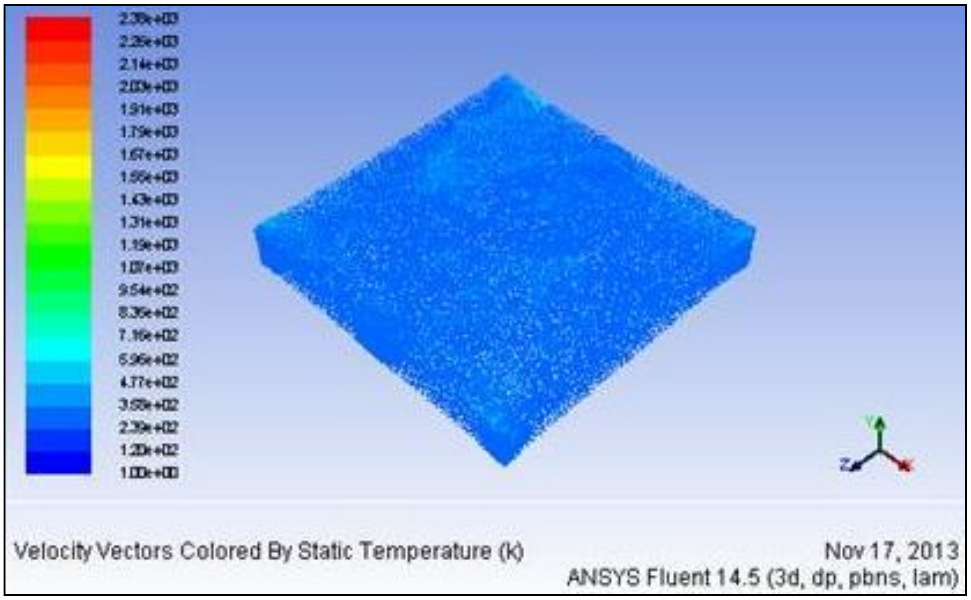


Figure 30: Average Interior Summer Temperature Simulation

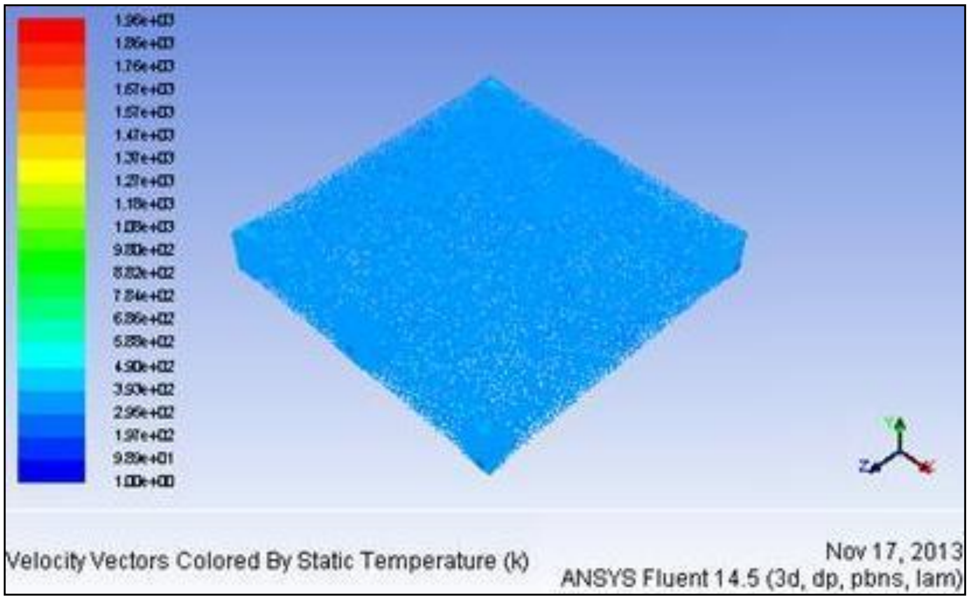


Figure 31: Average Interior Winter Temperature Simulation

We plan to install fan systems for the each of the six inlet hose components to produce the required air flow into the interior model system. The fan system is responsible for maintaining interior temperatures at 70^oF. The simulation process of the Ansys program showed that the fans are required to supply air mass into the interior system at a rate of 10 m/s at 62 ^{o}F at each of the six one inch diameter inlet hose components. We also plan to have four outlet hose systems which will not consist any type of fanning system but rather will produce a natural air flow rate equivalent to the air mass flow intake of the interior system.

