# Senior Project Report

# Solar Decathlon 2015

## Solar Cal Poly

**California Polytechnic State University San Luis Obispo**

Solar Cal Poly Project Engineers

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# Introduction

The US Department of Energy Solar Decathlon 2015 is an international competition between college teams who design, build, and test energy efficient homes powered only by the sun. The competition was first held in 2002 and has increased in complexity and popularity over the years. Multi-disciplinary teams from around the world partake in the event, drawing together students from many majors such as Architecture, Engineering, Business, Graphics and Communications and Computer Science. All teams must work cohesively in order to achieve the project goals. The winning team is the one that best blends affordability, consumer appeal, and design excellence in their house with optimal energy production and maximum efficiency while remaining a net zero environment in the home throughout the competition.

## Goals

The U.S. Department of Energy Solar Decathlon 2015 consists of 10 contests [1] that test the effectiveness of all aspects of the design for the competition. These contests are designed to test how well the houses perform and how livable and affordable they are. Each contest is worth a maximum of 100 points, for a competition total of 1,000 points.

Contests have quantitative and qualitative points. Our role as the three Project Engineers is to concentrate on the engineering parts of the competition. The Solar Decathlon houses should represent the best of modern sophisticated engineering. For the Engineering contest, a jury of professional engineers who are experts in their field will evaluate each house for the following [1]:

- Innovation - New technologies in the home that may be much more affordable than the current market products. New ways to tackle engineering design challenges.
- Functionality - The effectiveness of the house performance such as temperature, humidity and airflow control as well as how well the HVAC systems are designed to reduce energy usage.
- Efficiency - How much energy the design saves over a year as compared to typical systems keeping in mind the performance of all mechanical systems.
- Reliability - Designing systems that addresses the needs of the customer as well as reduces maintenance and energy loss without compromising the efficacy.
- Documentation - Drawings, construction specifications, energy analysis results and discussion, and audiovisual presentation that accurately reflect the constructed project.

The quantitative part of the engineering contest requires the Solar House to perform the following tasks [1]:

- Refrigerator: Refrigerator must stay between 34-40°F.
- Freezer: Temperature must be in range of -20°F–5°F.
- Clothes Washer: Must be able to successfully wash eight loads of laundry
- Clothes Dryer: Must be able to return the eight loads of laundry to their original weight
- Dishwasher: Must successfully wash five loads of dishes (one load = eight place settings)
- Cooking: Must successfully perform eight cooking tasks (one task = vaporize 5 lbs. of water in <2 hours)

## Engineering Project Definition, Justification, and Motivation

Goals and constraints are placed on the engineering team by the three principle stakeholders. These include the Department of Energy (DOE), society, and the California Polytechnic State University, San Luis Obispo. Each of these entities has its own requirements that overlap and diverge in some aspects. Catering to these stakeholders forms the basis for defining our project.

The DOE is the host of the competition and sets the most fundamental parameters. Without meeting their goals we would not be able to partake in the event. Therefore the mechanical engineering team was primarily tasked with ensuring that the engineering contest criteria of the DOE were met. The specified quantitative tasks from the contest rules constitute the target objectives of our project while the juried categories dictate the main methods by which we approach them.

The test conditions of the DOE are meant to simulate the realities of an actual home in use. Their building codes for example are largely derived from the international building code and the juried categories seek to emulate the demands of an actual client. In this way the DOE is largely a simplified representation of our second stakeholder in this project, society.

When we design for society we are not given clear and definitive objectives. Rather our engineering goals and constraints must be inferred from analysis as is done in the background section of this report. As an overarching goal, we are seeking to help tackle the societal problem of wasteful practices by promoting efficiency. Largely this means that our designs are geared towards improving quality of life in an energy efficient, sustainable and cost effective way.
Solutions must be practical, economic, efficient, manufacturable, environmentally friendly and comfortable if they are to be built, purchased, and used by individuals. The fact that a person or family may be actually paying for and living in the house after the competition, raises the bar for all the students involved. It is essential for the engineers to ensure that everything works and is up to U.S. housing and customer standards for safety reasons.

Many of the potential design concepts are reined in by the third stake holder, California Polytechnic State University, San Luis Obispo (Cal Poly). The school imposes constraints on the project because of limitations on resources. While the decathlon home itself is entirely designed and built on campus, all the individual parts may not necessarily be. Machining tools, supplies and budget made available to us by Cal Poly are all limiting factors when it comes to what can and cannot be feasibly done. At the same time however Cal Poly does have expectations for its students to represent the school. This project is the embodiment of the school's saying of "learn by doing" and we are expected to put forth our best effort to reflect that spirit. High marks in the competition are a therefore a large motivating factor for both the school and the participants.

As lead project engineers we are subject to these constraints and must make sure that all other teams we manage are also in compliance with the criteria. Additionally it is our role to coordinate with other disciplines to ensure that our designs do not infringe on their ability to meet their own goals. Aside from the management portion of our project, we are also specifically tasked with the development of the home's appliances, passive thermal systems, and mechanical room design. The specific goals for each of these and their relationship to the stakeholders are outlined in greater detail in the objective section of this report.

# Background

## The Big Picture

The engineering constraints of this project are largely dictated by the primary stakeholders mentioned in the previous section. While the competition is hosted by the DOE, whose rules and objectives are clear, the more nebulous requirements of the societal stakeholder are quite obfuscated. It is therefore very important to better understand what it means to be building a net-zero house which benefits society.

Such research is crucial for putting things in context. Having a firm grasp of what an effective project means in a larger sense is key to the managing duties of lead project engineers. A more holistic view of net-zero home design is also very important for working as informed members of a larger interdisciplinary team. The information more relevant to our role as design engineers can be found in the section of the background research entitled the "Engineering Details."

### The Importance of Net-Zero Buildings

The 2015 Solar Decathlon project is part of a continuing drive to refine and improve upon the practice of constructing net-zero homes. A net-zero home is one where the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy produced on the site. If energy production exceeds consumption then it may be referred to as an "energy-plus" building. In order to claim the title of a net-zero home, the building must drive down energy consumption, generally through efficiency, while increasing energy production.

