ME 450: FINAL REPORT

Team 29: Façade Testing Device

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ABSTRACT

In preparation for the EPA sponsored P3 competition, a team of architects is aiming to develop a thermally efficient façade system to reduce energy consumption in buildings. The façade system is composed of bio-composite shading elements between two transparent polymer panels. We have been asked to design and manufacture a reusable and durable thermal chamber that is able to measure the thermal transmittance and solar heat gain coefficient of various façade designs. These tests will be used to advise the geometric designs of the shading elements to maximize thermal efficiency.

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LIST OF ABBREVIATIONS AND ACRONYMS

ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASTM	American Society for Testing Materials
CAD	Computer Aided Design
CNC	Computer Numerical Control
CTS	Calibration Transfer Standard
DOE	Department Of Energy
EPA	Environmental Protection Agency
EPS	Expanded Polystyrene
FEHT	Finite Element Heat Transfer
ISO	International Organization for Standardization
MDF	Median Density Fiber
NFRC	National Fenestration Rating Council
OSB	Oriented Strand Board
P3	People, Planet, and Prosperity
QFD	Quality-Function-Deployment
SHGC	Solar Heat Gain Coefficient
SIP	Structural Insulating Panel
U-factor	Thermal Transmittance
USB	Universal Serial Bus

LIST OF VARIABLES

A_s	Specimen surface area
A_{sp}	Surround-panel surface area
C_{sp}	Surround-panel thermal conductance
h	Surface heat transfer coefficient
k_{sp}	Surround-panel thermal conductivity
N_i	Inward-flowing fraction of absorbed radiation
Q_{env}	Heat flow across the thermal chamber walls
Q_{in}	Heat input by the radiant heat source
Q_{net}	Total energy extracted
Q_{rad}	Irradiative heat that crosses the specimen
Q_s	Specimen heat flow
Q_{sp}	Surround-panel heat loss
Q_{sun}	Irradiative heat projected on the specimen
Q''_{sun}	Irradiative heat flux projected on the specimen
$SHGC$	Solar heat gain coefficient
T_a	Ambient air temperature measurement
T_1	Average specimen temperature inside the chamber
T_2	Average specimen temperature outside the chamber
T_c	Average ambient temperature outside the chamber
T_h	Average ambient temperature inside the chamber
T_{p1}	Average surround-panel temperature inside the chamber
T_{p2}	Average surround-panel temperature outside the chamber
T_{sp-in}	Surround-panel temperature on the inside of the chamber
T_{sp-out}	Surround-panel temperature on the outside of the chamber
T_w	Wall temperature measurement
t_{sp}	Surround-panel thickness
U_s	Thermal transmittance, U-factor
ΔT_s	Temperature difference across the specimen
ΔT_{sp}	Temperature difference across the chamber walls
α_s	Solar absorbance of a single-pane specimen
τ_s	Solar transmittance of specimen

1 PROBLEM DESCRIPTION

Most energy is generated by burning natural resources such as coal [1], which generates a serious environmental problem of air pollution. In addition, natural resources are scarce and non-renewable and some professional analysts expect most of these resources to be used within a century. This issue is more visible now than ever with high oil prices becoming increasingly unmanageable. In the quest for a resolution to this serious problem of resource scarcity, many specialists have studied energy consumption in the U.S. The results of these studies conclude that buildings account for 40% [2] of the total U.S. energy consumption.

The overall issue of resource scarcity, as well as the polluting nature of current energy extraction methods, has garnered the EPA's attention. One manifestation of this attention is the P3 competition. Short for People, Planet, and Prosperity, the P3 competition is sponsored by the EPA for university departments and students to develop and foster innovative and novel ideas for achieving the competition's objectives of improving people's well-being, saving the planet, and generating prosperity.

Professor Harry Giles, of the Architecture and Urban Planning department of the University of Michigan, submitted a proposal for the P3 competition to develop a new type of sustainable façade system. The façade system will integrate a fixed bio-composite shading device between two panels of a recyclable polymer. The goal of this design is to increase the thermal performance of the new façade over traditional systems (e.g. double glazing). This project was chosen by the EPA on the basis that is meets the goals of the P3 competition.

The current goal of the overall project is to create a new environmentally friendly façade system that is equivalent to or better than current façade systems in terms of energy efficiency and thermal performance. In order to tackle this problem completely and effectively material scientists, architects, and mechanical engineers will be working together to overcome the programs many obstacle and achieve its many goals. Each group has been given a specific task. The material scientists will be investigating bio-composite materials, polymers and adhesive system, while the mechanical engineers are to design and fabricate a thermal testing chamber to determine the thermal characteristics of the façade systems. The architecture team will conduct the actual design of the façade systems with the process being informed by the other functional groups along the way.

We, as the mechanical engineering team, are responsible for the design and production of a thermal chamber that will be used to test the thermal efficiency and determine the thermal characteristics of the façade system. Specifically, we are to build a reusable and durable thermal chamber that will allow for testing of the thermal transmittance (U-factor) and solar heat gain coefficient (SHGC) of prototype façade systems. The design will include consideration of the placement of heat sources to generate the necessary temperature gradients and testing conditions, as well as, the use of testing equipment and data collection methods.

For testing, we will be given representative façade samples with different shading geometries, which will measure 3 ft × 3 ft × (4-6) in (≈ 0.9144 m × 0.9144 m × (10-16) cm). Figure 1 shows a representative sample of the shading system that will be placed between two polymer panels.

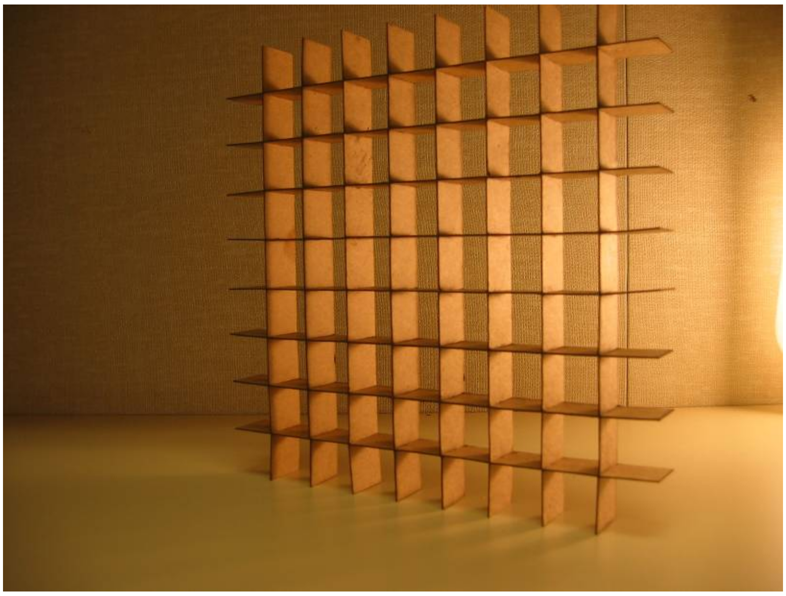

Figure 1: Picture of 4 inch x 4 inch x 4 inch square-grid-shading geometry

2 INFORMATION SOURCES

2.1 Literature Review

In our literature search, we found several methods for determining U-factor of building structures through testing. All of the methods are similarly constructed of a chamber surrounding either one or both sides of the test structure with a significant difference in temperature from one side to the other of the structure. The traditional hot box and guarded hot box have two chambers, one hot and one cold. The one chamber cold box uses the ambient room air as the hot side of the test structure. Dynamic modeling is used in some methods to determine the emissivity of the test structure. We were not able to locate extensive and relevant literature on direct testing of the solar heat gain coefficient; all of the methods described below are primarily for determining U-factor.

2.1.1 Testing Methods

Hot box: The operation of the hot box to determine the U-factor requires the measurement of temperatures, areas, and power. Uncertainties in testing are analyzed by the instrumentation used to make these measurements. Heat losses through the walls must be estimated, and power input to the hot chamber must be measured.

Guarded hot box: The guarded hot box consists of a hot box simulating indoor temperatures connected to a cold box simulating cold outdoor temperatures. The cold box's temperature is regulated through a refrigeration system and can be adjusted to simulate varying cold temperatures. The U-factor can be measured by finding the steady-state U-factor and thermal conductivity through the tested structure. Heat losses through the guarded hot box walls must be measured and taken into account in calculating the specimen properties, and the power input to the system must be measured.

Hot box with dynamic modeling: This method is similar to the traditional hot box but also uses dynamic modeling to estimate the emissivity of the test structure. Heat losses through the test cell walls can be determined during calibration. In addition to U-factor, thermal capacity and specific heat of a structure can be measured. Unlike the hot box and guarded hot box designs, the dynamic hot box does not require steady state conditions and hence, tests can be performed in less time. Power input to the hot box must be measured. U-factor can be directly measured through testing measurements; emissivity of the structure is measured by inputting temperature measurements into a dynamic model that analyzes the test cell as a thermal network.

One chamber cold box with dynamic modeling: This testing cell shown in Figure 2 uses the interface between a cold box, attached to a test structure, and constant temperature indoor air to measure U-factor. The cold box consists of an outer chamber that contains an air conditioning unit and an inner chamber, held in place by rails attached to the outer chamber floor that dampens temperature fluctuations caused by air conditioning. The testing cell is surrounded by a metal frame for structural support with 6cm inner polystyrene walls to ensure insulation. Similarly to the dynamic hot box method, U-factor is measured directly through testing and emissivity is determined through a dynamic model.

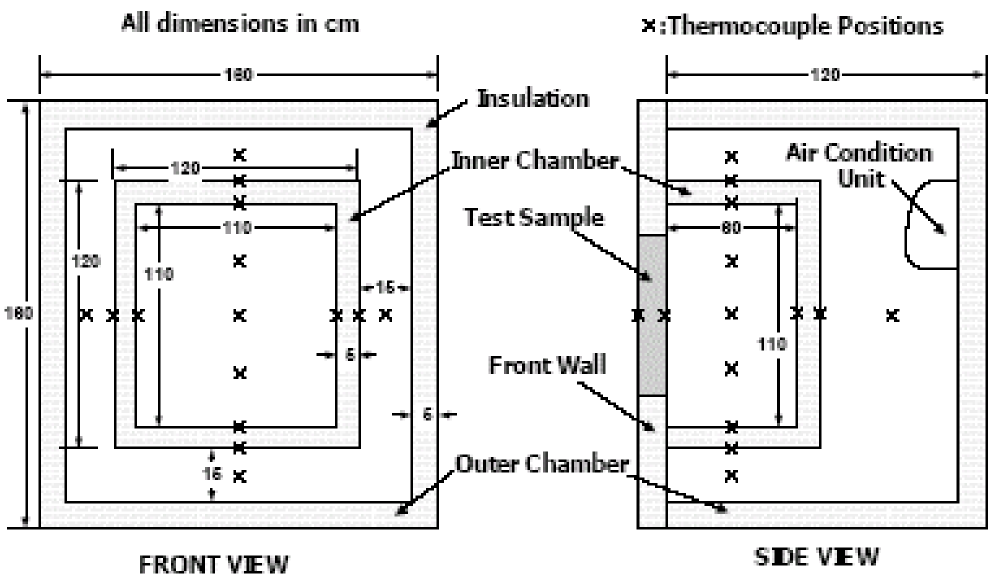

Figure 2: One chamber cold box schematic [3]

2.1.2 Patent Surveys

Patent survey for thermal performance [4]***:*** A pivotally mounted, seasonally adjustable window system has four transparent substrates. Its special sealing of the marginal edge of the substrates provides moisture-free dead airspaces between each substrate. Also a selective coating on each substrate brings the window to the first position, simulating summer conditions, with a shading coefficient of less than 0.20 and a U-factor of less than 0.250 BTU/hr-ft^2-°F (or 1.420 W/m^2-K). In the second position, simulating winter conditions, the window has a shading coefficient of greater than 0.25 and a U-factor of less than 0.250 BTU/hr-ft^2-°F (or 1.420 W/m^2-K) and about 50 percent reflectance to low temperature radiation in the wavelength of greater than 3 microns.

Energy conserving insulative window shade [5]***:*** This window system contains the shaded body comprising opposed walls of thin, sheet-like layers of flexible and resilient material joined together along spaced parallel adhesion lines to form a plurality of contiguous and parallel channels in the shade body. This allows the window system to reduce storage volume. The window system provides an effective convective seal and prevents convective air flow because of a strip-like sealing slat on the surfaces of the frame which oppose the edge portions of the shade body, a slot-like recess formed in the opposite edges of the shade body and the free edges of the sheet-like layers being flexed against the lateral surfaces of the sealing slat.

Seasonally selective passive solar shading system [6]***:*** The shading system of a group of static shading elements for each window of a building generally has non-horizontal and non-vertical slope and tilt angles. The slope and the tilt angles, determined by the latitude of the building and compass bearing of a plane through the window, will help with minimizing the solar heat gain in the summer and maximizing the solar heat gain in the winter.

System for controlling energy through window [7]***:*** A window has motorized blinds that control the entering solar radiation by changing their angular orientation. The photovoltaic sensors provide a signal representative of incident solar radiation. This signal then runs an electrical motor through a microprocessor control device to control the blinds angle.

Portable thermal chamber and testing system [8]***:*** A portable thermal testing system includes a portable thermal chamber box that a tested device can be inserted through. The thermal chamber box will be sealed from the external environment via sliding doors. Air at constant temperature will be evenly distributed over the tested device through the portable thermal chamber box.

2.1.3 Review of Industry Standards

Most fenestration (we consider fenestration products here because the prototype façade systems will have a dual function as a window) products are certified by the National

Fenestration Rating Council (NFRC) [9] and carry a label showing both the U-factor and SHGC of the system. The tests conducted to determine these values are done so in accordance with NFRC standards, as well as American Society for Testing Materials (ASTM) [10] and American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) [11] standards.

Of the available standards the NFRC standards have been deemed to be the controlling standards and hence are presented in more detail.

NFRC 100-series standards: The U-factors of fenestration systems are standardized and calculated based on the NFRC standards.

Purpose: One of the updated standard documents is NFRC 100-2004 ("Procedure for Determining Fenestration Product U-Factors"), which is the compilation of information from the 2001 ASHRAE handbook of fundamentals, most recent ASTM standards and 2001 ISO/FDIS 15099, etc. The other NFRC document is NFRC 102-2004 ("Procedure for Measuring the Steady-State Thermal Transmittance of Fenestration Systems"), which is the compilation of the ASHRAE handbook, ISO/DIS 8990 and many research papers.

Terminology and Definitions: Test specimen steady-state thermal transmittance, U_s (overall coefficient of heat transfer), is the heat transfer rate through a unit area of a test specimen and its boundary air films, induced by a unit temperature difference between the environment on each side.

Surface heat transfer coefficient, h, the time rate of heat flow from a unit area of a surface to its surroundings, induced by a unit temperature difference between the surface and the environment (based on convection and infrared radiation heat transfer).

Standard Test Equipments: A hot box apparatus (thermal chamber) is recommended in the ASTM C 1363-05 to test the thermal performance of the building façade units. The major components of a hot box apparatus are (1) metering chamber on one side of the specimen; (2) climate chamber on the other; (3) the specimen frame providing specimen support and perimeter insulation; and (4) the surrounding ambient space. The purpose of the metering chamber is to provide for the control and measurement of air temperatures and surface coefficient at the surface of the specimen under prescribed conditions and for the measurement of the net heat transfer through the specimen. The purpose of the climate chamber is to provide controlled conditions to the side of the specimen opposite the metering chamber. The test conditions specified are generally those associated with standard or normal outdoor conditions.

The basic hot box apparatus has been assembled in a wide variation of sizes, orientations and designs. Two configurations have been historically used for a majority of the designs. The first is the guarded hot box (Fig. 3), which has a controlled "guard" chamber surrounding the metering box. The second is the regular hot box (Fig. 4) which can be considered as a special case of the guarded hot box in which the surrounding ambient air is used as the guard chamber.

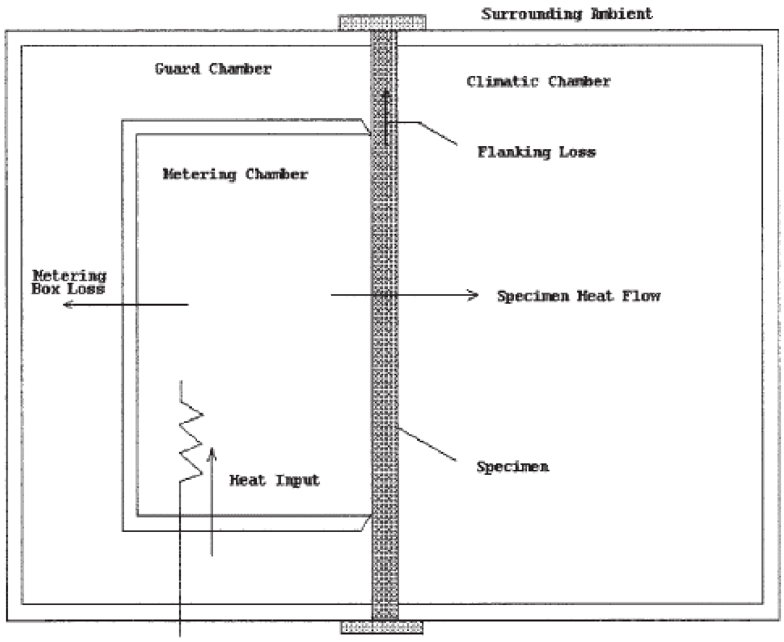

Figure 3: Typical guarded hot box schematic

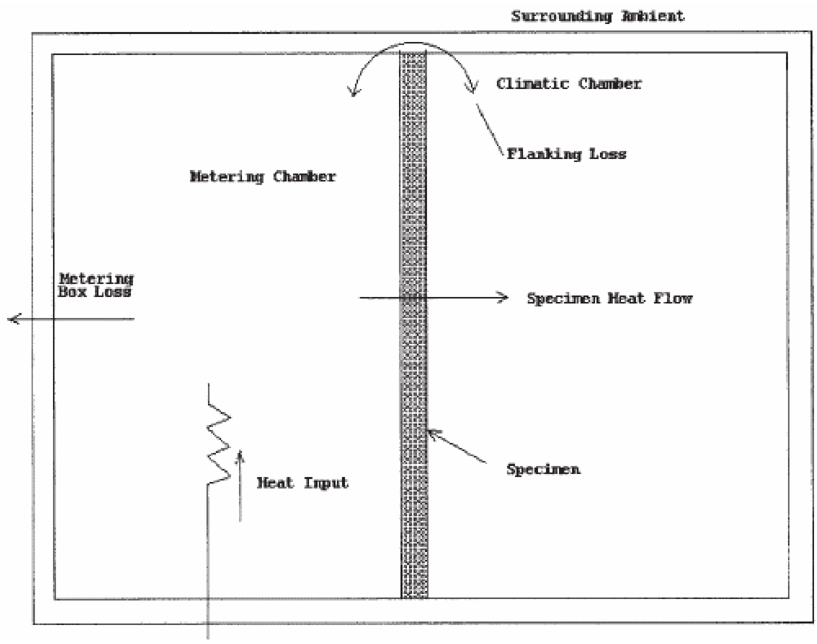

Figure 4: Typical regular hot box schematic

Materials used in the construction of the hot box apparatus (the surrounding panel) shall have a high thermal resistance (low thermal conductance at 75.2 °F (or 24 °C) no more than 0.007 BTU/hr-ft^2-°F (or 0.04 W/m^2-K)), low heat capacity and high air flow resistance (or low gas permeance). This thermal insulation material should also be homogeneous and have stable thermal properties independent of time and temperature during the tests. A recommended surrounding panel core material is expanded polystyrene (beadboard) or other closed cell foam materials since they combine both high thermal resistance, good mechanical properties, and ease of fabrication.

Standard calibration: To gain final confidence in the test result, it is necessary to benchmark the overall result of the hot box chamber by performing measurements on specimens having known heat transfer values and comparing those results to the expected values. The benchmark specimen for this calibration purpose, the heat flux transducer calibration transfer standard (CTS panel) is a homogenous panel whose thermal properties are uniform and predictable. Also the air leakage of the hot box is determined, before testing, at 1.566 lb/ft^2 (or 75 Pa), equivalent to approximately 36.417 ft/s (or 11.1 m/s) wind speed, to validate air leakage rates before and after the thermal performance test. Sealing techniques should be governed by two primary criteria: (1) the sealant applied should be of similar emittance (0.2) as the surface to which it is being applied; and (2) the sealant is applied in as minimal amount possible to achieve the reduction in air leakage.

Standard test conditions: U-factors obtained under this set of conditions have been shown to be valid for the range of weather conditions typical of North American climate [weather-side temperatures between 109.4 °F and –22 °F (or 43 and -30 °C) and wind speeds up to 21.982 ft/s (or 6.7m/s)]. The test specimen should be tested under the following set of conditions for U-factors for comparison purpose, t_h = 69.8 ± 33.8 °F (or 21 ± 1 °C), t_c = -0.4 ± 33.8°F (or -18 ± 1°C).

The air velocity on the room side of the test specimen should be less than 0.984 ft/s (or 0.3 m/s) to set the surrounding environmental condition similar to natural convection. For comparison purpose, the standard surface heat transfer coefficient measured on the room side of each CTS during calibration should be h_h = 1.233 BTU/hr-ft^2-°F (or 7.0 W/m^2-K) + 10%. For comparison purpose, the standard surface heat transfer coefficient measured on the weather side of each CTS during calibration should be h_c = 5.107 BTU/hr-ft^2-°F (or 29.0 W/m^{2}K) – 10%.

Different product types must be tested at different sizes according to the NFRC spec. For a double glazing building panel, the test model size should be about 6.562 ft × 6.562 ft (or 2 m × 2 m).

The U-factor results obtained do not reflect performances expected from field installations since they do not account for solar radiation and air leakage effects. The U-factor results are taken from specified laboratory conditions and should be used only for fenestration product comparisons and as input to thermal performance analysis that also include solar and air leakage effects.

NFRC 200 series standards: The NFRC 200 series standards (NFRC 200-2004 and NFRC 201-2004) are the standards that govern and detail the determination of the SHGC.

Purpose: NFRC 201 ("Procedure for Interim Standard Test Method for Measuring the Solar Heat Gain Coefficient of Fenestration Systems Using Calorimetry Hot Box Methods") specifies the equipment, calibration techniques, and test methods needed to gather data that can be used in accordance with NFRC 200 ("Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence") to determine the SHGC for fenestration systems.

Test Set-up: NFRC 201 gives a standard test set-up for the determination of the SHGC. Figure 5 shows the standard test set-up with the following major components: (1) test specimen (fenestration system), (2) thermal chamber, (3) thermal chamber internal heat exchanger, (4) thermal loop, and (5) external solar radiation source (actual or artificial).

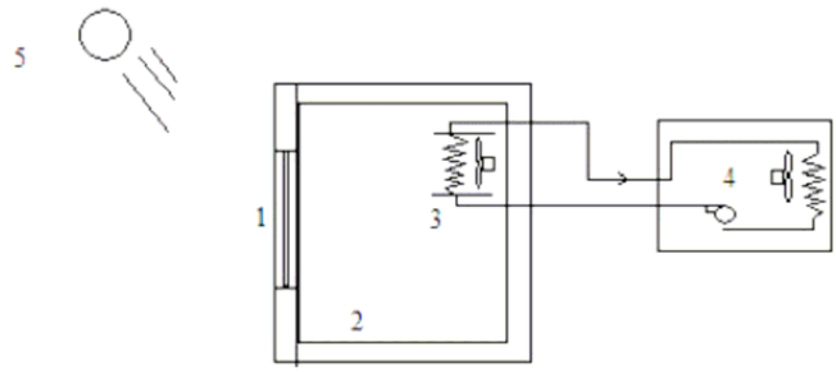

Figure 5: Typical test set-up, as set forth by NFRC 201-2004 for determination of SHGC with major components labeled.

The thermal chamber offers a concealed chamber with low heat leakage, the solar heat source irradiates on the fenestration system, and the heat exchanger and thermal loop control the internal thermal chamber temperature at a constant desired value.