3.8 Summary

In order to keep the interior temperature of our prototypes at a comfortable 70 ^{o}F, six inlets, each with individual fans, will be installed on one side of the prototypes. There will be four outlets to circulate the moving air throughout the prototype. With the active or passive system in place, the average interior temperature should be around 77^{o}F in the summer and 71^{o}F in the winter. Based on the heat transfer calculations, the air conditioning temperature should be about 62 ^{o}F and will be blown in at 2 ft/m^{2}. This extra cooling will drop the temperature down to our goal of 70 ^{o}F. Based on these calculations, a heating system will not be required for the prototypes during the winter months. With these conditions and fan implementations, the interior of our prototypes should be able to maintain a 70 ^{o}F interior temperature.

4.0 Finalized Designs

4.1 Final Prototype Designs

The first thing which will be constructed of each prototype is a wooden frame (see Figure 32 below) which will cause the interior space between the constructed walls to be the required 4.5ft x 4.5ft x 0.65ft. The frame will be constructed of square dowels which are originally 36in (3ft) in length, and since the length required of the wooden frame on all four sides is 4.5ft, the square dowels had to be cut in such a way that so that vertical support beams will be needed to support the frame in the middle of each wall.

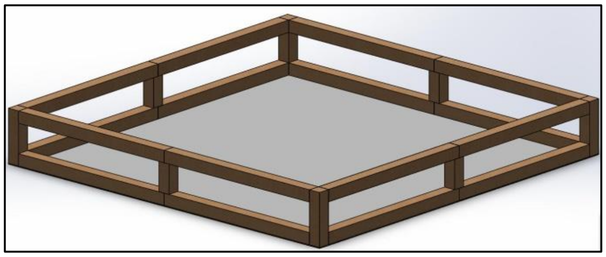


Figure 32: Wooden, Interior Frame for All Prototypes

The interior of each of the prototypes will originally be a simple hollow box made of paper and the cork insulation attached to the outside of this wooden frame (see Figure 33 below), then after completely constructing each box, the holes required for the A/C and venting system will be drilled.

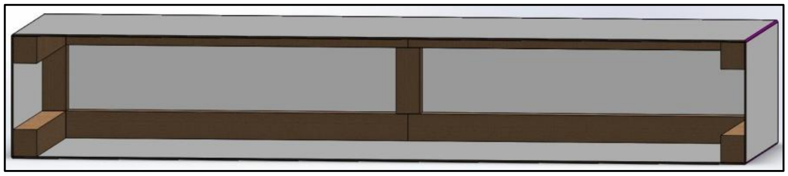


Figure 33: View of the Interior of Each Prototype

The walls which are attached to the outside of the wooden frame will consist of three main components: a poster board layer, the cork insulation layer(s), and then another poster board layer. Where these three layers of each wall meet, there will be a sealant of hot glue to connect all the walls together and reduce the heat transfer in these connecting sections. Figure 34 below shows what this would look like at the intersection of two wall sections (which only have one lay of cork insulation).

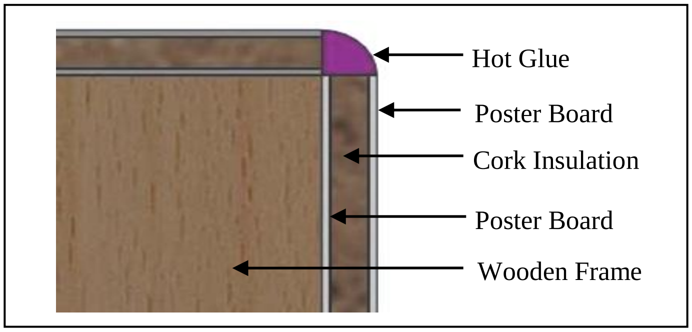


Figure 34: View of the Interior of Each Prototype

Figure 35 below shows what the control roof prototype is expected to look like, and since the poster board is already white, no additional painting of the roof is required.