The concept of a net-zero building is extremely important from both an individual and a societal level. On the grand scheme, the world's population is increasing dramatically and with it the demand for energy. Given the finite resources of our planet, sustainable growth can only be achieved by carefully balancing production and consumption. Ideally the human footprint on earth should also strive to be net-zero. On an individual level, the net-zero construction of a home can positively affect its cost and performance.

Both residential and commercial development represents a significant portion of our energy balance. Homes, offices, stores, restaurants, schools, and all sorts of other buildings consume a lot of energy and money. According to the U.S. Department of Energy, homes and commercial buildings account for more than 70% of all electricity used in the United States [2]. This amounts to about 40% of the nation's energy bill, costing in excess of $400 billion each year. On average the D.O.E. estimates that 20% or more of this energy and money is wasted. By reducing this inefficiency in the system, around $80 billion could be saved annually on energy bills [3].

Energy use also comes with an associated environmental cost. Energy production associated with U.S. buildings accounts for nearly 40% of the nation's man made carbon dioxide emissions, 18% of the nitrogen oxide emissions, and 55% of the sulfur dioxide emissions [2]. These greenhouse gases are known contributors to smog, acid rain, haze, and global climate change.
Such environmental effects have adverse consequences on human health and result in more induced costs. If left unchecked, global climate change can result in irreversible changes whose adverse effects will be felt worldwide. Building efficiency therefore is a large part of pollution mitigation. In the U.S. alone, improvements will help the nation achieve its goal of reducing greenhouse gas emission by 17% in the year 2020.

Improving this energy balance not only saves the environment and reduces operating costs for the country but also creates jobs. More than 116 million homes and nearly 80 billion square feet of commercial space in the U.S. were constructed prior to 1980; before the existence of today's efficient products and most equipment standards and building codes. These buildings represent large potential for energy savings. Improving this existing infrastructure and new buildings can lead to tremendous energy savings and result in significant job creation. Rethinking how we use energy will involve the implementation of new or improved technology, requiring investment in research and development. Manufacturers will be needed to supply the new technology and local installers will put everything in place. A plethora of new markets have already begun to develop around the concept of energy efficiency and are providing growth throughout the country.

Pursuing a net-zero approach will result in cost savings, job growth, pollution reduction, and improved business competitiveness which will help to ensure the long term sustainability of the world economy.

## Overview of Net-Zero Home Design

Net-Zero homes stand apart from typical homes because they take a more holistic view of the design process to increase efficiency. This involves an analysis of the costs and benefits of each solution. Cost considers not only the price of purchasing, installing, and maintaining the component but also includes many additional factors such as its carbon footprint and environmental impact. The consideration of benefits is also placed under higher scrutiny. When it comes to energy balance for instance it is typically more beneficial to provide solutions which reduce use rather than increasing production. This is due to the relatively low cost of improving a system’s efficiency as opposed to introducing a new system to compensate for the losses.

The mantra of “reduce before you produce” is a succinct rule of thumb. This approach means that net-zero homes will typically seek to eliminate energy demand through design choices first. Reducing use can be achieved in the broad categories of active and passive systems. Active systems require some sort of control system which draws energy while passive systems achieve their desired effect without using any control system. A common example for temperature control would have an active system involving an air conditioning unit with a condenser, pump, and heat exchanger while a passive system might rely on thermal mass to naturally absorb heat during a hot day and release it again at night.

Improving efficiency for every component of a home may sound like a good idea on paper but this is not always the best approach. Such a design could be too costly or might be outright impossible to implement. It is therefore important to understand the return on your investment when it comes to throwing resources behind energy savings. The National Renewable Energy Laboratory (NREL) provides research which shows that a typical residential site uses most of its energy on space heating, water heating, and space cooling [4]. These three alone account for 72% of the total energy use. While the values are sure to be different for varying home locations and sizes, their relative importance still stands.

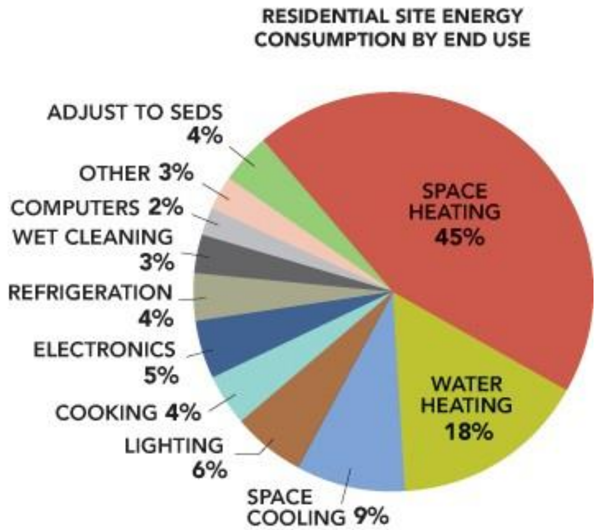



Figure 1. Residential Site Energy Consumption by End Use [5]

Implementing passive designs which target these high energy needs is very important for the future. Additionally active systems can be further improved by monitoring the home's energy use. Knowing when to turn these power drawing devices on and off can save a lot of energy in the long run. These controls can also involve input from the user which can help them create the home environment that suits their needs. Operability of devices allows the user to tailor performance to their own particular preferences.

The location of the home is also another determining factor in the development of passive systems. The site will have particular temperature or wind conditions which must be protected against or used to the benefit of the home's inhabitants. Precipitation can be highly relevant to rain water collection plans while solar irradiation can be used to heat water for domestic use. Additionally, the house's very architecture can inform the passive design of certain systems. An awning can prevent excessive irradiation from glazing while an angled wall might help channel wind currents to cross ventilate the house. Understanding the way a home inhabits and interacts with its environment is fundamental to sound design.

## Understanding Specifics of Net-Zero Home Design

The design of a net-zero home seeks to solve many more problems than a typical home so, as a result, has many more potential solutions. The Solar Decathlon is a large interdisciplinary project whose final design will be the accumulation of input from the entire team. There is however a large body of information to draw on when coming up with potential solutions.

A starting point for inspiration included lessons learned from Cal Poly's 2005 Solar Decathlon entry and a general review of past submissions over the last couple years. Additional insight was drawn from sources currently involved with the development and deployment of net-zero homes. This ranged from literature provided by green home development firms to blogs talking about easy adjustments that can be made to any house. More solutions were recommended by research groups such as the NREL and the New Building Institute. A wide range of rules of thumb were provided in presentations delivered by speakers working in different fields such as HVAC and architecture.