Standard Test Conditions: NFRC 200-2004 specifies the standard testing conditions as follows: (1) the average nominal temperature inside the thermal chamber shall be 75.2 °F (or 24°C); (2) the convection coefficient inside the thermal chamber shall be 1.356 BTU/hr-ft^2-°F (or 7.7 W/m^2-K) ± 5%; (3) at no time shall the solar irradiance be less than 215.46 BTU/hr-ft^2 (or 680 W/m^2); (4) the incident solar irradiance angle shall be no more than 5 degrees from normal; and (5) the aperture of the solar thermal chamber shall not be tilted more than 60 degrees from the vertical.

Calibration: The NFRC 200-2004 standard dictates that all of the equipment used during testing must be calibrated prior to calibrating the entire system as whole. This standard also specifies how often the equipment must be calibrated, and occasionally gives necessary accuracies of certain types of equipment.

Procedure: The testing procedure set forth by NFRC 200 is relatively simple to conduct. First, the system is calibrated by testing a fenestration product that has a known SHGC. This allows for determination of heat transfer across the thermal chamber at the standard temperature difference. After system calibration, testing of the uncharacterized fenestration system is straightforward. The solar heat source (the actual sun or some other artificial source) radiates energy at a specific value (at least 215.46 BTU/hr-ft^2 (or 680 W/m^2)) and is measured by a pyranometer close to the fenestration system. The heat extraction system then exports heat out of the system while any electrical energy added to the system is measured. With the data collected during testing the SHGC of the uncharacterized fenestration system is easily obtained by using a steady state energy balance.

Calculations: As previously stated the SHGC can be determined from a steady state energy balance of the overall system. Incorporating the definition of the SHGC and the U-factor the following equation is obtained:

$$SHGC = \frac{Q_{net} - U_s A_s \Delta T_s + Q_{env}}{A_s Q''_{sun}} \qquad (1)$$

Where Q_{net} is the energy extracted by the heat exchange system, U_s is the fenestration systems U-factor, A_s is the area of the fenestration system, ΔT_s is the temperature difference across the fenestration system, Q_{env} is a combination of the electrical energy added to the system as well as heat flow across the thermal chamber walls, and Q''_{sun} is the heat flux from the solar source.

ASTM standards: ASTM C 1363-05 ("Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus") gives general guidelines for the construction of a hot box for the testing of building materials, including fenestration products. Additionally, C 1363 gives guidelines for the characterization of the hot box, instrumentation, and testing of any specimen.

ASHRAE standards: ASHRAE 90.1-2001 ("Energy Standard for Buildings Except Low-Rise Residential Buildings") provided guidelines for the design of energy efficient buildings. Consideration is given to the "building envelope", heating and cooling systems, power, and lighting.

2.2 Advantages and Disadvantages of Following the NFRC

The NFRC method has both pros and cons associated with it. The advantages include set and repeatable conditions and easily measured quantities, but the complexity of the system and the tight measurement requirements make the testing difficult to carry out and uneconomical for this project. For these reasons the NFRC standards will not be strictly followed in the design of a new thermal chamber. Following the general method of determining the U-factor and SHGC we need to strike a balance between economics and accuracy.

2.3 Dual Chamber vs. Single Chamber Design

Due to time and budget constraints, the team had to choose either a dual chamber or single chamber hot box design to generate general concepts of the prototype. This section will explain how the team has chosen a single-chamber design and any advantages and disadvantages of this design.

2.3.1 The Dual Chamber Hot Box

The dual-chamber hot box is the primary form for thermal chamber testing when testing for the U-factor. It offers a metering chamber and a climactic chamber that has a controlled temperature. The climatic chamber is used so that any desired temperature gradient can be reached. This allows for testing of multiple atmospheric conditions, or repeatable conditions from test to test

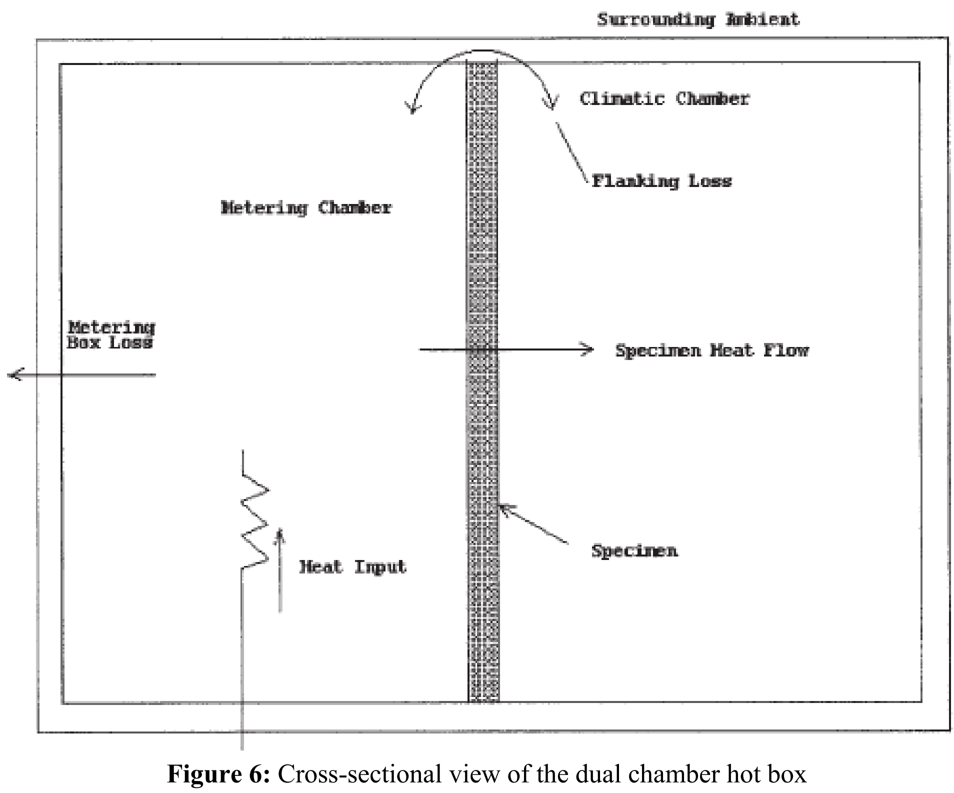

Figure 6: Cross-sectional view of the dual chamber hot box

2.3.2 The Single-Chamber Hot Box

Strictly speaking the use of the climatic chamber is not required. A carefully designed experiment can demonstrate this. If the climatic chamber can reach any temperature, including the standard ambient temperature of a room (77 °F or 25 ˚C), and stay constant then if the ambient in the room is 77 °F (or 25 ˚C) and constant it can act as the climatic chamber. In addition, the climatic chamber is too expensive, cumbersome, and complex to add to our system in the short time we have to build and test. The climatic chamber would double our material cost, size, weight and construction time. As well as require the design and implementation of a heat exchanging system. With the budget constraints of this program and the compressed time line, as well as with guidance from our sponsor, we have decided to use the single chamber hot box design, with the ambient serving as a "climatic chamber."

Disadvantages: The use of a single-chamber hot box has several disadvantages to overcome. First, we lose the capability to hold one side of the panel at a constant temperature other than ambient. This limits the effective range of conditions we can simulate (e.g. we cannot simulate any winter conditions, unless we test outside). Second, if we want to use only one heat source to test for the U-factor then the temperature gradient across the test façade panel will be different for every panel we test, because each panel will have a unique U-factor. This leads to the major issue of quantifying the losses that exist in the thermal chamber. As will be discussed in the 'Calibration' section, the heat loss across the surrounding panel will be a function of temperature, and because each panel will produce a unique temperature gradient, they will also produce a unique value for the loss term, Q_{sp}, in Equation 2.

We can, however, overcome these problems. The limitation on test conditions is not a critical problem, and is reduced further by the fact that we are trying to gauge the relative performance of several façade designs. Thus, if each façade is tested at the same conditions (whatever they may be) then the comparison should be accurate. If we were trying to measure the performance of a panel over a wide range of conditions then this would be impossible with a single chamber. Next, if we can calibrate the hot box losses as a function of temperature then we can choose the proper value for the chamber loss term based on the steady state temperature measurements. It is worth noting that with the dual chamber design only calibration at one temperature is required because the two chambers hold an equal temperature difference across test panels over multiple tests.

Advantages: There are many advantages to using a single-chamber design. First, there are counterparts to the disadvantages of the dual chamber design: lighter, smaller, less material, less cost, and less time. Second is the ease of design; there are no complex systems to deal with in the single chamber design (i.e. no heat exchanger), which also greatly simplifies the calculations and equipment we need to buy. The calculations are simplified by not having to track the amount of heat that is extracted by the heat exchanger. However, the biggest advantage is only having to build a single test apparatus. The dual chamber design is the primary form for U-factor testing, but not for determination of the SHGC. By using one chamber for the U-factor, we can now use this single apparatus to test for both the U-factor and SHGC.

3 CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

3.1 Quality Function Deployment

We used a Quality Function Deployment (QFD) worksheet to establish engineering specifications. First, a list of customer requirements was determined through discussions with Professor Giles, the project sponsor. The requirements were weighted one through ten based upon importance. We determined that the most important requirements were to fit the standard sized façade panels between 4-6 in. thick (to test a variety of designs) and to make use of the Structural Insulating Panels (SIPs) supplied by the Architecture department. We also found that durability and simplicity are important since the device will probably be used for many test cycles and operated by many different people. To ensure that the values we calculate are relatively accurate, the customer has requested that we design the device similar to the standards used in industry (NFRC, ASTM, ASHRAE). To be accurate, the device should also avoid heat loss to the environment and be well sealed. The tested panels should be easy to change out and the total device should be relatively mobile so that it can be moved out of the way when not being used.

Additionally, we were asked to build an artificial light source for SHGC testing. The light source should be designed to mimic solar radiation for both summer and winter conditions. Eventually the project will consider multiple latitudes throughout the world but currently we are focusing on Detroit. To meet these conditions, the light source must have a vertical adjustability of at least 3 ft. and lamp angles adjustable from 25 to 72 degrees.

Next, a set of engineering specifications was developed to describe the customer requirements. These were analyzed using a QFD in APPENDIX A. From this activity, we determined that fitting a 3 × 3 ft test specimen, having a thermal conductance less than 0.007 BTU/hr-ft^2-°F (or 0.04 W/m^2-K) and being able to accommodate specimen widths to be the most important. The fourth most important specification was being able to change out panels is less than 60 seconds. The remaining specifications are still very important to our design but have correlations with less important customer requirements. Table 1 summarizes the engineering requirements and shows their importance ranking.

As our project progressed, some of these Engineering Specifications changed. The most significant is that thermal conductance requirement was increased from being less than 0.007 to 0.044 BTU/hr-ft^2-°F (or 0.04 to 0.25 W/m^{2}K). Ideally, 0.007 BTU/hr-ft^2-°F (or 0.04 W/m^{2}K) would be used to stay consistent with the industry standards but we are constrained to using the Structural Insulating Panels (SIPs) supplied by the architecture department, which have a thermal conductance above this value. If the results from our testing were being used as publishable values, we would want to use a better-insulated material but because the goal of our project was to provide comparative testing, we determined this to be acceptable. Another change to our QFD was the addition of the ability to take at least eight temperature measurements. Through modeling and analyzing the thermal chamber we concluded that this is the minimum number of readings needed to produce consistent results. We would like to have as many measurements as possible but this is not practical due to financial constraints on the project.

Table 1: Detailed information of engineering specifications

Importance Ranking	Engineering Specification
1	Cross section area 3ft^2 (0.9144m^2)
2	Thermal Conductance is less than 0.044 BTU/hr-ft^2-°F (or 0.25 W/m^2-K)
3	Frame extends 4-6 inch (10.16-15.24cm)
4	Change panel in 60 sec
5	Take at least 8 temperature measurements
6	Moveable with 50 pound force (222 N) on a base

3.2 Benchmarking

The two most prevalent thermal chamber designs are the hot box and guarded hot box. The main difference between the two is that the guarded hot box has an extra chamber surrounding the metering chamber to help reduce heat loss to the environment. Accurate results are easier to achieve with the guarded hot box design because the environmental conditions do not need to be as closely controlled as they do in the regular hot box design. However, the regular hot box takes up less room and requires less material. We were unable to benchmark these two designs in the QFD because they could not be rated against our customer requirements, which are project specific and have different design parameters.

An example of a thermal chamber in commercial use is at the Oak Ridge National Laboratory in Tennessee. They use a rotatable guarded hot box to test U-factor in vertical and horizontal applications. This device, shown in Figure 7, is able to test specimens of various sizes.

Figure 7: Rotatable guarded hot box [12]

4 PROJECT PLAN

4.1 General Plan

The project plan has been divided into six stages: 1) problem definition, 2) literature survey, 3) concept generation, 4) prototyping, 5) testing, and 6) project review. Each stage consists of required tasks and deliverables as shown in Table 2. A report summarizing the progress of the project will be delivered at the time of each design review. A Gantt chart for the project has been outlined in APPENDIX B. The project's budget was originally set at $1000 but increased to $2000 to allow for the purchase of pre-programmed temperature measurement devices in order to shorten the prototyping stage. Because some of the equipment used was borrowed or provided free of charge, the project managed to stay under budget. The cost of items purchased totaled $1,118 as detailed in Appendix D.

Table 2: Stage, required task and deliverables of the project

Stage	Problem Definition	Research	Concept Generation	Prototyping	Testing	Project Review
Tasks	Project Scoping Design Requirements Desired Goals	Benchmarking Expert Collaboration Engineering Specifications	Brainstorming Design Selection CAD drawings Prototyping Plan	Thermal Modeling Product Construction Prototype Tests Modifications if necessary	Façade Testing Inform Façade Design	Sponsor Feedback Wrap-Up
Deliverables		Design Review 1 Project Proposal	Final Design	Design Review 3 Final Prototype	Design Review 4 Progress Report	Expo Final Report

Our design project is unique to ME 450 as it includes a substantial testing stage where the prototype is used to analyze the performance of various façade concepts to inform and improve the façade design process. Because of the testing stage, our project began the prototyping stage before most other ME 450 projects. The beginning date for prototyping was pushed back from the original scheduled date in Design Review 1 due to extra time needed to produce detailed CAD drawings and accommodate design suggestions from our sponsor. This would have pushed back our prototyping deadline, but because we purchased temperature-measuring equipment that did not require programming, albeit at a higher cost, we were able to shorten our construction and prototype testing tasks to meet our original deadlines.

The prototype was successfully completed by the scheduled date of March 16th. A detailed account of our prototyping schedule is located in Appendix C. Façade testing was originally scheduled for March 21st but this date was delayed because of the theft of some of our equipment. The testing phase included U-factor and SHGC tests on various façade panels, described in more detail in Section 11. SHGC testing includes tests with both the artificial light source and with natural lighting for validation. In total, five U-factor and sixteen SHGC tests are required.

U-factor testing was successfully completed and analyzed by April 4th; results are detailed in Section 13. SHGC testing was unable to be completed because of the uncontrollable delay in testing and also because of the unexpected amount of time required for each U-factor test. Instead, preliminary results for SHGC were calculated from natural light tests, discussed also in Section 13.

4.2 Prototype Production

4.2.1 Thermal Chamber Production

Due to the tight time schedule, a separate Gantt chart was created to focus specifically on prototype production. To be inline with the critical path of the overall façade project, the prototype was built by March 16th in order to allow sufficient set-up time to begin façade testing on March 21st.

The production schedule was created by first listing all the necessary steps and then fitting them into a timeline, which would allow for streamlining of independent processes as well as taking into account all team members' schedules. Each step has a list of potential problems (Issues), equipment and material lists, and the approximate time it will take. The list of potential problems allowed us to analyze and address problems before they adversely delayed the schedule. Equipment and material lists were made to ensure that we would be prepared for each prototyping session.

The production process has been split up into 4 categories; (1) SIP assembly, (2) front panel attachment, (3) door installation and (4) installation of internal equipment. The first step was SIP Assembly. This involved cutting out the large panels (dimensions available in Section 7.2 – Detailed Panel Dimensions) for each side of the thermal chamber, milling out the panels to fit the corners with a CNC machine (C.R. Onsrud 96C12) operated by Jeremy Freeman, adhering the panels together with wood and foam adhesive, reinforcing the structure with brackets and corner joints, and sealing the panel with caulk. Six-foot bar clamps were used to hold the panels together while the adhesives dried so that the walls would not move while fastening them with brackets. The brackets were attached by first drilling pilot holes with a cordless drill to minimize the chance of the wood cracking.

The front panel was made of a plywood frame (cut out using a 10 in. table saw) with a rubber seal on the inside. This frame was adhered to the rest of the thermal chamber with adhesive and screws and then caulked to seal it. Next, the door was installed. Because this surface is so critical to the performance of the chamber, polystyrene sections were cut out on a table saw and adhered to the foam contact surfaces of the door to help reduce wear on the foam and to provide a better medium to adhere the rubber door seal. Double-layered rubber seals were used on the door to provide extra sealing in case one of the seals had a gap for air to leak from. Finally, two hinges and force-applying latches were carefully screwed into the door. The hinge locations were adjusted to sufficiently compress the door seals and have proper clearances.

Thermocouple and ambient temperature loggers were installed inside the thermal chamber with Duct Tape. Thermocouples used to measure surface temperatures were covered with a cotton ball then taped to the surface to help block out ambient air temperature readings. Ambient air temperature loggers were hung inside with wires screwed to the top chamber wall. The installation locations can be seen in Figure 26. All thermocouple wires were run through the rubber door seals to data collection systems outside the chamber.

4.2.2 Artificial Light Source

We constructed an artificial light source designed by our sponsor (Figure 8) to imitate the sun so that SHGC tests could be performed inside. The light source was built out of Uni-Strut, a metal rail construction material developed by University faculty, which was abundant in the Architecture department.

Figure 8: Artificial light source constructed for SHGC testing

First, two eight foot tall Uni-Strut sections were cut from twenty foot stock using a horizontal band saw set at a fast blade speed. These pieces provided sufficient height to create the desired sun angles in both summer and winter conditions. Next, five 4 ft long sections were cut out. Two of these sections were for the light source base that stabilizes the structure. The other three sections were used to hold nine 500-Watt light fixtures. A plywood sheet (15.5 in. × 6 ft) was cut out using a table saw to provide lateral support to the 8 ft high beams. Five 11/16 in. diameter holes 17 in. apart were drilled into each beam with a drill press and the long side of the plywood then was joined using nuts and bolts.

The two 4 ft base beams were joined to the bottom of the height sections using L brackets and special Uni-Strut nuts and bolts (Figure 9). To attach the light-holding cross sections to the height sections, 2 holes (11/16 in. diameter 7 in. from center using a drill press) were drilled in the cross sections and the Uni-Strut nuts and bolds were used. The lights were mounted to the metal frame using 6 × 8 in. plywood mounting brackets (15/32 in. thick cut with a table saw). The light fixtures were mounted to the bracket with small bolts (Figure 10). The brackets had two holes drilled in the bottom (5/8 in. diameter with a cordless drill) that were used to mount to the cross sections using Uni-Strut nuts and bolts. Finally, two more 3 ft Uni-Strut sections were cut out to add additional lateral support to the base.

Figure 9: Uni-Strut nuts and bolts used to construct the artificial light source

Figure 10: Lights were mounted to the Uni-Strut cross-sections using wood planks and bolts

5 PROBLEM ANALYSIS

This project requires a thermal chamber to be built so that thermal testing can be conducted. Thus, in order to design an effective chamber the theory behind these tests must be investigated.

The engineering specifications we derived from our customer's requirements impact the design of the thermal chamber by defining sizes and ease of use, but they also impact some engineering fundamentals. Requiring the thermal conductance to achieve such a low value 0.007 BTU/hr-ft^2-°F (or 0.04 W/m^{2}K) affects the heat transfer properties of the chamber. The difficulty in the design lies with sealing the thermal chamber from extraneous heat and mass flows and characterizing such flows when present. The overall design of the thermal chamber will be driven by thermal performance and the ability to accept the standard test panel size. If the chamber fails at either of these it fails entirely.

5.1 Thermal Transmittance

5.1.1 Pre-designed Test Equipment and Calibration

To simplify the testing procedure and calculation method, we will be using a single chamber thermal chamber (Figure 11). The pre-designed equipment will be a simple thermal chamber hot box with only the metering chamber with a constant heat input. The input heat will come from a radiant heat source such as an incandescent lamp whose heat transfer rate can be easily determined by its electrical power usage.

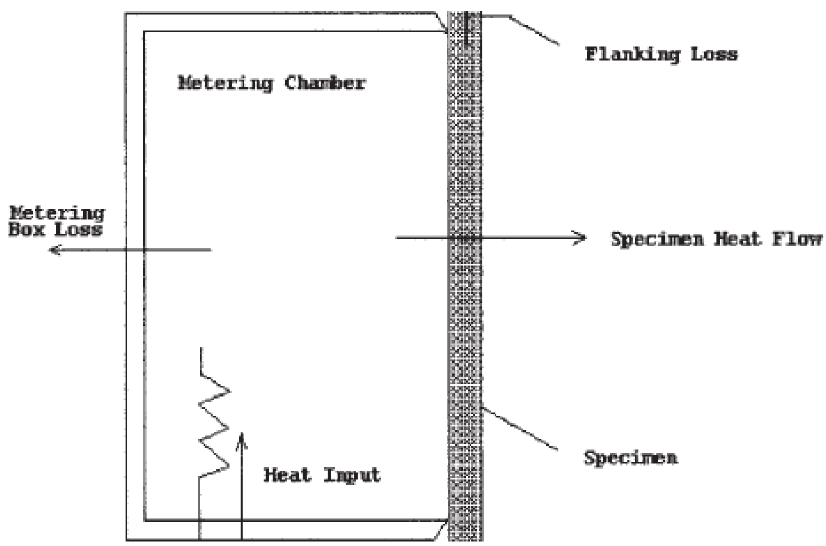

Figure 11: Simplified thermal chamber for testing

The calibration of the thermal chamber is based on the CTS panel or other practically used building panels whose thermal properties are stable and already known or predictable. For this project we will be using two glass panels and one panel of medium density fiberboard (MDF) as described in the 'Testing' section. The purpose of calibration in our experiment is to compare the thermal performance of existing fenestration systems with the expected values of our newly designed systems and to determine which of the prototype façades is the best performer. Also, the air leakage rates of the chamber will be minimized, using sealant, so that it can be neglected to simplify the calculation process.

5.1.2 Experimental Procedure

During calibration and testing, the following measurements should be done under steady-state conditions for determining the U-factor: (1) the average ambient temperature, inside and outside of the thermal chamber, T_h and T_c; (2) the average specimen temperature, inside and outside surface, T_1 and T_2; (3) the average surround-panel temperature, inside and outside, T_{p1} and T_{p2}. The specimen and surround-panel total heat transfer surface area, A_s and A_{sp} should be measured and calculated before the testing.

The following assumptions and criteria are essential to set up our testing standards so that the comparison of thermal performance is meaningful: (1) assume no wind flow around the thermal chamber, free convection; (2) assume air leakage and flanking flow is negligible; (3) the average ambient temperature should be set at the same value; (4) the steady-state period is determined if the measured temperatures vary within 5% of the average value during this period; (5) the size of the calibrated panel and the test panel should be the same.