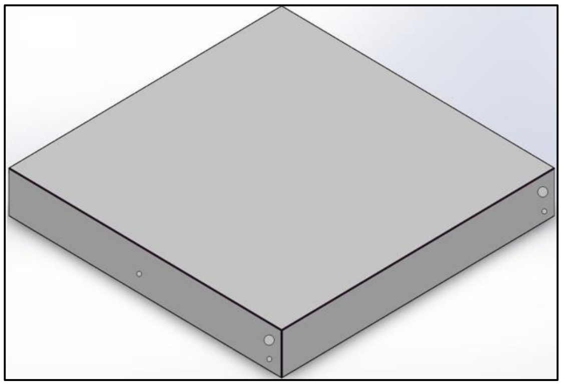


Figure 35: Control Roof Prototype

As described in section 2, the passive roof prototype will have stationary, reflective panels which are at a 43 degree angle and the roof will be painted black. These reflective panels will be constructed out of foam poster board with a layer of Mylar to act as the reflective material. In order to keep the reflective panels on the passive prototype in place a wooden frame with slots cut at the correct angle will be made, and the reflective panels will be glued into place on this wooden frame (see Figure 36 on the next page). Ideally, the reflective panels for the passive prototype will be 4.5ft long, so that each panel can span the length of the roof, but this is dependent on the stiffness of the foam poster board that will be used.

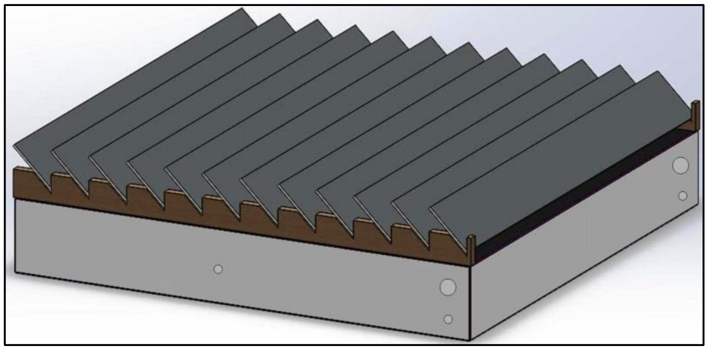


Figure 36: Passive Roof Prototype

The reflective panels for the active roof prototype will constructed of the same material as the passive prototype; however, the panels will only be 2.25ft, which is half the length of the roof, because if they were each the full length of the roof, then they might be too heavy for the motors to rotate. The panels will have a small metal rod attached to the underside so that they can be connected to the rotation system easy. Also, the reflective panels will be connect to a drive train or shaft system which will act as the rotating system and be controlled by 2 motors on each side of the two rows of panels, so there will be four motors in total. A wood frame with triangular slots will be used to support the side of the panels which is not attached to the rotation system. As for which system will rotate the panels, this must be decided upon based experimentation once the active prototype and panels are assembled. A model of the active prototype can be seen in Figure 37 below:

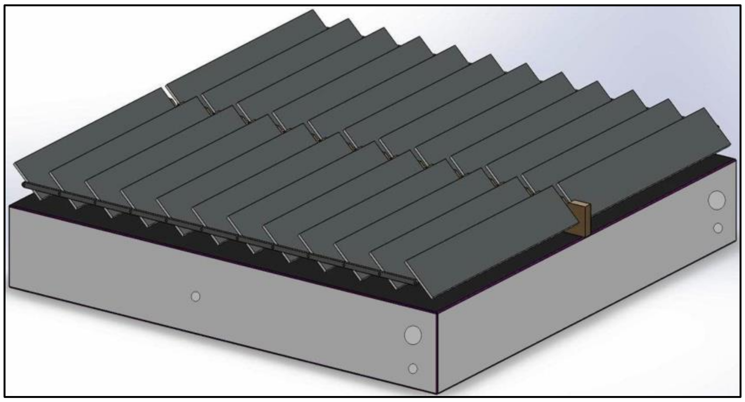


Figure 37: Active Roof Prototype

4.2 Estimated Cost

Based on the constructed models of the three different prototypes, the estimated bill of material is shown in Table 9 on the following page. The amount of each material needed was estimated based on how the materials would need to be cut in order to construct the different components of the prototypes, and the costs of each of those materials are based off of the price of that certain material from the most reliable supplier (like HomeDepot of Wal-Mart).

