TEAM SOLAR SIP

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Report to Dr. Shollenberger

STATEMENT OF CONFIDENTIALITY

The complete senior project report was submitted to the project advisor and sponsor. The results of this project are of a confidential nature and will not be published at this time.

STATEMENT OF DISCLAIMER

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EXECUTIVE SUMMARY

This report details the design process of the Solar Cal Poly ME Structural Insulated Panels (SIP) team. The three team members; Patrick Fillingham, Wesley Goodson and Kenneth Li have conducted research and analysis in order to determine how to best insulate the Solar House.

Working with the architects on the Solar Decathlon team, Team Solar SIP was able to determine where SIPs will be used, the type of material to be used as well as the thickness of the SIPS to be used. Initially the team worked on researching what options were out there and how they could be applied to the Solar House. The first decision to be made was whether to use Expanded Polystyrene (EPS), Extruded Polystyrene (XPS) or Polyurethane (PUR) hard cell foam in our SIP walls. We also needed to determine how thick the walls would need to be in order to keep the cooling and heating loads as low as possible. We also had to determine where it would be pertinent to use SIPs as opposed to using traditional floor, wall and ceiling layups. In order to make these decisions we employed the use of analysis tools such as ABAQUS for Finite Element Analysis, EES to solve heat transfer problems and DesignBuilder in order to model the overall effectiveness of the SIPs on the cooling and heating loads. After using these tools to accompany our research we were able to conclude that we would use 8 in. EPS SIPs on all external walls, we will use 8 in. SIPs for the roofs and that we will use traditional flooring in order to accommodate plumbing and electrical wiring.

INTRODUCTION

The U.S. Department of Energy (DOE) holds Solar Decathlon competitions biennially with the purpose of educating students and the public about the energy-efficient, money-saving, and environmentally friendly solutions available today. This competition also provides students with an opportunity to learn and prepare themselves towards the clean-energy task force.

Team Solar SIP has been assigned to design the Structural Insulated Panels (SIP) with integrated systems for the Cal Poly Solar Decathlon House. In order to make the house as efficient as possible, the insulation must work at a high level. Any thermal leaks in the floors, walls, or ceilings of a home can cause drastic effects in the thermal efficiency of the house by providing thermal bridges for heat to penetrate the building. In order to limit cost and maximize efficiency, Structural Insulated Panels will be used. Extensive research has been compiled in order to find the best fit for size, thickness, and material of the SIPs for the Cal Poly Solar House. The SIP will need to accommodate external temperatures up to 100 °F and as low as 40 °F. We will also have to work around the plumbing, ventilation and electrical design while still maintaining structural integrity and maximum insulation.

OBJECTIVE & SPECIFICATION DEVELOPMENT

The goal of Team Solar SIP is to provide the optimal insulation and structure for the walls, ceiling and floor of the Cal Poly Solar House for the U.S. Department of Energy 2015 Solar Decathlon Competition. In order to explore our objectives, research was conducted on past Solar Houses, SIP manufacturers, and other alternative insulation techniques. A Quality Function Deployment House was then constructed (Appendix 8) to help narrow down the objectives of our project.

After conducting research we were able to attain a variety of engineering and functional specifications and goals. These specifications were then applied to the QFD house of quality. First we will look at the quantifiable specifications, summarized in the table below.

Table 1. Summary of Quantitative Specifications

Parameter	Target Value	Tolerance	Risk	Compliance
R-Value	30 ft^2 °F/Btu	Min	M	I, A
Cost	7 $/$ft^2$	Max	M	I
Thickness	8 in	Max	M	I
Weight	7 lb/ft^2	Max	M	I, A
Structural Strength	20 psi	Min	H	T, A
Lifetime	30 years	Min	H	S

The most important specification will be the performance of the insulation, which is specified by the Thermal Resistance, or R-Value. Typical insulated walls will have an R-Value rating of 10-40, but they rarely perform as well as they are rated due to the degradation of the insulation and addition of splines and fasteners. Generally, SIPs are not subjected to the kind of degradation that other insulation is and therefore perform much closer to their published rating. SIP Rvalues range anywhere from 10-50 depending on their function. Due to the design specifications and necessity for efficiency, a large part of the energy savings of the Solar House will come from the performance of the insulation. After conducting research, we found that it is reasonable to expect a minimum R-Value of 30 while maintaining a thickness of less than 8 in. Due to these specifications, it is most likely that we will be using SIPs for the majority of the walls, floors and roofing.

Thickness plays a large part in both the functionality and the performance of SIPs. The thicker the SIP, the higher the R-Value. We would like to minimize the thickness of the walls in order to take up less space and give the architects as much flexibility as possible. The architects have set a maximum thickness for us of 8 in. Which is certainly reasonable to achieve while maintaining a high R-Value.

The next specification to look at is cost. Cost is always a factor in design and the Cal Poly Solar House is no exception. It is difficult to analyze the specification for cost since we do not have a specific budget provided for us. We do hope to have the SIPs donated to the Solar House. Cost would still be an issue, however, because the Solar House must be appraised for under $250,000. After conducting research and calling some SIP manufacturers, we were able to decide that paying any more than 7$ per square foot would be unreasonable. The highest performing SIPs range from $6-$8 per square foot, but we were able to find a variety of satisfactory SIPs for under $6 per square foot.

When analyzing the weight of the SIPs, it was difficult to come up with a specification as the weights of SIPs tend to vary, and we do not know the exact installation methods. After conducting research, however, we decided that anything more than 7 lb per square foot would be unreasonable. It would be ideal to minimize the weight of the SIP because it would make the installation process easier but it is difficult to set a specific target at this point.

The structural integrity of the SIPs is certainly important to the safety of the house. Most all SIPs are rated above 15 psi in both compression and tension. We decided to use compressive strength as our qualifying factor as the SIPs will be primarily loaded in compression. It is difficult, however, to set a specific requirement as we do not have a final design for the house yet and we do not have any analysis on the loads that the walls will have to withhold. In order to remain on the safe side for now, however, we have specified a minimum compressive strength of 20 psi.

The last quantifiable specification is the lifetime of the SIPs we plan on using. Due to their airtight nature SIPs tend to have long life spans and will keep performing at a high rate throughout their life. Unless a SIP is subjected to an air leak or moisture, they will last around 50 years without any maintenance necessary. For our structure we decided that a lifespan of 30 years without any maintenance was reasonable due to the function of the house we are constructing.

Along with the quantifiable specifications, we have a very important qualitative specifications as well. The SIPs that we decide to use will have to be flexible for the installation of integrated systems such as phase change material, electrical wiring, air ducts, and potential wall modifications. The ability to modify the SIPs to accommodate these other systems is incredibly important in the design of the house. For the most part SIPs are used in a standalone fashion and are rarely tampered with. Due to the nature of the Solar House, we will need to be flexible with the walls, floors, and ceilings that we plan on using SIPs for. We will want to use SIPs that have channels for electrical wiring, the ability to integrate phase change material, and a removable wood casing.

Additionally, the SIPs need to be non-toxic, mold-free, and fire-resistant. Mold growth will be largely limited by controlled ventilation in order to remove contaminants from the air and keep the humidity low. The Solar Decathlon measures humidity as a variable for home comfort, and the passive and active HVAC teams will be the primary members addressing this variable.

BACKGROUND

According to the U.S. Energy Information Association (EIA), in 2013, the energy sources for electricity were 39% coal, 27% natural gas, 19% nuclear power, 7% hydropower, and 6% renewable resources. Additionally, The World Coal Organization estimates that at this current rate of energy use, coal will only last about 112 years, and oil and gas reserves will last 46 to 54 years. This leads to a huge problem the world will be facing in terms of energy use and production. With a growing population, an increasing need for energy, and depleting resources, renewable resources will need to become a larger part of our world's energy production.

One of the fastest growing renewable energy source is solar power. The infographic in Appendix 9 demonstrates the potential benefits of simply installing solar panels into one's home. If it is possible to have a clean source of energy in your home to pay itself in about 15 years, a solar home that is designed to be energy-efficient and cost-effective from the beginning will be a contributing factor towards alternative energy.

With that in mind, the frame and walls of a solar home will be crucial towards its energy efficiency. The frame of the house provides passive cooling and heating and that will determine the amount of HVAC needed. Currently, there are two typical ways of providing the frame for a house. One is SIP framing, and the other is conventional wood framing. In most houses, a general wood frame is used and provides a durable, stable foundation. Conventional wood frames are cheap and adaptable. Structural insulated panels, on the other hand, provide better insulation and reduce air leaks in the home.

Conventional Wall Construction

Conventional residential walls consist of exterior sheathing on the outside of a middle layer of some insulating material. There are 2x4 or 2x6 wood studs located every 16 inches to provide structural stability. The insulating material in the middle of the sheathing is the primary contributor to the overall R-value of a conventional wall. This insulating material is typically blown cellulose, blown or batt fiberglass, or spray foam (such as polyurethane or polystyrene). It is also common to use a double-wall construction (Figure 1) to increase the overall R-value of a wall, account for thermal bridges such as windows, allow for internal electrical components on the inner wall, and improve structural stability. Another option is to use exterior foam sheathing, such as extruded or expanded polystyrene (XPS and EPS, respectively), though this is much more costly than a 2x6 wall constructed of blown cellulose due to the added cost of XPS, furring, and finishes for door and window openings.

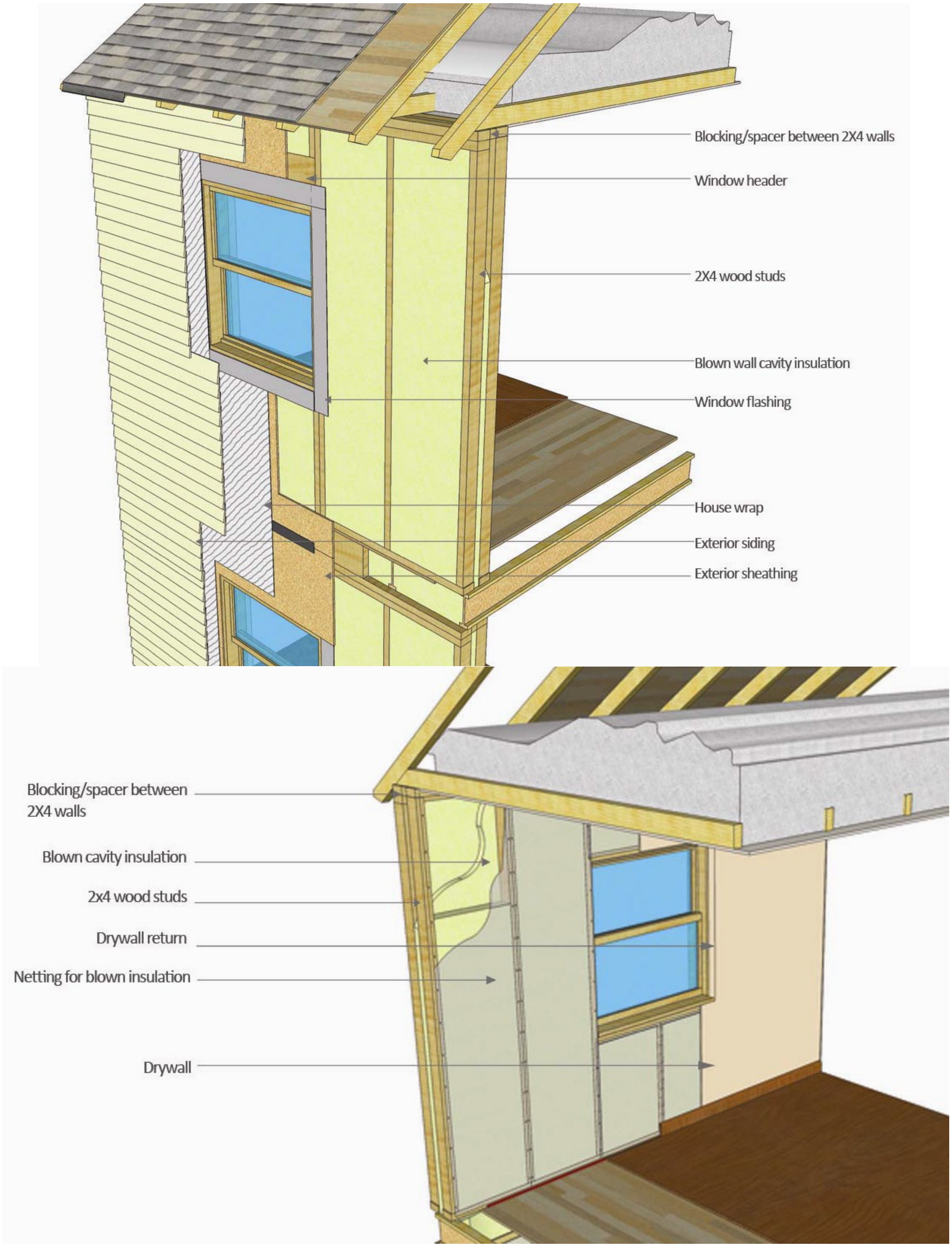


Figure 1: Cutaway view of a conventional residential double wall feature (Aldrich, Arena, Zoeller).

The issues with conventional walls lie with the ease of constructability. Without a defined paneling system, the walls must be constructed one stud at a time. This is a slow process, which increases labor costs. The alternative option of using Structural Insulated Panels is quicker and delivers better R-values than conventional walls. SIPs work best with homes that have a simple design with few angled corners and many straight lines. The Cal Poly Solar House qualifies as a “simple” design, and thus the choice of SIPs will lower labor costs and overall energy costs to the customer.

SIP Construction

A SIP typically consists of a sandwich structure (Figure 2). The panel is made of an exterior and interior sheathing that is usually made of oriented strand board (OSB) or gypsum wood. In between these sheathings is a type of foam insulation. This structure is what gives SIPs a superior insulating property over conventional wood frames. However, the downsides of SIPs are that they are a bit more expensive and less adaptable than conventional wood frames. Although the initial cost of SIPs are more expensive, the high insulating properties would offset the cost over time. The nature of the panel being less adaptable is due to the use of foam core. Having a foam core will prevent any pipes or wiring running through the panels. Pipes may not be running above or below these panels because if condensation reaches the foam core, the insulation properties will be severely weakened. For our purpose of providing the most energy efficient and cost effective home, SIPs are going to be the focus of this project.

Currently there are three main types of foam available, expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR). EPS has the lowest R-value and the lowest cost, while PUR has the highest R-value but the highest cost. Along with the material properties, the thickness of the SIPs, is highly correlated with its performance. The thicker the panels, the higher the total R-value and the better the insulation. For the outer sheathings, there are a wide range of materials to select from. Some types of available sheathing types are OSB, sheet metal, plywood, fiber cement, gypsum, and composite panels. The outer sheathing has much less contribution to the insulation properties of the wall but certain materials provide better resistant to fires, termites, and/or moisture. Designing the panels for the solar house will require numerous iterations of materials and thickness for the appropriate walls, roof, and floor locations.

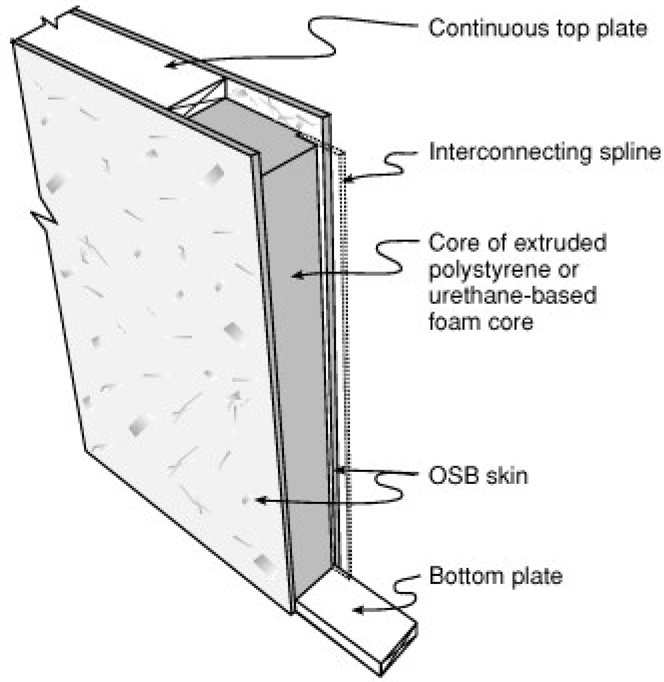


Figure 2: SIPs are sandwich-like walls with OSB exteriors and foam cores of varying thicknesses (Springtime Homes). Additionally, this picture depicts the use of OSB panel splines.

Although in a best case scenario no additional splines should be used to limit the amount of thermal bridging, transportation and convenience of SIPs limit the sizes that can be carried. SIPs are connected to each other by the use of splines, which are typically found in three different ways (Figures 3-5). These different splines provide varying insulation and structural effects, and the Architectural Engineering team will advise on which splines to be used.

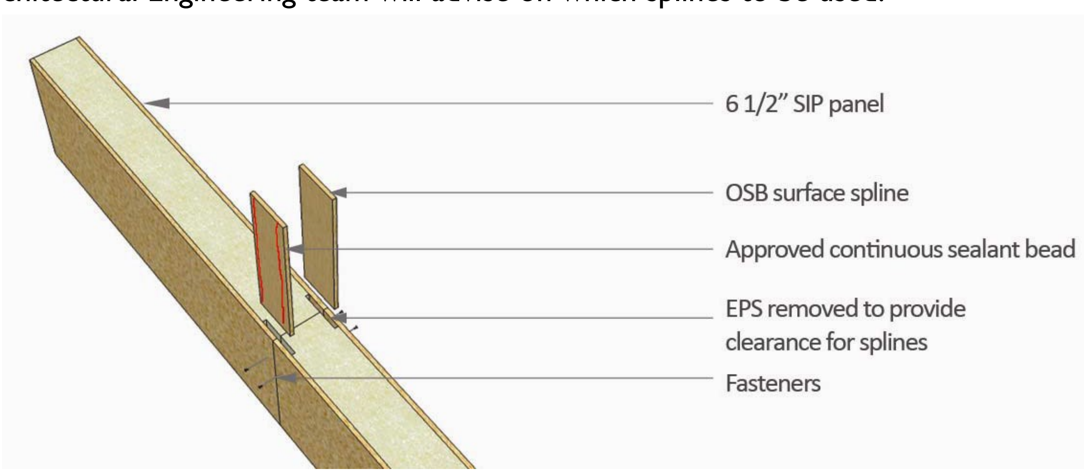


Figure 3: OSB panel splines (Aldrich, Arena, Zoeller).