5.1.3 Calculation of Thermal Transmittance (U-factor)

The surround-panel heat loss, Q_{sp}, can be determined with knowing C_{sp}, the surround-panel thermal conductance. The following equation represents this loss:

$$Q_{sp} = C_{sp} A_{sp} (T_{p1} - T_{p2}) \qquad (2)$$

The specimen heat flow, Q_s, is the difference between the heat input, Q_{in}, by the radiant heat source and the surround-panel heat loss:

$$Q_s = U_s A_s (T_h - T_c) = Q_{in} - Q_{sp} \qquad (3)$$

Thus the steady-state U-factor can be determined:

$$\mathrm{U_s} = \frac{Q_{in} - C_{sp} A_{sp} (T_{p1} - T_{p2})}{A_s (T_h - T_c)} \qquad (4)$$

Table 3: Radiant heat source power required to achieve noted temperature differences at given U_s

ΔT	U_s Max = 0.7 BTU/hr-ft^2-°F (or 3.98 W/m^2-K)	U_s = 0.6 BTU/hr-ft^2-°F (or 3.41 W/m^2-K)	U_s Min = 0.5 BTU/hr-ft^2-°F (or 2.84 W/m^2-K)
(°F)	**(BTU/hr)**	**(BTU/hr)**	**(BTU/hr)**
18	177	160	140
36	354	320	280
54	530	480	420
72	707	640	560
90	884	800	700
108	1060	960	840

In Table 3, we used Equation 4 to estimate the power input required for the radiant heat source to achieve various temperature differences between the inside and outside of the thermal chamber. Computer simulations performed by the Architecture department estimated the U-factor for the prototype façades to be 0.6 BTU/hr-ft^2-°F. The three values for the U-factor in Table 3 are centered on this value to give a range of possible of conditions. For simplicity we assume that the conductance of the surrounding panel is 0.044 BTU/hr-ft^2-°F (or 0.25 W/m^2 K), the surface area of the surrounding panel and the test specimen are 53.8 ft^2 and 10.8 ft^2 (or 5 m^2 and 1 m^2), respectively Also we assume that the temperature difference between the two sides of the surrounding panel equals to the inside and outside ambient temperature difference if we neglect the convection heat flux through the chamber. The minimum and maximum values for U_s were obtained from the Department of Energy as the general range for which the values fall. So to achieve a temperature difference of 36 °F (or 20 K) between the inside and outside of the chamber, a radiant heat source of power input from 280 BTU/hr to 354 BTU/hr (or 82 W to 104 W) should be competent.

5.2 Solar Heat Gain Coefficient

5.2.1 Theory behind Solar Heat Gain Calculations

The Solar Heat Gain Coefficient (SHGC) is defined by the NFRC (NFRC 200-2004) as "the ratio of solar heat gain through the fenestration system per unit area to solar radiation incident on the system per unit area, for a given angle of incidence and for given environmental conditions"

The NFRC 200-2004 standard also defines the SHGC in terms of system properties as follows:

$$SHGC = \tau_s + N_i \alpha_s \quad (5)$$

Where τ_s is the solar transmittance of the fenestration system, N_i is the inward-flowing fraction of absorbed radiation, and α_s is the solar absorbance of a single-pane fenestration system.

Alternately the SHGC can be calculated from the following equation:

$$SHGC = \frac{Q_{rad}}{Q_{sun}} \qquad (6)$$

where Q_{sun} is the irradiative heat that is projected on the fenestration system and Q_{rad} is the irradiative heat that crosses the fenestration system. The most significant obstacle to determining the SHGC is finding a way to measure or determine Q_{rad}.

5.2.2 NFRC Method for Determining SHGC

The NFRC 201-2004 standard details the calculation for determining the SHGC based upon the following figure [modified from 201-2004 with addition of heat arrows].

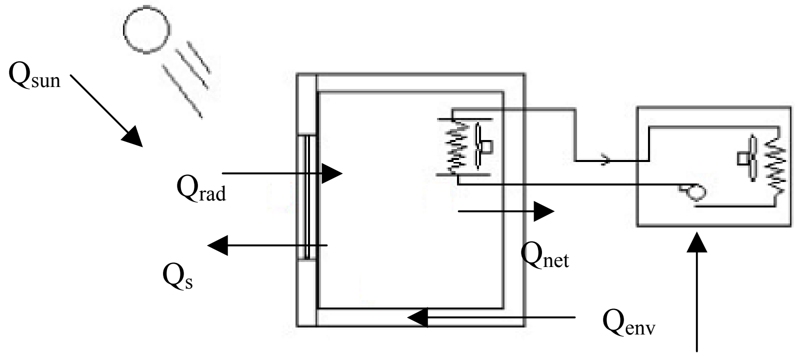

Figure 12: Typical NFRC set-up modified with heat flux arrows

Examining Figure 12, the following total energy equation can be written if the system has reached steady state:

$$Q_{rad} + Q_{env} - Q_s - Q_{net} = 0 \qquad (7)$$

where Q_{net} is the heat flow that is extracted by the heat exchanger, Q_{rad} is the heat flow across the system due to radiation, Q_s is the heat flow across the system due to temperature differences and convection, and Q_{env} is comprised of heat flow across the thermal chamber walls and any electrical energy added to run subsystems (e.g. pump for heat exchanger).

Utilizing the definition for the SHGC and U-factor, Equation 7 can be rewritten in the following form, allowing a quick calculation to determine the SHGC:

$$Q_{net} = SHGC \cdot A_s Q''_{sun} - U_s A_s \Delta T_s + Q_{env} \qquad (8)$$

Where A_s is the area of the fenestration system, U_s is the U-factor of the system, and ΔT_s is the temperature difference across the system.

5.2.3 Generalized Method for Determining SHGC

In general the use of a heat exchanger, as described by NFRC 201, serves the purpose of keeping the internal temperature of the thermal chamber constant, thus keeping the temperature difference across the fenestration product constant (assuming a constant ambient temperature). The primary reason this is important is the ability to have constant temperature differences from test to test, as well as only needing to characterize the thermal chamber at one temperature difference. If the temperature gradient changes from test to test so must the heat flow through the thermal chamber walls. Though the heat exchanger is filling these important roles, strictly speaking it is not necessary.

With the removal of the heat exchanging from the system Figure 13 represents the heat flow of the fenestration/thermal chamber system.

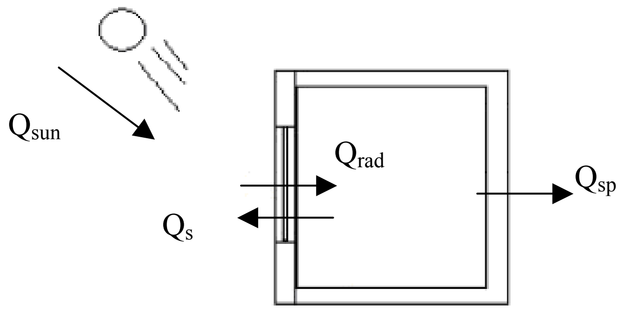

Figure 13: Adaptation from NFRC 201 with removal of heat extraction system and inclusion of heat fluxes

By inspection of Figure 13, the steady state energy balance can be written as follows:

$$Q_{rad} = Q_s + Q_{sp} \qquad (9)$$

where Q_{sp} is the heat flux across the thermal chamber walls due to temperature gradients. Equation 9 represents a simplification over the NFRC method for determining the SHGC (Equation 8); there is no longer a need to keep track of electrical energy into the system or the effects of a heat exchanger.

In order to conduct preliminary investigation into strength of artificial solar lamps required for testing it is convenient to, as a first order approximation, rewrite Equation 9 in terms of system parameters. By estimating Q_{sp} as steady one-dimensional conduction and using the definition of the SHGC and U-factor, the following equation can be written:

$$SHGC = \frac{U_s A_s \Delta T_s + C_{sp} A_{sp} \Delta T_{sp}}{Q''_{sun}} \qquad (10)$$

Where C_{sp} is the thermal conductance of the chamber walls (required by NFRC 201-2004 to be equal to or less than 0.007 BTU/hr-ft^2-°F (or 0.04 W/m^{2}K)), A_{sp} is the surface area of the internal chamber walls, and ΔT_{sp} is the temperature difference across the chamber walls (generally assumed to be equal to ΔT_s).

The trade off for removing the complexity of the original NFRC set-up (i.e. removing the heat exchanger) is the variability of ΔT_{sp} and ΔT_s between tests. This variability means that in order to accurately determine the SHGC of any system the heat flux through the walls of the thermal chamber must be characterized as a function of the temperature (see Sections 11.3 and 12).

Tables 4 represents the irradiance needed to achieve a certain temperature difference. We used Equation 10 with the same parameter values as discussed for Table 3. The values for the SHGC are estimates based on performance goals for summer conditions (0.12) when we want less incoming radiation and winter conditions (0.67) when we more incoming radiation. Given the large discrepancies in the tabulated values based on the possible ranges of the SHGC and U-factor any artificial solar heat source used for testing will have to have a variable output or be comprised of several smaller sources that can be combined to achieve different levels of total irradiance.

Table 4: Solar irradiance required achieving noted temperature differences at given U_s and SHGC

ΔT	**U_s Max = 0.7 BTU/hr-ft^2-°F (or 3.98 W/m^2-K)**		**U_s = 0.6 BTU/hr-ft^2-°F (or 3.41 W/m^2-K)**		**U_s Min = 0.5 BTU/hr-ft^2-°F (or 2.84 W/m^2-K)**	
	SHGC = 0.67	**SHGC =0.12**	**SHGC = 0.67**	**SHGC =0.12**	**SHGC = 0.67**	**SHGC =0.12**
(°F)	**(BTU/hr)**	**(BTU/hr)**	**(BTU/hr)**	**(BTU/hr)**	**(BTU/hr)**	**(BTU/hr)**
18	264	1475	239	1333	209	1167
36	528	2950	478	2667	418	2333
54	791	4417	716	4000	627	3500
72	1055	5892	955	5333	836	4667
90	1319	7367	1194	6667	1045	5833
108	1582	8833	1433	8000	1254	7000

6 CONCEPT GENERATION

The concept generation phase consisted of individual brainstorming, team discussion, and a "deep dive" session. First, team members individually sketched out their ideas for a proposed chamber design. Next, we met together as a team to explain our individual proposed designs, and discussed advantages and disadvantages of the concepts. Figure 14 and 15 are two examples of these sketches.

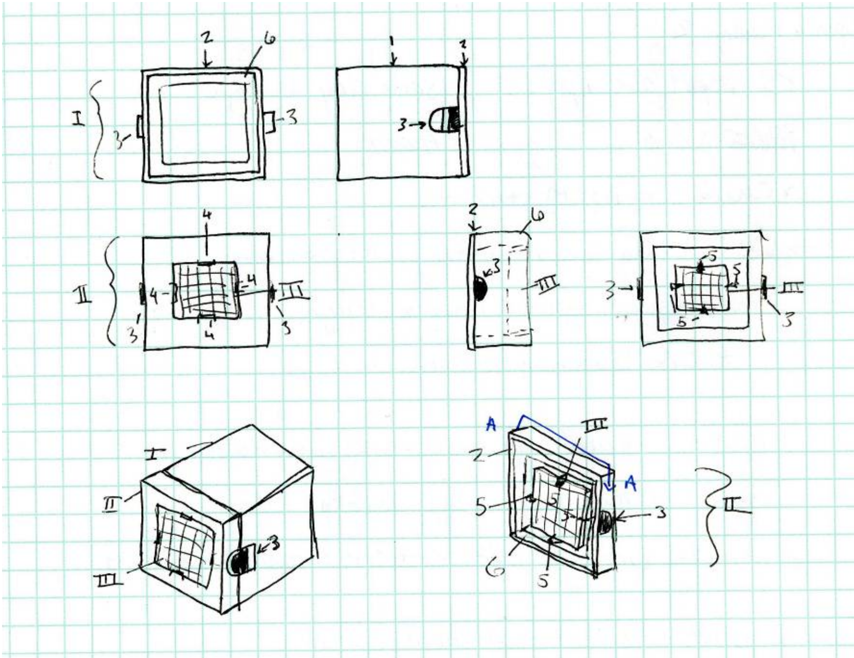

Figure 14: A proposed two-piece chamber design concept

Figure 14 is a two-piece chamber. The main chamber (I) holds the heater and the majority of the thermocouples and is open on the front. Both pieces have a protective shell on the outside made of either wood or sheet metal (1) and are lined with a compressible rubber seal around the open faces (2). The second piece (II) can be completely removed from the main chamber and reattached with briefcase latches (3). This piece holds the façades (III) with stationary clamps on the outside (4) and adjustable clamps on the inside (5). To ensure minimal heat losses, both pieces are insulated in the inside with expanded polystyrene (6). The main advantage of the two-piece design is that if different sized façades were to be tested, multiple doors could be made to accommodate the various sizes. The main issues with this design are maintaining an effective heat seal around the two pieces when they are clamped together, and also attaching the clamps to the inside of the door.

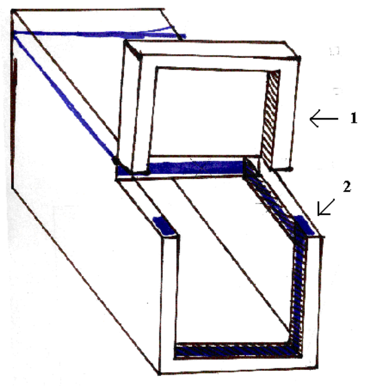

Figure 15: A proposed design concept with opening door on top

Figure 15 is a one-piece design concept. The design is a large, five-sided chamber with a hinged door that opens to the top (1). Similarly to the design in Figure 14, this chamber is insulated in the inside with expanded polystyrene and protected by a shell made of wood. Near the front of the chamber, slots are cut out in the sides to allow the façades to slip in from the top. The door would be clamped to the main chamber once a façade was placed in the slots. The main advantage to this design is that the weight of the door would help to create an air-tight seal between the door and the main chamber. The main disadvantages are the inability to accommodate varying widths of façades, and the difficult process of opening the door and inserting the façades. Since the chamber would have to be raised off of the ground for testing and the height of the chamber would be at least 4 ft (or 1.22 m), a person carrying out testing would most likely have to stand on a chair or table to open the door to insert and remove the façade.

After discussing our individually proposed designs, we held a "deep dive" session modeled after the IDEO process [13] to continue brainstorming. We proposed many different designs and then narrowed these down into a general concept and began working out the details of this design. The general concept we developed is shown in Figure 16.

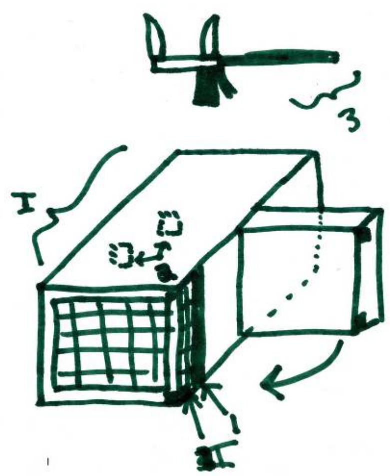

Figure 16: General concept chosen from "deep dive" session

The chosen design was influenced by previous concept of a hinged door attached to the main chamber. To avoid the disadvantage of having the door located on the top, we chose to include a door that opens to the side of the chamber. Figure 16 shows the main chamber of the design (I) and the façade (II) inserted toward the front of the chamber. Instead of slots, present in the previous design, the façade will be flush with the chamber walls. To keep the façade from tipping back during testing, a compressible rubber frame will be placed behind the façade (1). Wooden blocks will attach to the inner sides of the chamber (2) and spreaders will be placed between these blocks and the rubber frame (3). This setup creates a number of advantages: the rubber seal will both ensure structural stability of the façade and help to create an air-tight seal around the edges of the façade, and the adjustable spreaders will accommodate façades of varying widths. The main disadvantage of the design is that, because a front panel will have to exist for the façade to be pressed up against, the full 3 ft × 3 ft (≈ 0.914 m × 0.914 m) face of the façades will not be able to be tested. Instead, the testing area will be 2 ft, 8 in. × 2 ft, 8.25 in. (or 0.81 m × 0.82 m).

7 FINAL DESIGN OF THE THERMAL CHAMBER

7.1 Overview

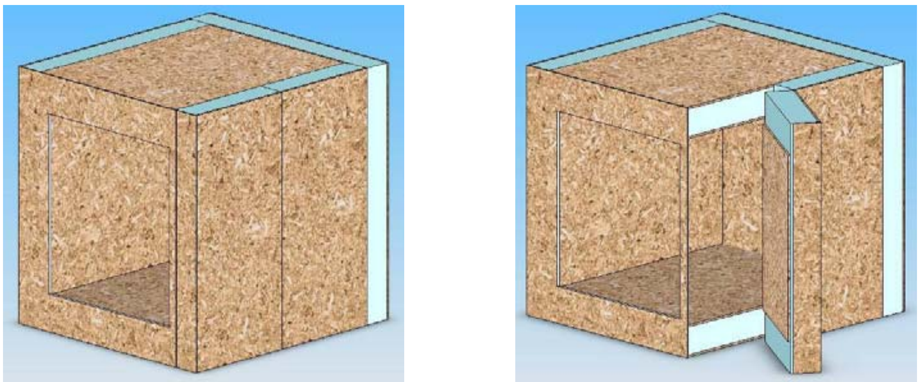

Figure 17: 3-Dimensional engineering drawing of the selected thermal chamber design when the door is closed (left) and when the door is opened (right)

The SolidWorks model of our final design of the thermal chamber is shown in Figure 17. As previously discussed, we chose to prototype a one-chamber thermal chamber due to its simplicity, and a lower expected cost. A heat source will be located inside the chamber for U-factor testing. A radiation source will be located on the outside of the chamber for SHGC testing. The chamber will be made of SIPs that are composed of a 5.625 in. (or 14.29 cm) thick inner layer of expanded polystyrene (EPS) part and 0.4375 in. (or 1.11 cm) thick outer layers of oriented strand board (OSB) on each side of the EPS. The chamber panels will be joined together using an adhesive. For structural stability, L-brackets will be used around the inside edges of the chamber. In addition, to minimize air leakages, a rubber seal will be used around the edges of movable parts that are in contact with the atmosphere.

Figure 18 shows the schematics of the thermal chamber assembly. To make the chamber, 7 different panels are required; (1) front panel, (2) back panel, (3) top panel, (4) bottom panel, (5) left panel, (6) right panel, and (7) door panel. The following section will discuss more about each panel with dimensions as well as corner details and door assembly details.

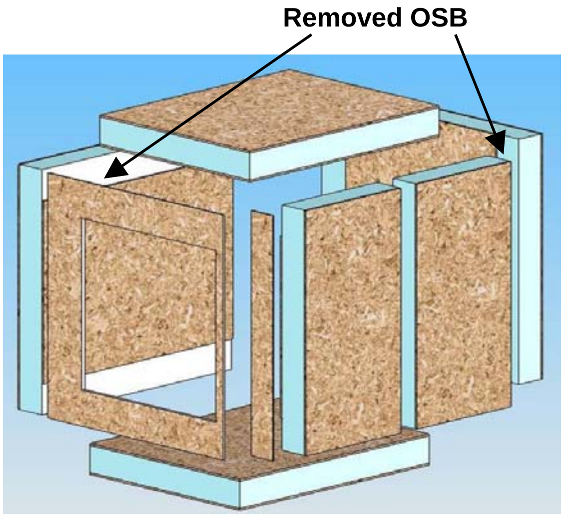

Figure 18: 3-Dimensional engineering drawing of the assembled thermal chamber showing removed OSB

7.2 Detailed Panel Dimensions

The panels of the thermal chamber are described below as modeled in AutoCAD.

Front Panel: This panel is unique to the other panels as it is manufactured with a 0.375 in (or 0.95 cm) thick sheet of plywood instead of SIPs. It will have a square shaped cavity cut out of it for testing the façade prototypes. The dimensions of the front panel are shown in Figure 19 [14].

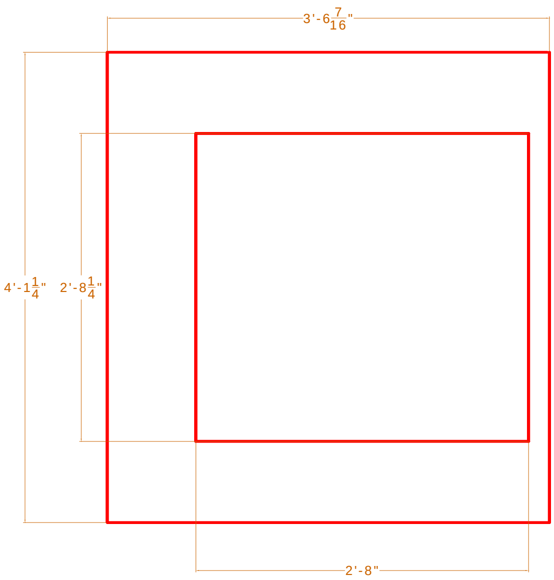

Figure 19: Dimension of the front panel [14]

Back Panel: The dimensions of the back panel are shown in Figure 20 [14]. Due to contact with other panels, 6.5 in. (or 16.51 cm) of OSB will be removed from one side, as shown in Figure 18.

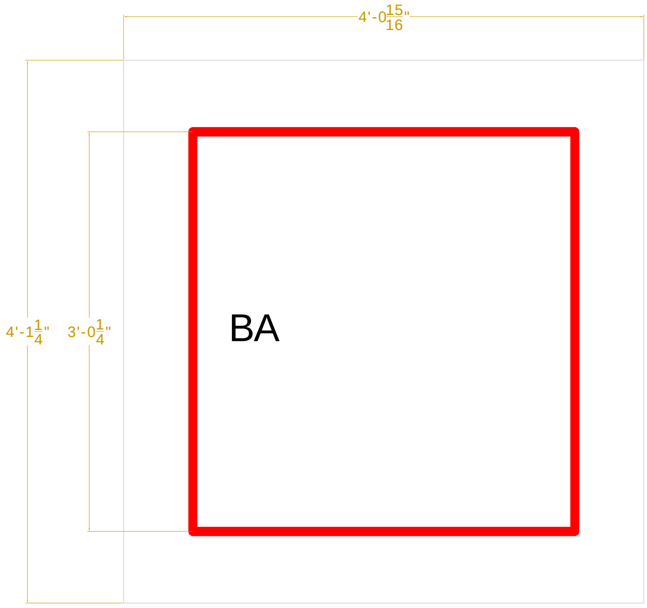

Figure 20: Dimensions of the back panel [14]

Top and Bottom Panels: The top and bottom panels will share the same dimensions as shown in Figure 21 [14]. No OSB will be removed for the top and bottom panels.

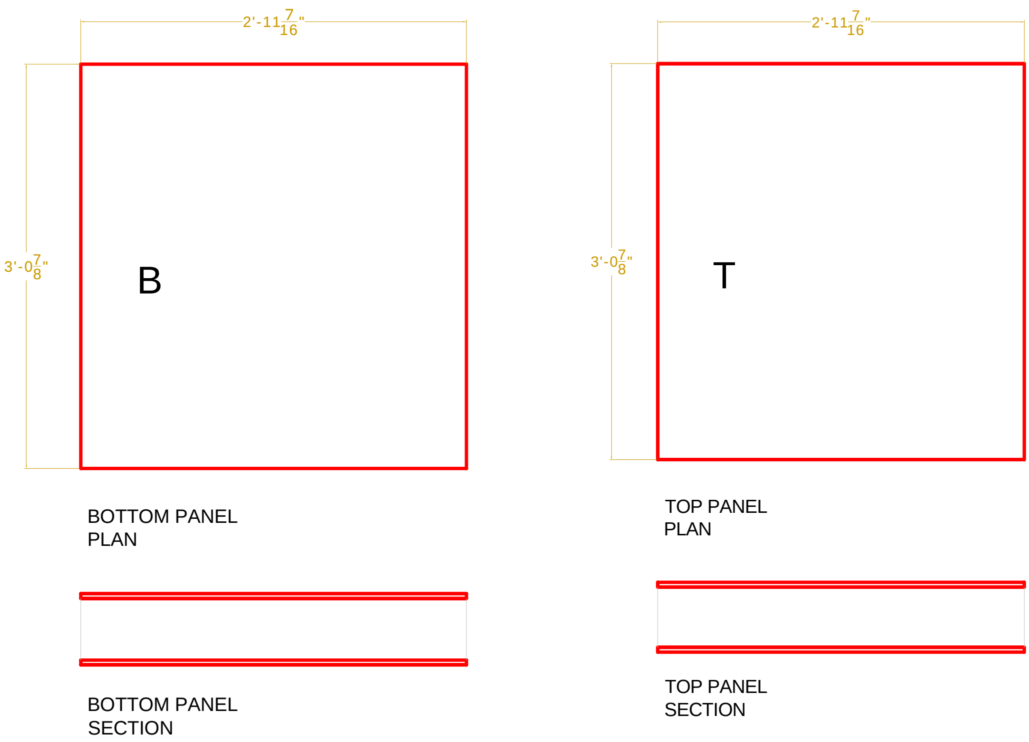

Figure 21: Dimensions for the bottom panel (left) and the top panel (right) [14]

Left *Side Panel:* The dimensions of the left side panel are shown in Figure 22 [14]. Due to its contact with other panels 6.5 in. (16.51 cm) of OSB will be removed at the top and bottom.