Technical specialists also shared their knowledge to help optimize the performance of specific systems. Consulting with them helped determine the pros and cons of one technology compared to another. Individuals with intimate knowledge of their field were also be able to offer tips on best practices for design and installation which were not made obvious in textbooks or manuals.

## Barriers to Net-Zero Home Design

Even if a design were to win the D.O.E. contest, it would not necessarily meet our objectives for providing practical solutions to be used in the industry today. This is because the contest does not, nor can it, fully recreate the real world constraints of the market. Some of the facets to consider include how easily solutions can be used in new or retrofitted buildings. A technical report by R. Anderson and D. Roberts for NREL points out builders tend to avoid risky technologies that do not have a high likelihood of delivering proven benefits [6].

In particular homeowners, homebuilders, and contractors tend to avoid technologies that:

- Increase risks
- Increase overall costs
- Have the potential to cause customer complaints
- Require additional training or oversight of subcontractors
- Require use of new and unfamiliar suppliers, materials, or equipment
- Require additional planning steps or code approvals
- Have the potential to increase future home warranty and callback costs.

This means that there is an additional component of risk versus reward that must be considered. The NREL provides a useful comparison chart for various net zero home solutions. Similar analysis will need to be developed over the duration of the project as we move forward.

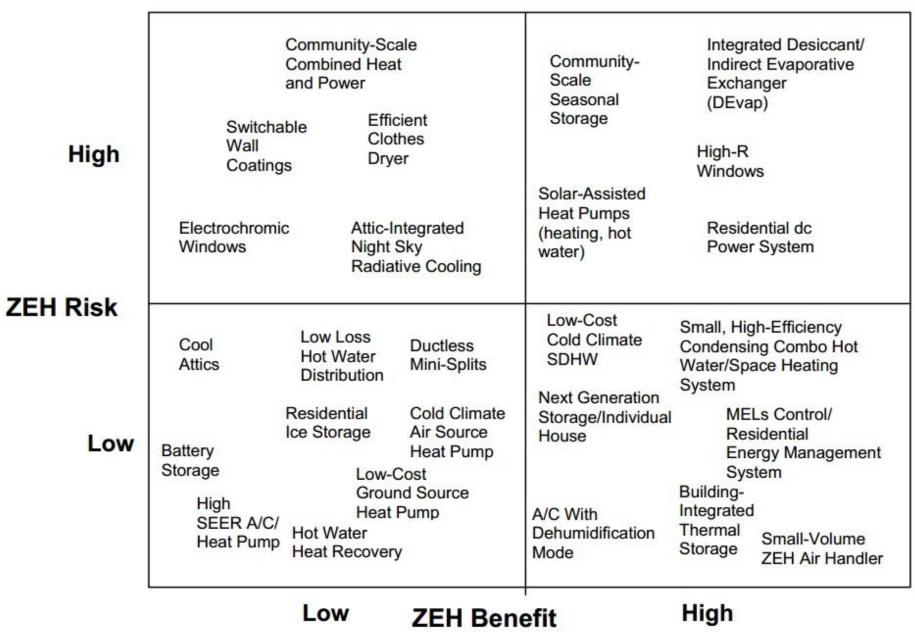



Figure 2.Overview of Option Risks and Benefits Relative to ZEH Technology Gaps [7].

## Current Incentives and Regulations Surrounding Net-Zero Buildings

Given the important benefits of efficient buildings, there are many incentives and regulations surrounding their construction. The groups which play a large role in establishing these policies in the United States include the federal government, state governments and U.S. territories, local governments, and larger electric and gas utilities.

The Database of State Incentives for Renewables and Efficiency (DSIRE) is one of the most comprehensive sources of information on incentives and policies in the United States.
Established in 1995, DSIRE is currently operated by the N.C. Solar Center at N.C. State University, with support from the Interstate Renewable Energy Council, Inc. and is funded by the U.S. Department of Energy [8].

DSIRE states that incentives and policies supporting energy efficiency are divided into two main groups:

- Financial Incentives include a variety of tax incentives, rebates, grants, loans, green building incentives, and certain other types.
- Rules, Regulations & Policies include public benefits funds, energy efficiency resource standards, appliance/equipment efficiency standards, building energy codes, energy standards for public buildings, and certain other types.

DSIRE provides a convenient glossary which includes descriptions of each specific incentive and policy type. Summary maps, tables, and a search tool also help users determine which policies might apply to a specific project. A search can be specified by state, incentive type, technology, implementing sector, and eligible sector. This knowledge is very important for saving money on a project. Driving down the cost of a net-zero home is a critical objective for all of the project stakeholders.

The implementation of efficient solutions is not restricted in use to the United States only. Because the benefits could be applied globally, the solutions should also be applied globally. There are many entities today which already have programs in place to address this issue internationally.

Some of the leading groups which are involved in global energy efficiency include [8]:

- Clean Energy Solutions Center - Policy Resources
- European Union PV Legal Database
- Geothermal Resources Council (GRC)
- Indian Renewable Energy and Energy Efficiency Policy Database
- International Energy Agency (IEA)
- International Renewable Energy Agency (IRENA)
- Renewable Energy & Energy Efficiency Partnership
- Solar Energy International (SEI)
- United Nations Development Programme - Environment and Energy
- United Nations Statistics Division - Energy Statistics
- World Bank - Energy Division

## The Engineering Details

### Engineering Team Leadership

Our team's role as the Project Engineers for the Solar Cal Poly house meant that we were the first engineers involved in the project. As a result, we were tasked with much of the initial ground work to get the Solar Decathlon design under way. This involved a great deal of precedent research which was passed on to other teams.

A large portion of this information was gathered from past Solar Decathlon homes [9]. The 2013 competition was heavily scrutinized in our research. All of the team submissions were examined with greater attention being paid to determining why particular teams scored higher or lower in certain categories.