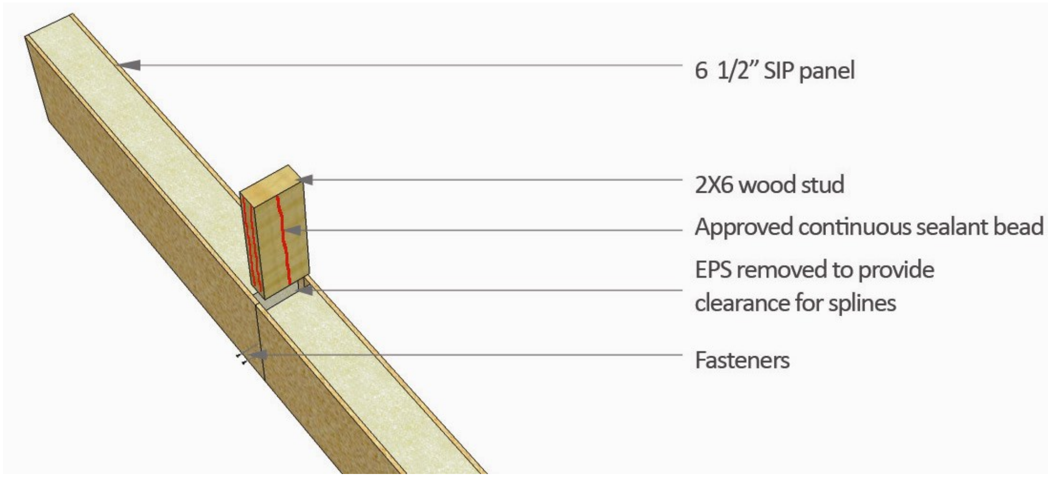


Figure 4: 2x6 stud panel spline (Aldrich, Arena, Zoeller).

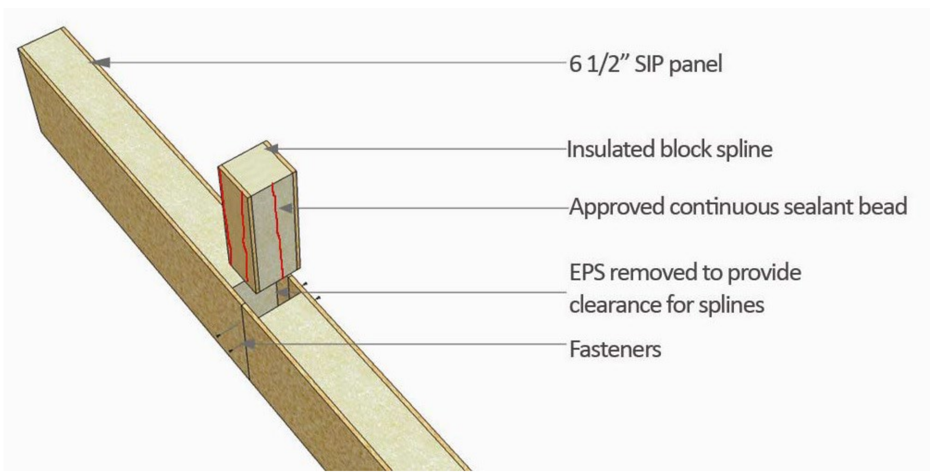


Figure 5: Insulated block spline (Aldrich, Arena, Zoeller).

If no additional load requirements are needed, typically surface or block splines will be used. These two types provide no additional support and its only purpose is to faster two SIP panels together with minimal thermal bridging in mind. The stud or structural splines provide additional allowable loads that is typically used in locations with a large span such as the roof. The down side is more material that induces thermal bridging.

Current SIP Companies

Because the SIP industry is relatively new, there are only a few companies that have made a remarkable impression in the market. There are currently dozens of companies that make SIPs, and they all offer roughly the same general design, performance, and cost. Most SIPs cost between five and seven dollars per square foot depending on the use of polyurethane, extruded polystyrene, or expanded polystyrene as the foam core material; though it is difficult to obtain even rough price estimates from companies. The main differences between SIP companies are found in the customizability of SIPs, such as the use of custom molds or cavities within the cores of the walls. Our research has shown that it is difficult to find a reliable or trustworthy SIP company that has products which perform as advertised. Because of the large number of SIP manufacturers, one must rely on the advertised materials and modes of construction in order to make an educated projection about the performance of one SIP company when compared to another.

When comparing SIP manufacturers, it is convenient to compare advertised R-values, browse customer testimonials, and find any awards that the company could have won. Insulpan was awarded the National Association of Home Builders (NAHB) Building Systems Council 2004 Excellence in Home Design Award. Insulpan also advertises that 66% of builders preferred their SIPs to other brands in a "recent national building industry survey." Insulpan uses OSB boards with ESP insulation, and they claim to achieve an R-Value of 28.0 on an 8-¼" wall. Contrastingly, Thermocore uses PUR SIPs and claims that EPS insulation has an R-Value of 3.5 to 4.0 per inch, while their PUR insulation achieves 7.0 to 7.5 per inch. Additionally, the 2013 Purdue Solar Decathlon team used Thermocore SIPs because they were more cost-effective than other options.

Past Solar Decathlon Examples

Additionally, we looked at previous top teams from the 2013 Solar Decathlon. The first place winner of the 2013 competition was Team Austria. They used 10 in. XPS rigid insulation for their roofs and their floor was 6 in. XPS foam. Their walls were also 6 in. but instead of standard sheathing, they used concrete. This is done because they had small diameter tubes running inside the walls to pump water to the heat exchanger located on the roof to cool the house in the summer. In second place was, Team Las Vegas which used spray foam insulation in the construction of their home. They claimed to achieve an R-Value of 29.33 in the walls, 53.4 in the roofing, and 46 in the floors. Additionally, the 2013 Stanford team used R-Control SIPs in their home and did not advertise their effective R-Value. It is difficult to find information about which products past Solar Decathlon teams used because the SIPs are not typically ordered without a large amount of customization which vary the advertised components. Contrastingly, the 2005 Cal Poly team constructed its own SIPs. Their house achieved R-Values of 22 for the walls, 36.6 for the roof, and 31.9 for the floor and this helped contribute to their team being awarded second place for the Dwelling competition, which assesses how comfortable the living conditions are inside the home.

Alternative Insulation Options

Phase Change Materials (PCMs) are substances with a high heat of fusion which stores large amounts of energy during the phase change. Instead of the energy being transferred into the house so that a temperature rise occurs, the energy is stored in the PCM and used to break the chemical bonds so that a phase change occurs. PCMs are designed and purchased for select climates so that the phase change occurs at a desired temperature for the client involved.

For constructing and designed the SIPs, the DOE has provided two documents. One is the 2015 Solar Decathlon Rules and the other is the Building Code. These two documents provide the regulations and standards that will need to be followed when designed the panels. In particular, foam insulation will always need to be covered by an ignition barrier. Thus the interior and exterior sheathing will need to be properly guarded against ignition. Alternate materials, such as phase change material, will need to be certified and must carry an ICC Evaluation Services report. All alternative materials will need to be documented properly on drawings and follow the building codes and rules.

In addition to the rules and regulations, the SIPs will need to be designed with and around other subsystems of the house. Since any cutout of the SIP will decrease its inherent insulation properties, proper placement will be crucial. Wiring, plumbing, HVAC system, and window placement will all need to be considered when using SIPs.

Standard Insulation Testing

A blower door is a machine used to test the airtightness of buildings. A machine is mounted to an external door of the house with all other external doors being shut and all interior doors left open, and air is forced into or out of the building to create a positive or negative pressure differential. The external door is then shut, and the pressure drop over a period of time is measured. The airtightness of a home is crucial to its insulation and the ability to keep heat in or out of the house. It may be possible to install a blower door into the Solar house upon its completed construction.

Additionally, an R-Value test of the wall can be performed using temperature probes on either side of the wall, a material of known thickness and thermal conductivity, and an additional temperature probe outside the material. This creates a simulated 1D conduction model, where at steady state the heat flux is constant. This test can be simply performed on the Solar house and will verify if our SIPs are of the advertised quality.

Finally, the SIPs must pass safety specifications for structural and fire-safety properties. SIPs are manufactured to NTA national standards, though they must also be installed correctly in order to maintain this standard of structural integrity. Additionally, the minimum residential fire-safety standard is a Class II Fire Safety Rating, though we have been able to find numerous SIP manufacturers which surpass this minimum requirement and achieve a Class I Rating--the highest rating achievable.

DESIGN DEVELOPMENT

After conducting sufficient background information on the applications, benefits and limitations of structural insulated panels we came up with a variety of wall, floor and ceiling layouts and conducted preliminary engineering analysis to help us decide which of the layouts we should use for the Solar House. Using our background research we were able to narrow the selections down to a few different options.

The first decision we had to make is where we would use structural insulated panels. From our background research we knew that the more SIP's we can use the better the overall insulation would be in the house. There are several disadvantages to using SIPs however. Due to their rigid structure it is difficult to run any electrical wiring and impossible to run any plumbing through the SIPs. This means if the entire house is constructed using SIPs it would be impossible to properly plumb and wire the house. Thankfully, the idea for the Solar House includes a "core" where all of the electrical, mechanical and water systems are mostly contained. Due to this fact we hope to be able to use SIPs for all of the surfaces outside of the core. This includes all exterior walls, the roofing and the flooring. The flooring will be the most difficult to use SIPs on, however, as we may still need to run electrical wiring through the floor in the areas of the house that are not part of the core. Analysis on the benefit of using SIPs vs traditional insulated flooring will be discussed later in the report. The image below illustrates where we plan on using SIPs in the house. The floor plan indicating the desired location of SIPs is shown in Appendix 2.

The second decision we needed to address was the type of structural insulation we would be using in our SIPs. There are three commonly used foam types, as discussed in our background section: Polyurethane (PUR), Extruded Polystyrene (XPS) and Expanded Polystyrene (EPS). There are advantages and disadvantages for each and in order to help us decide which insulation was best for the Solar House we constructed a cost comparison table shown below and a pros and cons table shown on the next page.

Table 2. Cost Estimate Comparison of SIPS

SIP Thickness (inch)	Cost per square foot	Total Material Cost
EPS 6 inch	$4	$13,336
EPS 8 inch	$5	$16,670
XPS 6 inch	$5	$16,670
XPS 8 inch	$6	$20,004
PUR 6 inch	$6	$20,004
PUR 8 inch	$7	$23,338

Table 3. Comparison of Rigid Foam Insulation

Foam Type	Advantages	Disadvantages
Polyurethane (PUR)	High moisture resistance Great R-Value retention Fire resistance High structural strength Highest R-Value per inch High air tightness	High cost Harder to install Less construction flexibility
Extruded Polystyrene (EPS)	High Structural Strength Higher R-Value per inch More Fire Resistant	High R-Value degradation Higher cost Harder installation Subject to mold and moisture penetration
Expanded Polystyrene (XPS)	Cost effective Easy Installation Good R-Value Retention Recyclable High air tightness	Lower structural strength Subject to mold and moisture penetration Poor fire resistance Low R-Value per inch

As demonstrated in the table, Polyurethane is the optimum rigid foam, but it cost much more than the Polystyrene options. As discussed in the Objectives Section, R-Value is our primary focus with cost, structural stability, and lifespan as our secondary specification. Factors such as recyclability and fire protection are also important factors. With the design specifications in mind we were able to come up with three different wall, floor and roofing designs to conduct our engineering analysis on in order to determine the best fit for the Solar House.

Walls

The walls of the Solar House are the most critical aspect of the insulation as the majority of the heat transfer for the house will be through the wall. Because of this it is vital to insulate the walls properly. After analyzing our background research we determined that we would analyze the Polyurethane and the Expanded Polystyrene options for the walls. Along with the type of foam we also must determine the thickness of the SIP we want to use. Typical wall SIPs span from four to eight in.. We determined that our three best options would be a six inch polyurethane wall, a six inch EPS wall, and an eight inch EPS wall.

Table 4. Comparison of three proposed wall designs with R-Value and modeled cooling load.

Wall Model	Projected R-Value	Cooling Load Kbtu-hr
Outer surface 0.1000in 0.1 in Siding(Wood, drop, 7.8 in.)(not to scale) 0.6000in Oriented strand board (OSB) 4.8000in PUR Polyurethane Board (Diffusion TIGHT) 0.6000in Oriented strand board (OSB) 0.5000in 0.5 in. (12.7 mm) gypsum board Inner surface	30.1	13.3
Outer surface 0.1000in 0.1 in Siding(Wood, drop, 7.8 in.)(not to scale) 0.6000in Oriented strand board (OSB) 4.8000in EPS Expanded Polystyrene (Heavyweight) 0.6000in Oriented strand board (OSB) 0.5000in 0.5 in. (12.7 mm) gypsum board Inner surface	23.9	13.9
Outer surface 0.1000in 0.1 in Siding(Wood, drop, 7.8 in.)(not to scale) 0.6000in Oriented strand board (OSB) 4.8000in PUR Polyurethane Board (Diffusion TIGHT) 0.6000in Oriented strand board (OSB) 0.5000in 0.5 in. (12.7 mm) gypsum board Inner surface	31.2	12.8

Along with determining the rigid foam insulation we would be using it was also necessary to determine the other aspects of the walls. In order to conduct engineering analysis we needed an exact cross section of the walls we will be analyzing. Typical SIPs use either CDX plywood or Oriented Strand Board (OSB). There are benefits and disadvantages for each, but after some short research we concluded that OSB is the industry standard for SIP walls and that CDX plywood is generally used for roof and flooring.

In order to test these three wall types DesignBuilder software was used to conduct a Cooling Design Analysis. The DesignBuilder model constructed by Bryce Willis was used for the analysis. DesignBuilder uses a big picture approach to determine the heating and cooling loads necessary to keep the house at the desired temperatures. A detailed cross section of each of the three wall options was constructed in DesignBuilder. A complete cooling analysis for an average day in the month of October in Irvine, California was then conducted in order to determine the energy savings or losses we would encounter with each wall choice. A typical house of the size that we are constructing requires around one ton of refrigeration (12 kBtu/hr), so that was our rough target in the analysis. Recognizing that the DesignBuilder model will not be 100% accurate, we used the results more as a comparison tool than an exact measurement of the heating and cooling loads. The results for the three different wall choices with a well-insulated roof are summarized in the table below.

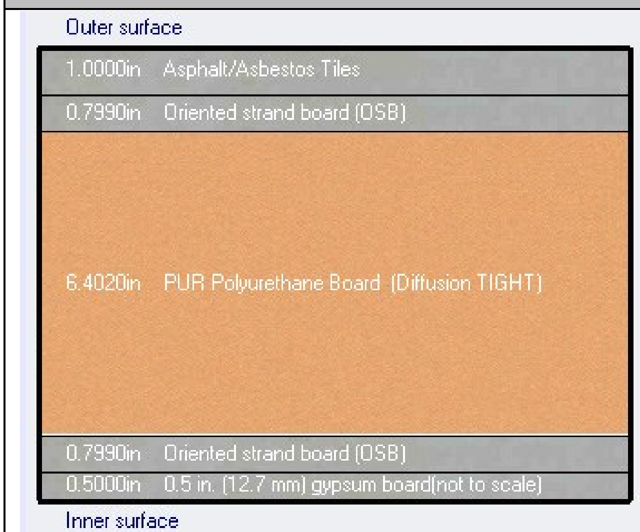
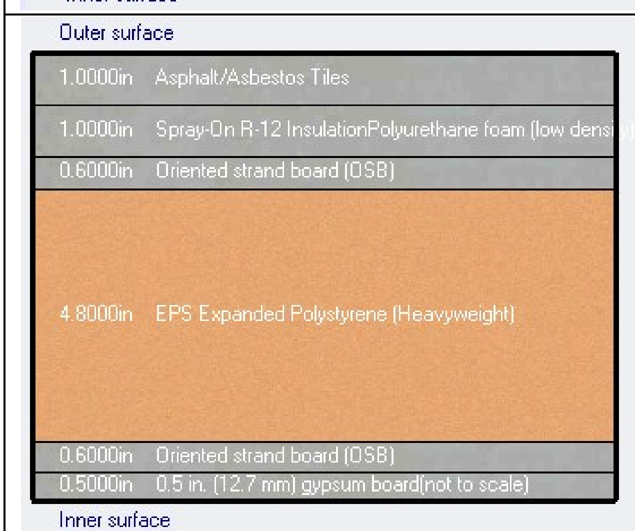
After conducting the analysis it is clear that the 8 inch EPS model will perform the best with regard to insulation by a slight amount. The six inch PUR wall also performed well but the six inch EPS wall did not perform well enough to remain in consideration. We have narrowed it down to the six inch PUR or an eight inch EPS. These two walls would have similar costs as our initial cost research has shown that a typical eight inch EPS wall will cost five dollars per square foot while a typical six inch PUR wall will cost around six dollars per square foot. Both of these choices meet all of the specifications discussed in the Objective Section. Both the PUR and EPS options have a lifetime guarantee of at least twenty years which meets that minimum objective. The compressive strength of both options are well above 20 psi. The PUR is certainly the leader in fire safety as the EPS will likely need a supplemental fire retardant. Each of the options also meet the weight requirement with the PUR being denser, but due to the fact that we would be using less of it both options will weigh approximately the same. Due to the fact that the EPS wall performs better in the cooling design and is less expensive than the PUR wall it is our leading choice right now, the PUR is still in contention however, as it performs much better in all other aspects. In the future a detailed cost-benefit analysis will have to be conducted in order to determine which choice will truly be the best for the Solar House.