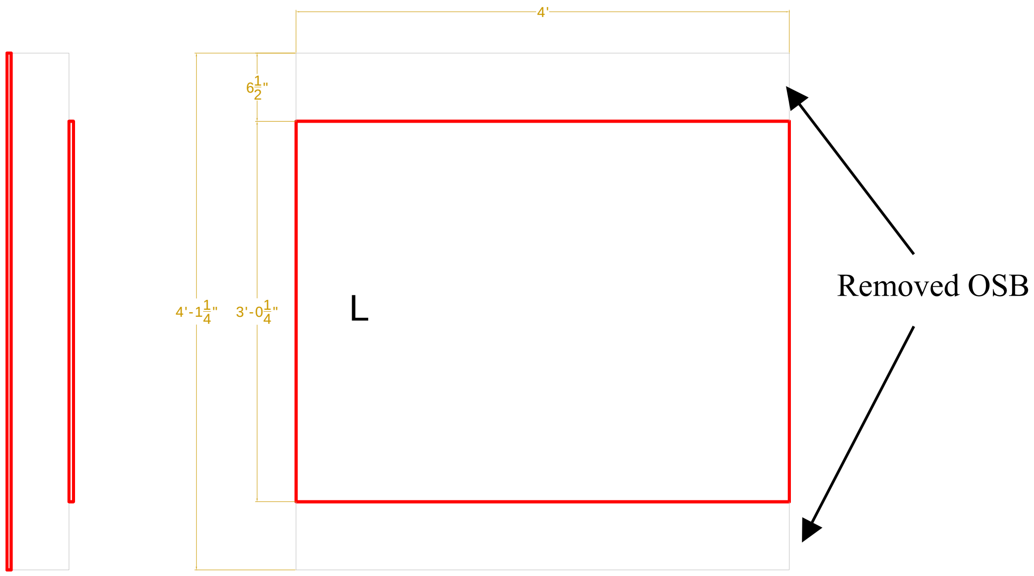

Figure 22: Left side panel drawing with dimension

Right Side and Door Panel: The dimensions of the right panel and door panel are shown in Figure 23 [14]. Due to its contact with other panels, 6.5 in. (16.51 cm) of OSB will be removed from the top and bottom.

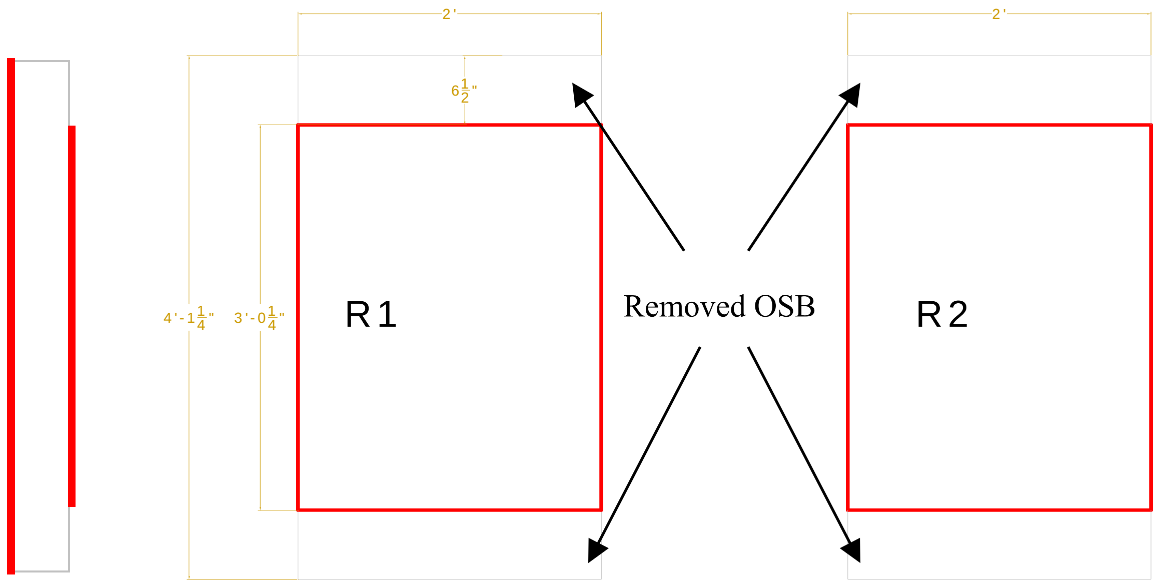

Figure 23: Dimension for the door panel (left) and the right side panel (right) [14]

7.3 Assembly Details

As Section 7 explained, there will be many assembly details such as L-shaped brackets, rubber seals, blocking systems, etc. These details are necessary for durability. In this section, the typical corner assembly details and the door assembly details will be discussed.

Typical Corner Assembly Details: Figure 24 [14] shows the typical corner assembly details of the thermal chamber. L-brackets will be attached to the inner and outer corners of the thermal chamber using adhesive sealant and fasteners.

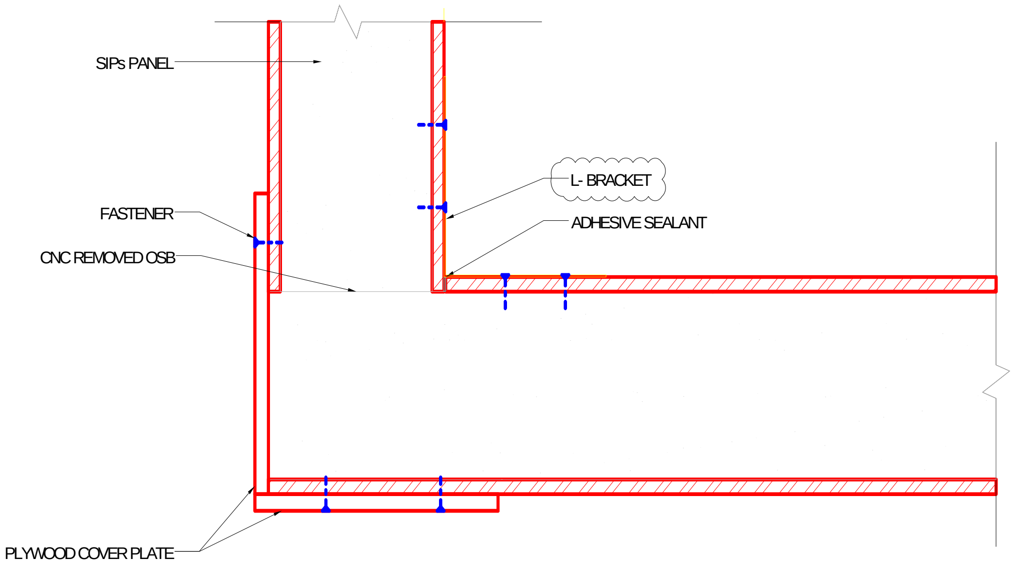

Figure 24: AutoCAD model of typical thermal chamber corner assembly details [14]

Door and Façade Fixture Details: Figure 25 [14] shows the details of the door and façade fixture system from the top view. The door, attached to the right-side panel by hinges, will be closed firmly by a clamping mechanism. The door will be covered with a compressible rubber seal to prevent air leakage. A movable blocking system will be placed behind the façade system to prevent the façade from falling back during testing and compress the seal.

We need to accommodate the varying façade thickness of 4 - 6 in. (≈ 10 - 16 cm), whereas the height and the width of the system are fixed. Therefore, adjustable spreaders will be placed between these façade blocking systems and the sealing frame.

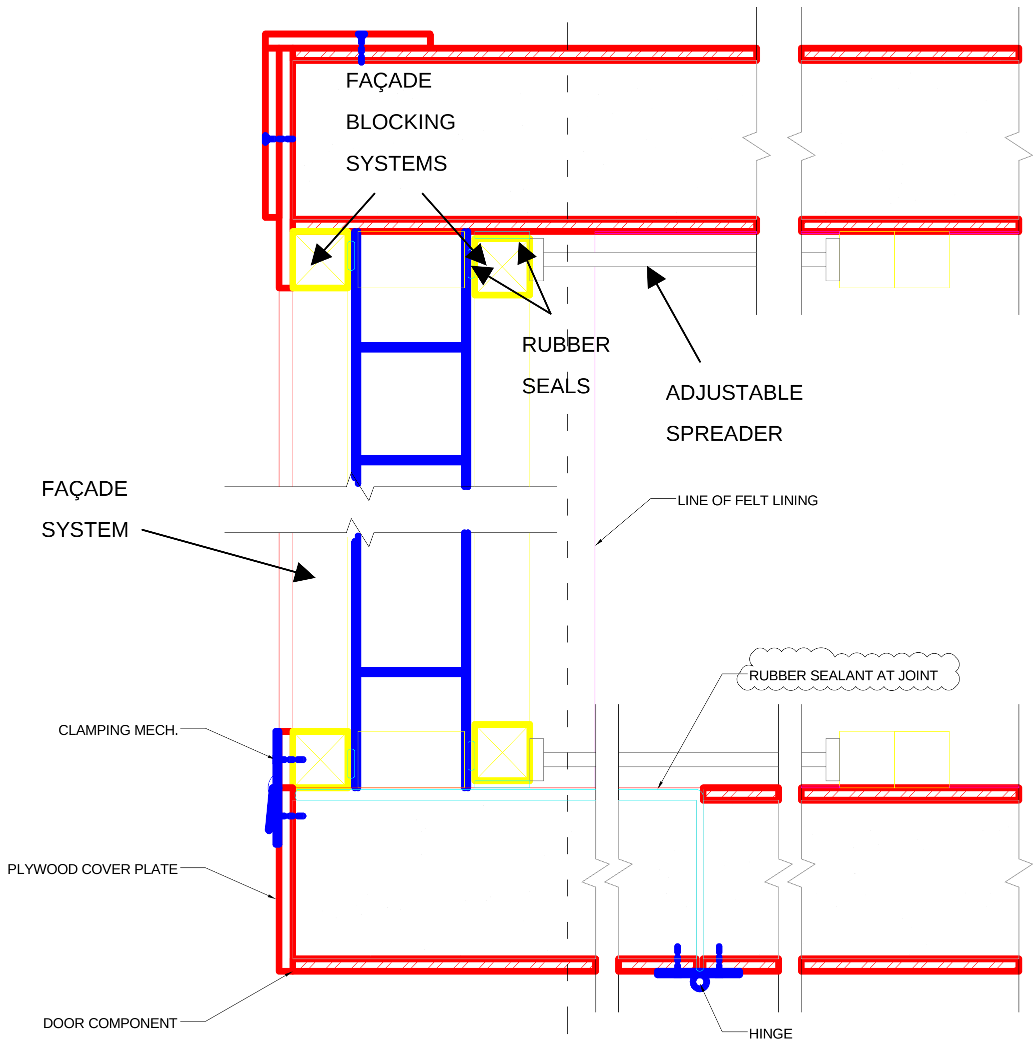

Figure 25: AutoCAD model of thermal chamber door assembly details [14]

Temperature Measuring Devices: In total 11 temperature measurements are required for our testing process and data analysis. Figure 26 shows the locations of each device. "Tw" represents a wall (surface) temperature that will be measured using thermocouples attached to HOBO H12 type K thermocouple loggers. "Ta" represents an ambient temperature that will be measured using HOBO pendant temperature loggers. Also some software and accessories are required; including HOBOware for Windows and a USB interface cable, for use with the pendant loggers and BoxCar 3.7 for Windows and a serial interface cable for use with the thermocouple loggers. These measurement locations are selected based on the thermal simulation results of the temperature profiles that will be discussed in Section 9.

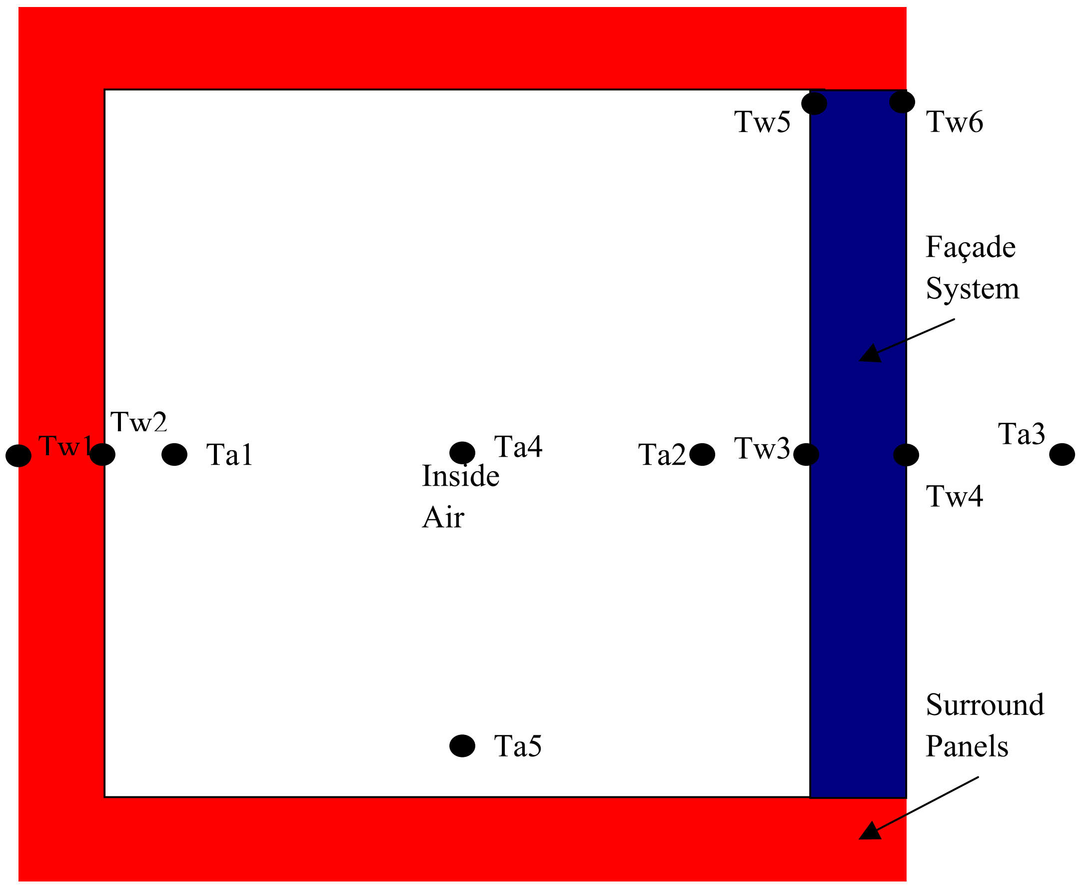

Figure 26: Layout of temperature measurement locations

7.4 Design for Manufacturability/Assembly

This project is intended to be a one of a kind chamber built specifically for testing the unique façade designs for the P3 competition. As a result the design and manufacturing decisions we made were constrained by the manufacturing methods and tools available in the architecture department.

When deciding on a final design, heavy influence was placed upon the ease of manufacturability due to the short lead-time needed to complete the chamber. The shear size of our chamber limited our concepts to designs that could be manufactured in the architecture department shop, which had table and band saws, drill presses and various miscellaneous hand tools. One such consideration that was taken into our final design was the thermal conductance of the chamber's surrounding panels. In line with NFRC standards, the thermal conductance should be less than 0.007 BTU/hr-ft^2-°F (or 0.04 W/m^2K). To meet this requirement the supplied SIPs would have to be 3.28 ft thick, making the final design approximately a 10 ft cube, which is too large to be mobile, beyond the cutting capabilities of the available tools, and too expensive to produce. This manufacturing problem was solved by reducing the specified conductance of the walls, allowing them to be thinner. The downside to this solution was increased heat loss through the chamber walls, but we were able to calibrate the system to ensure more accurate conclusions were reached.

Another important manufacturing and assembly consideration was the availability of components used in the design. We had to use components that were readily available locally and would be easy and quick to assemble so that we would not have down time waiting for specialty parts to arrive. This limited our design to fasteners and raw materials available at common hardware stores like Home Depot. One example of this is in the design of our internal blocking system which functions to apply force on the façade to seal out outside air. Some of our preliminary designs for this system were complex and would require days to order parts, assemble, and make adjustments to. In the final design we opted for a simple spreader system, which utilizes four independent bars, clamps with the application points turned in opposite directions. This was a good solution because the components for the system were readily available and the system was quick to assemble, ultimately giving us more time to conduct testing.

8 DESIGN MODIFICATIONS

Before the prototyping process, we reviewed our final design to check if any design modifications were necessary. We determined changes were needed on the front blocking system of the thermal chamber.

8.1 Front Blocking System

After discussion with our sponsor, we concluded that the front blocking system should be removed from our original design. As shown in Figure 25 [14] on page 38, the front blocking system was originally designed to assure equal pressure would be applied to the front and back of the façade system to prevent any possible fracture or bending. However, the presence of the front blocking system would cause a shading effect on the façade system as shown in Figure 27 [14]. This shading effect would influence our testing results (especially during SHGC testing) because the thermal analysis was based on the assumption that the entire façade system would be exposed to the same or similar thermal environment. If this assumption is violated considerably, our temperature analysis would be incorrect since we cannot assume a constant temperature at the surface of the façade system.

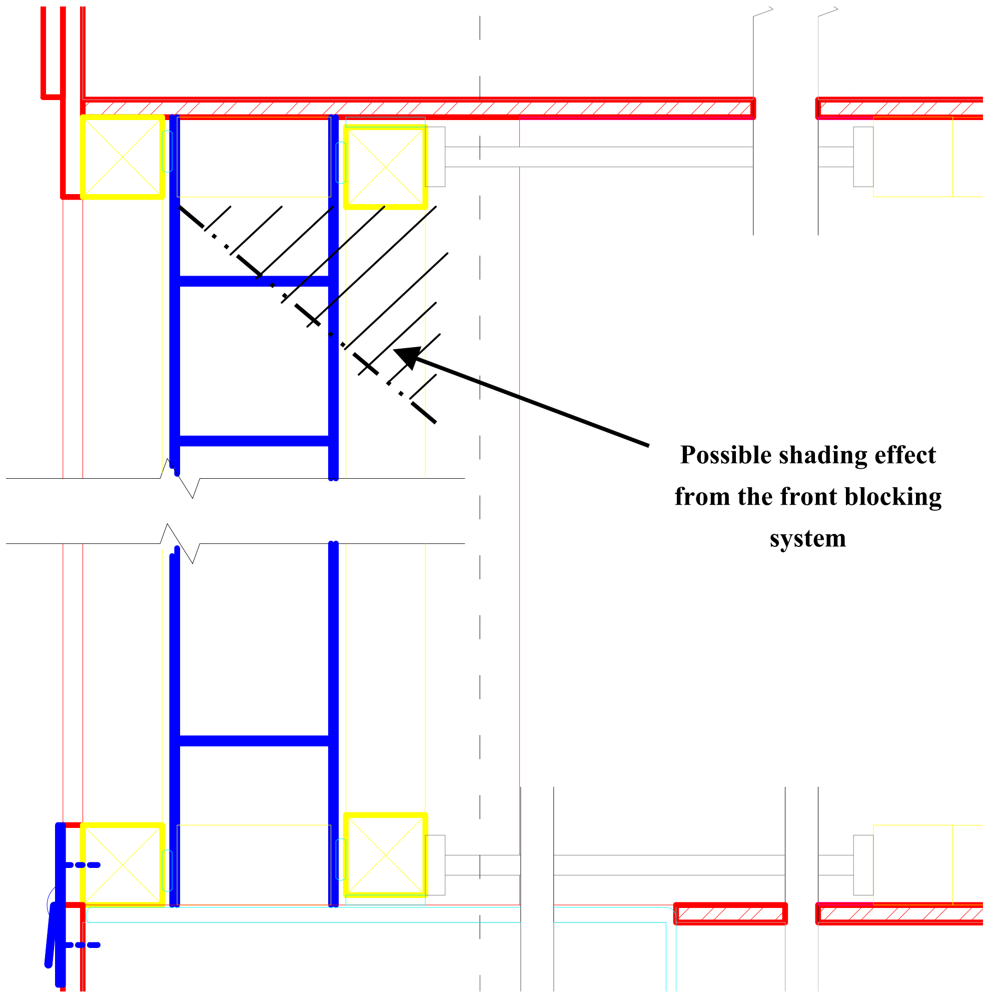

Figure 27: AutoCAD representation of possible shading effect on the façade system from the front blocking system [14]

Because of the front panel, there will still be equal pressure on both the front and back of the façade system without the front blocking system. Therefore, we decided to remove the front blocking system as shown in Figure 28 [14]. This simplified our design as well as reduced material cost. In addition, the façade system will have a minimal shading effect, which will increase the accuracy of the thermal testing results.

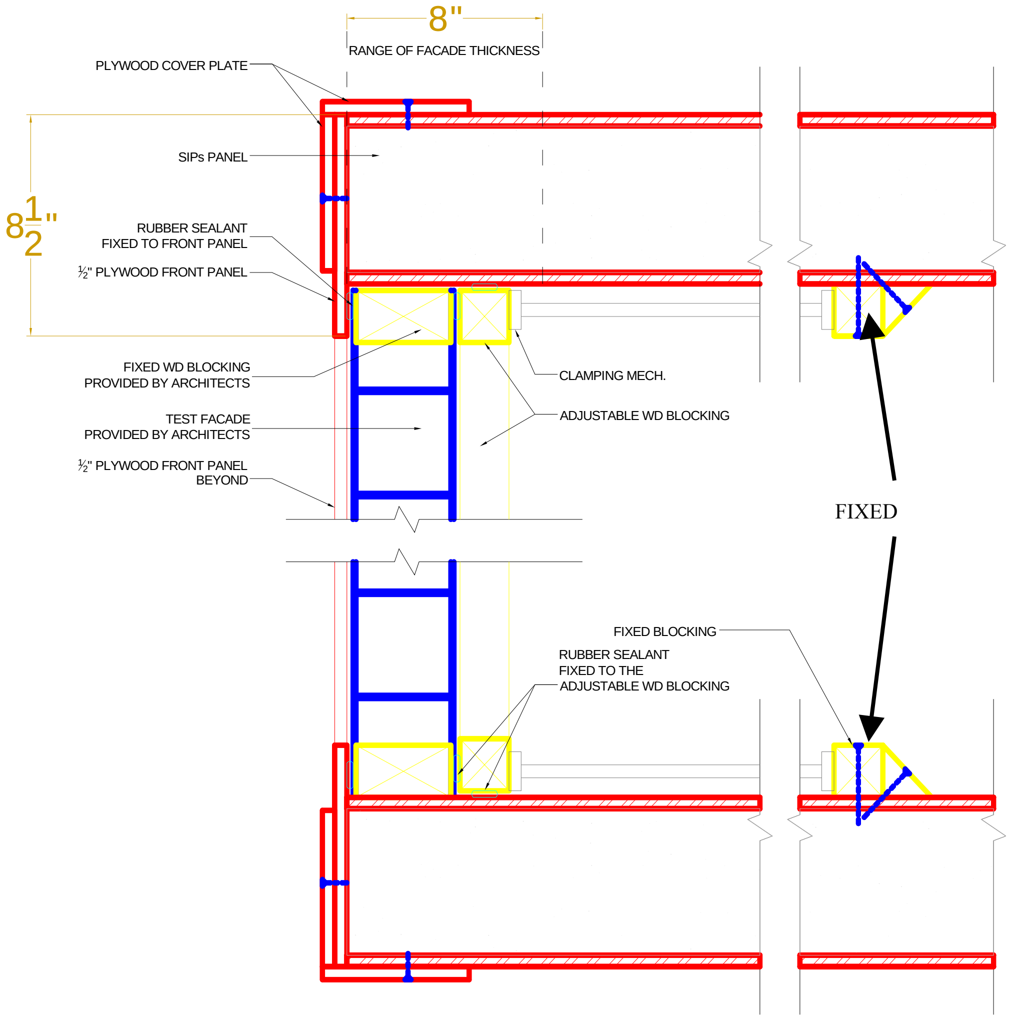

Figure 28: AutoCAD engineering drawing of the modified front façade fixture system [14]

8.2 Blocking System Dimensions

Originally, we planned to use 2 × 2 in. (or 5.08 × 5.08 cm) wood bars to manufacture both the movable and fixed blocking systems. However, commercially available wood is standardized to 1.5 × 1.5 in. (3.81 × 3.81 cm). To accommodate this, the blocking system was changed to these dimensions. Due to the reduction of the blocking system dimensions, the width on each side of the front panel was changed from 9 in. (or 22.86 cm) to 8.5 in. (or 21.59 cm).