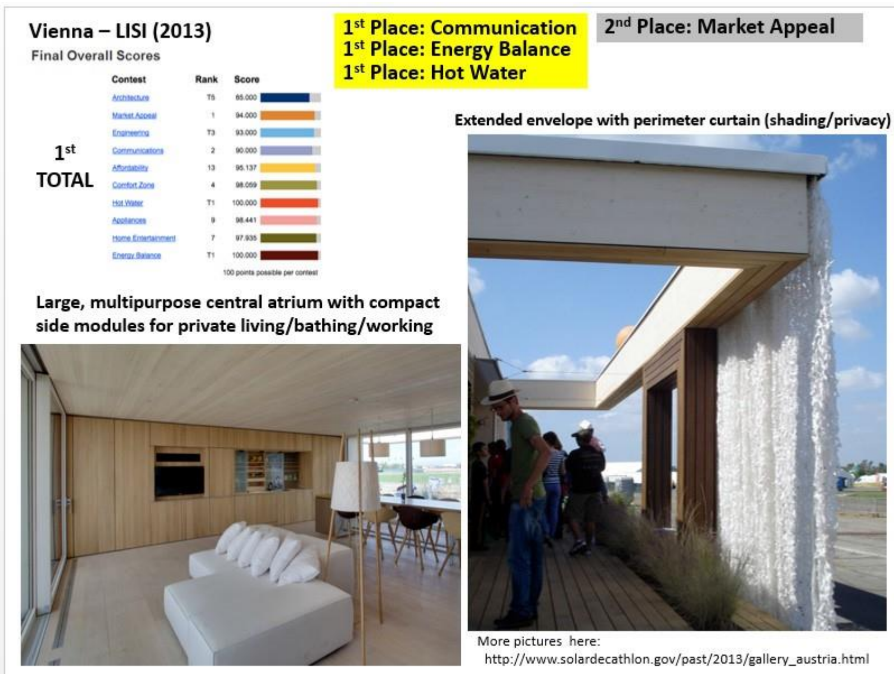



Figure 3. An example slide of the presentation given on precedent research from the 2013 competition [9]

The main takeaways from this research are that successful teams make use of:

- Centralized mechanical/electrical systems
- Bathroom and kitchen near mechanical room
- Reduce required plumbing and wiring
- Exterior envelope encasing the house (common but not a necessity)
- Increases shading, privacy, and aesthetic appeal
- Natural Lighting
- Effective wall windows, clerestory windows, skylights, solar tubes, reflected light
- Space Efficiency
- Multipurpose areas
- Open house up to the outside to increase available space
- Stow away furniture, appliances, and partitions
- Marketability

- Cheapest house which best delivers on customer needs
- Design is easy to transport (house parts fit on flatbed trucks)
- Design is easy to assemble (modularity of elements, relatively simplistic)
- Design is affordable (elements are commercially available)
- Materials are “green” (locally sourced or recycled, low environmental impact)
- Aesthetic appeal (fits customer’s environment, themed but modern interior)

Another guiding principle for the Solar Decathlon competition was the timeline. Though the contest typically spans two years, there are many intermediate deadlines which need to be met. On top of the official requirements coming from the DOE, there was also an ongoing internal set of deadlines set by the Cal Poly team. These largely ran parallel to the external DOE deadlines and were very important to meet or risk derailing the entire project. We needed to be able to understand this to ensure that our engineering tasks and those we delegated were met in a timely manner.

**U.S. Department of Energy Solar Decathlon 2015 Deliverable Status Sheet**

*The latest version of this status sheet will always be available via the Yahoo Group.*

| Due Date | Deliverable Name | | 14-Day Resubmission | Penalty Points for Figure 1 in Rules* | Confidential* | SD Rules Reference | Format (For additional details, see Appendix F in the SD Rules) | Method of Delivery to NREL | Cal Poly | Clemson | Crowder/Drury | Florida/Singapore | Mass/Central America | Missouri S&T | NY City Tech | Sacramento State | Stanford | Stevens | Team NY Alfred | Team Orange County | Team Tennessee | Texas/Germany | U at Buffalo | UC Davis | West Virginia/Rome | Yale | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thursday, March 13, 2014 | **Team Excitement Video** | | N | n/a | | n/a | MOV/WMV | Dropbox | | | | | | | | | | | | | | | | | | | |
| Thursday, April 24, 2014 | Schematic Design Summary | | N | n/a | X | Appendix D-1 | PDF | Dropbox | | | | | | | | | | | | | | | | | | 1 | |
| | Target Construction Cost (preliminary) | | N | | X | Contest 5 | Cost in USD | E-mail | | | | | | | | 1 | | | | | | | | | | | |
| May 27-28, 2014 | Schematic Design Webinar | | | n/a | | | Participation | | | | | | | | | | | | | | | | | | | | |
| Thursday, August 28, 2014 | Preliminary Website | | N | 1 | | Appendix D-8 | URL | E-mail | | | | | | | | | | | | | | | | | | | • Must meet minimum requirements as defined in the Rules |
| Thursday, October 09, 2014 | Design Development Phase | BIM | Y | 2 | X | Appendix D-3, D-4, D-5 | RVT (Revit)*** | Dropbox | | | | | | | | | | | | | | | | | | | • Minimum 80% complete design documentation |
| | | Drawings | | | X | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | • Must demonstrate code compliance |
| | | Project Manual | | | X | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | • Corrections and resubmittal due 14 days after receipt of reviewer comments |
| | Health and Safety Plan (preliminary) | | N | 1 | X | Appendix E | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| | Target Construction Cost (revised) | | N | 1 | X | Contest 5 | Cost in USD | E-mail | | | | | | | | | | | | | | | | | | | |
| Thursday, December 18, 2014 | Computer-Animated Walkthrough | | Y | 1 | | Appendix D-2 | MOV (Quicktime) | Dropbox | | | | | | | | | | | | | | | | | | | • Corrections and resubmittal due 14 days after receipt of reviewer comments |
| | Computer-Generated Renderings | | Y | 1 | | Appendix D-2 | ZIP (Image Files) | Dropbox | | | | | | | | | | | | | | | | | | | • Corrections and resubmittal due 14 days after receipt of reviewer comments |
| January 9-10, 2015 | Design Development Meeting | | | n/a | | | Participation | | | | | | | | | | | | | | | | | | | | |
| Thursday, February 12, 2015 | Construction Documentation Phase | BIM | Y | 3 | | Appendix D-3, D-4, D-5 | RVT (Revit)*** | Dropbox | | | | | | | | | | | | | | | | | | | • Minimum 95% complete design documentation |
| | | Drawings | | | | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | • Must demonstrate code compliance and reflect final design |
| | | Project Manual | | | | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | • Corrections and resubmittal due 14 days after receipt of reviewer comments |
| | Health and Safety Plan (95% complete) | | Y | 1 | | Appendix E | PDF | Dropbox | | | | | | | | | | | | | | | | | | | • Includes Project Manager's, Construction Manager's and Health and Safety Officer's proof of recent OSHA 30-hour construction safety training<br>• Corrections and resubmittal due 14 days after receipt of reviewer comments |
| | Target Construction Cost (final) | | N | n/a | X | Contest 5 | Cost in USD | E-mail | | | | | | | | | | | | | | | | | | | |
| | Stamped Structural Drawings | | N | | X | Rule 6-1 | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| | Stamped Structural Calculations | | N | | X | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| Thursday, April 23, 2015 | Project Summary | | Y | 2 | | Appendix D-9 | ZIP | Dropbox | | | | | | | | | | | | | | | | | | | • Corrections and resubmittal due 14 days after receipt of reviewer comments |
| Thursday, June 25, 2015 | Public Exhibit Materials | | Y | 2 | X | Appendix D-10 | PDF | Dropbox | | | | | | | | | | | | | | | | | | | • Corrections and resubmittal due 14 days after receipt of reviewer comments |
| Thursday, June 25, 2015 | Final Safety Plan | | N | n/a | | Appendix E | PDF | E-mail | | | | | | | | | | | | | | | | | | | • Approved Final Safety Plan is required for competition participation |
| Six weeks prior to start of assembly** | As-Built Phase | BIM | N | 3 | | Appendix D-3, D-4, D-5 | RVT (Revit)*** | Dropbox | | | | | | | | | | | | | | | | | | | • Late submissions received after the time period indicated in the Rule 3-7 will not be provided to the juries for review. |
| | | Drawings | | | | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| | | Project Manual | | | | | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| | Audiovisual Presentation | | | 2 | | Appendix D-7 | MOV (Quicktime) | Dropbox | | | | | | | | | | | | | | | | | | | |
| | Jury Narratives | | | | X | Appendix D-6 | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| | Final Public Exhibit Materials | | | 1 | X | Appendix D-10 | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |
| | Final website | | | 1 | | Appendix D-8 | URL | E-mail | | | | | | | | | | | | | | | | | | | |
| Four weeks after end of disassembly** | Final Report | | | n/a | | Appendix D-11 | PDF | Dropbox | | | | | | | | | | | | | | | | | | | |