Table 9: Estimated Bill of Material and Cost

For	Material	Size	Supplier	Price per Unit	Quantity Needed	Cost
Frame/ Panel Cradles	Square Wooden Dowels	36"x1"	HomeDepot	$3.50	72	$252.00
Walls	Poster Board	0.02"x22.0"x28.0"	Walmart	$0.99	36	$35.64
	White Duct Tape	20 Yards	OfficeDepot	$4.99	1	$4.99
Insulation	Light Cork Roll	24"x96"x3/32"	Hobby Lobby	$14.99	22	$329.78
Screws	Nails	2-1/2" (1 lb)	HomeDepot	$9.37	1	$9.37
Sealing	Hot Glue Gun	n/a	Hobby Lobby	$6.99	1	$6.99
	Hot Glue Sticks	20 pieces	Hobby Lobby	$6.99	2	$13.98
Panels	Mylar	25'x4'x2mm	HomeDepot	$29.97	1	$29.97
	Foam Poster Board	3/16"x22.0"x28.0"	Walmart	$3.00	7	$21.00
Control Systems	Arduino Uno	ATmega328/5V	Radioshack	$27.99	2	$55.98
Active panel motor	Arduino servo motor	1"x0.5"x1.15"	Adafruit	$9.95	4	$39.80
Temperature Monitor	n/a	4"x3.05"x1.5"	MicroDAQ	$285.00	1	$285.00
Inlet Fan	n/a	1"x1"x0.4"	Micro Center	$9.99	18	$179.82

It is very important to note that the total cost estimate of $1264.32 for constructing the three prototypes does not include the price of the A/C units at this time. This is due to the fact that our team has not yet been able to find reasonably priced and small sized A/C units for the prototypes.

4.3 Summary

The three prototypes will all have the same basic internal structure made out of a wooden frame with poster board walls, then the cork insulation, and finally another layer of poster board. Hot glue will be used to seal the gap between the connections of each of the walls.

The reflective panels for both the active and passive roof prototypes will be constructed from foam poster board and then a top layer of Mylar. The panels of the passive roof prototype will be held in place at the required 43° angle by a wooden frame with slots cut into it, and the panels of the active roof prototype will be connected to a rotation system (either a drive train or a shaft system, to be decided upon later during testing) which will be controlled by four motors. The panels of the passive roof prototype will be the length of the prototype, while the active roof panels will be half the length of the prototype.

The estimated cost of construction for all three prototypes is $1264.32, and that estimate does not include the cost of the A/C units for the prototypes because an appropriate one has not yet been found.

5.0 Conclusion

The need statement behind this project is that the power usage to keep the interior of large, warehouse like, buildings at a cool comfortable temperature is too high, so our project will investigate the effectiveness of two different roof systems. The two roof systems which will be tested are the passive and active roof, but then the data from these two roof systems will be compared to a control roof system

The passive roof prototype will have stationary, reflective, roof panels which are angled at 43^o, and the active roof prototype will have reflective, roof panels which will rotate automatically, by use of a set of four motor controlled by an audrino board, throughout the day as the sun moves in the sky.

All prototypes will be a scale model of a small, 30,000 square foot Wal-Mart building. The scaling factor was calculated using the available material for insulating the prototypes, and the prototype insulation was chosen to be 3/32inch cork. Using the scaling factor it was found that the interior dimensions of the prototypes should be 0.65feet by 4.5feet by 4.5feet. In order to make the insulation for the prototype to be scaled properly to the insulation that would be used in a large warehouse building, the walls of the prototypes will have one layer of cork, the ceilings will have three layers and the floor will have two layers.

The walls of the prototypes will be constructed of 3 components fastened together: poster board, cork, and then another layer of poster board. These walls will then connect to a wooden frame which will be built from 1inch square dowels, and hot glue will be used to seal the corners where the walls meet. The reflective panels for the passive and active roof prototypes will be made from foam poster board and then a layer of Mylar.

During testing, the interior of all prototypes must be consistently around 70^oF, and this temperature will be measured by using the, selected, automatic temperature measuring system. This temperature measuring system will send the temperature readings of each prototype to an audrino board and then the audrino board will turn on the appropriate A/C system.

By heat transfer analysis, it was found that a heating system was not required during the testing of these prototypes, so only an A/C system is needed to keep the interior of the prototypes consistently at 70°F. The A/C system which we have chosen to go with is the automatic air, which will blow cold air into the prototypes using six inlet holes that are 1inch in diameter, and then the hot air will naturally vent out of the four outlet holes that are 2inch in diameter.