9 THERMAL ANALYSIS

To ensure a proper testing set-up, we performed a thermal analysis that allowed us to make reasonable assumptions about the temperature contours created from testing. From these assumptions, we were able to determine how to estimate the temperatures of the thermal chamber walls and façade system with only eleven thermocouples. It is worth it to note that the wattage of the heat sources we are using in these simulations are not indicative of the heat sources we used during actual testing. These simulations are still suitable as we were only trying to gauge the temperature profiles of the thermal chamber at steady state, and not the actual final temperatures.

9.1 U-Factor Simulations

To get estimate temperature profiles around the thermal chamber before physical calibration and testing, we used FEHT (Finite Element Heat Transfer) [15] to perform a 2D simulation and FLUENT (Computational Fluid Dynamics software) [16] to perform a 3D simulation of heat transfer. Both simulations are based on the real material properties we used for the thermal chamber construction. The surround-panel thermal conductivity is 0.0231 BTU/hr-ft-°F (or 0.04 W/m-K) [17], the ambient outside temperature is 77 °F (or 25 °C), the radiant heat source used for simulation is 68.24 BTU/hr (or 20 W), the solar heat source used for simulation is 238.85 BTU/hr (or 70 W), the convection coefficient outside the panel and the façade system are approximately 0.176 BTU/hr-ft^2-°F and 0.211 BTU/hr-ft^2-°F (or 1 W/m^2-K and 1.2 W/m^2-K) according to the previous iteration results. In the model, a standard window glass with conductivity of 0.451 BTU/hr-ft-°F (or 0.78 W/m-K) is used to represent the façade system.

9.1.1 2D Simulation with FEHT

We modeled the center cross-section plane of the thermal chamber with a radiant heat source of 68.24 BTU/hr (or 20 W) by specifying a heat generation rate of 1.931 BTU/hr-ft^3 (or 20 W/m^3) for the inside air volume (Figure 29). We divided this cross-section model into triangular shaped meshes with the façade system more finely meshed than the chamber, shown in Figure 29. The maximum number of grid points available for FEHT is 1000; there are 783 grid points and 1488 elements in the cross-section model. The temperature contours are shown in Figure 30 for the surrounding panels and façade system temperature gradients in detail. Specific temperature ranges are chosen in those figures to demonstrate the temperature gradients for the façade system and the surrounding panels in detail. The same demonstration method is also used in the 3D analysis and SHGC analysis. The ranges are the same in the 2D and 3D cases, in Sections 9.1.2 and 9.2, to evaluate the similarity of the temperature profiles calculated from both finite element programs. The purpose of this finite element analysis is to estimate the temperature ranges of the chamber walls, the façade system, and the inside of the chamber.

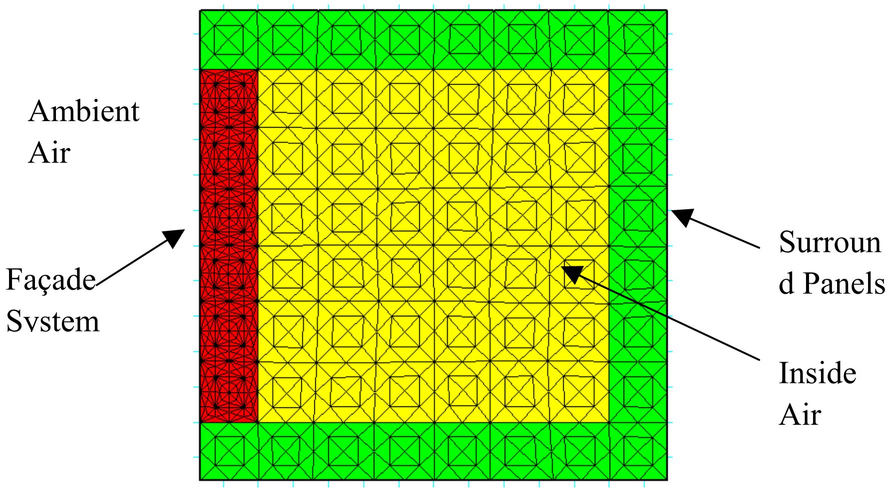

Figure 29: Meshed thermal chamber with the façade system

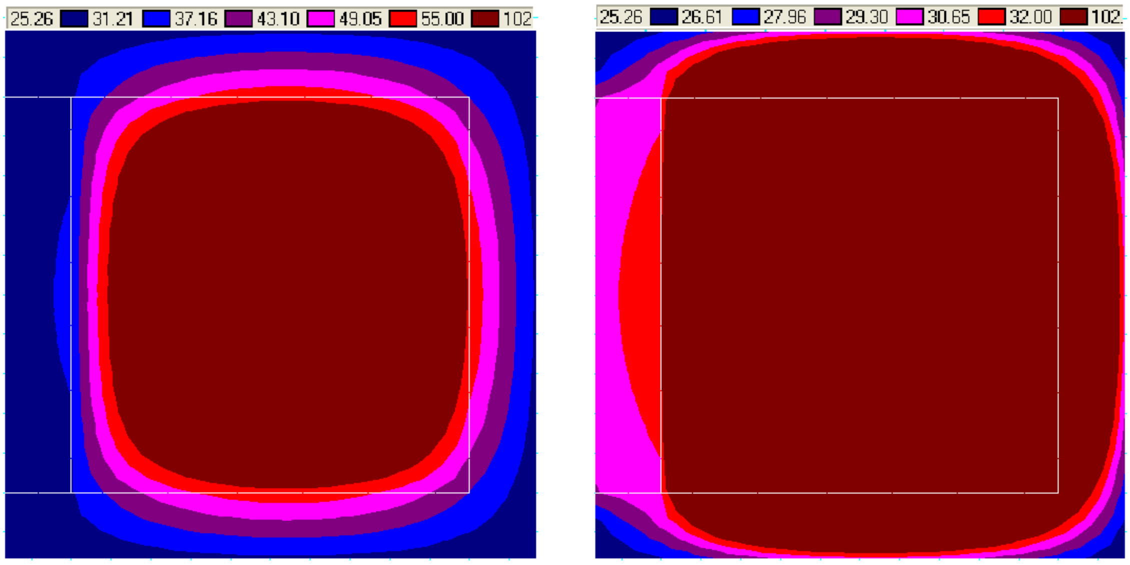

Figure 30: Temperature gradient of surrounding panels (left) for temperature range of 25.26 °C to 55 °C, and temperature gradient of façade system for temperature range of 25.26 °C to 32 °C (right)

9.1.2 3D Simulation with FLUENT

We modeled the whole thermal chamber volume by specifying a heat generation rate of 8.94×10^3 BTU/hr-ft^3 (or 9.26×10^4 W/m^3) for a small cube in the center of the chamber, which represents the radiant heat source of 68.24 BTU/hr (or 20 W) (Figure 31). Using GAMBIT as a preprocessor, we meshed the model in hybrid shapes using a mesh size of about 0.787 inch (or 2 cm), which is shown in Figure 31.

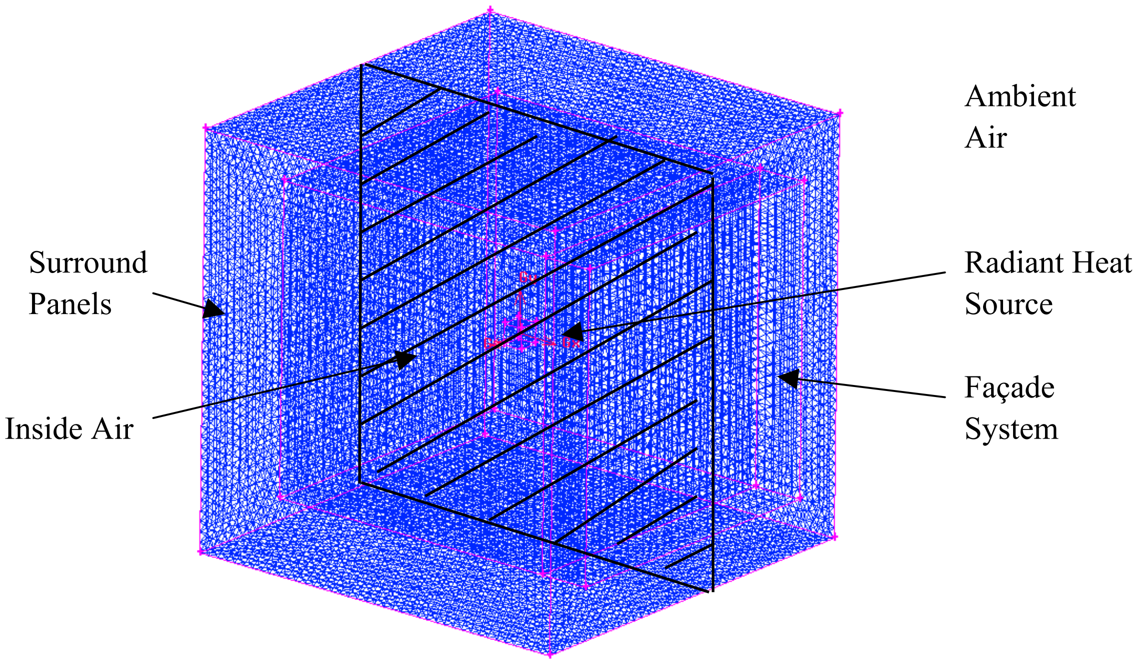

Figure 31: 3-D meshed thermal chamber with heat source (the shaded surface is a cross section of the center of the chamber, where the 2D contours were determined)

The temperature contours are shown in Figure 32 and 33 for the cross section plane through the centerline of the thermal chamber, showing the surrounding panel and façade system temperature gradients in detail.

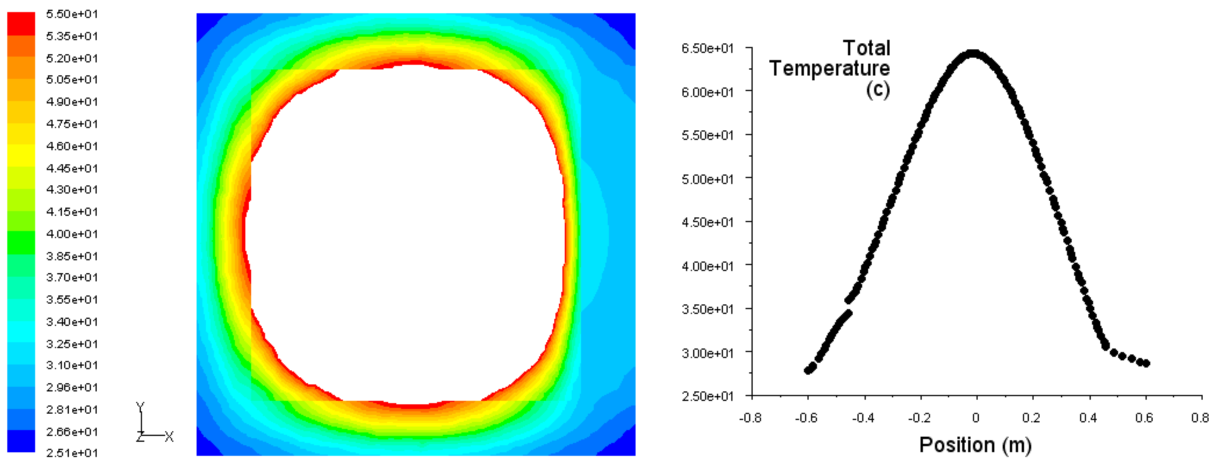

Figure 32: 2-D contours of temperature of surrounding panels, at center plane, for temperature range of 25.1 ˚C to 55˚C (left), and the temperature plots along the center line on the inside of the bottom panel (right); the asymmetric profile is due to large heat transfer through the façade

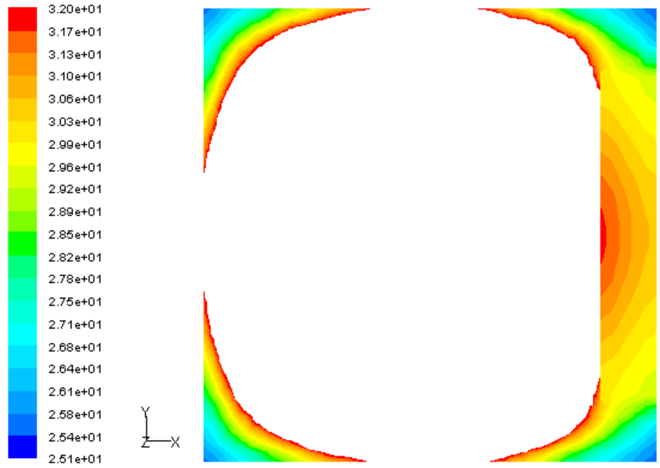

Figure 33: 2-D temperature gradient of façade system in detail for temperature range of 25.1 ˚C to 32 ˚C

The velocity profile is shown in Figure 34, which proved that the convection inside the chamber is very small. The 3D temperature contours are shown in Figure 35, 36, and 37 for the façade system, the outside wall, and the inside wall, respectively. These temperature profiles show an approximate linear temperature gradient along the inside and outside walls, which allowed us to take the average temperatures from the measurements specified in Figure 28. The average temperature on the inside surface of the facade will be the average of measurement value Tw3 and Tw5. The average temperature on the outside surface of the facade will be the average of Tw4 and Tw6. By assuming that the inside edge temperatures are the same as Tw5, we can get the average inside wall temperature from the average value of Tw2 and Tw5. The outside wall temperature will be approximately Tw1 since the temperature gradient is small for the outside walls.

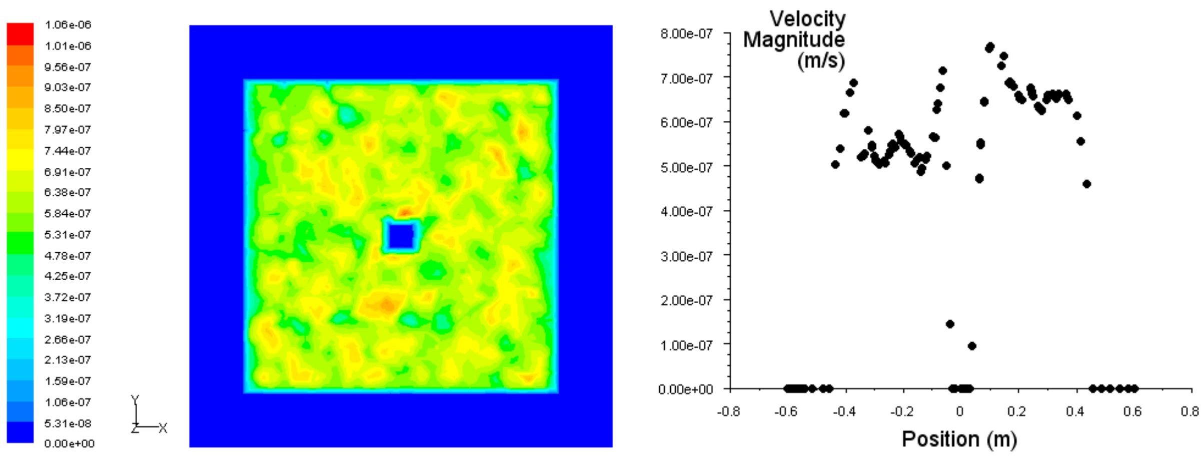

Figure 34: 2-D contours of velocity magnitude (m/s) for air inside the thermal chamber, which is shown to be negligible, and the velocity plots along the center line on the inside of the bottom panel (right)

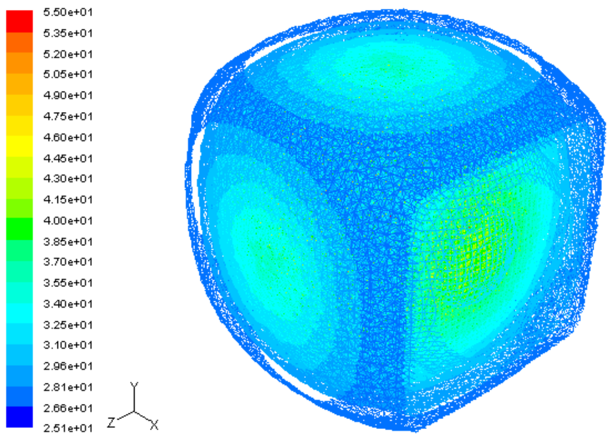

Figure 35: 3-D contours of temperature for the outside surface of the surrounding panels and the façade system for temperature range of 25.1 ˚C to 55 ˚C

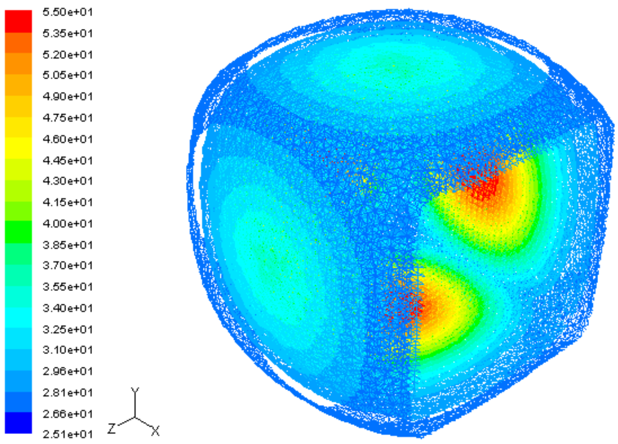

Figure 36: 3-D contours of temperature for the outside surface of the surrounding panels with the façade removed to show the inside surfaces for temperature range of 25.1 ˚C to 55 ˚C

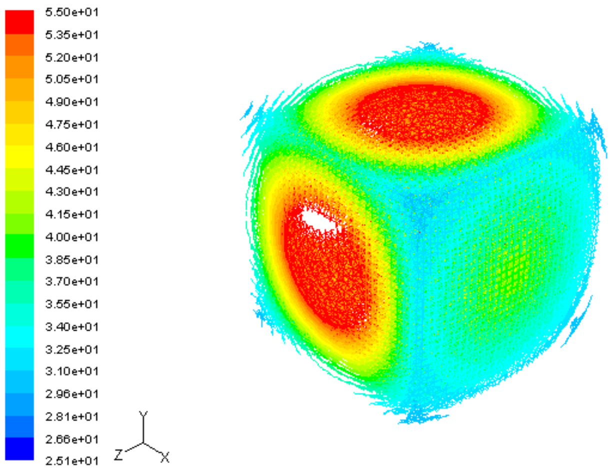

Figure 37: 3-D contours of temperature for the inside surface of the surrounding panels and the façade system for temperature range of 25.1 ˚C to 55 ˚C

9.2 SHGC Simulations

9.2.1 2D Simulation with FEHT

We modeled the cross section plane of the thermal chamber with a heat transfer rate of 238.85 BTU/hr (or 70 W) by specifying a heat flux of 22.18 BTU/hr-ft^2 (or 70 W/m^2) for the outside surface of the façade system. The temperature contours are shown in Figure 38 for overall profile, the surrounding panels, and the façade temperature gradient.

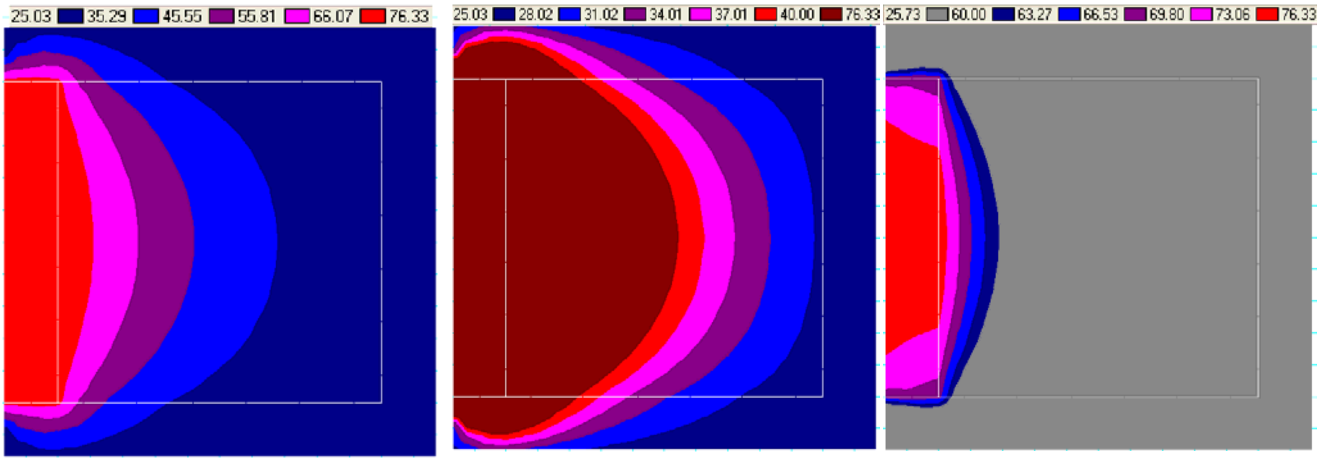

Figure 38: Temperature contours of the total thermal chamber for temperature range of 25.03 ˚C to 76.33 ˚C (left), surrounding panels for temperature range of 25.03 ˚C to 40 ˚C (center), and temperature gradient of the façade system for temperature range of 25.73 ˚C to 76.33 ˚C (right)

9.2.2 3D Simulation with FLUENT

We modeled the thermal chamber volume by specifying a heat flux of 22.18 BTU/hr-ft^2 (or 70 W/m^2) through the façade system outside surface, which represents the heat transfer rate of 238.85 BTU/hr (or 70 W). The temperature contours are shown for the cross section plane through the centerline of the chamber, showing the overall profile of the chamber (Figure 39), the façade system temperature gradient in detail (Figure 40), and the panels surrounding the façade (Figure 41).

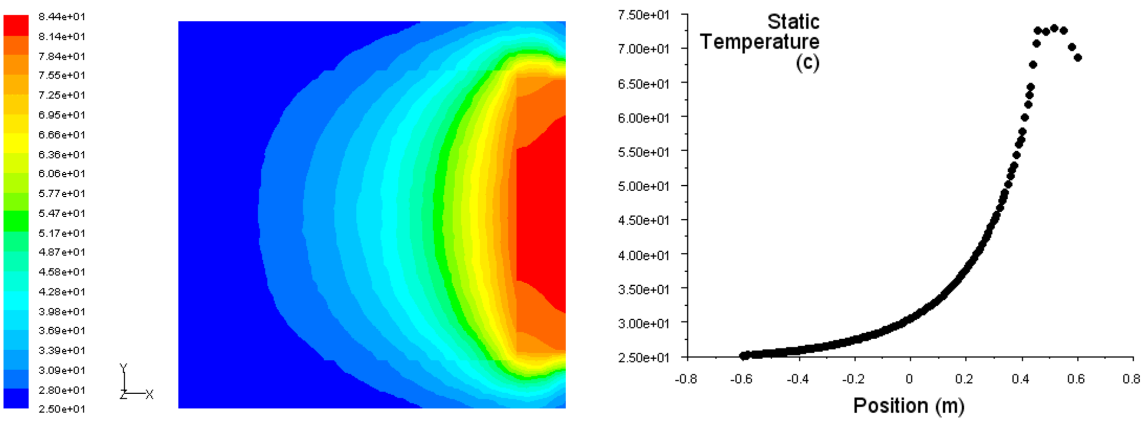

Figure 39: 2-D contours of temperature of the total thermal chamber for temperature range of 25 ˚C to 84.4˚C (left), and the temperature plots along the center line of the inside of the bottom panel (right)

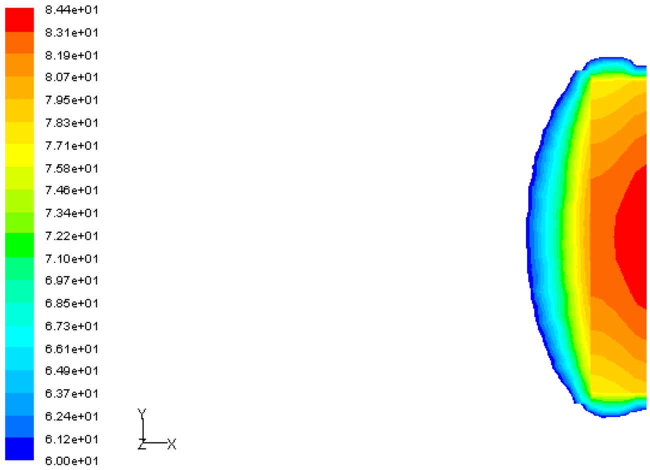

Figure 40: 2-D temperature gradient of the façade system for temperature range of 25 ˚C to 84.4˚C

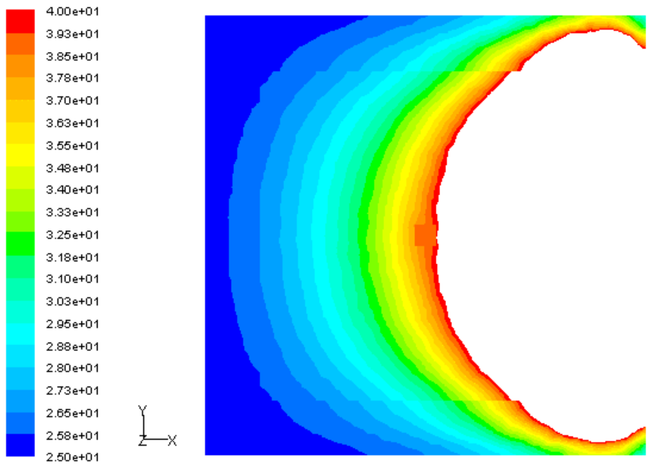

Figure 41: 2-D contours of temperature of surrounding panels for temperature range of 25 ˚C to 40 ˚C

The 3D temperature contours are shown for the outside of the façade (Figure 42) and surrounding panel (Figure 43), and the inside of the chamber (Figure 44). These temperature profiles also show an approximate linear temperature gradient along the inside and outside walls, which allowed us to take the average temperatures from the measurements specified in Figure 28. The average temperature on the inside surface of the facade will be approximately the measurement value Tw3. The average temperature on the outside surface of the facade will be Tw4. By assuming that the inside edge temperatures are the same as Tw5, we can get the average temperature of the top and bottom inside walls from the average value of Tw2 and Tw5. The left wall temperature will be Tw2, which will be relatively low since it is the farthest wall from the façade. The outside wall temperature will be approximately Tw1 since the temperature gradient is small for the outside walls.