Figure 4. The official list of deliverables and their due dates as specified by the Department of Energy [10].

From the deadlines listed above, we helped the management team put together a reasonable timeline for the engineering side of the project. This was constantly updated to reflect the evolving scheme of the house and the progress of other teams. Tasks were then either performed by our team or delegated to the other engineering teams. For this project, we were specifically in charge of appliances, passive thermal system design, and the mechanical room layout.

## Appliances

The Appliances contest in the Solar Decathlon relies heavily on the performance of the appliances in the home. Therefore, to achieve top scores in this contest, the appliances chosen must be able to perform the tasks set before them. Each appliance must be carefully considered and reviewed to confirm that they will be able to pass the DOE requirements. Although the Appliances contest may be the main contest in which the appliances must be able to do well in, the appliances chosen must also be considered carefully for energy use. Another contest in the competition measures the energy use of the home, the Energy Balance contest. In the Energy Balance contest, the home must not use over 175 kWh per the nine days of competition, Day 11 to Day 19, in order to receive the full amount of points. Therefore, the appliances chosen must also take into consideration the energy usage because of its scarcity.

## Appliances and Energy Efficiency

Appliances in 2014 and 2015 have made great leaps and bounds in the efficiency category. Although the appliance may have the same functions, much care has gone into the energy use (and water use, if applicable) of the appliance. In order to meet the requirements for the engineering contest, certain appliances were required to be purchased off the shelf. We wanted to look for appliances on the shelf that were energy efficient thus, the team decided to find appliances that had an Energy Star rating since it provided a trusted U.S standard for appliance energy efficiency. Not all appliances are Energy Star tested, so we only evaluated those that Energy Star had in its different databases. Appliance categories like the combination washer and dryer, microwave oven, and stove top do not have Energy Star ratings, so other criteria was sent when analyzing the choices for those appliances.

Energy Star is an international standard for energy efficient consumer products, which originated in the United States. Devices carrying the Energy Start service mark generally use 20%-30% less energy than required by federal standards [11].

Products with the Energy Star rating must meet the following criteria [12]:

- Product categories must contribute significant energy savings nationwide.
- Qualified products must deliver the features and performance demanded by consumers, in addition to increased energy efficiency.
- If the qualified product costs more than a conventional, less-efficient counterpart, purchasers will recover their investment in increased energy efficiency through utility bill savings, within a reasonable period of time.
- Product energy consumption and performance can be measured and verified with testing.
- Labeling would effectively differentiate products and be visible for purchasers.

These points are general, meaning it applies to all products, but for the two appliances we were able to evaluate based off of the Energy Star ratings, there was more specific criteria for the specific product.

Refrigerators: Refrigerators of any size smaller than 39 cubic feet of capacity may carry the Energy Start label if they use 10% less energy than the minimum federal efficiency standards. Another factor that we took into account was the fact that a top-freezer refrigerator that has earned the ENERGY STAR uses less energy than a 60-watt light bulb[x].

Dishwashers: For dishwashers to receive the Energy Star label, they must use less than 295 kWh per year and consume less than 4.25 gallons of water per cycle. This assumes that the number of cycles that the dishwasher is used is 215 [13].

With these considerations in mind when we chose our appliances, we were better able to evaluate and analyze the most efficient appliance for each product, even when appliances that we needed were not evaluated by Energy Star. The Energy Star guidelines also served as a basis for our evaluations for the stovetop, microwave oven, and washing machine. The online guidelines made us focus on and look for appliances that were more energy efficient based on what we had learned from Energy Star.

## Passive Design for Thermal Regulation

Ensuring a comfortable and energy efficient environment inside the home requires an understanding of heat transfer. If we are to control and moderate heat, then we must know where it is coming from and how it enters the house.

A primary source of heat is irradiation from the sun. The position of the sun however is dynamic, changing both during the day and the year. This imposes variable heating conditions which must be accounted for. Orientation, shading, glazing, and reflecting are the main ways to control this thermal irradiation.