By basic thermodynamic analysis of the air mixture, it was found that the temperature of the air blowing from the A/C unit needs to be approximately 65°F in order to keep the interior of the building at about 70°F.

To construct all three prototypes it is estimated that the total cost will be around $1,264.32; however, this amount does not include the cost of the A/C systems for the prototypes, because an appropriate sized unit has not been found yet.

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Appendix A: Matlab Code to Calculate the Average Convection Coefficient (h_{avg})

```
% Date Created: 11/15/2013
% Presentation Date: 11/18/2013
% Authors: Capstone Team 06
% Head Editor: Krysten Whearley
% Program Description: Calculating the Convection Coefficient (h) for the
%                      Free Convection above the Prototype Roof

function main
% List Givens
To = (5/9)*(75-32)+273;          % To=75F (Need all temps in K)
Ti = (5/9)*(70-32)+273;          % Ti=70F
L = 4.5*0.3048;                  % Length of roof ft to m
rho = 5.67*10^(-8);              % W/m2K4 (Stephan-Boltzman Constant)
e_black = 0.92;                  % Emissivity Black Roof (Passive & Active)
e_reflect = 0.05;                  % Emissivity Polished Aluminum (Refelective Panels)
e_white = 0.99;                  % Emissivity White Roof (Control)

% List Assumptions
seasons=input('Enter 1(Fall/Winter) & 2(Summer/Spring): ');
     % Input initital guess for Ts of roof to calc h for air above roof
Ts_guess_F = input('Guess of Ts: ');
Ts_guess = (5/9)*(Ts_guess_F-32)+273; % Convert T(F) to T(K)
  if seasons==1
      T_inf = (5/9)*(46.67-32)+273;   % for Fall/Winter: T_inf=46.67F
      G_irrad = 647.9167;             % W/m2
  elseif seasons==2
      T_inf = (5/9)*(68.83-32)+273;   % for Summer/Spring: T_inf=68.83F
      G_irrad = 923.9583;             % W/m2
  end

% Calculate Properites of the air using Tf using Table A-4 in Fundamentals
% Heat and Mass Transfer Edition 7
Tf = (Ts_guess+T_inf)/2;
fprintf('Tf = %f K\n',Tf);
   B = 1/Tf;
   if Tf<=300
       T_low=250;
       T_high=300;
       v_low = 11.44*10^(-6);
       v_high = 15.89*10^(-6);
       k_low = 22.3*10^(-3);
       k_high = 26.3*10^(-3);
       Pr_low = 0.720;
       Pr_high = 0.707;
   elseif Tf<=350
       T_low=300;
       T_high=350;
       v_low = 15.89*10^(-6);
       v_high = 20.92*10^(-6);
       k_low = 26.3*10^(-3);
       k_high = 30*10^(-3);
       Pr_low = 0.707;
       Pr_high = 0.700;
   end
   v = ((Tf-T_low)/(T_high-T_low))*(v_high-v_low)+v_low;
   k = ((Tf-T_low)/(T_high-T_low))*(k_high-k_low)+k_low;
   Pr = ((Tf-T_low)/(T_high-T_low))*(Pr_high-Pr_low)+Pr_low;

%------------------------------------------------------------------------%
% Calculating h
Gr_L = abs((1/(v^(2)))*(9.81*B*(Ts_guess-T_inf)*L^(3)));
Ra_L = Gr_L*Pr;
  % For Free Convection of Horizontal Plate with Upper Hot Surface
  if Ra_L<10^(7)
```

```
      Nu_L = 0.54*Ra_L^(1/4);     % Eqn 9.30
  elseif Ra_L>10^(7)
      Nu_L = 0.15*Ra_L^(1/3);     % Eqn 9.31
  end
h = Nu_L*(k/L);

%-------------------------------------------------------------------------%
% Calculating Ts values
roof = input('Enter 1(Control), 2(Passive) & 3(Active): ');

if roof ==1     % For Control Roof
   alpha_cont = 1;    % for all seasons percent absorbtivity
   % aTs+bTs^(4)=c Put into Wolfram to solve for Ts
     a = h;
     b = e_white*rho;
     c = (alpha_cont*G_irrad)+(h*T_inf)+(e_white*rho*T_inf^(4));
   fprintf('%f*x+(%e)*x^(4)=%f\n',a,b,c);   % Input into Wolfram Alpha
   Ts_K = input('Input Ts(K): ');
   fprintf('h = %f W/m2K\n',h);
   Ts_F = (9/5)*(Ts_K-273)+32;               % Convert Ts(K) to Ts(F)
   fprintf('Ts = %f deg F\n',Ts_F);

elseif roof==2               % For Passive Roof
   if seasons==1
       alpha_pass = 0.65;    % for Fall/Winter percent absorbtivity
       e_pass = e_black;
   elseif seasons==2
       alpha_pass = 0.35;    % for Spring/Summer percent absorbtivity
       e_pass = e_reflect;
   end
   % aTs+bTs^(4)=c Put into Wolfram to solve for Ts
     a = h;
     b = e_pass*rho;
     c = (alpha_pass*G_irrad)+(h*T_inf)+(e_pass*rho*T_inf^(4));
   fprintf('%f*x+(%e)*x^(4)=%f\n',a,b,c);   % Input into Wolfram Alpha
   Ts_K = input('Input Ts(K): ');
   fprintf('h = %f W/m2K\n',h);
   Ts_F = (9/5)*(Ts_K-273)+32;              % Convert Ts(K) to Ts(F)
   fprintf('Ts = %f deg F\n',Ts_F);

elseif roof==3            % For Active Roof
   if seasons==1
       alpha_act = 1;     % for Fall/Winter percent absorbtivity
       e_act = e_black;
   elseif seasons==2
       alpha_act = 0;     % for Spring/Summer percent absorbtivity
       e_act = e_reflect;
   end
   % aTs+bTs^(4)=c Put into Wolfram to solve for Ts
     a = h;
     b = e_act*rho;
     c = (alpha_act*G_irrad)+(h*T_inf)+(e_act*rho*T_inf^(4));
   fprintf('%f*x+(%e)*x^(4)=%f\n',a,b,c);   % Input into Wolfram Alpha
   Ts_K = input('Input Ts(K): ');
   fprintf('h = %f W/m2K\n',h);
   Ts_F = (9/5)*(Ts_K-273)+32;              % Convert Ts(K) to Ts(F)
   fprintf('Ts = %f deg F\n',Ts_F);
end

end
```