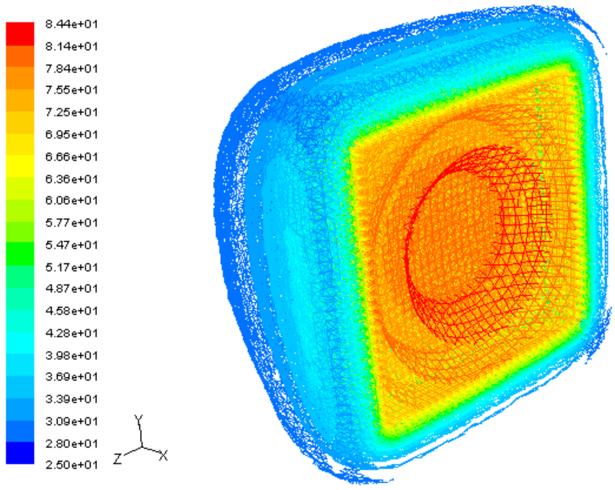

Figure 42: 3-D temperature contours for outside surface of the façade system and the surrounding panels for temperature range of 25 ˚C to 84.4˚C

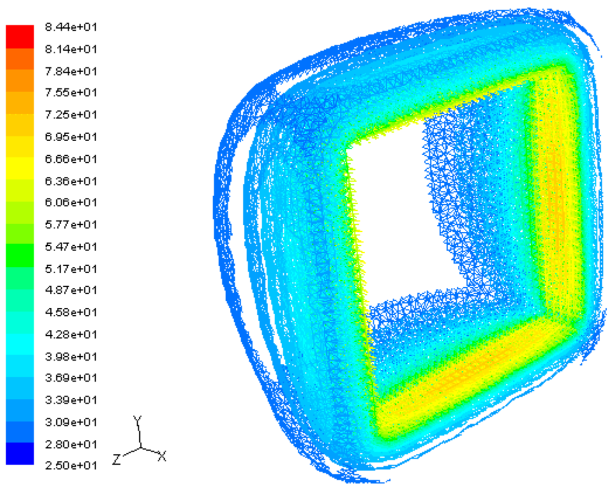

Figure 43: 3-D temperature contours for the surface of the panel surrounding the façade for temperature range of 25 ˚C to 84.4˚C

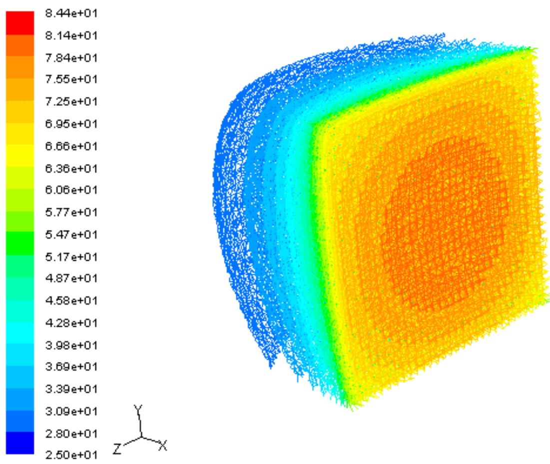

Figure 44: 3-D temperature contours for the inside surface of the chamber for temperature range of 25 ˚C to 84.4 ˚C

10 VALIDATION PROCESS

A validation process is necessary in order to confirm that our design meets the specified requirements. This process began with verifying that our thermal chamber and testing equipment met the specified engineering requirements and will finish with U-factor and SHGC tests. Most of the engineering requirements were met through the design and construction of the thermal chamber and artificial light source, but a few tests will be necessary to validate the ability of our design to measure the SHGC and U-factor.

Both the thermal chamber and the artificial light source were designed and constructed to meet the engineering requirements. The usage of SIPs to construct the chamber met the requirement that the chamber walls have a thermal conductance less than or equal to 0.044 BTU/hr-ft^2-°F (or 0.25 W/m^2-K). Eleven thermal couples were installed in the chamber, meeting the requirement that at least eight temperature measurements be taken. The chamber can also successfully fit the 3 ft × 3 ft × 4-6 in. (≈ 0.914 m × 0.914 m × 10-16 cm) test panels. A wooden base with wheels has also been constructed, enabling the chamber to be moved with well under a 50 lb (or 220 N) force.

A few tests were needed to ensure that the thermal chamber and testing equipment could reliably measure the SHGC and U-factor of the test panels. The first test performed was a smoke test. This was carried out by dousing lit woodchips with water and placing them inside the thermal chamber. The woodchips filled the chamber with smoke, allowing us to identify any potential holes in the chamber walls. After the test was performed, the identified holes were sealed with rubber or caulk to prevent air leakage during testing. The U-factor tests will be validated by comparing their results to computer-simulated estimates of the façade systems' U-factors, which are around 0.6 BTU/hr-ft^2-°F. The SHGC tests will be validated by comparing the results to tests performed outdoors, weather permitting, using natural light instead of the artificial light source.

11 TESTING

To determine the SHGC and U-factor of the façade systems that are being developed, the chamber must be calibrated and two tests must be completed.

11.1 Testing For Thermal Transmittance

To find the U-factor, we will be conducting a simple test that uses one 100-Watt light bulb and 11 temperature measurements as previously described. The light bulb will be placed inside the thermal chamber and will supply the heat needed to create a temperature gradient across the façade.

The actual test will consist of only supplying power to the light bulb, thus supplying heat to the system, and waiting for steady state. Once steady state is reached the following figure and equations will be employed to determine the U-factor.

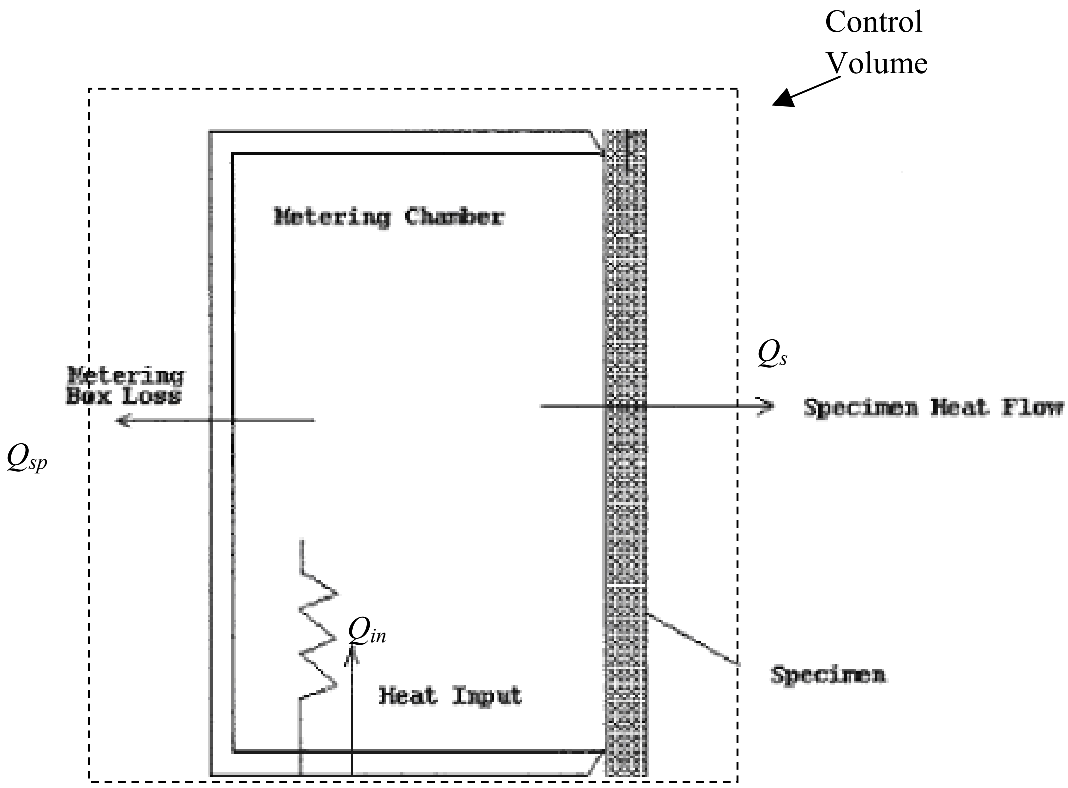

Figure 45: One chamber hot box with control volume and heat flows for U-factor testing

If we draw a control volume around the thermal chamber, the following equation can be written at steady state:

$$Q_{in} = Q_s + Q_{sp} \qquad (11)$$

where Q_{in} represent the heat input into the system via the light bulb, Q_s is the heat flow through the façade panel, and Q_{sp} represents the heat loss through the surrounding panel walls, which will be discussed in the calibration section.

Equation 11 can also be rewritten using the definition of the U-factor as follows:

$$U_s = \frac{Q_{in} - Q_{sp}}{A_s (T_h - T_c)} \qquad (12)$$

where U_s is the U-factor for the façade panel, A_s is the area of the façade panel, and T_h and T_c (calculation detail see Appendix E) are the ambient temperatures on the hot and cold side of the façade panel, respectively.

By examining Equation 12, we find that we know Q_{in} (the wattage rating of the light bulb) and the area of the façade panel (from a simple measurement). We can also easily measure the temperature on both sides of the façade panel using thermocouples (the accuracy of the determined U_s will depend on our ability to accurately measure these temperatures). This leaves two unknowns: *Qsp and Us*. Because we want to find the U-factor, we must determine the heat loss through the surrounding panels in another way. We will accomplish this through calibration against façades that have a known U-factor as described in Section 11.3.

11.2 Testing for the SHGC

The procedure for testing the SHGC will be similar to that of the U-factor testing. We will be using the same temperature measurements, but there will be a change in the light source. Instead of a light bulb on the inside of the chamber, we need to imitate the sun by placing a high-energy light source outside the testing chamber. The light source will need to have a variable output and be able to change position to replicate the position of the sun in the sky. Initial estimates dictate that the light source should be capable of emitting approximately 400 BTU/hr for winter conditions and 3000 BTU/hr for summer conditions at the façade surface.

The light source will be comprised of nine 500-Watt halogen lamps. The light source will have 3 degrees of freedom: (1) the angular motion of the lamp, which is built in; (2) each lamp will be able to move horizontally along one of three horizontal Uni-Strut rails, and (3) each of the horizontal rails will be able to move vertically on two vertical Uni-Strut rails. Figure 46 shows a representation of the light source and the SHGC test set-up. The thermal chamber is lifted off the ground to simulate the presence of a base that was constructed by the Architecture department.

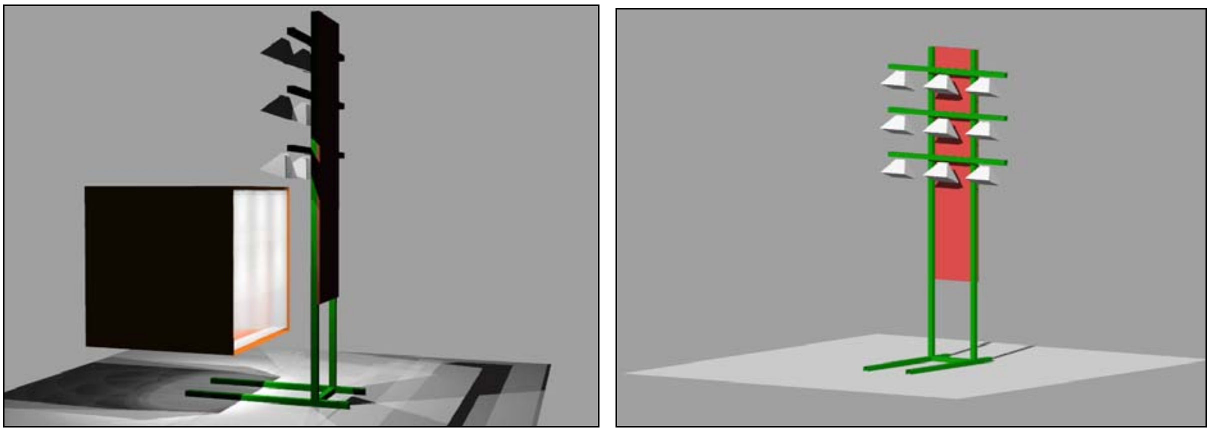

Figure 46: CAD model representations of the nine lamp light source for SHGC testing (right) and the SHGC testing set-up (left) [18]

The testing will be carried out by supplying power to the artificial light source and positioning the source in the correct orientation to replicate the sun's position. The thermal chamber will be heated by the fraction of the radiation that penetrates the façade panel. Once steady state is reached the test will stop. The following figure and equations represent this test and are valid at steady state.

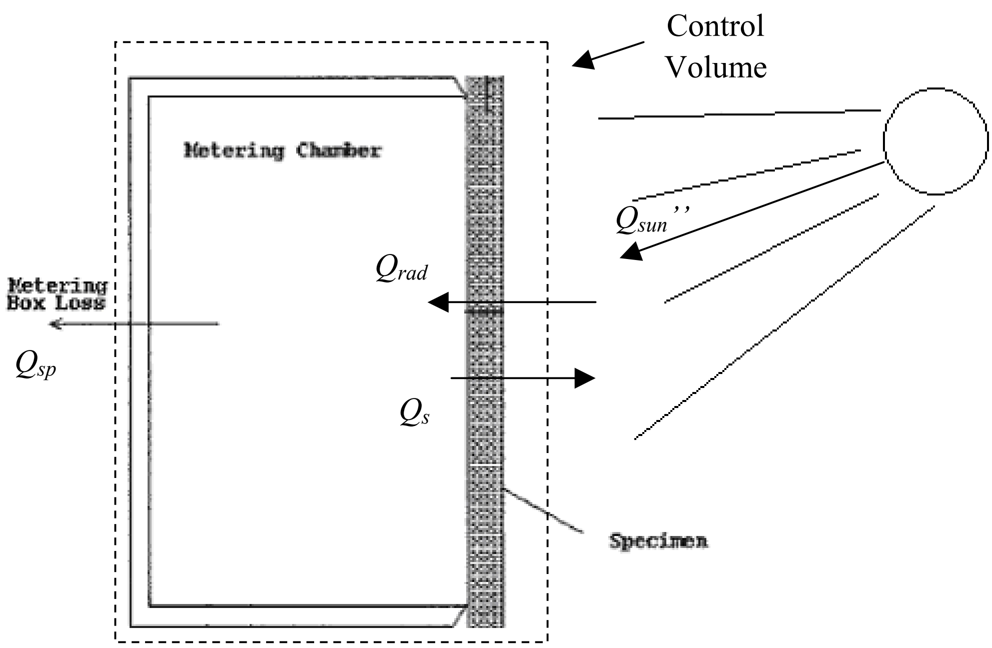

Figure 47: One chamber hot box with control volume and heat flows for SHGC testing

Drawing a control volume around the thermal chamber and performing a steady state energy balance yields the following equation:

$$Q_{rad} = Q_s + Q_{sp} \qquad (13)$$

where Q_{rad} is the portion of the solar radiation that passes through the façade panel, and Q_s and Q_{sp} are as previously defined.

Using the definition of the SHGC and the U-factor, Equation 13 can be rewritten as follows:

$$SHGC = \frac{U_s A_s (T_h - T_c) + Q_{sp}}{A_s Q''_{sun}} \qquad (14)$$

where Q''_{sun} is the radiation heat flux that is emitted by the solar heat source, T_h and T_c are the ambient temperature on the hot and cold side of the façade panel, respectively (for calculation details, see Appendix F).

By examining Equation 14, we can see that the only parameters we don't know and cannot measure directly are the SHGC and Q_{sp}. Again, by calibrating the thermal chamber before the testing is carried out, we can determine the losses that will be present and can adjust our calculations accordingly.

11.3 Calibration

In order to accurately measure the SHGC and U-factor the thermal chamber itself must be understood. To do this we must understand the heat flows that pass through the chamber walls.

If we stop to think how the heat flow through the panel will occur and vary, we are led to Figure 48, which is a representation of the one-dimensional conduction that takes place. The ambient temperatures on the inside and outside of the surrounding panel are denoted as $T_{sp\text{-}in}$ and $T_{sp\text{-}out}$ (for calculation details, see Appendix G), U_{sp} is thermal transmittance (U-factor), and A_{sp} is the area of the surrounding panel.

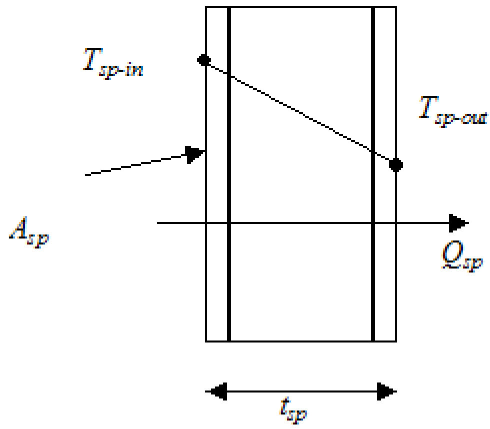

Figure 48: 1D conduction across surrounding panel

The equation that defines the steady 1-D conduction is as follows:

$$Q_{sp} = \frac{k_{sp} A_{sp} (T_{sp-in} - T_{sp-out})}{t_{sp}} \qquad (15)$$

It is obvious from this equation that the surround-panel heat flow is a function of the temperature gradient across the panel. Since this is the case, the calibration of the thermal chamber must be carried out as function of temperature. Due to the use of only a single chamber hot box with no heat exchanger, the surround-panel temperature gradient will be different for every panel tested. By calibrating the chamber against three panels with a known property (i.e. a known U-factor) we can determine how Q_{sp} fluctuates with temperature, and thus make out calculations of the SHGC and U-factor more accurate.

Rearranging Equation 12 and using the definition of the U-factor:

$$Q_{sp} = Q_{in} - U_s A_s (T_h - T_c) \qquad (16)$$

Where U_s is the U-factor of the façade, As is the area of the faced (3ft × 3ft), and T_h and T_c are the temperatures of the hot and cold faces of the façade, respectively.

Thus, by testing panels with known U-factors, it is possible to determine the heat flow through the SIPs (i.e. the losses) in terms of the temperature difference across the surround panels

11.4 Testing Matrix

The goals of the testing for this project are 3 fold: (1) determine the U-factor for the prototype façade panels, (2) determine the SHGC under artificial light for both summer and winter conditions, and (3) weather permitting, validating the artificial light SHGCs against SHGCs determined using natural light.

The parameters that will be varied during testing are (1) façade thickness (2) façade shading matrix size and geometry, and (3) the color of the shading system. In order to cut back on costs, the façade prototypes will allow for disassembly. However, for comparison, one prototype will be constructed with adhesive, in the same fashion as the actual façade would be constructed, instead of with clamps. Table 6 shows the panels that will be tested, including the standard panels that will be used for calibration, and associated parameter values.

Table 6: Test panel matrix showing both standard and prototype panel data.

Standard Sample Panels				
Panel No.	**Materials**	**Thickness (in)**	**U-factor (Btu/hr/ft2/°F)**	**Connection**
1	Single glass clear	0.125	1.02	N/A
2	Double glazing clear	0.125-0.5-0.125 (glass-air-glass)	0.48	Filler & Silicone
3	Single MDF	1.5	0.49	N/A
Façade Prototype Panels				
Panel No.	**Geometry and Cell Size(in)**	**Thickness (in)**	**Core Color**	**Connection**
4	Square-4	4	Natural	Epoxy
5	Square-6	4	Natural	Clamp
6	Square-6	6	Natural	Clamp
7	Square-6	4	White	Clamp
8	Square-6	4	Black	Clamp
9	Hexagonal-6	4	Natural	Epoxy
10	Tetragonal-6	4	Natural	Epoxy

Table 7(a) shows the desired testing matrix for the ten panels, while table 7(b) shows the tests that were actually conducted, in the short amount of time we had to conduct our tests. It is the intent of our sponsor to continue testing beyond our involvement in the project. All panels will be tested for U-factor, with the standard panel results (1-3) being used to calibrate the loss term in Equations 14 and 15. The prototype panels will all be tested for SHGC in both artificial and natural light and for both summer and winter conditions. The summer condition SHGC tests will simulate a sun angle of 72°, while the winter condition will simulate a sun angle of 25°. These angles are easy to simulate with the artificial light source because its position can be changed at will.

However, in order to conduct the natural lighting tests under the same conditions, the thermal chamber will have to be tilted. The main purpose of performing both artificial and natural light tests is two fold: (1) artificial light tests allow the SHGC to be tested without regard for the weather, and (2) by testing against natural light we can validate the artificial light test results. This validation is needed because the solar spectrum can only be approximated by the artificial light source.

The current artificial light source uses halogen bulbs, but is ineffective in uniformly heating the thermal chamber due to the amount of scatter in the emitted light. Future considerations might be given to Fresnel lamps or Xenon Arc lamps in order to more accurately and uniformly emulate the solar spectrum.

Table 7 (a): Test matrix we wanted to perform for all panels.

Panel No.	U-factor	SHGC Artificial Light	SHGC Natural Light
1	C	N	W
2	C	N	W
3	C	N	W
4	Y	S/W	S/W
5	Y	S/W	S/W
6	Y	S/W	S/W
7	Y	S/W	S/W
8	Y	S/W	S/W
9	Y	S/W	S/W
10	Y	S/W	S/W
	Key	C = Used for Calibration Y = Test is Performed N = Test is not Performed W = Winter Condition only S/W = Both Summer and Winter Conditions	

Table 7 (b): Test matrix we did perform for all panels.