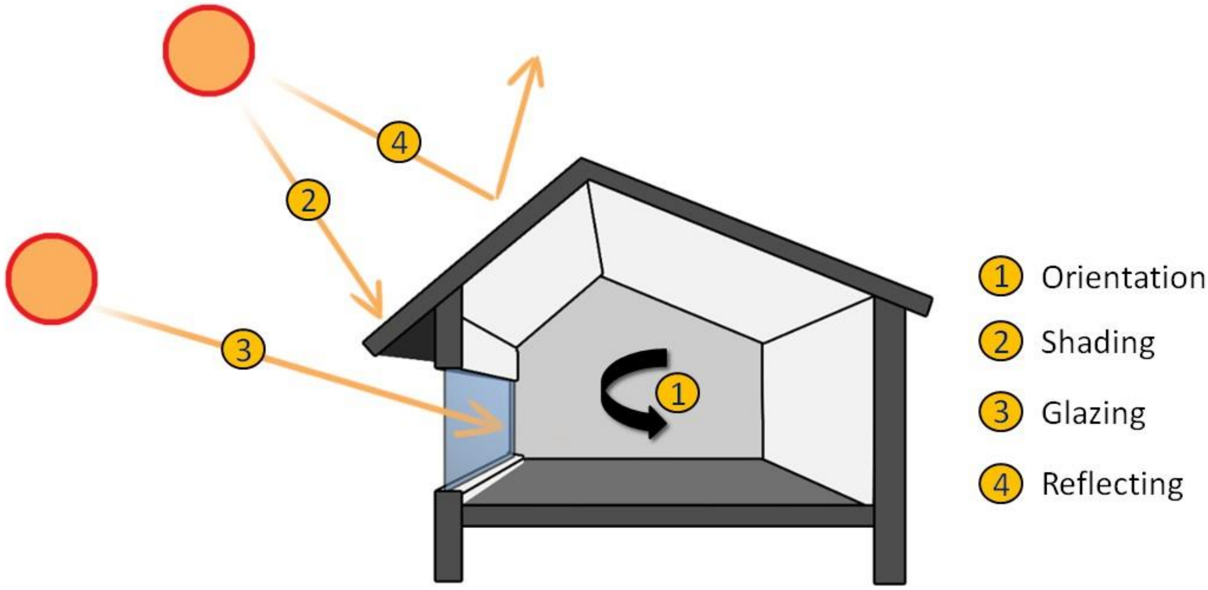



Figure 5.Overview of the factors affecting solar irradiation of a residential building.

Orienting the building properly is important because it affects the size of the area subjected to irradiation. A home with most of its walls facing north and south rather than east and west is generally more effective. This is because southern exposure allows the sun to provide free lighting during the year and natural heating from solar gain during colder winter months.
Decreased western exposure is advised because a setting sun can overheat a building from this side and cause discomfort [14].

Shading should be used to block solar gain during specific time periods. In summer for instance, a home will already be warm enough and cooling is required while during the winter heating will be necessary. Luckily these two design conditions mirror the path of the sun. In the summer the sun is higher than in the winter. Fixed or deployable shading elements can therefore take advantage of the difference incident solar angles. When dimensioned correctly, a shading device can provide cooling by blocking peak summer irradiation while allowing lower winter light to penetrate the building and provide heating. Operable elements such as blinds or screens can also give an occupant even more control over their preferred access to the sun [9].

While the purpose of shading is to block solar gain, the use of glazing is to allow solar gain. Light is important as a free source of illumination and heating. A balance however must be struck to provide comfortable lighting without uncomfortable heating. To achieve this, both the amount and efficiency of glazing must be considered. A general rule of thumb for the appropriate amount of glazing is to look at the window to floor ratio. In net-zero homes, this is recommended to be at 20% for the entire house and 12% for southern exposure. Further optimization however is required.

Efficiency of the glazing is an important factor. For instance, windows do not necessarily need direct solar

gain to illuminate an interior. Therefore shading devices are often most efficient when used to prevent sunlight from directly striking a window and overheating the home.
Additional measures can also be taken to control the fraction of solar radiation admitted through a window. This is measured using the Solar Heat Gain Coefficient (SHGC). This value is expressed as a range from 0 to 1 with lower values indicating less heat gain and more shading.

Energy Star recommends using windows whose SHGC is as low as 0.30 [10]. Further dropping the SHGC becomes detrimental because it reduces the potential free heat gain during winter. These target values can be achieved using high performance windows or by applying solar control window film to alter the SHGC. New technology can allow for dynamic control over the SHGC in response to environmental conditions. Smart windows for example can change their opacity by altering their chemical state. This can be achieved by applying a voltage which could be supplied with passive temperature sensing devices such as thermocouples.

Reflection is another important design factor and is used to keep solar irradiation from being absorbed. This is effective in minimizing or maximizing the effects of solar gain. Minimizing the solar gain is a principle that functions in much the same way as the idea of shading. Overheating is prevented by selecting material properties of exterior walls or roofs to prevent the absorption of incident energy from the sun. Paint, pigment, gloss, glass, and surface roughness are several of the many ways to alter solar absorption. Tuning these variables is particularly effective when applied to roofs which are exposed to the sun throughout the day.

However just as shading is meant to permit light under certain conditions, so too is reflection used to make the most use of the light that is allowed into a space. The variables which were applied to exterior surfaces can also be applied on interior surfaces to let light bounce into all corners of a room. Special architectural features such as light shelves can be placed by windows to reflect the incoming light up into the room rather than simply keeping it on floor adjacent to the glazing. Special blinds and louvers with coated surfaces are also used to this effect. Allowing light to penetrate even deeper into a building can be achieved using a combination of collection and reflection elements. One of the best examples of this is a solar tube [11]. These devices use a semi hemisphere to catch light from outside the house and then send it to a desired location using a tube made of reflective material. This light can travel relatively long distances before being dispersed into an otherwise dark area.

Even if detrimental solar irradiation of the house were completely prevented, the sun’s effects would still be felt. This is because the entire planet is warmed by the sun and the environment surrounding a house will receive irradiated solar heat. Passive design will therefore also have to consider this thermal heat flow using barriers, storage, and evacuation.