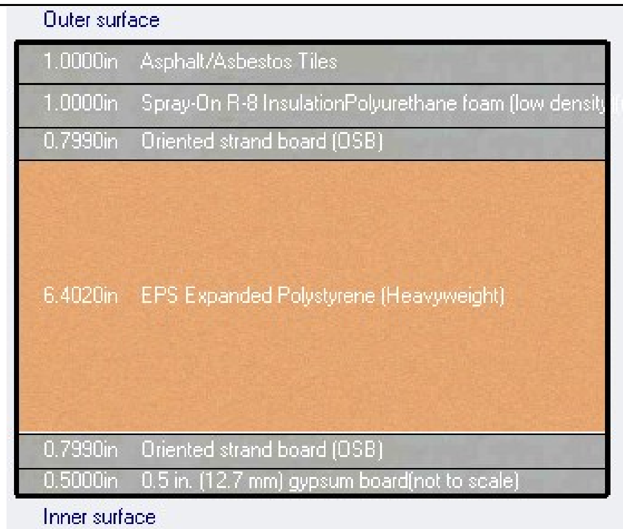
Roofs

The process for analyzing the roof structure was very similar to that of the walls. When using SIP's on the roofing there are a few extra things to consider, however. When using SIPs for roofing it is especially important to consider the structural stability, which is not something we have been particularly concerned with up to this point as the Structural Engineering team has been dealing with the structural analysis. In order to comply with their needs we have been working together to understand what is required of the SIPs we will be using for the roof. We have confirmed that as long as we are able to choose a SIP manufacturer who is code certified, we will not have to worry about the structural analysis so we will focus once again primarily on the R-Value and other insulation properties.

Once again we came up with three initial roof designs to analyze in design builder. There is a little more flexibility with the roof spatially and it is common practice to use spray foam as well as the SIP in order to maximize the insulation and minimize the cost. We constructed two EPS roof cross sections that include spray foam on top of the SIP, we also constructed a PUR cross section which does not contain the spray foam. These preliminary designs were mostly based off of research conducted on what is commonly done in industry. The results for the DesignBuilder analysis using the three different roofing options with the 8 inch EPS wall are shown in the table below.

Table 5. Comparison of the three proposed roof designs.

Roof Model	Projected R-Value	Cooling Load Kbtu-hr
	33.8	12.8
	26.4	13.2

	33.1	12.9

After conducting the DesignBuilder analysis it is clear that the six inch EPS design will not be an option as it simply does not perform as well in the cooling design, and after discussing options with the Structural Engineering team we found out that structurally eight in. maybe be needed in order to ensure stability. Deciding between the other two options will be much more difficult, however, and we may have to analyze the effects of adding spray foam further. The PUR and EPS with spray foam performed nearly identically in the cooling design analysis. Without extensive cost analysis it appears that both options would cost very near the same amount, somewhere around seven dollars per square foot. The roofing is probably the area of insulation that still requires the most analysis and research.

Moving forward we will have to analyze the effect of using more or less spray foam on the overall insulation of the house. From this analysis it appears that the roofing will not have as large of an effect on the cooling design, which makes sense as heat rises, therefore we expect the roof to have a greater effect on the heating design, which we have had some trouble modeling. We will have to analyze the effect of roofing on the heating loads in order to make an informed decision on how we want to roof the house. We will consider using more spray foam as well as incorporating spray foam with the PUR design in order to optimize the insulation. This analysis was also conducted on a DesignBuilder model that was not an accurate depiction of the final Solar House. More design builder analysis will be necessary to confirm our initial results.

Floors

Since the flooring analysis was inconclusive in Design Builder, we decided to use a supplementary program to analyze our options. The following analysis is done in ABAQUS 6.11, a finite element analysis (FEA) program. A heat transfer analysis was done for thicknesses 6, 8, 10, and 12 inch, EPS foam, SIP flooring. The layup of those panels are 0.75 inch wood finish followed by the SIP itself. Depending on the thickness, the SIP panel consist of 10% of the overall thickness on each side with the remaining amount of EPS foam sandwiched in between.

The film temperatures of the panel was set to 70°F inside and 80°F outside. Once the part was assigned with the correct properties and meshed, analysis can be done. The results are shown in Table 6 and Table 7. For the cost per square foot, we looked at Raycore a company we were able to get a free cost estimate for. It seems that for every 2 inch increase in thickness, the cost goes up by about a dollar per square foot. Using a dimensioned diagram, the flooring that will need to be insulated came out to be around 767.5 square feet. From there, we can get an estimated cost of the raw materials, not including shipping. Once the analysis was done, a heart transfer unit in in-lbf/in-s was given. The unit was then converted to something that was more useful. The calculation also verified that our model was theoretically accurate and representative of our layups. There was no error between the hand calculation and FEA model of more than 5.21% difference. Shown in Table 6, there is only a 3% percent error from using a heat transfer formula and FEA analysis. For example, the FEA Model Heat Transfer value for a 6 inch SIP describes that for every inch of material, the floor loses 0.7608 BTUs of energy every hour.

Table 6. Comparison of SIP floor models

SIP Thickness (inch)	FEA Model Heat Transfer (BTU/in-hr)	Calculated Heat Transfer (BTU/in-hr)	Percent Difference
EPS 6 inch	0.7608	0.7231	5.21 %
EPS 8 inch	0.5873	0.5661	3.75 %
EPS 10 inch	0.4550	0.4549	0.02 %
EPS 12 inch	0.3791	0.3801	0.26 %

From this model we can conclude that there are diminishing returns with increasing thickness of the SIPs. From this model we can conclude that, the thicker the panels are indeed better, but now the deciding factor will be costs. If SIPs are to be used, we can say that the flooring will not be thicker than 10 inch as the cost of the 12 inch panel will most likely outweigh its benefits.

Additionally, Richard Beller, the architectural advisor has given us a conventional floor layup as opposed to SIPs which are not as common. The floor layup consists of 5 vertical layers and 2 different horizontal layers. From top to bottom, there is the 0.75 inch finish, 0.75 inch CDX plywood, 5.5 inch Icynene open cell spray foam, 1 inch closed cell spray foam, and an outer 0.5 inch CDX plywood layer. Horizontally, there are 2 inch studs that span the open cell foam every 16 inch center to center. We put this model in ABAQUS in order to compare the results. Since the drawn layup is 8.5 in., we compared that to our 8 inch SIP previously analyzed. Table 7, sums up the results.

Table 7. Comparison of SIP and Spray foam flooring insulation.

Layup	FEA Model Heat Transfer (BTU/in-hr)	Average Percent Difference
8 inch EPS SIP Flooring	0.5873	14.44 %
Spray Foam Flooring	0.6787	

As shown, there is about a 14-15% difference between the two layups according to our FEA. This is reasonable given that we assumed the SIP panels to be one large panel without any stud that funnel the heat like that in the conventional spray foam flooring model. In reality, there will be some separation of SIPs and fasteners that will conduct the heat away from the foam causing a smaller difference. With that in mind, the conventional spray foam flooring may be supported and manufactured better by most companies. The spray foam is also cheaper than SIPs with a relatively close heat transfer between the two. At this point, the spray foam flooring is projected to be better than the 8 inch SIP flooring.

Sheathing

In terms of sheathing, Table 8 provides a general scope to the different of sheathing materials available. For our purposes, OSB and plywood will be our main considerations. Since cost will be a determining factor, OSB or plywood will get the job done at a much lower price than another of the other materials shown.

Table 8. General SIP Sheathing Information

Sheathing Type	Benefits	Drawbacks
Oriented Strand Board (OSB)	Load bearing; readily available; tested; large panel size up to 8' x 24'	Subject to mold and a reduction in structural capacity if exposed to moisture; not fire resistant; must be treated for termites; difficult substrate for most common joint tapes
Sheet Metal	Resistant to mold; can be load-bearing; very light; unlimited lengths when made from coil stock	Must be galvanized or stainless steel; not load bearing
Plywood	Lateral strength	Availability; price; limited panel size; subject to mold and reduced structural capacity if exposed to moisture for a prolonged period of time; not fire resistant; must be treated for termites

Fiber Cement Siding	Resistant to mold, termites, and fire	Availability; weight; testing; limited panel size
Magnesium Board	Resistant to mold, termites, and fire	Availability; testing; limited panel size
Fiberglass Mat Gypsum Sheathing	Resistant to termites and fire	Not structural; limited panel size
Composite Structural Siding Panels	Resistant to mold and termites; pre-primed materials available	Not fire resistant

Since the conductivity of both OSB and plywood are the same, an FEA model will not give us conclusive results. To determine which sheathing will be used at various locations, other properties of the material are examined. According to the American Plywood Association (APA), OSB swells 10-15% more than plywood when subjected to water. Another advantage of plywood is that it sags about 6-8% less than OSB when subjected to constant loads and temperature. University of Massachusetts, Amherst describes that plywood is also typically lighter and stiffer by about 7%. With that in mind, plywood is also more expensive. Although plywood seems have better performance overall, the final decision will be made after consulting with potential manufacturers. Since each company provide different materials, it is difficult to justify whether the performance of plywood will outweigh its increased costs. As of now, the current direction is that there will be OSB sheathing on the walls and roof, with plywood sheathing on the floor. Since most of the electrical components at this point will be running underground, the increased stiffness and less potential swelling seems like the better option.

DESCRIPTION OF FINAL DESIGN

After preliminary design development, more detailed research and analysis was necessary before coming to a final decision with regard to the insulation of the house. Our initial design development pointed us in the direction of using 8 in. expanded polystyrene SIPS on the external walls and roofing of the house, so we set out to confirm our initial findings. In order to come to a final decision professionals in the SIP industry were contacted regarding safety and longevity, cost estimates were received from SIP manufacturers and detailed analysis was conducted on the effect of placement, thickness, and foam type of the SIPs. After our final round of design development, research, and analysis, we are confident that we have selected the best option for insulating the Cal Poly Solar house.

SIP Material

After our initial decision to go with EPS we wanted to conduct further research to ensure that we wouldn't be better off going with Polyurethane SIPs. Polyurethane has many advantages, such as its resistance to moisture degradation, fire safety, and higher insulation properties. We have now been assured by our own research and from discussion with SIP manufacturers that for our situation, EPS will be the best option. As the house will be located in southern California it will not be subject to high humidity or an abundance of rain. This means that moisture degradation should not be a primary concern. When discussing fire safety with SIP manufacturers, we have been assured that all care has been taken to produce EPS SIPs that are up to and exceed fire safety code regulations. Polyurethane SIPs undoubtedly have higher RValues per inch of thickness than EPS SIPs. We would be able to use 6 in. of PUR SIPs to obtain only slightly lower R-Value of 8 in. of EPS. We were able to work out with the architects, however, that saving the extra two in. of space was not necessary. The final thing that drove us to using EPS was the fact that a local dealer can supply us with EPS SIPs, but we cannot obtain PUR SIPs locally. A local company is a dealer of Premier SIPs. Buying locally will result in a large reduction of shipping cost and it is very possible that we will be able to get SIPs donated from Premier SIPs. These factors make it clear that EPS SIPs will be far cheaper than PUR and still function well for the Solar House.

SIP Locations

A rough drawing of the SIP locations for the house is given in Appendix 2. This drawing shows that the SIPs will be installed in the walls and roofs of the outer modules of the home, while the inner module will not have any SIPs. Further work must be done on this drawing to be supplied to manufacturers. There will be callouts for chases, plumbing lines, windows, doors, joists, and more specified dimensions.

Because of the use of SIPs in the ceilings of the outer modules, there can be no recessed lighting installed there. This is because the recessed lights can cause excess heat to the insulation, and this heat can create condensation and moisture issues that can degrade the RValue of the insulated foam. This can be avoided by the use of a "drop" ceiling, where the visible ceiling above one's head in the house is a thinner wooden paneling that is not load bearing.

The mechanical room is now of specific interest to our group. We will most likely no longer be conditioning the air in the mechanical room in order to save on the energy costs associated with the extra cooling load. The mechanical room will need to be maintained at a temperature below 95 °F in order for the inverter and other electrical equipment to operate efficiently. We conducted analysis to determine how low the R-Value of the mechanical room walls will have to be. After conducting the analysis, it is clear that we will not want to use SIPs in this room. Even with walls with R-Value around 10 (ft^2-F-hr/Btu) we will still need to expel heat from the room. In order to do this, ventilation ducts will be installed at the bottom and the top of the room, with the possibility of a low power intake fan to help the ventilation process. The exact details of this ventilation system still need to be worked out with the passive HVAC team.

Construction Documents

We have chosen to proceed with Premier SIPs, who are based out of Washington and have dealerships all over California, including in Paso Robles. The shipping cost alone is a large reason why we are going with this company, because the cost of shipping 1000 square feet of wooden panels is large when they must be carried by trucks. Additionally, Premier SIPs supply a quality product which has been supported by many reviewers and even other SIP companies. They also carry polystyrene insulation, which will be used for our house. Finally, our team and Alan Hanson, the outreach coordinator for Simpson Strong Tie, have been in contact with distributor Terry Turner at Premier SIPs and have been discussing possible donations and discounts for their products.

The majority of SIP construction and installation files are standardized and specified by each manufacturer. The specifications each company requires in order to manufacture the proper SIPs include detailed drawings of dimensions, window/door locations, overhang locations, roof angles and means of support, screw/nail locations and types, panel cuts and spline locations, slab locations, partition specifications, electrical chases, plumbing lines, and alphabetized panels for installation. Many of these must be accomplished by an architecture team that has experience and knows the standards for these practices. In the interim, the standard construction and installation specifications are supplied by the manufacturer and must be communicated to the architects so they know how the house will be built.

The construction files in Appendix 1 detail the means by which SIPs are assembled and joined together. Appendix 1-A shows how wooden panels must be installed on the borderline of doors, windows, openings, and ceilings for load bearing purposes. Horizontal panels are installed first, followed by vertical panels.

Appendix 1-B calls out the location and types of nails and studs to be used as well as showing the locations of 1-½ in. electrical chases in the walls. These chases run horizontally at 16 in. and 45 in. above the ground and intersect with vertical chases every 4 ft. These chases will be sufficient for the Control Systems Team's purposes and should not require any customization for manufacturing. The "king stud" mentioned in the callout is the name given to a stud which runs all the way from the bottom plate to the top plate. Other studs include "cripple studs," which start at either the top or bottom plate but do not continue the whole way to the other plate, and "trimmer studs," which start at some opening that does not connect with either top or bottom plate. Trimmer studs are typically installed alongside king studs for support.

Appendix 1-C shows how windows are installed when there is a panel break in the middle of the window that must be joined by a spline. The panel break results in new load specifications that must be followed in order for the wall to be structurally sound. The load specifications are found on the Premier SIPs website and is also listed in the References section of this document.

Appendix 1-D shows how bottom plates are installed with the SIPs. These bottom plates are essential because they keep the SIPs at a small height above the foundation of the house where moisture collects. This drawing also details how the electrical wiring is routed through the intersections of horizontal and vertical chases. There is a 4 in. hole cut through the SIP to access the wiring, and when the wiring is complete, the hole must be filled with the insulation material that was previously removed.

Appendix 1-E details the manner by which inner partitions are connected to the SIPs. Inner partitions are made of stick paneling, which uses 2x4 vertical wooden panels located every 16 in. to bear the load of the building. These panels additionally have horizontal chases at 16 in. and 45 in. to coincide with the chases on the SIPs.

Appendix 1-F shows where the Premier Mastic is installed for windows and other types of openings. The location and types of nails are also specified in this drawing.

Appendix 1-G is a cross sectional view of SIP connecting with the roof sheathing and trusses. Here, it is important that there are no gaps where air may enter into the building. This is prevented with a wind wash to keep the joint insulated.

Electrical outlet installations are detailed in Appendix 1-H. The hole created by the outlet must be filled with foam insulation so that no thermal bridging occurs.

Drainage systems and pipes are shown in Appendix 1-I. This drawing will be important for the plumbing and water systems teams who need to deal with the movement of water around and through the SIPs.

A cross section view of a spline connection between two SIPs attached vertically together is detailed in Appendix 1-J.

Air Quality and Fire Safety Specifications

Because of the airtight nature of SIPs, the house needs to be ventilated to keep the interior comfortable. Methods of ventilation are recommended by Premier SIPs on their technical bulletins page of their website. They suggest using heat recovery ventilators (HRVs) in areas of high humidity, such as the kitchen; exhaust only systems to naturally ventilate and infiltrate the house with fresh air; ventilating windows that utilize a small grille which is manually operated on a specified number of windows in the house; and/or air cleaners which do not work particularly well with the removal of gaseous pollutants or radon control. These suggestions will be followed by the team as a whole, and the HVAC sub-team is handling most of these ventilation concerns.

Premier SIPs are tested under the fire safety standards of ASTM - E119, ASTM - E84, and UBC 26-3. Due to the use of gypsum boards alongside with proper installation, the SIPs surpass conventional fire safety codes. Additionally, SIPs do not release abnormal toxic gases when under combustion. Typical gases released include carbon monoxide, carbon dioxide, and water vapor--which are typical for most non-toxic combustible materials.

Finally, Premier SIPs do not “off-gas,” or release any harmful gases into the air from the materials of the insulation. A typical gas of concern is formaldehyde. Under the ASTM - E1333 test entitled “Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber, Standard Face and Back

Configuration," formaldehyde concentration in the air was tested down to a sensitivity of 0.03 parts per million. The conclusion of the test was that the concentration was below the minimum detectable level of the testing equipment, proving that the SIPs do not off-gas.

In order to proceed with the procurement of the materials for the house, we have to collaborate with the architectural engineering team in completing a fully dimensioned and detailed drawing of the house. This type of work cannot be completed by our SIP team alone because of the large amount of standardized specifications that must be done. Appendix 3 shows an example for the type of dimensioned drawing that will be completed by both the SIP and architectural teams. This drawing calls out the locations of electrical chases, the sizes of sheathing on every panel, the dimensions of windows and all panels, the locations where panels are split and joined by splines, and all connections to inner partitions and floors. Additionally, trusses and construction specifications are organized with datums and captions.

Appendix 4 is an additional document which will visually aid in the final construction of the house. The panels in this drawing are clearly shown where they are assembled and joined so that the final assembly of the house is made easier. Typically, when SIPs are ordered and arrive at a job site, all the panels are individually dispersed around the site in strategic locations for quick assembly. Because our house is of a moderately small scale, there will not be an overwhelming number of panels to be assembled. However, it is good practice to always label, alphabetize, and organize the panels in both the drawings and at the job site so that mistakes with installing the SIPs can be avoided.

ANALYSIS RESULTS

After our preliminary analysis we were able to come to an initial conclusion that using 8 inch EPS SIPs would be the best fit for the house, but it was clear that more analysis was necessary to confirm our decision absolutely and in order to move forward with the HVAC systems in the house we needed to know exactly what type of performance we would be getting out of the SIPs we chose. In order to reassure the built in R-Values of DesignBuilder, detailed FEA analysis was conducted on the walls, floors and ceilings. We now know exactly what the floor and roofing will be: due to structural concerns we will be required to use 8 in. SIPs and from a need for electrical wiring in the floor we will be using a traditionally joisted and insulated floor. Analysis was conducted on the new floor cross section as well as the 8 in. SIP ceiling, the 6 in. SIP wall and the 8 in. SIP wall. Once these R-Values were obtained we were able to feel more confident in the DesignBuilder model and used this model to ensure that with the chosen insulation we would keep cooling loads as low as possible. Analysis was also conducted to determine what was to be done with regard to the insulation and ventilation of the mechanical room.