Panel No.	U-factor	SHGC Natural Light
1	C	N
2	C	N
3	C	N
4	Y	W
5	Y	N
6	Y	N
7	N	N
8	N	N
9	Y	N
10	Y	N
	Key	C = Used for Calibration
		Y = Test is Performed
		N = Test is not Performed
		W = Winter Condition only

11.5 Test Schedule

The original test schedule had calibration occurring on March 17th. However, we were slightly behind schedule and we used the early part of the 17th to set-up our equipment and gauge the capability of the test set-up in preparation for calibration. Unfortunately, around 7:00 p.m. on the 17th our laptop and some temperature measurement equipment were stolen from out test station. We were forced to reorder some equipment and secure another computer. Because of this, calibration and testing was delayed until Friday, March 24th. With testing needing to be completed by Friday, March 31st, there was a large time strain on testing. Table 7 shows that there were a total of 31 tests that need to be performed. Because there is such a time constraint, we will be organizing the testing in order of importance. Thus, the calibration tests of panels 1-3 will be performed first, followed by U-factor tests, and then artificial light SHGC tests of the prototype panels (panels 4-8). The natural light SHGC tests will be performed if both time and weather permit. This schedule slip has voided our original test schedule, and a new schedule is under development.

12 CALIBRATION RESULTS

The calibration of thermal chamber is done using 3 standard panels: single glass, double glazing and MDF. Table 8 shows the resultant data from these three tests.

Table 8: Calibration test data for 3 standard panels

Standard Panels	Single Glass	Double Glazing	MDF
T_h (°C)	53 ± 0.5	45 ± 0.5	45 ± 0.5
$T_c = T_{out\text{-}sp}$ (°C)	21 ± 0.5	21 ± 0.5	22 ± 0.5
T_h-T_c (°C)	32 ± 0.7	24 ± 0.7	23 ± 0.7
$T_{in\text{-}sp}$ (°C)	64 ± 0.5	45 ± 0.5	48 ± 0.5
$T_{in\text{-}sp}$ - $T_{out\text{-}sp}$ (°C)	43 ± 0.7	24 ± 0.7	26 ± 0.7
Q_s (Watt)	202 ± 4.4	71 ± 2	70 ± 2.1
Q_{sp} (Watt)	48 ± 4.4	29 ± 2	30 ± 2.1

T_h was taken to be the average internal air temperature of the standard panel, as measured by two ambient temperature loggers. T_c is the ambient temperature of the testing facility. The error on these two temperatures is due to the error in the measurement equipment, and is ± 0.5 °C. The error for the temperature difference is a combination of the errors for both T_h and T_c and is ± 0.7 °C. Q_s was calculated from Equation 3, based on the known U-factor of each panel.

Finally, Q_{sp} was determined from Equation 16, with the steady state source wattage from Table 6, substituting for Q_{in}. The error in Q_s and Q_{sp} are equal based on Equation 16 that has only one other term that is assumed to be a known number with no error. Thus, the error of these heat flow terms is based on the temperature measurement error as given in Table 8.

Figure 49 shows the calibration curve of the heat loss through the SIPs, Q_{sp}, vs. ($T_{in\text{-}sp}$ - $T_{out\text{-}sp}$). The linear correlation coefficient between these two parameters is 0.99 indicating a strong linear relationship. Thus, the regression line that was fit to the three calibration data points, with the following equation $Q_{sp} = (T_{in\text{-}sp} - T_{out\text{-}sp}) + 4$, where Q_{sp} is in Watts and ($T_{in\text{-}sp}$ - $T_{out\text{-}sp}$) is in °C, represent a good approximation to the heat losses. To determine the error in the regression equation the least and greatest sloped lines that encapsulate approximately 95% of the data points and error, are "drawn" in. The greatest sloped line has a slope of 1.35 with an intercept of 14, and the least sloped line has a slope of 0.69 and an intercept of – 6.75. Taking these into account the error on the regression equations slope and intercept are ±0.3 and ±10, respectively. The large error in the intercept is of little importance, as the slope if the most significant parameter in the regression equation.

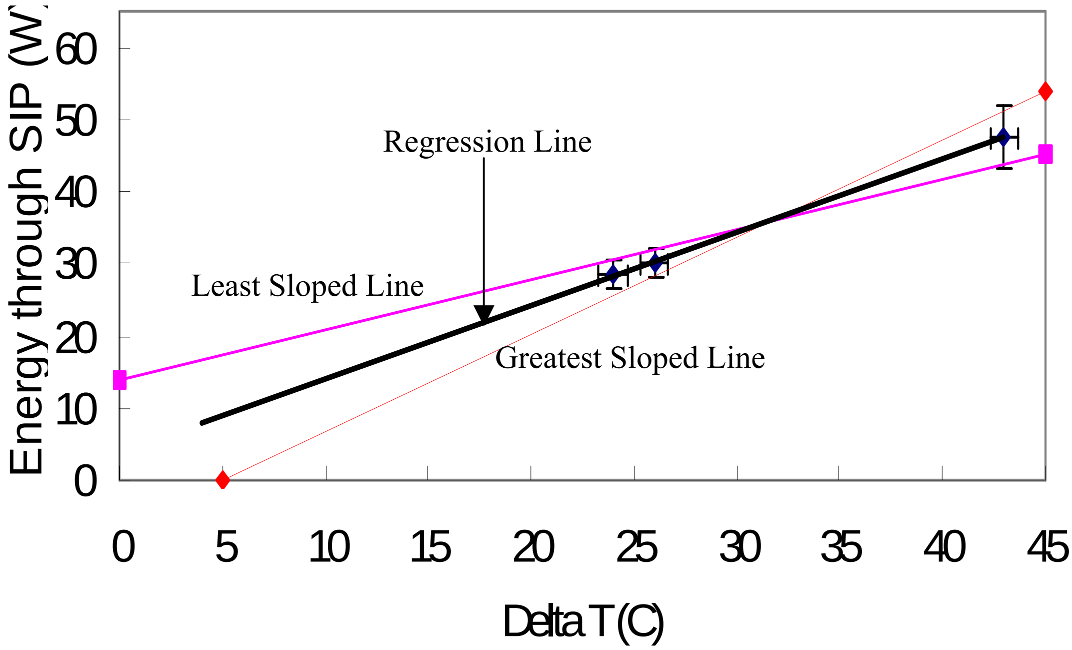

Figure 49: Calibration curve for heat loss through the SIPs. Also shown are the regression line for this data, and the enveloping error lines that encapsulate 95% of the data.

Now that the regression equation has been determined for the heat loss through the SIPs, with respect to temperature difference across the façade, each prototype façade panel test can be made more accurate by determining the losses based on the measured prototype façade temperature difference.

13 TEST RESULTS

Originally, we used a 100 Watt incandescent light as the heat source to reach the steady state for U-factor testing, but it was determined that the time to reach steady state with only this source would be too long for us to complete our tests in time. To reach the steady state faster, we used an extra 250-Watt infrared light and a 1500-Watt space heater to rapidly heat up the chamber to about 65 °C, when the space heater would automatically shut off. Once this happened, we left the 250-Watt light and 100 Watt light on for 2 hours. Finally we shut off the 250-Watt light and left the 100-Watts light to reach steady state, which took about another 4 hours. Following the test matrix in Section 11, we tested the U-factors of all 5 different façade panels, which are shown in Table 9. The panels varied in geometry (hexagonal, square, tetrahedral), cell size (4 or 6 in.), and color (natural, black, white).

Because the time constant for reaching steady state for SHGC testing was so long (~8 hours), we were unable to complete all SHGC tests under both natural lighting and the artificial light for winter and summer conditions. Results for the tests that were completed are included in Table 9; results for the remaining tests are pending.

Table 9: Test results of U-factor and SHGC for sample panels

Panel No.	U-factor (BTU/hr/ft^2/°F)	SHGC (Natural Lights)
9	0.56 ± 0.03	Pending
4	0.56 ± 0.03	0.62 ± 0.05
5	0.58 ± 0.03	Pending
6	0.60 ± 0.03	Pending
10	0.58 ± 0.03	Pending

The simulated U-factor determined by our sponsor shows about 0.60 BTU/hr/ft^2/°F for each panel. Our U-factor tests results vary from 0.56 to 0.60 ± 0.03 BTU/hr/ft^2/°F, which matches the simulation results very well. The SHGC expected by our sponsor is about 0.15 for summer condition and 0.70 for winter condition. Our test shows that the SHGC for one of the sample panels equals 0.62 ± 0.05 for winter condition, which also shows the validation of our design. So the most well insulated panel is the hexagonal natural colored 4" deep panel and the square natural colored 4 × 4 × 4 in. panel. The 6 × 6 × 6 in. panel has the least insulation because more air circulation inside the larger panel cell increases the convection heat loss.

14 DESIGN SAFE ANALYSIS

After completing a safety analysis using the program Designsafe, several failure modes were discovered. This section discusses the possible failure modes, the recommendation to utilize failure modes, factor of safety used in the analysis, and reusability of the prototype.

14.1 Overall Prototype Safety

The hot box does not have any dangerous particles inside or outside. We have ensured that our working area is clean and organized. To keep the testing area separate from the general architecture laboratory room, we put four screens around the hot box. Only people involved in the project—specifically the sponsor, one PhD architect student and our mechanical engineering team—are permitted to use the thermal chamber and testing equipment. These people are all well informed about the procedures for using this equipment.

Overall, the thermal chamber and testing equipment was judged to be generally safe. Potential unsafe cases are discussed in Section 14.2.

14.2 Possible Failure Modes and Failure Modes Utilization

One potential unsafe case is the possibility of a user hitting his/her head when installing façade panels and temperature measurements inside the thermal chamber. The size of the thermal chamber is about 4 ft × 4 ft. The user must reach quite far inside the thermal chamber to collect and install the temperature measurements. This creates a concern of users bumping their heads on the ceiling of the chamber. Unfortunately, putting any material on the ceiling as a cushion is not allowed since we are testing the insulation of the hot box and the thermal characteristics of the designed façade panels. Fortunately the ceiling of the chamber is quite blunt and made of wood, reducing the risk of serious head injuries. To minimize risk to users, we suggest warning users explicitly to be careful of their head when installing equipment within the chamber.

The Second safety issue is the possibility of applying excessive force to the façade fixture system. The fixture system is required to press the façade system tightly to the front frame to minimize any air leakage. A part of the fixture system is the adjustable spreaders that will be applied on each corner of the façade panel. Ideally, equal amount of force should be applied to each corner to properly install the façade system. The use of excessive pressure may break the façade system or displace the shading elements in the façade. To avoid any fracture of the façade system, users must be aware of putting appropriate pressure onto the façade, and watch for possible bending of shading elements when operating the spreaders.

Our major safety concern was wiring the artificial light source to a high voltage source. This required special care due to the use of a high voltage source. To ensure that this was carried out correctly and in a safe manner, we requested this task to be performed by a professional electrician. This task was properly and safely completed.

14.3 Factor of Safety

To determine the factor of safety properly, we've researched on the safety factor data as shown in Table 8.

Table 8: Suggested (Design) Factors of Safety for Elementary Work [19]

Factors of Safety	Description
1.25 – 1.5	For exceptionally reliable materials used under controllable conditions and subjected to loads and stresses that can be determined with certainty - used almost invariably where low weight is a particularly important consideration.
1.5 – 2.0	For well-known materials under reasonably constant environmental conditions, subjected to loads and stresses that can be determined readily.
2.0 – 2.5	For average materials operated in ordinary environments and subjected to loads and stress that can be determined.
2.5 – 3.0	For less tried materials or for brittle materials under average conditions of environment, load and stress.
3.0 – 4.0	For untried materials used under average conditions of environment, load and stress.
3.0 – 4.0	Should also be used with better-known materials that are to be used in uncertain environments or subject to uncertain stresses.

The thermal chamber will be used in reasonably constant environmental conditions—inside the testing area environment for U-factor testing and the warm and sunny environment for SHGC testing. Also, the chamber will be subjected to loads and stresses that can be determined readily. Based on these considerations, we determined that the safety factor will be around 1.5 – 2.0 based on the description provided in Table 8. Due to some cases of tilting the chamber for SHGC testing to obtain required sun angles, it will be more proper to use the safety factor of 2.0.

14.4 Reusability of the Hot Box

Our prototype is made up of SIPs that are rigid with protective OSB covering the internal EPS. Since one of the most important customer requirements was reusability, we tried to design the hot box that will be reusable for at least 10 years from now.

This prototype life is only valid when the thermal chamber is not exerting too much pressure or force due to dropping or lifting. In addition, the hot box should not be tilted too much because of the heavy weight of the box. The thermal chamber is made up of six panels and one frame that is joined with adhesives and L shape joints. These types of joint mechanism work very well, when it's tested on a flat ground. However, when it's tilted too much in one or multiple directions, one joint will receive excessive pressure that could cause the chamber to break.

The expected life of the thermal chamber should satisfy our consumer, as long as it is used appropriately.

15 DESIGN CRITIQUE

There are a number of improvements that could have been made to our design process. Most of these improvements were overlooked in order to save time. During the design process, it would have been beneficial to prepare 3D CAD drawings of the design including all parts. This was omitted to avoid delaying the start of production. However, a few issues during production could have been avoided if these drawings were prepared. Also, it would have been beneficial to perform a dynamic thermal analysis of the thermal chamber to estimate the time that it would take to reach steady state. We performed a steady-state analysis of the chamber, which gave us important temperature profile information, but a dynamic analysis could have given us a better idea of how much time would be required for each test.

There are a few important improvements that could have been made in our final design. The adjustable spreaders are cumbersome to use at the moment, as they require reaching quite far into the thermal chamber. This could be remedied by replacing the spreaders, as outlined in Section 16.2. Also, the width of the right-side strip of the front face should have been larger. After repeatedly clamping the door to this strip, it has begun to bow out. This could have been avoided by specifying a larger width of this strip. Alternatively, we have provided recommendations in Section 16.2 to strengthen this part of the constructed thermal chamber. Finally, the size of the thermal chamber could have been reduced. The height and width of the chamber were determined from the size of the façade panels, but our sponsor chose the depth was chosen somewhat arbitrarily so that the chamber was close to being cubical. If the depth was set to the minimum amount possible to still fit all of the equipment inside, the time constant of the chamber would be minimized. This would allow the chamber to respond to any change in heat source in the shortest amount of time, reducing the required time to reach steady state and significantly speeding up the testing process. Unfortunately, this cannot be remedied in our chamber but if another one were to be made, this aspect could be improved.

16 CONCLUSIONS AND RECOMMENDATIONS

16.1 Conclusions

The goal of our design is to create a testing apparatus that will comparatively evaluate the U-factor and SHGC of the façade models. Industry standards (ASTM, NFRC and ASHRAE) were used as guidelines to develop comparative values. The important engineering requirements that our thermal chamber design focused on were a 9 ft^2 (≈ 0.836 m^2) cross sectional area, a frame that adjusts to fit façade systems of widths from 4 to 6 in. (≈ 10 to 16 cm), and an insulation thermal conductance less than 0.044 BTU/hr-ft^2-°F (or 0.25 W/m^2-K). The requirements for the artificial light source were a vertical adjustability of at least 3 ft (0.914 m) and a variable angle from 25º to 72º. The design meets all of these requirements.

Based upon time and budget constraints, as well as customer requirements for a simple design, we have chosen a one-chamber thermal chamber for our final prototype design, shown in Section 7. The 2D and 3D thermal analysis, discussed in Section 9, allowed us to estimate the temperature ranges and contours of the thermal chamber and façade panels during tests. From this analysis, we were able to determine how to record the required temperature measurements using only eleven thermal couples, shown in Figure 26 on page 35. The construction of the thermal chamber was completed by March 16^{th}, but façade testing was delayed from our original scheduled date of March 21^{st} due to the theft of some of our equipment.

Because of the delay in our testing date, and because the time required to reach steady state for SHGC testing was so long (~8 hours), we were unable to complete all SHGC tests by the deadline. All U-factor tests, however, were completed and analyzed. The most well insulated panel is the hex natural colored 4" deep panel and the square natural colored 4 × 4 × 4 in. cell dimension panel. The 6 × 6 × 6 in. cell dimension panel has the least insulation because more air circulation inside the larger panel cell increases the convection heat loss.

16.2 Recommendations

We have made a few recommendations to improve the final design of the thermal chamber. As mentioned in Section 15, it is awkward to adjust the spreaders. This could be remedied by replacing the two spreaders on the far side of the thermal chamber with a spreader made from a worm gear and a handle. This type of spreader could be adjusted easily from a distance closer to the door, which would greatly increase the usability of the chamber. Also as mentioned in Section 15, the right-side strip of the front panel has begun to bow out. We recommend attaching a c-shaped metal plate to this strip that would overlap the top and bottom of the chamber. This should provide enough force to the strip to strengthen it and prevent it from bending. Holes would also have to be drilled into the metal plate so that the door clamps could be attached.

We have also included some recommendations for the artificial light source. Although our team was only involved in the construction—and not the design—of the light source, our suggestions may be useful to further testing and related projects. Ultimately, the light source did not offer parallel light required for SHGC testing. Ideally, to simulate solar radiation the light source should provide light rays that are parallel to each other. Since the artificial light source contains many light bulbs that emit scattered light, it is difficult to approximate a parallel source. When the light source was positioned near the thermal chamber, an uneven light distribution resulted and created hot spots on the façade. Unfortunately, the light source could not be positioned far enough from the chamber to better approximate parallel rays and maintain the required intensity. This could be remedied by using higher wattage light bulbs so that the source could be positioned further from the chamber. Another option is to purchase light bulbs that can provide more parallel rays; such bulbs are called "parallel lights". Fresnel lamps can be used to effectively provide parallel light, however they are quite expensive.

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18 ACKNOWLEDGEMENTS

Jeremy Freeman for helping extensively with 2D CAD drawings and prototyping efforts.

19 BIOGRAPHIES

19.1 Eun-Ae (Michelle) Cho

My name is Eun-Ae or Michelle Cho. I was born in Seoul, Korea and lived in Korea for 16 years. Then I moved to Jakarta, Indonesia to study in International School. I graduated from Jakarta International School and came to the University of Michigan in Ann Arbor. To be frank, I applied for Aerospace Engineering at first, but my parents didn't like it because Aerospace Engineering is a very specified field that has limited area to be applied whereas Mechanical Engineering has a broader field to be applied. That's why I'm in interested in mechanical engineering. This is my last term of senior year. I've already applied to several graduate schools for Fall 2006 term. However I want to work in real world more than to go to graduate schools, because I'm not still sure what I like most. I wanted to major in music when I was in high school, but I've found that you never major in something that you like the most. I'm still playing the flute and piano as a hobby. I really like the University of Michigan, since it has the Hill Auditorium with fabulous musicians coming every year. I'm enjoying my life in Ann Arbor. I like all kind of sports, especially swimming and golf. I love children, so I'm teaching junior high school students at the bible study school on Sundays. These days, I'm little sad that this term might be my last term to stay in Ann Arbor.

19.2 Brandon Cox

My name is Brandon Cox and I am from Madison, Wisconsin. I initially decided to major in Mechanical Engineering because of a high school teacher who taught an introduction engineering class that was great. I also enjoyed working on cars (I restored a classic 1979 Volkswagen Bus) and wanted to work in the auto industry so the University of Michigan seemed like a great fit for me. Now that I have been through 3 years of engineering classes my interests have switched to manufacturing and business. This past summer I interned as a process excellence engineer at a medical manufacturing plant and really enjoyed it. We molded a variety of silicone components used in surgery and I was able to see the effects my work had on the products and the company's bottom line. Last semester I was a Field Engineer co-op for the oilfield service company Schlumberger based in Houma, Louisiana about 30 miles south-west of New Orleans. My segment installed well completion or measurement tools on offshore rigs, mostly in the Gulf of Mexico and off the coast of California. This was a great experience in terms of interacting with extremely diverse groups of people and traveling all over the country. Also I got to experience the effects of Hurricanes Katrina and Rita firsthand. It was amazing to see the destruction weather can cause. I will be graduating next December and am still unsure of summer plans. I have to opportunity to intern for Schlumberger internationally but am keeping my options open and plan to interview with companies more aligned to my interest in manufacturing and business.

19.3 Katie Kerfoot

Katie Kerfoot was born in New Hampshire and grew up in Houghton, MI (yes, in the Upper Peninsula). She spent a year of her childhood in Plön, Germany and considers Plön, Houghton, and Ann Arbor her homes. She is interested in Mechanical Engineering as a medium to allow her to make things for people and the environment. That, and there are far too few women in engineering. She is also minoring in Political Science. Katie will be completing her bachelor's degree in December 2006. She has spent the last two years working in the Optimal Design Laboratory, focusing on aesthetics in the engineering design process. Her future goals are to pursue a Ph.D. related to design and incorporating policy and positive environmental impacts. Some of her favorite things include traveling, dancing, and artistic expression.

19.4 Shangchao Lin

Born in Suzhou, China, a large and old city currently with 6 million citizens, I was the beloved boy of my family. I like to read, watch and then think, just too curious about whatever I can't understand or explain. Originally I planned to go to medical school because my mum is a very competent doctor. But my enthusiasm in building and creating innovative and challenging objects like robots and spacecrafts determined my future career as a mechanical engineer or scientist. I spent my freshman and sophomore years in Shanghai, which is even larger and tempting. As a transfer student I became a junior of

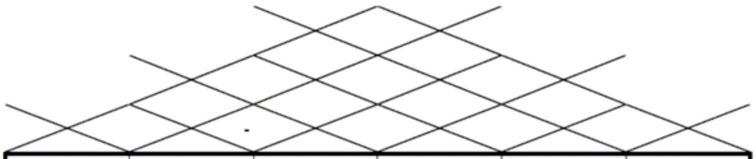
University of Michigan and I am graduating this semester. After graduation I will go to graduate school for further study and finally finish my PhD degree. I am a deep thinking guy and usually sit in the corner quietly and think as far as I can, never speak a lot. I will contribute myself to the development of modern technology and do my research in an academic college or laboratory.

My research interest is now in combustion analysis and building energy technology, whatever related to heat transfer and fluid dynamics. I am working in the Industrial Assessment Center (IAC) set up by Department of Energy. Also I am a research assistant in the Combustion and Environmental Lab to study the flame spread related to fire safety issue. The most attractive research project I want to involve in is probably the future development of engine propulsion using nuclear power.

19.5 John Stepowski

John Stepowski was born in Dearborn, MI and grew up in Oak Park, MI. He was originally enrolled at the Dearborn campus of the University, but transferred to the Ann Arbor campus in his junior year. His interest in Mechanical Engineering was fostered by a life-long affinity to math and science. John will be graduating in May 2006 and will continue working at the US Army Tank Automotive Research, Developing and Engineering Center (US Army TARDEC) where he has been working since August 2003. Along with working at TARDEC, where his focus is introducing composites into the ground vehicle fleet in novel ways, John will simultaneously be pursuing his master degree in Mechanical Engineering. Future plans also include an MBA and possibly a law degree with a concentration in patent and intellectual property.