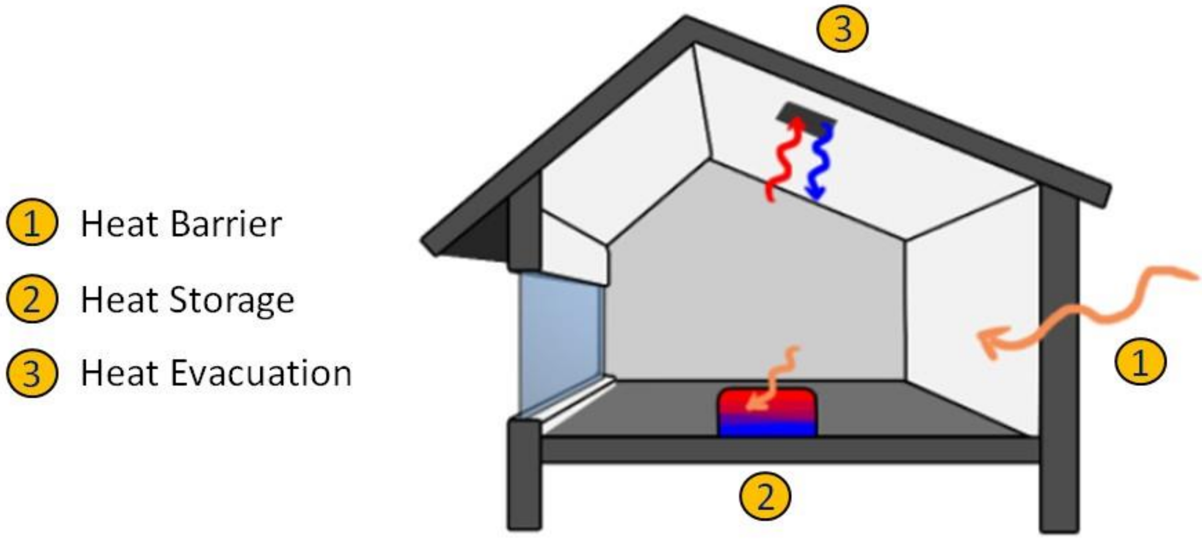



Figure 6.Overview of the means to control the thermal heat flow into and out of conditioned space.

Creating a barrier to thermal heat flow is the best way to ensure as little energy as possible is used to regulate the interior conditions of a house. Ideally a structure would be so well insulated from the exterior that once optimal conditions have been reached inside, they will not change.
This is however impossible considering the fact that high levels of insulation are expensive and an impermeable house is inhabitable. It becomes important then to ensure that a proper thermal seal exists for the majority of the house and that the required breaks in this envelope, such as windows and doors are properly insulated.

The performance of insulation is determined by its thermal resistance, known as the R-value. In the building and construction industry, these values are calculated for particular materials or assemblies of materials. The higher the R-value, the better the building insulation's theoretical effectiveness. Increasing the thickness of insulation adds to the R-value and can be a simple solution [12]. Green roofs take advantage of this feature by packing soil and biomass onto a structure.

Adding more and more insulation however has diminishing returns. Not only can the increased material be costly or take up too much space, but it can also be missing the root of the problem. Another dimension of the insulation problem is thermal bridging. Often an assembly of materials will have a lower performance due to the simply due to the fastening method employed. This is particularly relevant to a solar decathlon house which is meant to be made of assembled modular sections. Metal components such as screw and nails and even wooden studs can have large negative effects on the effective R-value. The best kind of insulation technique is one with the largest continuous surface and therefore least thermal bridging. Structurally insulated panels (SIPs) are designed for just this purpose. These are made from a large core of insulated foam with an exterior cladding. SIPs can be built to cover large sections of wall, floor, or roof space and are fast becoming a go-to choice for net-zero home design.

The chinks in the armor of a well-insulated house are at the areas where the envelope must be pierced. Windows for instance have the notorious reputation for leaking heat. A set of poorly insulated windows can easily counteract the benefits of the strategies mentioned above.
Investing in quality windows therefore has a large payoff. The performance of window is reported using a U-factor. The U- factor is a measure of conduction of non-solar heat flow and is scaled from 0 to 1. A lower value means greater insulation. Energy Star recommends using a U- value of around 0.3 [10]. Such

a value can be achieved using double or triple pane windows which used trapped gas as an insulator. The frame of a window is also a huge potential source for thermal bridging and so it is recommended that the least amount of faming for the same amount of glazing be used. This means that instead of getting 10 square feet of glazing using two windows, each of which is fully framed, it is better to consolidate the windows into a single pane with a decreased framing perimeter.

Inevitably some heat will make it past the outer walls. The next line of defenses is stationed in the house. One of the main ways to deal with this heat is to store it in some form of thermal mass. This can take the form of a solid, liquid or phase change thermal mass. The idea with all of them is to serve as a heat bank. Deposits are made during the day as heat is absorbed and withdrawals are made at night when heat is released. In this way, a home's interior temperature swings can be evened out around a comfortable level. Solid thermal mass is perhaps the most ubiquitous because all building materials have the innate ability to store heat. Their capacity to do so however depends on their specific heat. This is where specialty materials with higher heat capacities are used. Some solid material such as brick or concrete can have this property but they are also very heavy. Liquids on the other hand are often able to store much more heat without being too large or heavy. Lastly phase change materials have the greatest ability to store and release heat. They do so by using the large energy differences between states. While phase change material can be very effective, it is also expensive and requires the system to work within certain temperature ranges to trigger the phase change. As a result they are best used in very specific locations where they have been designed to work in optimal conditions.

Another option to treat the heat inside a house is to evacuate it. This is typically done with active systems, but can also be achieved using natural techniques. The most prominent means of evacuating heat is to use natural convection. Operable windows are often a simple and effective option. By placing them strategically, a designer can allow an open window to cross ventilate a house. This can be achieved by having windows on two sides of the house. Windows which open up to areas with different ambient temperatures will create a thermal gradient which will cause air to circulate. A breeze helps the house cool off and can also help convect heat off of its occupants. Openings can also be placed near the floor and ceiling to take advantage of the natural distribution of heat. Hot air will rise through a high opening and create suction near the floor which can draw in cooler air. Creating a temperature difference to induce air flow is the main goal of solar chimneys which use sunlight to provide heating. If site conditions allow, operable openings could even take advantage of surrounding wind patterns for ventilation.