Updated Finite Element Analysis Model

The purpose of the Finite Element Analysis model is validate our findings with design builder. An updated FEA heat transfer model was done on the walls, roof, and floors to confirm our results from design builder. The previous model mentioned earlier was used to compare the heat transfer value obtained from the layout of a SIP flooring and a stick flooring. In addition to that analysis, we used FEA as another source to validate the heat transfer values. Since DesignBuilder is our main simulation for the cooling and heating loads, we wanted to make sure the values provided were accurate.

Before any comparison is made, hand calculations for the 1D heat transfer were made to validate the results from ABAQUS itself. Although this has been done previously, we had a range from 0.02% to 5% error. Since this is simple 1D analysis, there should be absolutely no discrepancy between our calculations and model. The hand calculations and model results were reviewed until there were 0% error between the two.
Previously, we had analyzed the heat flux of the SIPs but a better comparison can be made using the R-value for communication purposes. With an updated model, the heat flux (q") values given were used to calculate the R-value using the equation, R = (T2-T1)/q". In short, the R-value is measurement of heat flow through an object by having a temperature difference on both sides. For more information see the R-value Test in Chapter 5. The first step was to validate the manufacturer's specifications through FEA and confirm that their value is accurate and that our model correctly reflects those values. Once the model was built, inputs and boundary conditions were added. ABAQUS requires a film coefficient to be specified, which ranges from 10-1000 W/m^{2}K for air. A value of 30 for the film coefficient was used throughout each model to be conservative. Typically manufactures use a temperature difference of 50°C, with one side of the panel at 100°C and the other at 50°C. Those conditions were put into the model and the result is a heat flux value which is then converted to the R-value.

Table 9: Comparison between manufacturer's advertised R-Value and FEA analysis

Whole Wall Model	Manufacturer's Specified R-value (ft^2°Fhr/BTU)	FEA Model R-value (ft^2°Fhr/BTU)	Average Percent Difference
6 in. PUR SIP	41	28.3	15.4%
6 in. EPS SIP	23	22.9	0.43%
8 in. EPS SIP	29	30.5	5.17%

Table 9 shows the comparison between the R-values of the FEA model and those specified by the manufacturers. Nearly all manufacturers have the same R-value for the same type of SIP and that makes analyzing the differences much simpler. For the EPS SIPs, the differences are relatively close enough given the number of variables that are present. It is never specified how detailed the panels that manufactures test are and whether or not they included every screw and how detailed their "whole" wall is. The comparison for the 6 in. PUR is not ideal and we are unsure why the difference is so large.

Once the FEA model is confirmed to be match those of industry standard, then a more realistic approach is taken to estimate our required cooling and heating loads. The results from the FEA model mentioned above confirms that splines and fasteners were not taken into account when the R-value of the panel is measured. The result is an artificially high R-value that would not give us the most accurate estimates for our HVAC loads. Thus, the next step is to model the typical splines that would be used during construction.

As mentioned in Figures 3, 4, and 5 under the SIP construction section of the report, there are generally three types of SIP splines that are used. Block and surface splines are very similar in the amount of wood that is used to splice the panels together so only one model is used to represent those two types. Although panels can come in many different dimensions, a typical 4'x8' panel will be used in the model. The splines are spaced so that they only occur every 4 feet and the entire span of all the panels are made to be 20 ft.

Table 10: Comparison between DesignBuilder R-value and FEA analysis

Whole Wall Model	DesignBuilder Model R-value ($ft^2{}^\circ F hr/BTU$)	FEA Model R-value ($ft^2{}^\circ F hr/BTU$)	Average Percent Difference
6 in. PUR SIP	30.2	28.3	6.49%
6 in. EPS SIP	23.9	22.9	3.25%
8 in. EPS SIP	31.1	30.5	1.95%
8 in. EPS Roof with Outsulation	33.9	34.7	2.33%
Stick Frame Floors	N/A	25.5	N/A

We were unsure whether or not DesignBuilder takes into account the thermal bridging from the splices and fasteners. Table 10 compares the R-value of the FEA model and what we were using in Design Builder. The result of the 8 in. EPS walls and the roof show agreeable numbers and will not be changed. The floors, however have been a problem in DesignBuilder as we were unable to get an accurate model. Another result to look at is the 6 inch PUR R-values. Both Design Builder and FEA show around an R-value of 30 for the 6 inch SIPs, while manufacturers state a value of 41. Based on the thermal conductivity value for the PUR, the lower R-values seem more realistic. In order to be conservative, we will stick with the values from

DesignBuilder to calculate our cooling loads. FEA was also used as a supplementary program to help determine an R-value for the floors based on the stick frame, spray foam insulation provided by Professor Beller.

Final DesignBuilder Analysis

Once we were confident in the R-Values obtained from the FEA model of the walls, ceilings and floors, the DesignBuilder model was modified to accurately depict the SIPS we would be using. We modeled the house external walls with an accurate average R-Value of 30.5 for the eight inch SIPs and with an R-Value of 22.9 for the 6 inch SIPs. Due to construction limitations we now know that we will have to use 8" SIPs for the roofing and that we will not be using SIPs for the floor. After working with the active and passive HVAC teams to ensure that we had an accurate and functioning DesignBuilder model we were able to obtain cooling loads using the accurate R-Values for the walls, ceilings and floors.

Due to the finalization of the floor and ceiling the only results to compare were for the 8 in. and 6 in. SIPs. The results were incredibly similar to our preliminary analysis. The results are depicted in the table below.

Table 11: Comparison of using 8 in. or 6 in. EPS SIPs on the external walls in DesignBuilder.

SIP Thickness (in.)	R-Value (ft^2-F-hr/Btu)	Cooling Load (kBtu/hr)	% Difference
6"	23.1	13.2	N/A
8"	30.9	12.1	8.3%

The table shows that we will save over eight percent on cooling costs using the 8 inch SIP. This increase is incredibly significant when we are working on a tight energy budget. Therefore we believe it is crucial to use the 8 in. SIPs. Using these numbers from the most recent and accurate DesignBuilder model, which has been confirmed with FEA modeling we are now incredibly confident in our decision to use 8 in. EPS SIPs.

Mechanical Room Analysis

When we were presented with the new energy budget it became clear that we were going to have to cut costs everywhere we possibly could. This included not conditioning the air in the mechanical room. Without air conditioning it was very possible that the conditions in the mechanical room would become too hot for operation. The inverter must operate below 95°F (35°C) due to the heat generated in the room and the possibility of high outdoor temperatures a quick heat transfer analysis was conducted in order to determine what the insulation of the mechanical room should be in order to have the inverter operate efficiently and safely. A simple 1-D convection and conduction heat transfer analysis to determine the relationship between R-value of the mechanical room insulation the outside temperature and the inside temperature of the mechanical room. Using typical heat loss and generation properties of the water heater and electrical equipment in the room it was assumed that around 700 Watts of energy will be generated in the mechanical room. It is assumed that the interior temperature of the mechanical room will always be hotter than the outside temperature and that this generated heat will all have to leave through the walls. Based on the basic heat transfer equations given by Dr. Shollenberger, shown in Appendix 7. An EES code was written and used to conduct a parametric study and generate the plot below.

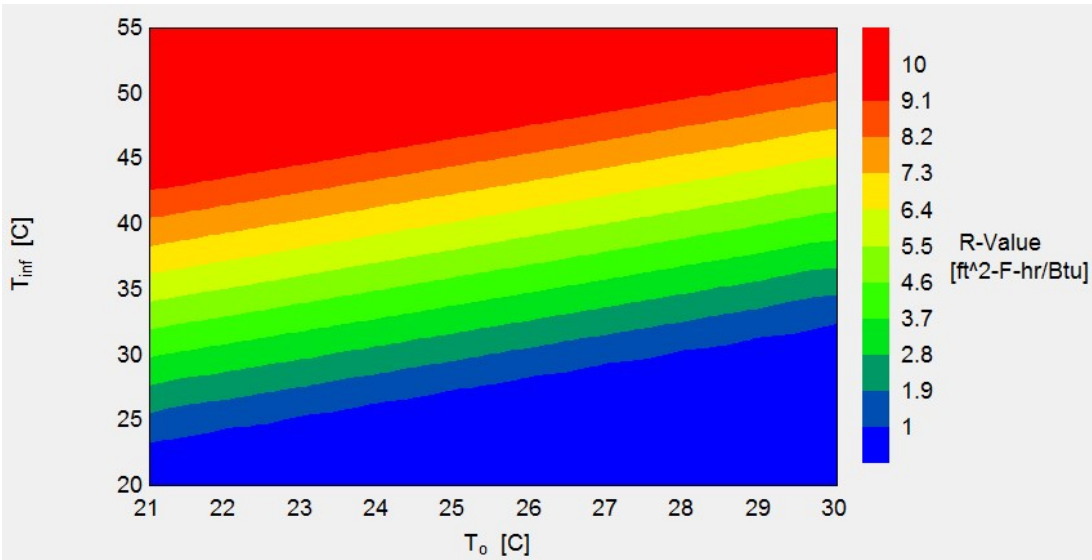


Figure 6: Contour plot displaying the indoor temperature of the mechanical room against the outdoor temperature for R-Values (in English units for industry standard) of the walls of the mechanical rooms.

It is clear from the plot above that without any sort of ventilation, the mechanical room will overheat even with very low R-Value walls. Even with a very crude analysis we can be confident that some sort of ventilation will be necessary, especially for very hot days. Now it must be determined for specific wall insulations and outdoor temperatures, how much heat will we need to remove with ventilation in order to keep the mechanical room at its safe operating temperature of 95°F. In order to illustrate how much excess heat will need to be removed from the mechanical room another contour plot was constructed in EES.

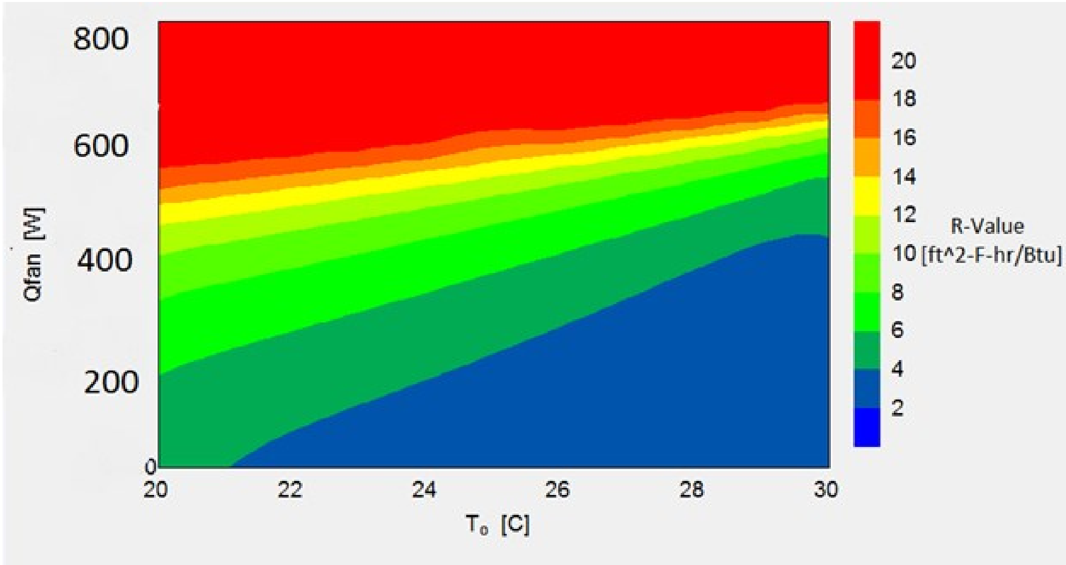


Figure 7: Contour plot comparing the amount of heat needed to be expelled from the mechanical room with relation to the outdoor temperature and the R-value of the walls.

It is clear that the worse the insulation the less the fan will have to work, which would save on energy costs. From this analysis we can conclude that low R-Value walls will be needed for the mechanical room. We will also need to design a ventilation system with the passive HVAC team in order to keep the room at a reasonable temperature.

COST ANALYSIS

As a part of the preliminary design of the SIPs for the house, our team acquired a rough cost estimate from the manufacturer Raycore. We simply supplied Raycore with a drawing of the house that dimensioned the walls and showed where window and door location and sizes were, and Raycore supplied us with a cost estimate per Appendix 5. This cost estimate is the product of the square footage of wall and roof panels multiplied by a dollar per square foot value for the materials. Raycore also supplied a “DIY Discount” which amounted to roughly $2300 for the house. It is unknown whether this discount will apply to our house because it is not known whether we will be personally building the house or if that job will be left to a third party contractor.

Additionally, the concern of whether a contractor will be responsible for building the house brings up more issues with the acquirement of a Bill of Materials. If a contractor is to build the house, then he is responsible for knowing the number and types of fasteners and top/bottom wooden panels such as those found in Appendix 1.

However, with the development of the architectural drawings, we will be able to find an exact cost estimate for the materials. We can estimate the cost based on Raycore's estimate, but the exact value is unknown until the drawings are finalized.

TESTING

R-Value Testing

One of the necessary tests to determine the ability of an insulating material is the R-value test. This test uses a temperature difference to measure the materials ability to restrict heat flow. The test requires the use of a two chamber hot box apparatus to imitate the conditions provided by the ASTM C1363 code. Typically there is a metering chamber for the higher temperature and a climatic chamber for the lower temperature. For R-value tests, there is usually a mean temperature of 75°C that is one side at 100°C and the other at 50°C. The climatic chamber also uses wind to emulate the conditions of winter. The device measures the amount of energy needed to maintain the temperatures, and using those measurements, an R-value can be calculated.

There are various types of heat transfer values that manufactures provide, but the main ones are the clear wall R-value and whole wall R-value. The clear wall R-value measures only the insulating foam and sheathing. The whole wall R-value takes into account the splines, fasteners, and various construction methods. This value is meant to better represent an R-value that is most accurate as possible to the final product.

PRODUCT REALIZATION

Due to the nature of the Solar Decathlon project, the manufacturing side of SIP construction is vastly different than other senior projects. The large scale of construction calls for contractors, faculty members, and many team members to participate in building the house. As of the current date, due to a decision-making process that was out of the control of Team Solar SIP, the house is not completed. The SIP walls were ordered in early May, which is as far as Team Solar SIP could aid in the SIP process before construction. The construction site itself currently stands as a level ground with a housing steel foundation in place. The plan for the rest of the Solar Decathlon team is to hire new engineers for the summer term to work roughly 30 hours per week on the project's construction. Team Solar SIP cannot comment on the prototyping efforts or any recommendations for future manufacturing due to the current state of construction.

DESIGN VERIFICATION

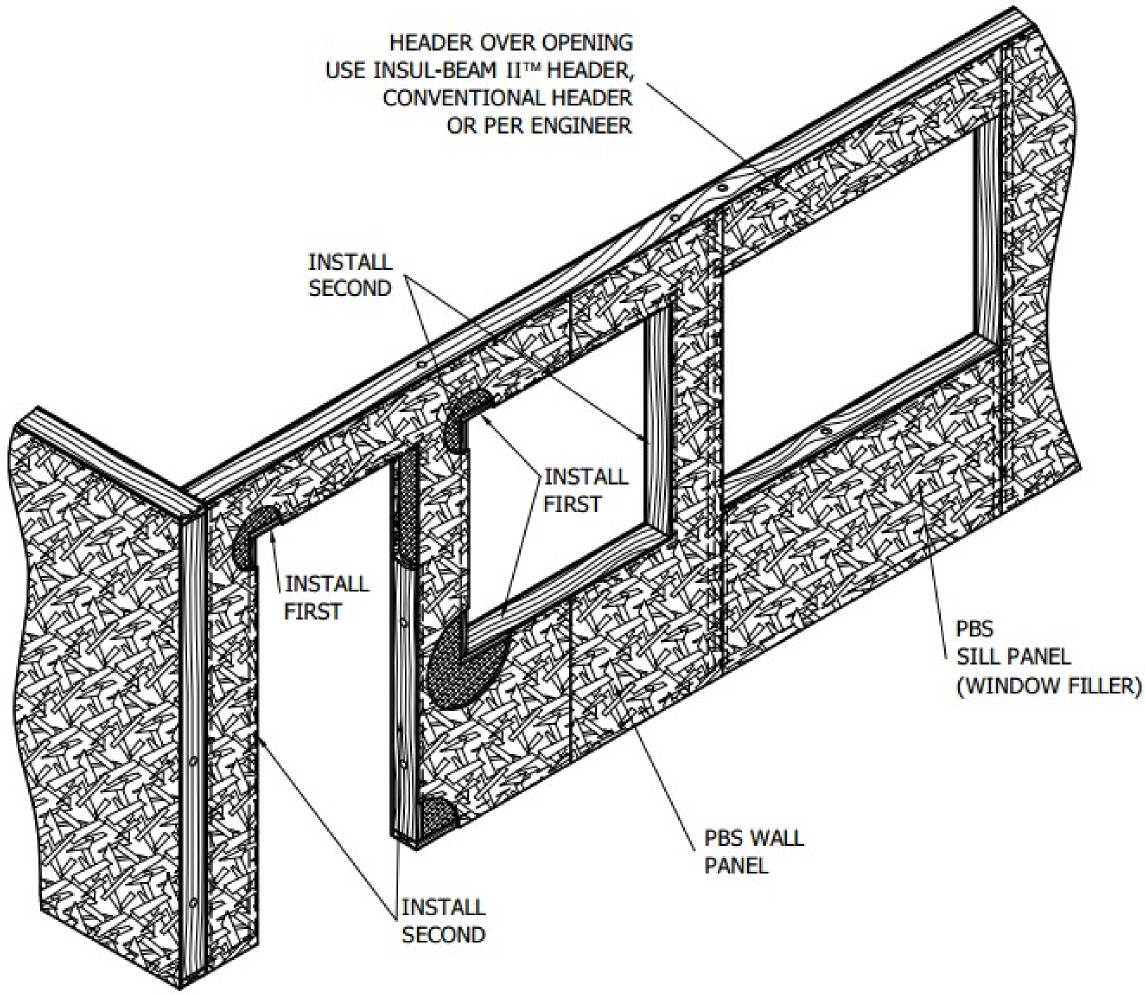
As an addendum to the previous chapter, Team Solar SIP cannot comment on testing the SIP walls or the house's thermal or structural performance. There are tests that may be performed, as per the Testing chapter in this report, but these must be completed after the house is finished. At that point in time, it would be infeasible to consider a deconstruction of the house for any significant modifications such as altering the wall sizes, thicknesses, or insulation types.