Appendix B: Matlab Code to Calculate the Time it would Take the Inside of the Prototypes to Reach $T_{uncomfortable}$=75°F using Transient Conduction

```
% Date Created: 11/15/2013
% Presentation Date: 11/18/2013
% Authors: Capstone Team 06
% Head Editor: Krysten Whearley
% Program Description: Calculating the Time it takes the Interior of the
%                      Prototypes to Reach 75 F from 70 F


function main
% List Givens
To = (5/9)*(75-32)+273;          % To=75F (Need all temps in K)
Ti = (5/9)*(70-32)+273;          % Ti=70F

% List Assumptions
seasons=input('Enter 1(Fall/Winter) & 2(Summer/Spring): ');
     % Input initial guess for Ts of roof to calc h for air above roof
  if seasons==1
      T_inf = (5/9)*(46.67-32)+273;  % for Fall/Winter: T_inf=46.67F
  elseif seasons==2
      T_inf = (5/9)*(68.83-32)+273;  % for Summer/Spring: T_inf=68.83F
  end

% Input h value Found from "Capstone_h.m"
h = input('Input h: ');


%Finding Weighted Average Properties of Prototypes
t_c = (3/32)*3*(1/12);   % ft (Thickness of Cork Ceiling Insulation)
t_a = 0.65;              % ft (Height of Inside Ceiling)
  % Values from Table A-3 and A-4 for Cork and Air at T=300K
  dens_c = 120;      % kg/m3
  dens_a = 1.1614;
  k_c = 0.039;       % W/mK
  k_a = 0.0263;
  Cp_c = 1800;       % J/kgK
  Cp_a = 1.007*1000; % kJ/kgK to J/kgK

dens_avg = ((t_c*dens_c)+(t_a*dens_a))/(t_c+t_a);
k_avg = ((t_c*k_c)+(t_a*k_a))/(t_c+t_a);
Cp_avg = ((t_c*Cp_c)+(t_a*Cp_a))/(t_c+t_a);

%-------------------------------------------------------------------------%
%Finding Properties (from Table 5.1 for Plane Wall)
Volume = (4.5*4.5*0.65)*0.028317;   % ft3 to m3
Surf_Area = (4.5*4.5)*0.09290304;   % ft2 to m2
Lc = Volume/Surf_Area;              % Characteristic Length
Bi = (h*Lc)/k_avg;
fprintf('Bi = %f \n',Bi);

 Bi_low = input('Input Bi low: ');
 Bi_high = input('Input Bi high: ');
   L1_low = input('Input L1 low: ');
   L1_high = input('Input L1 high: ');
      L1 = ((Bi-Bi_low)/(Bi_high-Bi_low))*(L1_high-L1_low)+L1_low;
   C1_low = input('Input C1 low: ');
   C1_high = input('Input C1 high: ');
      C1 = ((Bi-Bi_low)/(Bi_high-Bi_low))*(C1_high-C1_low)+C1_low;

%-------------------------------------------------------------------------%
%Finding Time it Takes for the Interior of Prototype to Reach To=75F
alpha_cond = k_avg/(dens_avg*Cp_avg);      % m2/s
```

```
    % Solve Fo from Eqn 5.44
    Fo = (1/(L1^(2)))*log((1/C1)*((To-T_inf)/(Ti-T_inf)));  % in Matlab log=ln
    Fo_abs = abs(Fo);
    % Solve t from Eqn 5.12
    time_s=(Lc^(2)*Fo_abs)/(alpha_cond);
    time_min = time_s/60;
    fprintf('time = %f min\n',time_min);
end
```