APPENDIX A (REVISED QFD CHART)

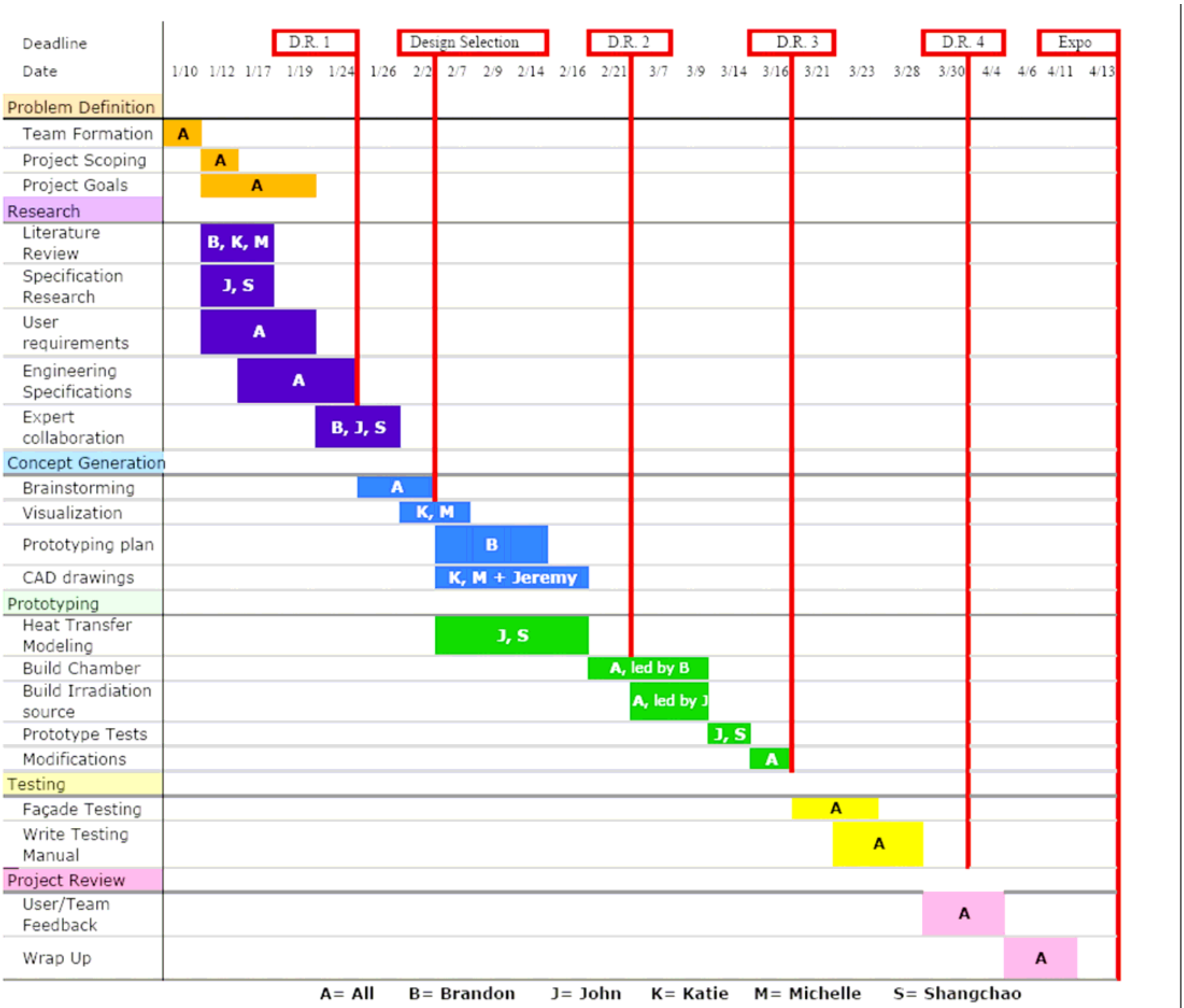


	Weight	Cross section area 3ft x 3ft (.9144m x .9144m) (+)	Frame extends 4-6" (10.16-15.24cm) (*)	Change panel in 60 sec (-)	Moveable with 50 lb (22N) Force	Take at least 8 temperature measurements	Thermal Conductance is less than 0.044 BTU/hr-ft^2-°F(0.25 W/m^2-K)
Will Fit standard panel 4-6" thick (adjustable)	10	3	9	3	1		
Reusable. Durable	9			3			
Similar to Standards	9	9	3			3	9
Relatively Accurate	9	9	3	3		9	9
Sealed	8	3	1			3	3
Protective casing	6				3		3
Easy to use/change panels	6	3	3	9			
Relatively Mobile	4	9	1	1	9		3
Uses Structurally Insulated Panels (SIP)	10	3			3		9
Simple	8	1	3	3		3	3
Total		308	198	166	94	156	330
Normalized		0.25	0.16	0.13	0.08	0.12	0.26
Importance Rating		**2**	**3**	**4**	**6**	**5**	**1**
Measurement Unit		ft^2	in.	sec	lb	#	BTU/hr-ft^2-°F

(As of March 22nd, 2006)

Each of these parameters has a unit of measurement, positive or negative sign indicating whether a smaller or larger value will be more desirable and target values which our final prototype will be graded against. Relationships between these parameters can be seen in top of the matrix. The body of the matrix was filled out with relationship strengths of one, three or nine based upon the engineering specifications importance to meeting customer requirements. These strengths are multiplied by the corresponding requirement weights and added to determine which engineering specifications are most important to focus on during design. The three most important specifications had very strong relationships with the customer requirements for accuracy and similarity to standards, both of which have large weights.

APPENDIX B (REVISED PROJECT GANTT CHART)



APPENDIX C (PRODUCTION GANTT CHART)

Prototype Production Schedule

	Steps	Issues	Equipment	Materials	Approximate time (hours)	2/16	2/17	2/18	2/19	2/20	2/21	2/22	2/23	2/24	2/25 to 3/5	3/6	3/7	3/8	3/9	3/10	3/11	3/12	3/13	3/14	3/15	3/16
						Thur.	Fri.	Sat.	Sun.	Mon.	Tues.	Wed.	Thur.	Fri.	SPRING BREAK	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.	Sun.	Mon.	Tues.	Wed.	Thur.
SIP Paneling	Cut SIP panel sides and door (5 sides, 1 door)		Circular Saw, Hand Saw, 3 people	SIP	1pm - 6pm Thursday																					
	Mill plywood out of joint locations	time, CNC operation (Jeremy)	CNC machine, 2 people		Thursday Evening/Friday 12 hours																					
	Cut and install spreader support frame	Spreader length, spreader contact surface area?, drill pilot holes to prevent the plywood from splitting?	table or band saw, power drill with screwdriver attatchment, screwdriver, 2 people	plywood wood adhesive (98'x 7/16"), small triangle joints(16), screws	4																					
	Apply wood adhesive to wood joints, foam caulk to foam, assemble with big clamps, install triangle and L support joints	Getting 4' clamps, drying time for adhesive, drying time?, piecing panels together as they dry, pilot holes?	2 caulk guns, 4' clamping device, power drill, screw driver, drill bits?, 3 people	wood adhesive, foam caulk (8'x6") Large triangle joints (28), L joints for outside (28), screws	20																					
	Seal inside of chamber with caulk		1 caulk gun, 1 person	insulation caulk	1																					
	Cut and Install Movable support frame w/ rubber seal on outside	slidable surface to install to box, which foam to use	2 people	Foam, Rubber Seal	4																					
Attach Front Panel	Cut Front Panel from Plywood	Width of frame (Thickness of rubber strip, how close spreaders can operate to wall, spreader contact surface area), cutting out the middle of panel	table saw and or band saw, jig saw, 2 people	plywood	2																					
	Apply adhesive to front panel, mount rubber stripping, let dry		2 people	adhesive (wood to rubber), rubber stripping	2																					
	Apply adhesive to outside of front panel, mount to SIP panels, let dry with big clamps		big clamps, 2 people	wood adhesive	2																					
	Screw front panel to SIP panels, caulk joints	pilot holes?	power drill, drill bit, 2 people	screws, caulk	1																					
Door Installation	Install rubber stripping to door and to SIP door contact area, let dry	alignment	2 people	adhesive, rubber stripping	2																					
	Mount the door, screw to panel, install hinge to door and then to chamber	alignment, offset ammount, compressed rubber stripping	band saw, power drill, screwdriver attachment, screwdriver, 2 people	band saw, screws, wood adhesive	1																					
	Install latching mechanism	type of latch	power drill, screwdriver attachment, screwdriver, 2 people	screws, latch	1																					
Install Internal Equipment	Mount thermocouples, temperature loggers and run wires	thermocouple locations and relavent mounting equipment	power drill, drill bit?, 2 people	thermocouples, wire, screws, adhesive	3																					
	Install Heating Equipment			Heat Lamp, 20W, 40W, 250W bulbs	1																					

APPENDIX D (ITEMIZED PURCHASE LIST)

UPC	Description	Prices Each	Qty	Total	Taxable	Total + Tax	Purchased From
Store Purchases							
10788	500W Flood Light	$15.98	5	$79.90	y	$84.69	Lowe's
110118	500W Flood Light	$15.98	3	$47.94	y	$50.82	Lowe's
166065	3/8 RTD SHTG	$13.39	1	$13.39	y	$14.19	Home Depot
166073	1/2 RTD SHTG	$13.99	1	$13.99	y	$14.83	Home Depot
22078492778	Foam Adhesive	$3.97	2	$7.94	y	$8.42	Home Depot
22078604720	LQNLLXFB 10.5"	$2.37	7	$16.59	y	$17.59	Home Depot
30192018156	Acetone	$5.69	1	$5.69	y	$6.03	Home Depot
30699209514	Plastic Baggds	$0.98	1	$0.98	y	$1.04	Home Depot
30699209521	Screws	$3.57	1	$3.57	y	$3.78	Home Depot
33923000376	4" BRLSPNHNG	$4.29	2	$8.58	y	$9.09	Home Depot
33923014335	5 3/4 P 482	$2.49	1	$2.49	y	$2.64	Home Depot
33923485258	4 ins cr 99	$4.99	2	$9.98	y	$10.58	Home Depot
33923930277	3" Mend Plate 4pk	$1.79	1	$1.79	y	$1.90	Home Depot
33923930321	21/2 Corner Bracket	$2.59	3	$7.77	y	$8.24	Home Depot
33923930338	3" Corner Bracket	$3.19	7	$22.33	y	$23.67	Home Depot
38548806661	Clamp	$16.67	4	$66.68	y	$70.68	Home Depot
39003094846	4" Caster	$9.97	2	$19.94	y	$21.14	Home Depot
39003095126	4" Caster w/ Brake	$12.81	2	$25.62	y	$27.16	Home Depot
43374438468	WeatherStrip	$9.89	7	$69.23	y	$73.38	Home Depot
44074429978	Catch	$2.27	2	$4.54	y	$4.81	Home Depot
44315037108	6x6 T-strap	$2.25	4	$9.00	y	$9.54	Home Depot
44315088216	Wafer Screws	$7.97	1	$7.97	y	$8.45	Home Depot
44315348709	22" Strap	$0.82	2	$1.64	y	$1.74	Home Depot
44600711782	Lighter Fluid	$3.99	1	$3.99	y	$4.23	Home Depot
46677135355	25WG16.5C	$2.19	1	$2.19	y	$2.32	Home Depot
46677135379	40WG16.5C	$2.19	1	$2.19	y	$2.32	Home Depot
47362847621	Wood Chips	$3.99	1	$3.99	y	$4.23	Home Depot
51131587090	Duct Tape	$6.17	1	$6.17	y	$6.54	Home Depot
51527151041	Sealant	$4.49	4	$17.96	y	$19.04	Home Depot
52427500083	5oz Gorilla Glue	$12.97	1	$12.97	y	$13.75	Home Depot
70258600018	Lighter	$3.86	1	$3.86	y	$4.09	Home Depot
71928329077	Table Lamp	$12.99	1	$12.99	y	$13.77	Meijer
73754151878	Super Glue	$4.97	1	$4.97	y	$5.27	Home Depot
74985004568	16oz. Great St	$5.33	2	$10.66	y	$11.30	Home Depot
81999104511	4'x8' 3/4" plywood	$28.88	2	$57.76	y	$61.23	Home Depot
85995000525	10qt. Pail	$6.86	1	$6.86	y	$7.27	Home Depot
90214000101	2"x6"x8' HT wood	$3.98	8	$31.84	y	$33.75	Home Depot
90489037315	2"x2"x8' wood	$2.19	5	$10.95	y	$11.61	Home Depot
715487158730	3/4" MDF	$19.99	1	$19.99	y	$21.19	Home Depot
764666109315	Screws	$4.11	1	$4.11	y	$4.36	Home Depot
6920000601097	Caulk Gun	$1.96	1	$1.96	y	$2.08	Home Depot
N/A	Truck Rental	$19.00	2	$38.00	y	$40.28	Home Depot
N/A	Polystyrene 0.03"	$4.95	1	$4.95	n	$4.95	TCAUP Media Center
					Subtotal	**$747.97**	

Part Number	Description	Price Each	Qty	Total		Total	Website
H12-002	HOBO Type-K Thermocouple	$94.05	6	$564.30		$564.30	http://www.inmtn.com/store/
UA-001-08	HOBO Pendant Logger-8K	$43.33	5	$216.65		$216.65	http://www.inmtn.com/store/cart
N/A	BoxCar 3.7 Software	$19.80	1	$19.80		$19.80	http://www.inmtn.com/store/cart
N/A	HOBOware Software	$94.05	1	$94.05		$94.05	http://www.inmtn.com/store/cart
SP2065	Pyranometer	$169.00	1	$169.00		$169.00	_solar_measurement.htm?1
					Total	$1,811.77	

Items that were already on hand, but will need to be purchased for a future build						
Description	**Price Each**	**Qty**	**Total**	**Suppllier**	**Phone**	**Website**
Structural Insulating Panel	$5/sq.ft	120 sq.ft	$600.00	Peninsula Panel, Dexter, MI	(734) 426-4817	N/A
1500 Watt Space Heater	$24.99	1	$24.99	N/A	N/A	http://heating-and-cooling.hardwarestore.com/33-167-portable-electric-heaters/metal-electric-heater-667719.aspx
250 Watt Heat Lamp	$8.99	2	$17.98	Home Depot	N/A	http://www.homedepot.com
100 Watt Light Bulb	$1.00	1	$1.00	Home Depot		http://www.homedepot.com
Varioud UniStrut Hardware				Unistrut Detroit Service Company	(734) 722-1400	N/A

APPENDIX E (U-FACTOR TESTING)

Assuming spherical conduction dominated heat transfer (Figure E.1), the heat transfer rate:

$Q = -A\frac{k}{dr}dT = -4\pi r^2 \frac{k}{dr}dT$, where Q = 20 W which equals the heat generation rate.

By solving this differential equation, we got:

$T(r) = T_0 + \frac{Q}{4\pi k}(\frac{1}{r} - \frac{1}{L})$ (Figure E.2), where T_0 = $T(L)$, k = 0.03 W/mK, $r = L$ -> $R = \sqrt{2}L$.

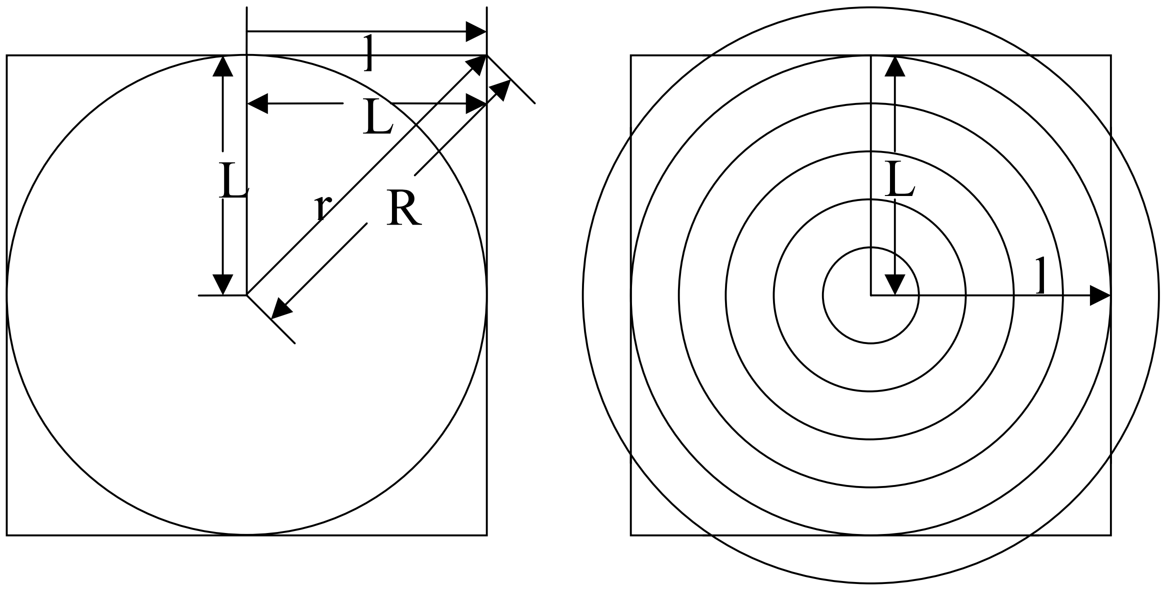


Figure E.1: Front view of the thermal chamber with spherical temperature contour in volume (left), and the top view of the thermal chamber with circular temperature contour on surface (right)

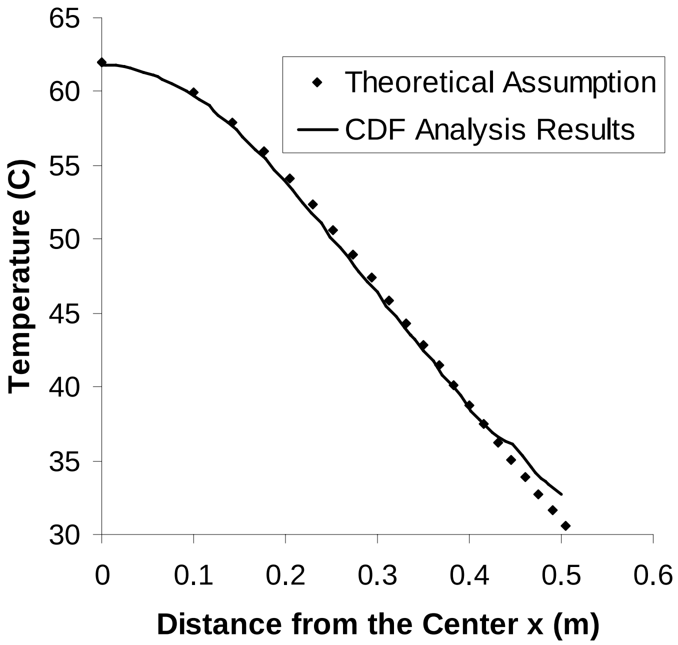


Figure E.2: Temperature profile from theoretical assumption calculation matches well with the CDF analysis results along the center line on the inside of the bottom panel

So we got the temperature distribution along l:

$T(l) = T_0 + \frac{Q}{4\pi k}(\frac{1}{\sqrt{l^2 + L^2}} - \frac{1}{L})$, where *l = 0 ->L, L = 0.5 m.*

The weighted average temperature on square surface will be:

$$\overline{T} = \frac{\iint_A T(l)\,dxdy}{L^2} = \frac{\iint_A T(\sqrt{x^2 + y^2})\,dxdy}{L^2} = \frac{\int_0^L \int_0^L [T_0 + \frac{Q}{4\pi k}(\frac{1}{\sqrt{x^2 + y^2 + L^2}} - \frac{1}{L})]dxdy}{L^2}$$

"Tw" are surface temperature measurements using thermocouples and loggers and "Ta" are measured by ambient temperature loggers (see location and definition in Figure 23). Tw3 and Tw5 are taken at a distance of about 5 mm to the facade wall as ambient inside temperature according to air film theory. Thus:

$T_h = \overline{T} = \frac{\int_0^L \int_0^L [T_0 + \frac{Q}{4\pi k}(\frac{1}{\sqrt{x^2 + y^2 + L^2}} - \frac{1}{L})]dxdy}{L^2}$, where T_0 = Tw3, and T_c = Ta3.

For T_0 = 50 °C, the weighted average temperature $\overline{T}$ = 28 °C.

APPENDIX F (SHGC TESTING)

T_h = Tw3 and T_c = Ta3 assuming evenly-distributed solar light intensity on the facade surface.

APPENDIX G (CALIBRATIONS)

For U-factor testing calibration:

$T_{sp\text{-}in} = \overline{T} = \frac{\int_0^L \int_0^L [T_0 + \frac{Q}{4\pi k}(\frac{1}{\sqrt{x^2 + y^2 + L^2}} - \frac{1}{L})]dxdy}{L^2}$, where T_0 = Tw2, and $T_{sp\text{-}out}$ = Tw1.

For T_0 = 62 °C, the weighted average temperature $\overline{T}$ = 40 °C.

For SHGC testing calibration:

$T_{sp\text{-}in} = \overline{T} = \frac{\int_0^L \int_0^{2L} [T_0 + \frac{Q}{4\pi k}(\frac{1}{\sqrt{x^2 + y^2 + L^2}} - \frac{1}{L})]dxdy}{2L^2}$, where T_0 = Tw5, and $T_{sp\text{-}out}$ = Tw1.

For T_0 = 80 °C, the weighted average temperature $\overline{T}$ = 44 °C.

APPENDIX H DESIGN SAFE ANALYSIS

Application:	Team 29: Facade Testing Device	Analyst Name(s):	Eun-Ae (Michelle) Cho, Katie Kerfoot, Shangchao Lin, Brandon Cox, John Stepowski
Description:		Company:	Team 29
Product Identifier:		Facility Location:	High Bay
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users set-up or changeover	mechanical : head bump on overhead objects when installing the panel inside the chamber	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD
All Users set-up or changeover	mechanical : break up during operation excessive pressure applied from the door and the fixture system?	Catastrophic Remote Unlikely	Moderate	restricted users	Serious None Negligible	Low	Complete [4/17/2006]
All Users set-up or changeover	electrical / electronic : unexpected start up / motion	Slight Remote Unlikely	Low	restricted users	Serious None Negligible	Low	Complete [4/17/2006]
All Users set-up or changeover	electrical / electronic : software errors thermocouples are not functioning properly?	Serious Remote Unlikely	Moderate	restricted users	Serious None Negligible	Low	Complete [4/17/2006]
All Users set-up or changeover	material handling : instability some of the panels are not glued	Slight Frequent Probable	High	glue?	Serious None Negligible	Low	TBD
All Users shut down	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	TBD
All Users parts replacement	mechanical : fatigue replacing facade can cause some parts to be worn out??	Serious Occasional Unlikely	Moderate	safety mats / contact strip	Serious Remote Unlikely	Moderate	TBD
All Users parts replacement	mechanical : head bump on overhead objects	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users quality testing	heat / temperature : severe heat not really severe..but it's pretty hot.	Slight Remote Possible	Moderate	restricted users	Serious None Negligible	Low	Complete [4/17/2006]
All Users installation	mechanical : head bump on overhead objects	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD
All Users finishing task(s)	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]
All Users clean up	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]
operator load / unload materials	mechanical : fatigue	Slight Occasional Unlikely	Moderate	safety mats / contact strip	Serious Remote Unlikely	Moderate	TBD
operator load / unload materials	mechanical : head bump on overhead objects	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD
operator position / fasten parts and components	mechanical : fatigue	Slight Occasional Unlikely	Moderate	safety mats / contact strip	Serious Remote Unlikely	Moderate	TBD
operator position / fasten parts and components	mechanical : head bump on overhead objects	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD
operator position / fasten parts and components	mechanical : break up during operation	Catastrophic Remote Unlikely	Moderate	restricted users	Serious None Negligible	Low	Complete [4/17/2006]
operator shut down	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]
operator finishing task(s)	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician connect lines / wires	electrical / electronic : improper wiring	Catastrophic Remote Unlikely	Moderate	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
electrician / controls technician test circuits	electrical / electronic : lack of grounding (earthing or neutral)	Catastrophic Remote Unlikely	Moderate	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician test circuits	electrical / electronic : overvoltage /overcurrent	Catastrophic Remote Unlikely	Moderate	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician measure / cut / bend electrical conduit	mechanical : cutting / severing	Slight Remote Negligible	Low	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician assemble / install electrical conduit	electrical / electronic : improper wiring	Serious Remote Unlikely	Moderate	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician install / repair circuit	electrical / electronic : energized equipment / live parts	Catastrophic Frequent Unlikely	High	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician install / repair circuit	electrical / electronic : lack of grounding (earthing or neutral)	Catastrophic Frequent Unlikely	High	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician install / repair circuit	electrical / electronic : improper wiring	Catastrophic Remote Unlikely	Moderate	professional electrician completing the job	Minimal None Negligible	Low	Complete [4/17/2006]
electrician / controls technician install / repair circuit	electrical / electronic : overvoltage /overcurrent	Catastrophic Frequent Unlikely	High	professional electrician completing the job	Serious Remote Negligible	Low	Complete [4/17/2006]
leader / supervisor inspect parts	mechanical : head bump on overhead objects	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD
leader / supervisor walking along / by equipment	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]
leader / supervisor assist skilled trades	mechanical : head bump on overhead objects	Slight Occasional Possible	Moderate	head protection	Serious Remote Negligible	Low	TBD
leader / supervisor assist skilled trades	material handling : instability the facade is very unstable if not glued	Slight Frequent Probable	High	glue?	Serious None Negligible	Low	TBD

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
leader / supervisor check alignment	mechanical : fatigue too much pressure, many times of reusing the hot box	Serious Occasional Unlikely	Moderate	safety mats / contact strip	Serious Remote Unlikely	Moderate	TBD
passer-by / non-user walk near machinery	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]
passer-by / non-user work next to / near machinery	None / Other : Not a hazard	Minimal None Negligible	Low	N/A	Minimal None Negligible	Low	Complete [4/17/2006]