CONCLUSIONS AND RECOMMENDATIONS

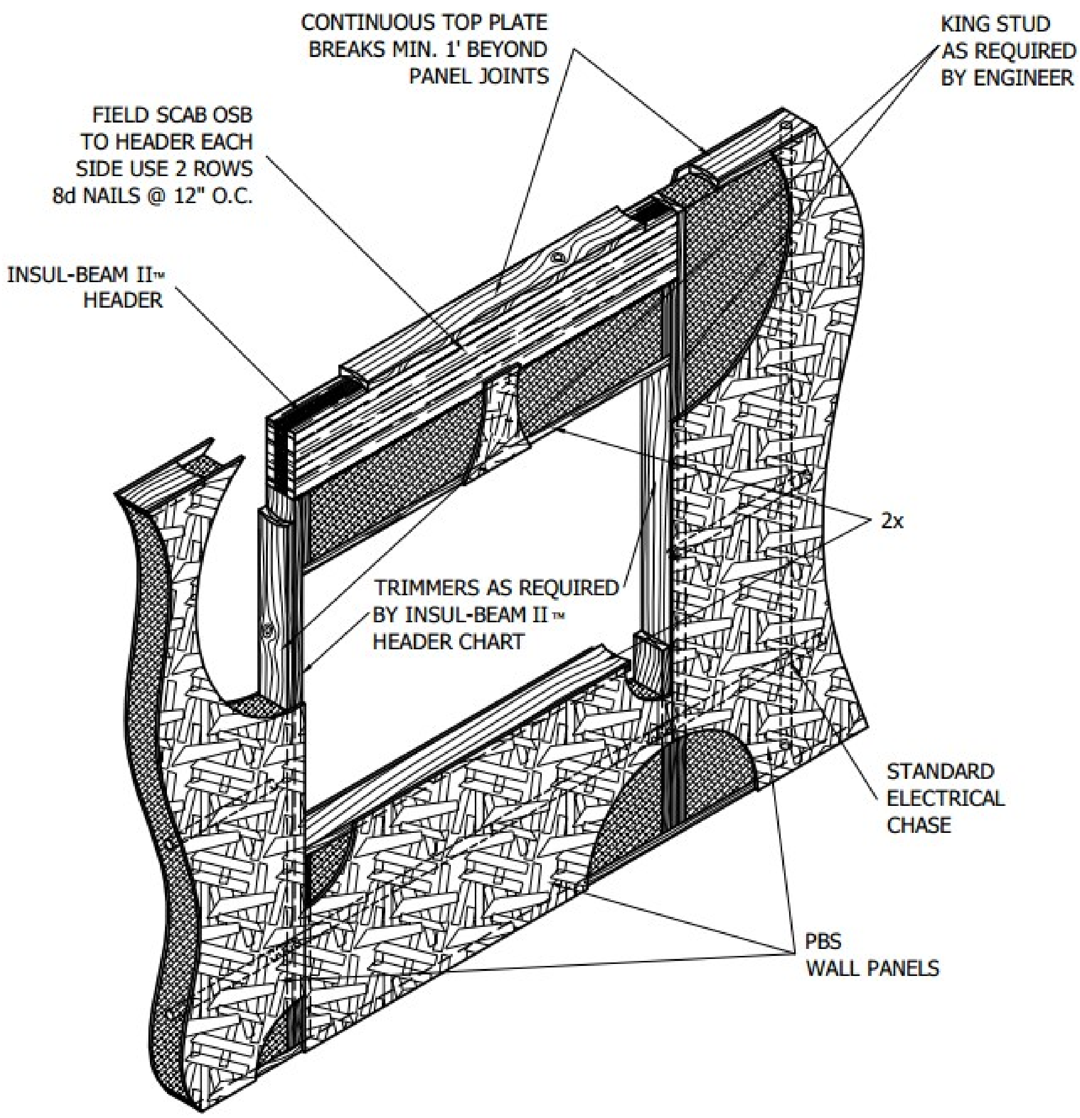
The Solar Decathlon house will have 8 in. EPS SIPs from Premier SIPs on the walls and roofs of the outer modules. The inner partitions and the core exteriors will be conventional "stick" walls. We have verified the notion that SIPs are more than 60% energy-efficient than conventional walls through simulations with DesignBuilder. The final cooling load that the HVAC team must supply to the house is 12.1 kBtu/hr, and they have purchased an air conditioning unit with a size of 17 kBtu/hr. Premier SIPs were contacted after the architecture team completed their construction drawings and the walls were ordered within two weeks. With the help of the marketing team and a few faculty members, Premier SIPs also took $1000 off the cost of the walls. The current state of the house is that it is under construction with many hands working hard to create a finished product.

In further Solar Decathlon projects, we would recommend a better collaboration with architects, structural teams, and manufacturers from an earlier point in time. It would be helpful to have consistent teams that work on the project from start to finish in order to advise and work more efficiently. Early contact with manufacturers is important to become more familiar with the SIP products, conventions, codes, and standards prior to further research into R-Value and insulation types. Further work could be done with CFD software in order to have more robust calculations that may not have the same issues as DesignBuilder, though these programs have much higher learning curves. Overall, the process of researching and becoming more familiar with a technology that is foreign to normal mechanical engineering studies is of very high value to future students.

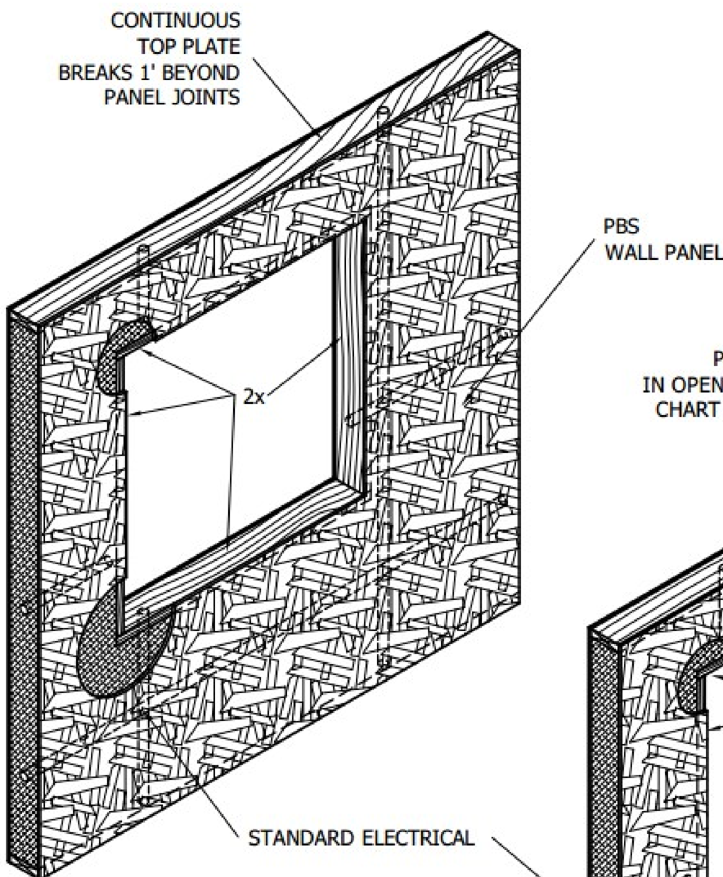
APPENDIX 1-A: PREMIER SIP CONSTRUCTION DRAWINGS



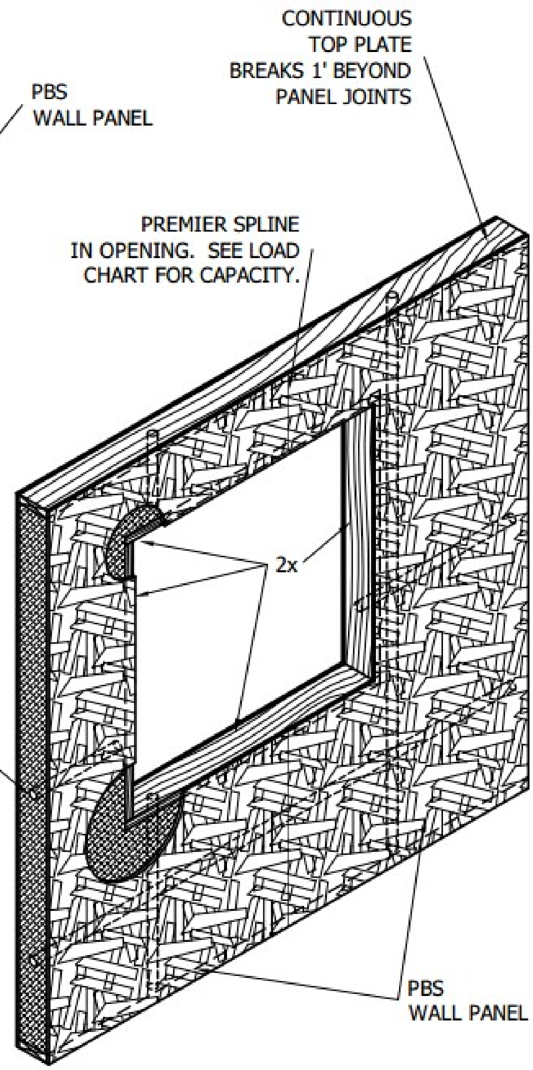
APPENDIX 1-B: PREMIER SIP CONSTRUCTION DRAWINGS



APPENDIX 1-C: PREMIER SIP CONSTRUCTION DRAWINGS



WINDOW WITHOUT PANEL BREAK

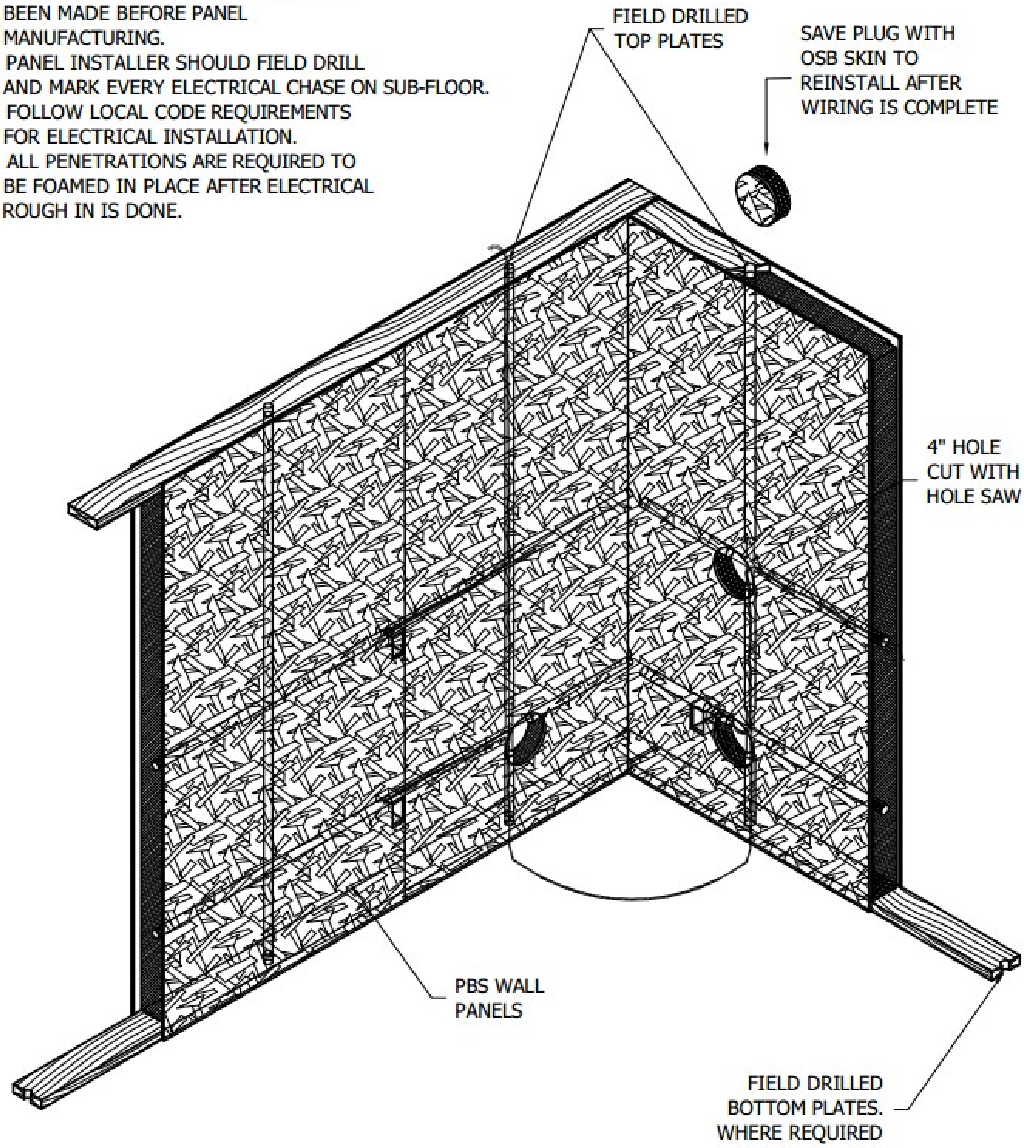


WINDOW WITH PANEL BREAK

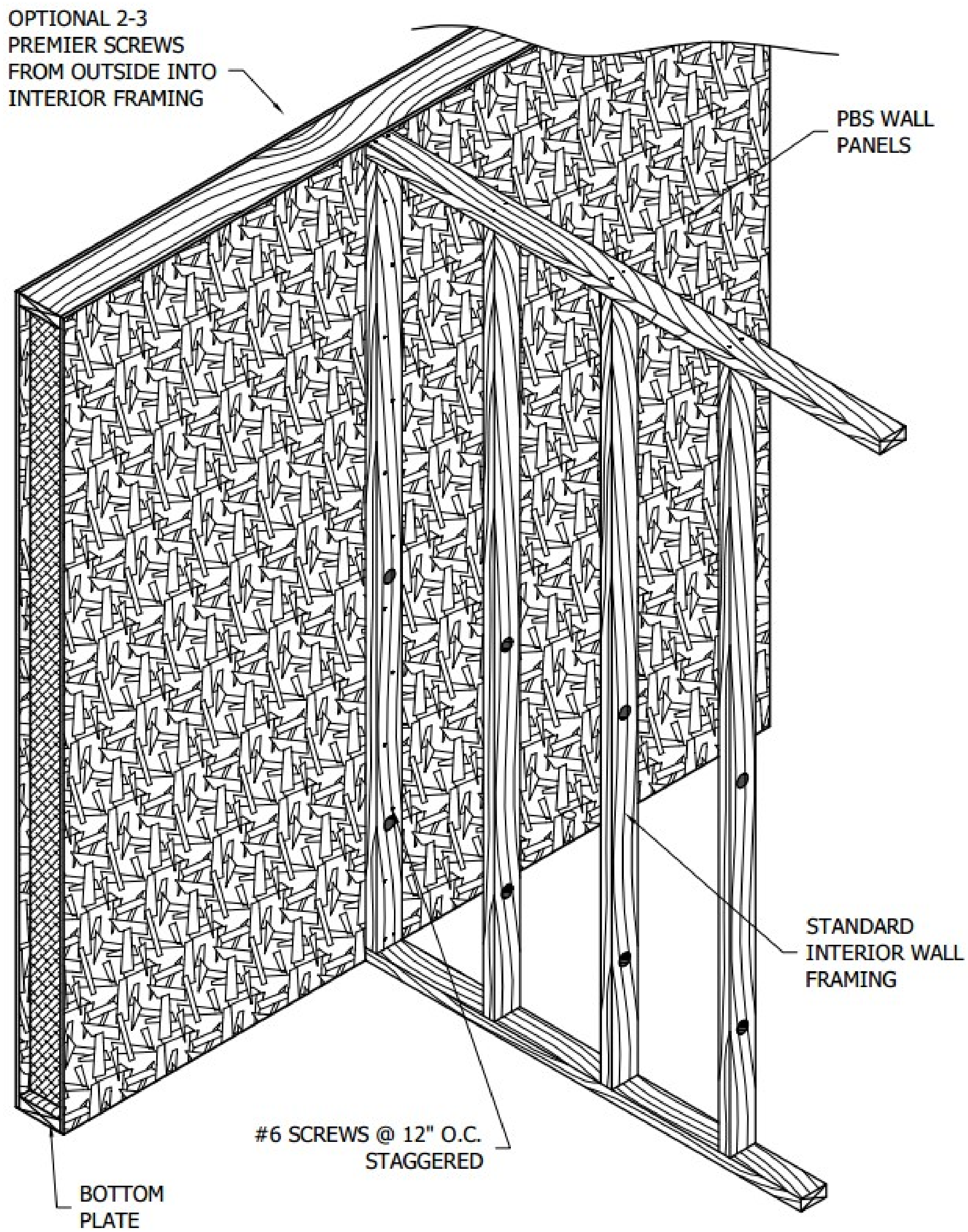
APPENDIX 1-D: PREMIER SIP CONSTRUCTION DRAWINGS

NOTES:

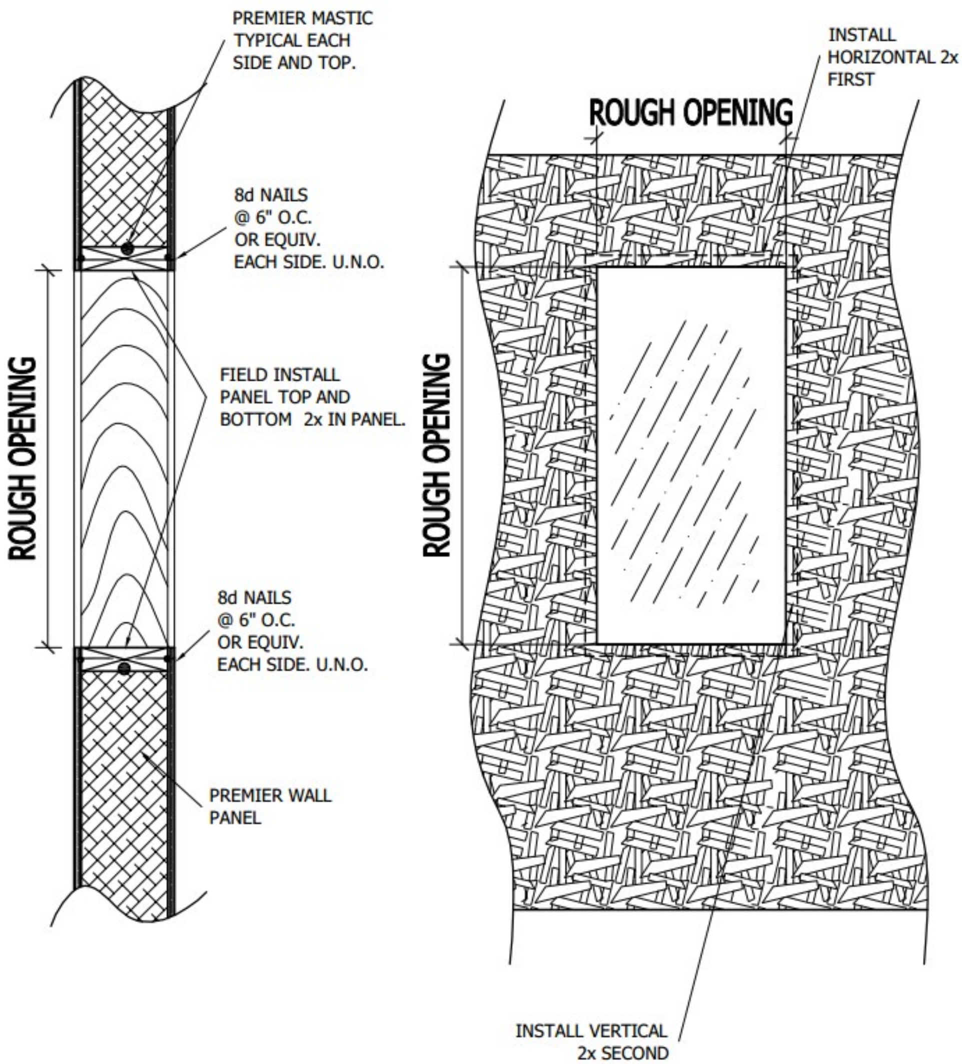
1. FACTORY PROVIDED HORIZONTAL ELECTRICAL CHASES ARE STANDARD 16" AND 45" ABOVE BOTTOM OF PANEL AND ROUGHLY 48" O.C. VERTICALLY UNLESS PRIOR ARRANGEMENTS HAVE BEEN MADE BEFORE PANEL MANUFACTURING.
2. PANEL INSTALLER SHOULD FIELD DRILL AND MARK EVERY ELECTRICAL CHASE ON SUB-FLOOR.
3. FOLLOW LOCAL CODE REQUIREMENTS FOR ELECTRICAL INSTALLATION.
4. ALL PENETRATIONS ARE REQUIRED TO BE FOAMED IN PLACE AFTER ELECTRICAL ROUGH IN IS DONE.



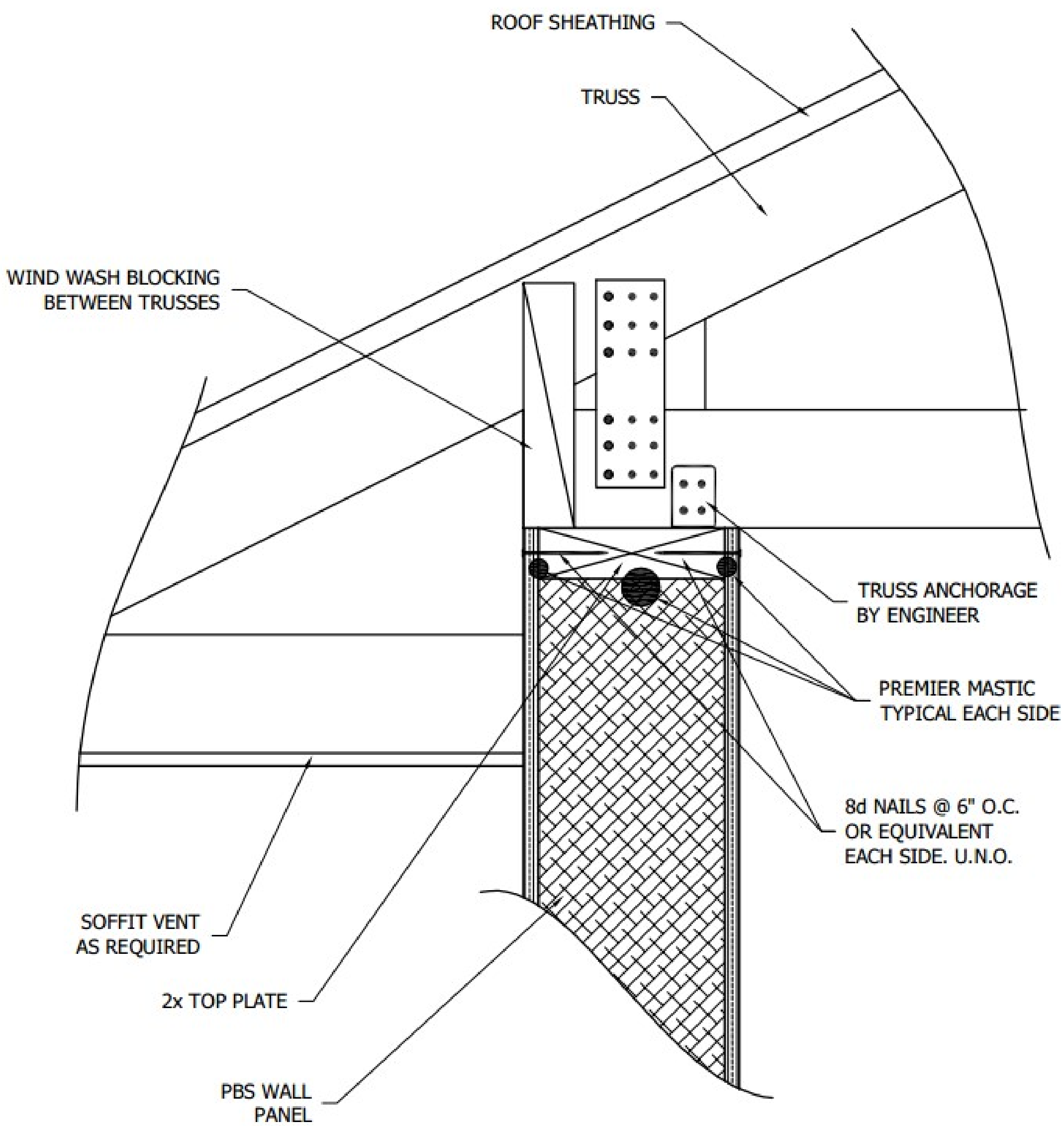
APPENDIX 1-E: PREMIER SIP CONSTRUCTION DRAWINGS



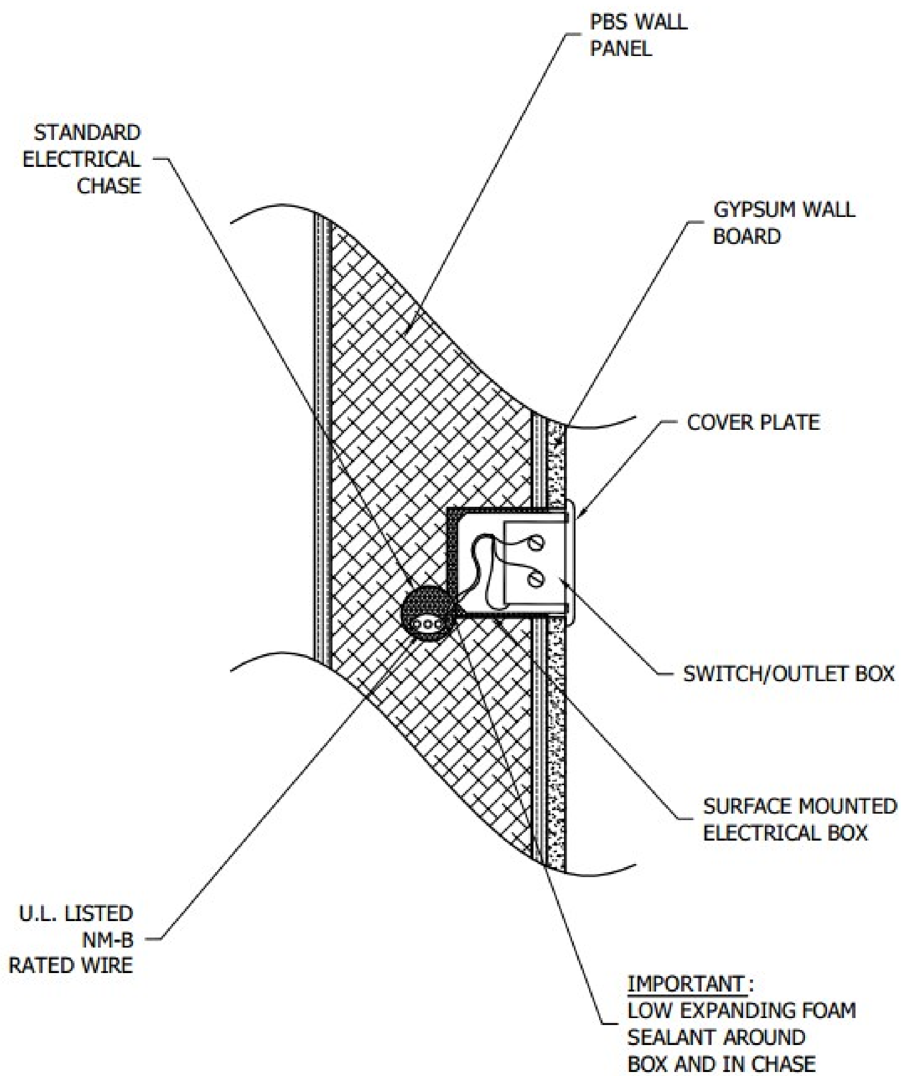
APPENDIX 1-F: PREMIER SIP CONSTRUCTION DRAWINGS



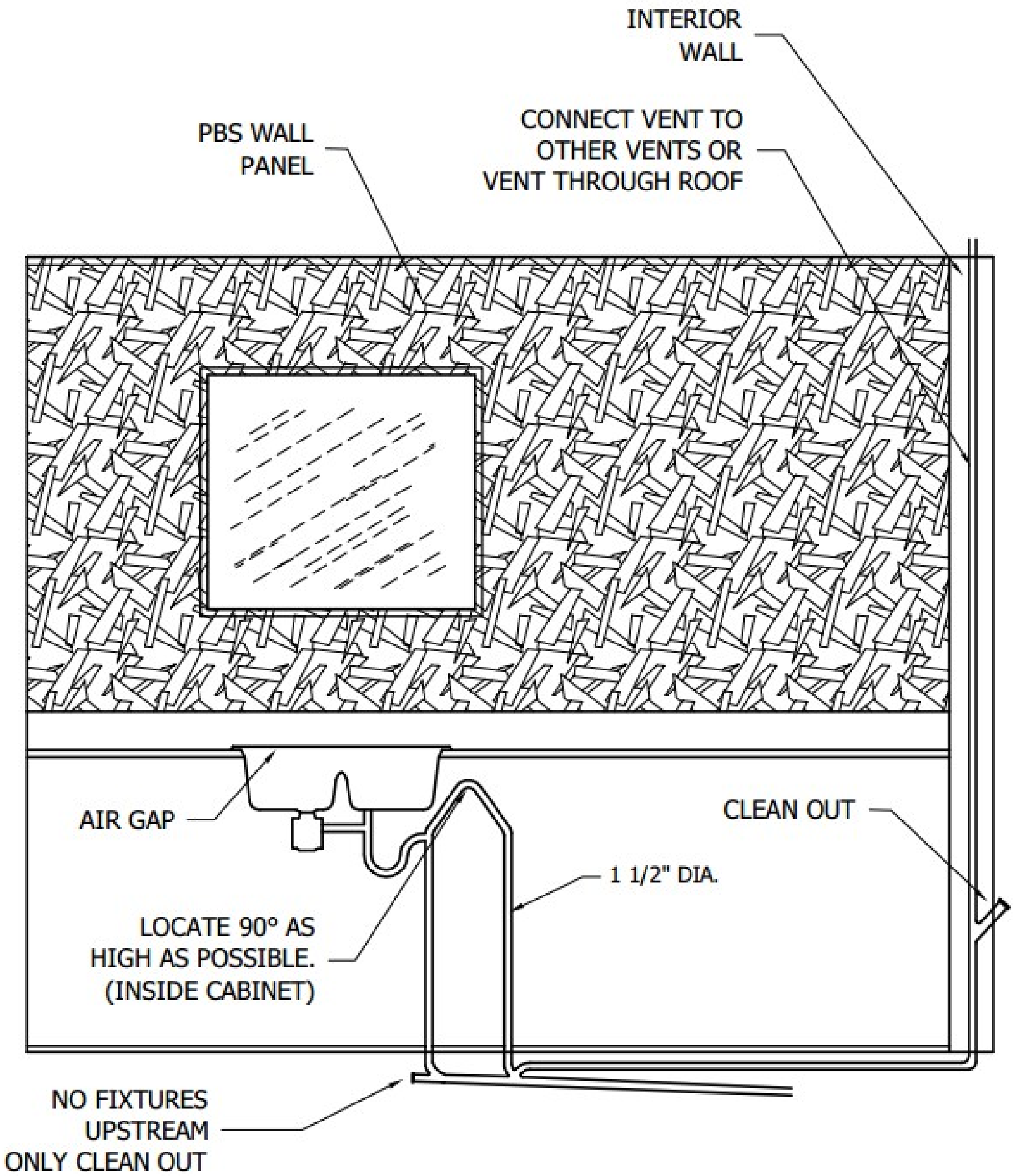
APPENDIX 1-G: PREMIER SIP CONSTRUCTION DRAWINGS



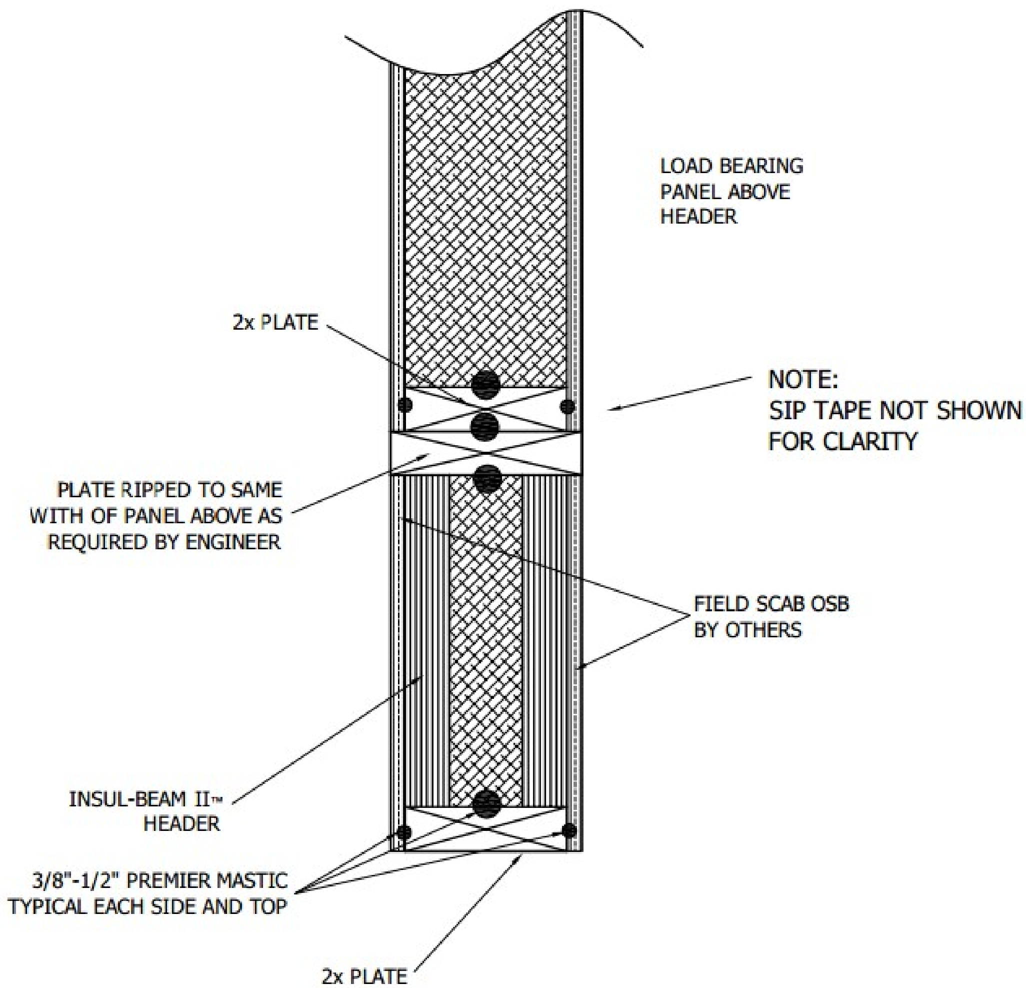
APPENDIX 1-H: PREMIER SIP CONSTRUCTION DRAWINGS