Appendix C: Matlab Code to Calculate the Ra_L Numbers for Varying $T_{ceiling}$

```
% Date Created: 11/16/2013
% Presentation Date: 11/18/2013
% Authors: Capstone Team 06
% Head Editor: Krysten Whearley
% Program Description: Calculating the Ra number for the internal convection
%                      of varying ceiling and floor temperatures


% List Givens
T2(1) = (5/9)*(70-32)+273;  % Floor, T1=70F
i= 70;                      % Begin at 70F (Need all temps in K)
count=1;
while i<95
    T1_70(count) = (5/9)*(i-32)+273;  % (Need all temps in K)
    count=count+1;
    i=i+5;
end

T2(2) = (5/9)*(75-32)+273;   % Floor, T1=75F
j=75;                        % Begin at 75F now
count=1;
while j<95
    T1_75(count) = (5/9)*(j-32)+273;
    count=count+1;
    j=j+5;
end

L = 4.5*0.3048;              % Length of roof ft to m

% Calculate Properites of the air using Tf using Table A-4 in Fundamentals
% Heat and Mass Transfer Edition 7
for l=(1:length(T1_70))
T_avg = (T1_70(l)+T2(1))/2;
   B = 1/T_avg;
   if T_avg<=300
       T_low=250;
       T_high=300;
       v_low = 11.44*10^(-6);
       v_high = 15.89*10^(-6);
       Pr_low = 0.720;
       Pr_high = 0.707;
   elseif T_avg<=350
       T_low=300;
       T_high=350;
       v_low = 15.89*10^(-6);
       v_high = 20.92*10^(-6);
       Pr_low = 0.707;
       Pr_high = 0.700;
   end
   v = ((T_avg-T_low)/(T_high-T_low))*(v_high-v_low)+v_low;
   Pr = ((T_avg-T_low)/(T_high-T_low))*(Pr_high-Pr_low)+Pr_low;

Gr_L = abs((1/(v^(2)))*(9.81*B*(T1_70(l)-T2(1))*L^(3)));
RaL_70(l) = Gr_L*Pr;
end


for m=(1:length(T1_75))
T_avg = (T1_75(m)+T2(2))/2;
   B = 1/T_avg;
   if T_avg<=300
       T_low=250;
       T_high=300;
       v_low = 11.44*10^(-6);
```

```
        v_high = 15.89*10^(-6);
        Pr_low = 0.720;
        Pr_high = 0.707;
    elseif T_avg<=350
        T_low=300;
        T_high=350;
        v_low = 15.89*10^(-6);
        v_high = 20.92*10^(-6);
        Pr_low = 0.707;
        Pr_high = 0.700;
    end
    v = ((T_avg-T_low)/(T_high-T_low))*(v_high-v_low)+v_low;
    Pr = ((T_avg-T_low)/(T_high-T_low))*(Pr_high-Pr_low)+Pr_low;

Gr_L = abs((1/(v^(2)))*(9.81*B*(T1_75(m)-T2(2))*L^(3)));
RaL_75(m) = Gr_L*Pr;
end
```