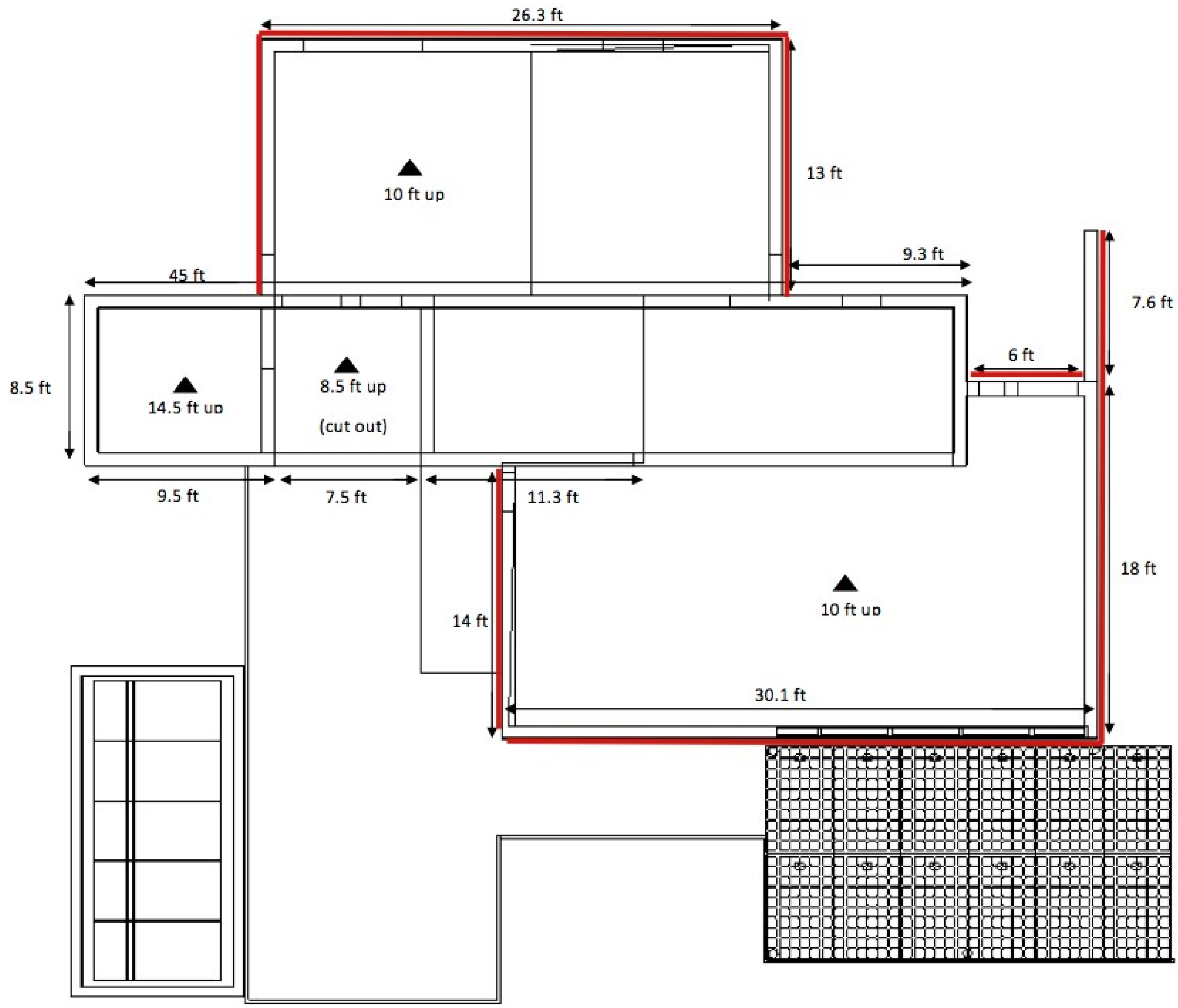
APPENDIX 1-I: PREMIER SIP CONSTRUCTION DRAWINGS



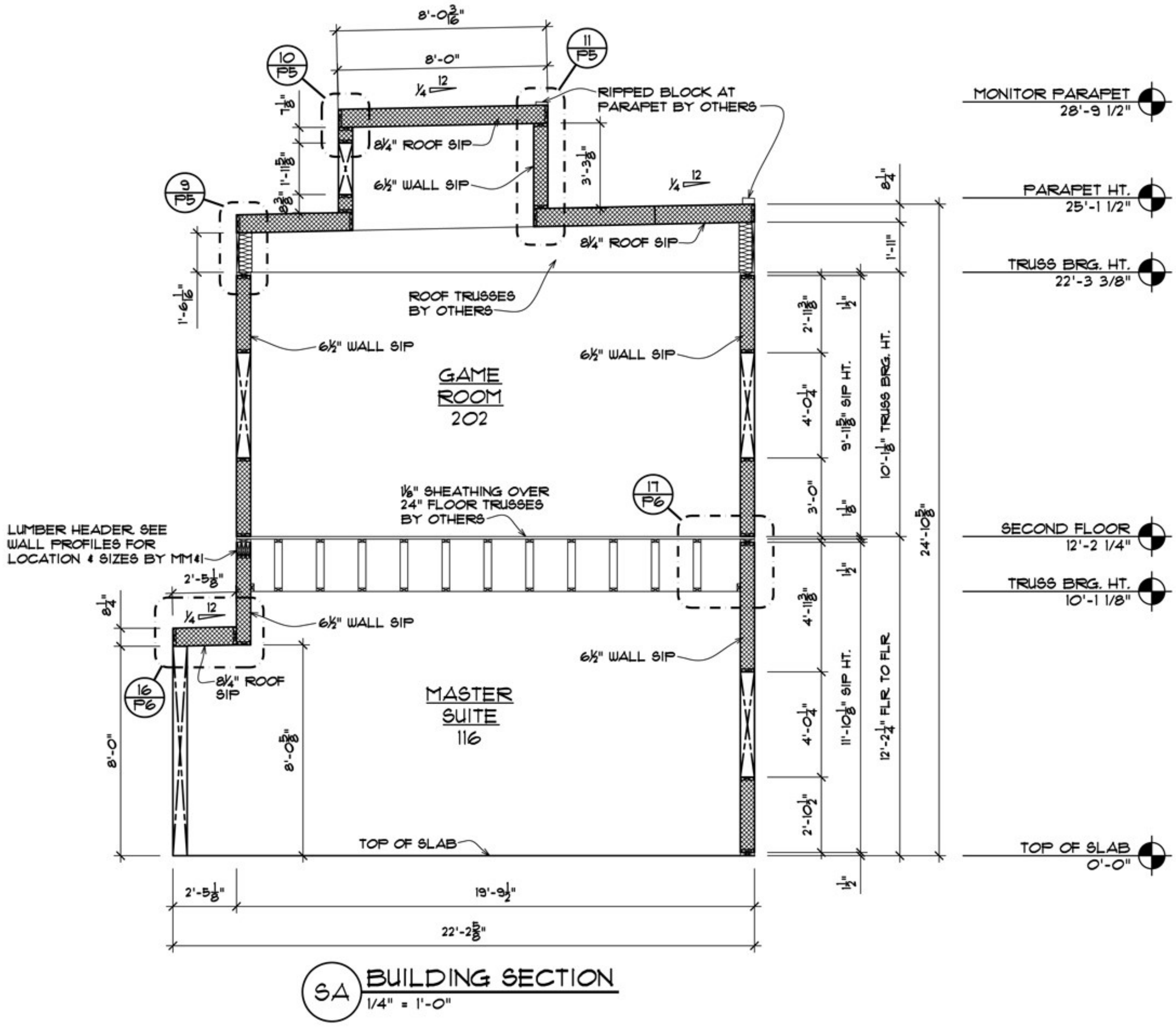
APPENDIX 1-J: PREMIER SIP CONSTRUCTION DRAWINGS



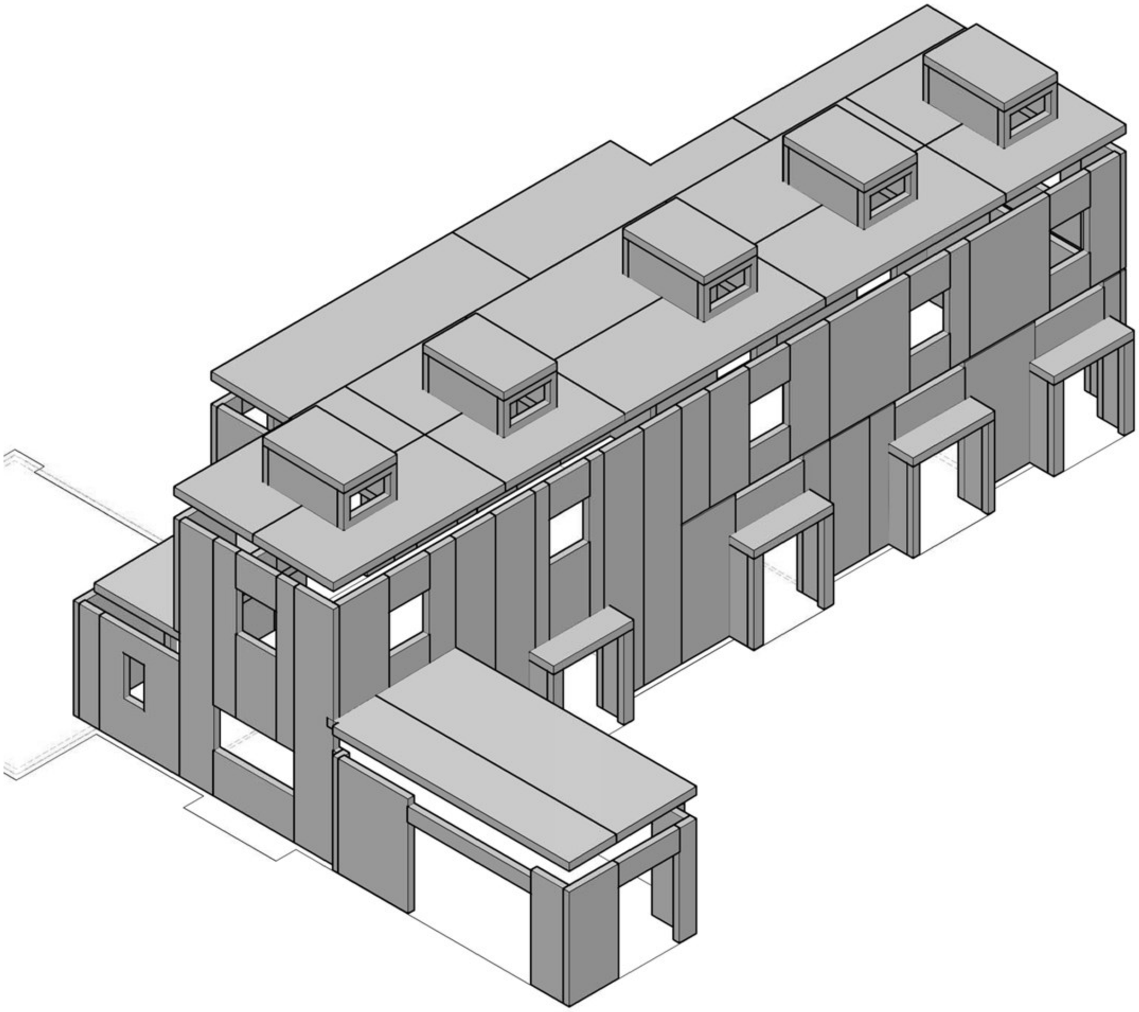
APPENDIX 2: SIP LOCATIONS (IN RED)



APPENDIX 3: CONSTRUCTION DIMENSION EXAMPLE



APPENDIX 4: CONSTRUCTION DRAWING EXAMPLE



APPENDIX 5: RAYCORE COST ESTIMATE

RAY-CORE INC
ENERGY SAVING ROOF WALL & HEADER SYSTEMS
www.raycore.com

Estimate

Date: 11/6/2014
Estimate #: 110614-22
Customer ID: GOO-0000
Expiration Date: 12/6/2014

Name: Wes Goodson
Phone:
Email: westogoods@gmail.com

Shipping:

Project Name: Goodson DIY Project
Sales Person: Jeremy Miller

Panel Quantity	Quantity In Square Feet	Product Description	Panel Type: Traditional / Staggered / Inset / Shiplap / Other:	Spacing: 16" o.c. / 24" o.c. / 12" staggered / Other:	Square Foot Price	Line Total
		Wall Panels				
46	1840	5.5"x4'x10' (R-42) (Precut 92 - 5/8")	Traditional	16" o.c.	$ 5.99	$ 11,021.60
	1840	**DIY Discount**			$ (0.81)	$ (1,490.40)
		Roof Panels				
38	1216	7.25"x4'x8' (R-52)	Traditional	24" o.c.	$ 6.85	$ 8,329.60
	1216	**DIY Discount**			$ (0.66)	$ (802.56)

Unit Quantity	Quantity In Linear Feet	Headers (combination of 8', 10', or 12' lengths)	Linear Foot Price	

Unit Quantity		Deposits/Miscellaneous	Per Unit Price	

Subtotal	$ 17,058.24
Sales Tax	
Total	$ 17,058.24

All panels come with the foil radiant vapor barrier (unless specified) adhered to both sides of the panel by a closed cell, Class-1 fire rated, polyurethane foam.

Quotation prepared by: KO

Shipping not included in total unless specified.

This is an estimate for items listed above. By accepting this estimate you accept and agree to be bound by these terms and conditions. In good faith, any retail price quoted on any estimate given by RAY-CORE, INC. will be valid for up to thirty (30) days from the estimate date, except for market conditions beyond RAY-CORE's control. Special sale discounts to be limited to the thirty (30) day term of this estimate. Prices do not include shipping and handling unless otherwise noted, and shipping quoted is only an estimate with final shipping cost to be established within seven (7) days of shipping. Sales tax will be added to all orders placed or picked up within the state of Idaho. Some states require their residents to file a tax return at the end of each year for all untaxed purchases and to pay the appropriate sales tax on those purchases, if any. RAY-CORE is not responsible for the collection of sales tax outside the state of Idaho and this becomes the responsibility of the consumer. RAY-CORE may have assisted you in the pricing process by providing an estimate of materials, but is not responsible and/or liable for the accuracy of quantities in this estimate. The owner/contractor is solely and exclusively responsible for determining your needs and the material quantities ordered. To ensure customer satisfaction, we encourage you to carefully review the quantity of product estimated above and confirm to meet your needs and specifications. RAY-CORE, INC. will not be held responsible for excess or shortage of materials. RAY-CORE panels are custom manufactured to the specifications of your specific order. Upon receipt of deposit to initiate production, this order shall be considered a contract to purchase and a sale. All sales are considered final.
Payment terms unless otherwise specified in writing are as follows:

50% Deposit of Estimated Price to Initiate Order
Balance Due Upon Order Completion and Prior to Delivery (Please allow at minimum 3-5 days to process shipping)

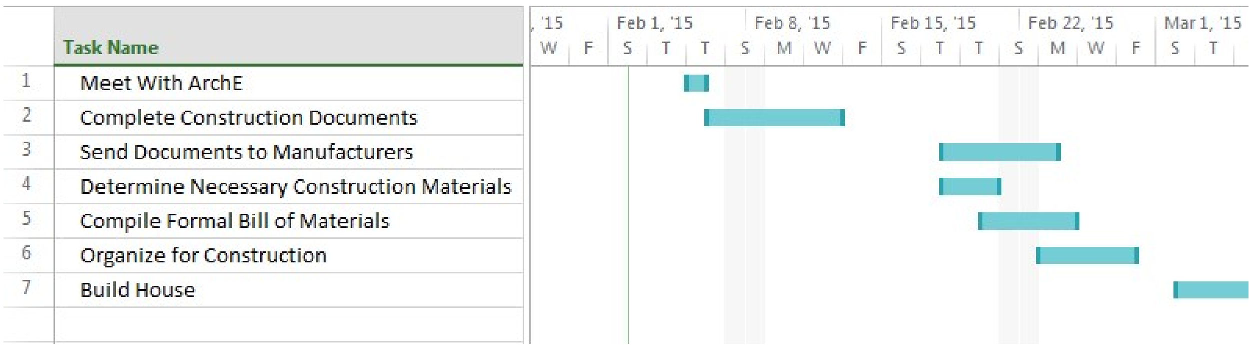
To place order, sign and date below and return to RAY-CORE, INC. with required 50% deposit.

Please indicate the approximate date you would like to receive your order:

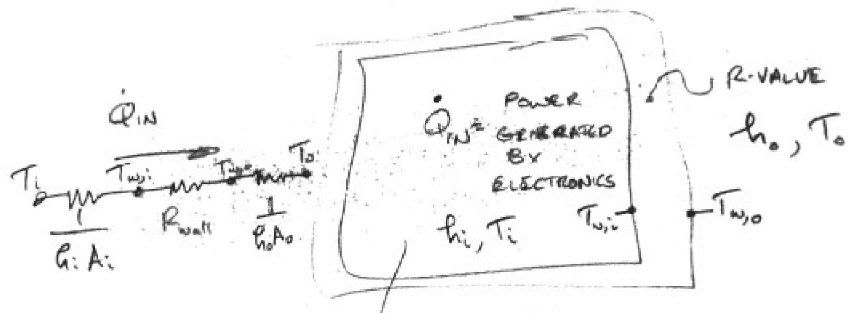
Thank you for your business!

305 East Elva Street : Idaho Falls, ID : 83401 : 208.552.4880 : sales@raycore.com

APPENDIX 6: GANTT CHART



APPENDIX 7: HEAT TRANSFER REFERENCE



$$\dot{Q}_{IN} = \frac{(T_i - T_o)}{\Sigma R_t}$$

$$\Sigma R_t = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o \cdot A_o}$$

$h_i \cong 5\ W/m^2 \cdot K$

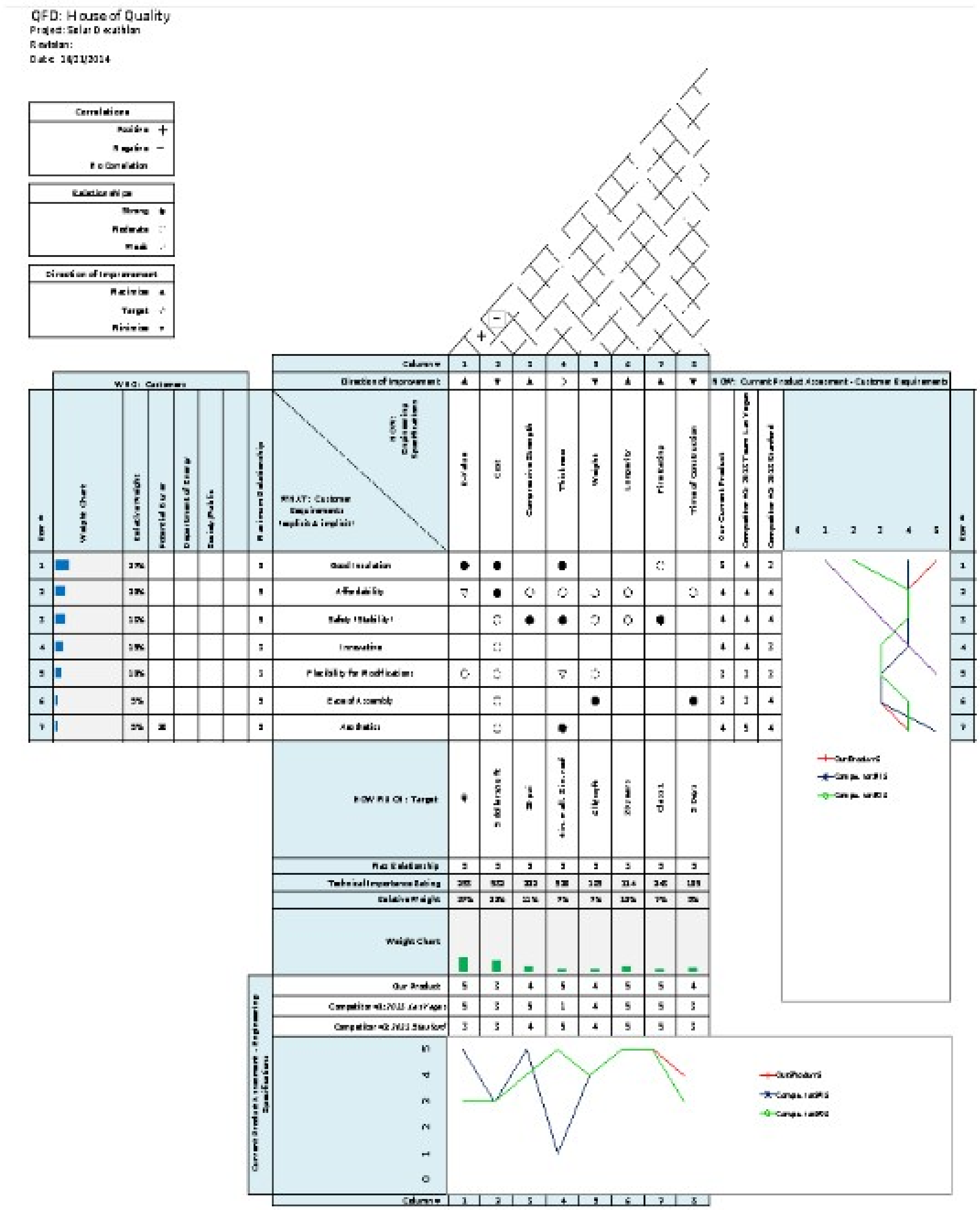
$h_o \cong 5\ W/m^2\ K$

$$\dot{Q}_{IN} = h_i A_i (T_i - T_{w,i})$$

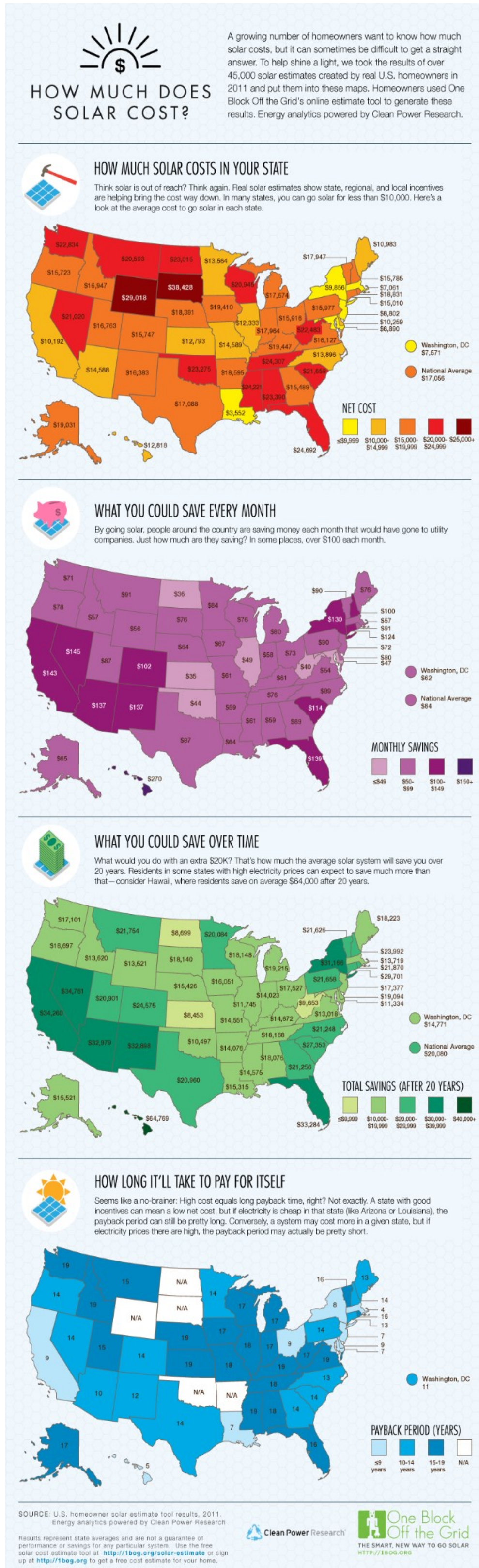
$$\dot{Q}_{OUT} = h_o A_o (T_{w,o} - T_o)$$

$$Nu_i = \frac{h_i L}{k_f} = f(Gr, Pr)$$

APPENDIX 8: QFD HOUSE OF QUALITY



APPENDIX 9: COST OF SOLAR



APPENDIX 10: FEA MODEL IMAGES

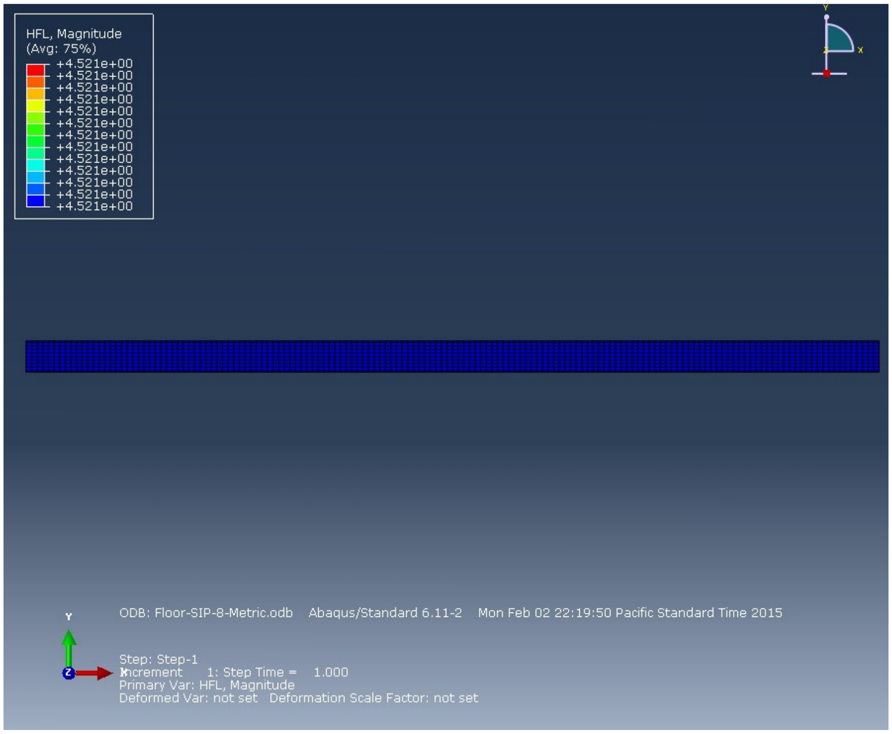


Figure 6: FEA Heat transfer model of an 8 in. EPS SIP without splines.

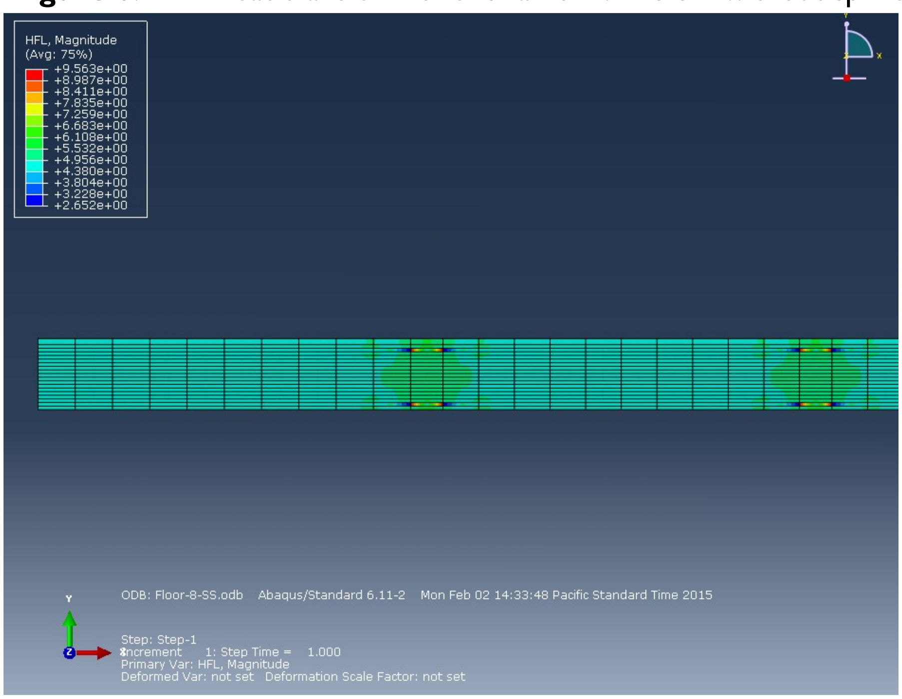


Figure 7: FEA Heat transfer model of an 8 in. EPS SIP with surface splines.

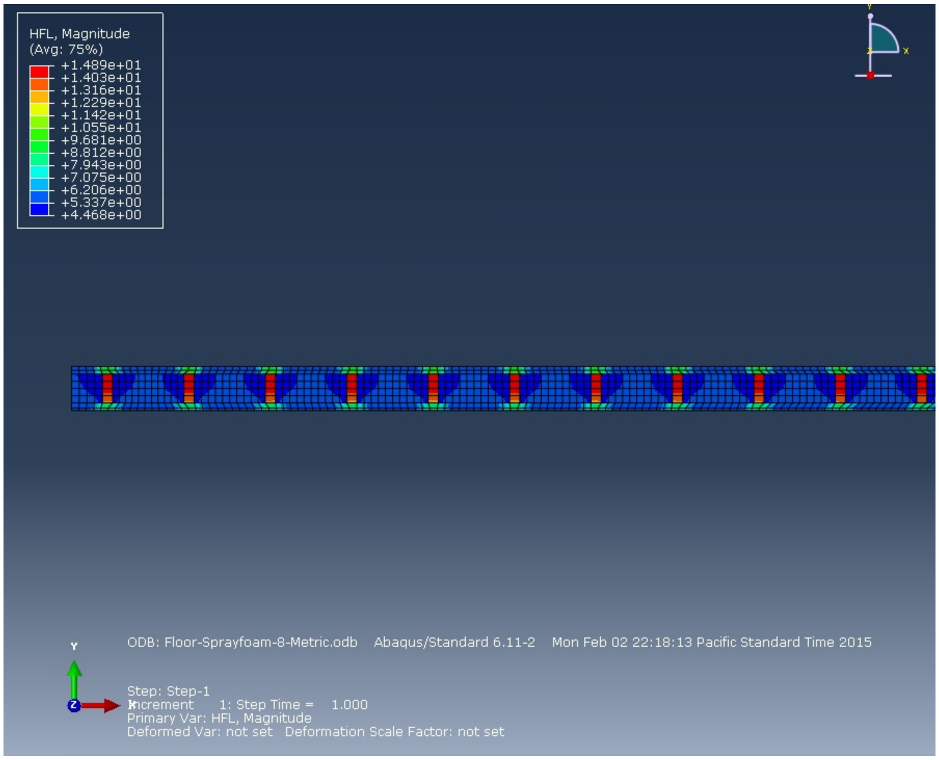


Figure 8: FEA Heat transfer model of the 8 in. stick frame flooring with spray foam insulation.

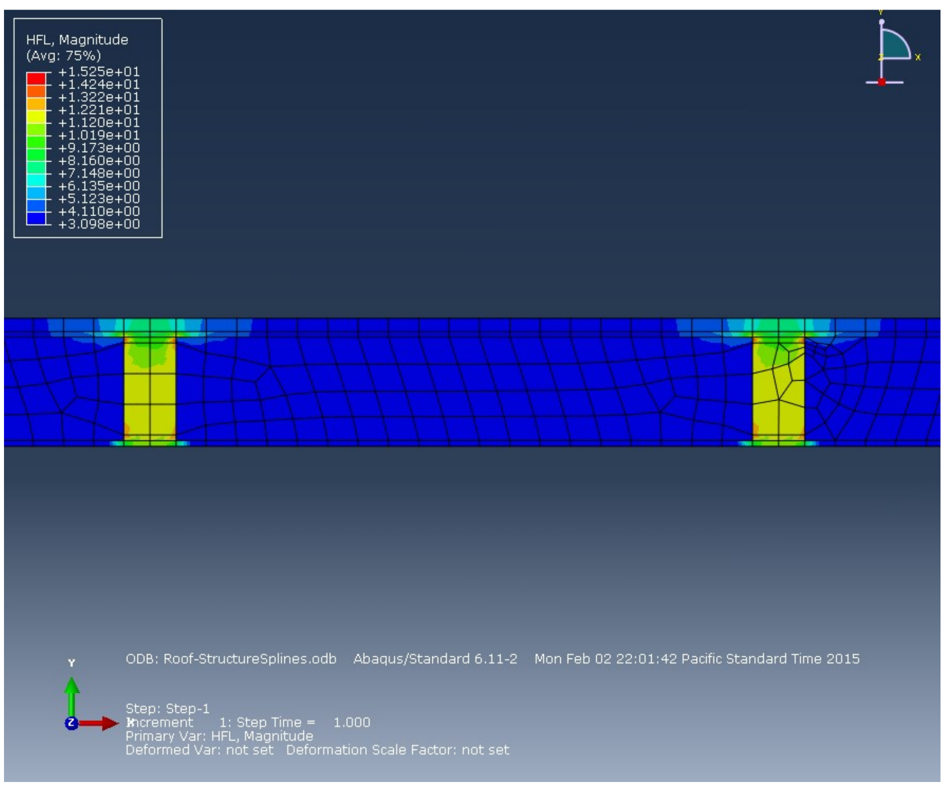


Figure 9: FEA Heat transfer model of the 8 in. EPS SIP with surface splines and a 1 in. layer of spray foam polyurethane on top.

APPENDIX 11: REFERENCES

Aldrich, Robb A., Lois Arena, and William Zoeller. "Practical Residential Wall Systems: R-30 and Beyond." Web. 14 Nov. 2014. http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST2_017_EE6-5.pdf

"Building Science: For Asheville Builders and New Home Buyers." Springtime Homes. Web. 14 Nov. 2014. <http://www.springtimehomes.com/green_building_science>.

"Fire Resistive Assemblies." *Premier SIPs*. Premier SIPs, 14 June 2011. Web. 23 Jan. 2015. <http://premiersips.com/wp-content/uploads/2014/04/Tech-Bull-07b-fire-resistiveassemblies.pdf>.

Fisette, Paul. "Choosing Between Oriented Strandboard and Plywood." Building and Construction Technology. University of Massachusetts, Amherst, 1 Jan. 2005. Web. 14 Nov. 2014.

"How Much Does Solar Cost?" Clean Power Research. Web. 20 Oct. 2014.

"Insulpan SIPs." Insulpan Structural Insulated Panel Systems. Insulpan. Web. 14 Nov. 2014.

Interview. Corey Nigh, Allen Iverson, Chris Bloom, Pete Dunnigan, Will Walsh. 22 Jan. 2015. Web.

Kosny, Jan, Nitin Shukla, and Ali Fallahi. "Cost Analysis of Simple Phase Change MaterialEnhanced Building Envelopes in Southern U.S. Climates." Building

"Mechanical Ventilation of SIP Structures." *Premier SIPs*. Premier SIPs, 15 June 2011. Web. 22 Jan. 2015. <http://premiersips.com/wp-content/uploads/2014/04/Tech-Bull-09bmechanical-ventilation-of-sip-structures.pdf>.

"Premier SIPs & Off-Gasing." *Premier SIPs*. Premier SIPs, 15 June 2011. Web. 23 Jan. 2015. <http://premiersips.com/wp-content/uploads/2014/04/Tech-Bull-16c-premier-panels-offgasing.pdf>.

"Premier SIPs Load Charts." *Premier SIPs*. Premier SIPs. Web. 23 Jan. 2015. <http://premiersips.com/wp-content/uploads/2014/04/Premier-SIPS-Load-Charts-.pdf>.

"R-Values." Thermocore Structural Insulated Panel Systems. Thermocore. Web. 14 Nov. 2014.

"Recessed Lights in Premier SIPs." *Premier SIPs*. Premier SIPs, 2 June 2014. Web. 23 Jan. 2015. <http://premiersips.com/wp-content/uploads/2014/04/Tech-Bull-17d-recessed-lights-inpremier-panels.pdf>.

Simon, Keith, and Michelle Weinfield. "Structural Insulated Panels (SIP)." Whole Building Design Guide. Ed. Thomas Moore, Kent Robinson, Chip Weincek, and Richard Keleher. National Institute of Building Sciences, 5 Aug. 2013. Web. 14 Nov. 2014.

“Structural Insulated Panels” Whole Building Design Guide. National Institute of Building Sciences. Web. 5 Aug. 2013.

Technologies Program (2013). U.S. Department of Energy. Web. 19 Oct. 2014. <http://www.nrel.gov/docs/fy13osti/55553.pdf>.

"Tell Us about Your next SIP Project." Structural Insulated Panels. SIPA, 1 Oct. 2014. Web. 19 Oct. 2014. <www.sips.org>.

"U.S. Department of Energy Solar Decathlon 2013: Stanford University." As Built Construction Documentation: Project Manual. Stanford University, 22 Aug. 2013. Web. 14 Nov. 2014. <http://www.solardecathlon.gov/past/2013/pdfs/su_manual.pdf>.

“U.S. Electricity Generation by Energy Source” U.S. Energy Information Administration. Web. 13 Jun. 2014.

"Where Is Coal Found?" Fossil Fuel Reserves. World Coal Organization. Web. 20 Oct. 2014.