## Phase Change Materials

A majority of the energy consumption of residential houses is due to active HVAC systems. Thus, it is essential that passive heating and cooling technologies are used to improve energy efficiency of the house. Research shows that an effective way to reduce the energy demand on HVAC systems is to use thermal mass [12]. A good thermal mass can store large amounts of thermal energy. The thermal storage capabilities are a function of material mass, specific heat and temperature difference between the material and the external temperature. Traditional thermal mass materials include water, stone, brick, concrete etc. In order to achieve adequate heat storage, a large amount of these materials are required to be included in the house design. This further leads to the significant increase of the volume and weight of the house. With the development of Net-Zero homes, lighter and more transportable houses are required for which traditional thermal mass may not be feasible. Thus, a solution is to use the latent thermal storage by using Phase Change Materials (PCMs) [12].

PCMs can store a large amount of energy changing phase while maintaining a constant temperature. The temperature range at which they change phase can be altered to suit the environmental conditions of the desired location. Researchers have identified a large number of substances with a high latent heat of fusion at any required temperature range [13], and there are PCM for almost any melting/solidification temperatures.

Factors that affect PCM application [14]:

- local climate
- building design and orientation
- the location of PCM
- type and amount of material used
- the switch temperature, the encapsulation method
- process by which PCM is charged/discharged

Phase change materials are widely used in various applications of building design such as [15]:

- PCM as Middle Layer in Wall
- PCM as Internal Layer in Wall
- PCM with Wall and Air-Conditioning System
- PCMs with Roof System
- PCMs with Floor Heating System
- PCMs with a Building Cooling System

## Types of PCM

Inorganic Phase Change Materials

Inorganic PCMs cover a wide range of temperatures. Although inorganic PCMs have similar latent heat per unit mass as organic PCMs, their latent heat per unit volume is generally higher because of their higher density.

Organic Phase Change Materials

Organic PCMs are most often composed of organic materials such as paraffin, fatty acids, and sugar alcohols. For building applications, paraffinic PCMs are the most commonly used in housing applications. This is because their melting temperature and phase change enthalpy increase with the increase in carbon chain length. Thus, paraffinic PCMs can be altered to achieve a certain type performance.

Bio-based Phase Change Materials

Bio-based PCMS are created from animal fat such as beef tallow and lard as well as oils from plants such as palms, coconuts, and soybeans. They are not toxic and can be recycled through thousands of cycles without experiencing any material degradation. They are chemically stable and can last for a long period of time due to its hydrogenated hydrocarbons.
In addition, fat- and oil-based PCMs offer similar or improved performance as compared to traditional organic PCMs since they are cheaper and more fire resistant [16].

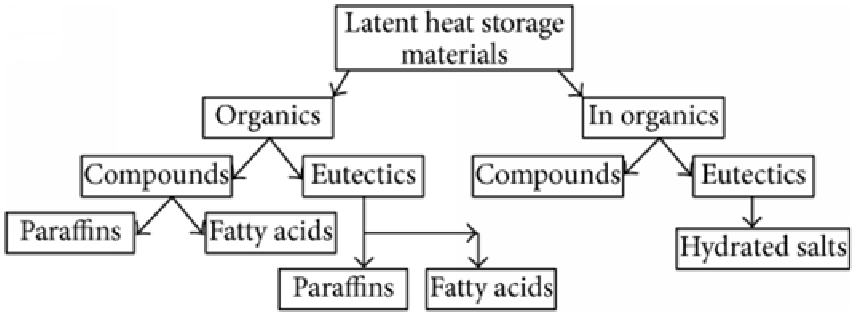



Figure 7. Classification of phase change materials.

## Phase Change Material Concerns

There are some restrictions on PCM passive applications: [12, 17]

Primarily the PCM is reliant on external temperature swings to induce a change of phase. Without significant variations in temperature, the material will not be able to store or release enough appreciable energy. If the external temperature does not drop below the set point temperature at night, then the PCM will not solidify be ready for reuse use the next day. On the other hand, if the external temperature stays constant, the PCM would remain in the same phase and not absorb any thermal energy.

Even if suitable temperature variations are present, these will not always have the anticipated effect due to inefficient heat transfer. Inadequate heat transfer between the air and PCM due to poor air movement in rooms is a chief concern. The German team in 2009 Solar Decathlon [17] used a fan to improve the performance of their PCM in the walls which proved very successful. However, the use of active systems along with PCM is complex and may pose many issues such as maintenance cost for all active systems, cost of operation and purchase.

## Mechanical Room

The mechanical room of a solar decathlon house is meant to link all the active systems together. The devices located in this room typically include heating equipment, thermal storage, water storage, intake, and exhaust ventilation, filtration, ductwork, pumps, and electrical panels [18]. While some devices can be placed in other areas of the house, it is generally good practice to keep potentially noisy or hot devices away from occupied space. This helps ensure that active systems perform their tasks without adversely affecting the comfort of those in the home.
Providing extra insulation, oversizing ductwork, and placing equipment on vibrational damping material such as rubber are some of the ways the mechanical room performance can be improved [19].

The layout of the room should provide enough space for appropriate equipment clearances and proper safety considerations. At the beginning of the project, the dimensions for the mechanical room were primarily a function of what previous teams had managed to design. From our research of the 2013 Decathlon homes mentioned previously, we found that the smallest designed mechanical space was 25 square feet while the largest was up to 80 square feet.

Additional dimensional estimates came from preliminary selection of equipment to be located in the mechanical space. The most important components to be considered were the HVAC units, the water storage devices, and the electrical breaker box.

A typical residential water tank will generally be sized up to a maximum of about 80 gallons [20]. A standard unit of this size will have a diameter around 24 inches with an additional clearance of 4 inches around the sides [21]. Electrical circuit breakers themselves are not too large but are required to have a clearance space around them which is at least 30 inches wide, 36 inches deep, and 78 inches high [22]. Lastly the HVAC equipment also needs consideration.
Typical household air handlers are around 30 inches wide, 20 inches deep, and 50 inches high [23]. Typical ventilation units such as heat recovery ventilators are about 22 inches wide, 15 inches deep, and 30 inches high [24]. These dimensions however do not have as large an impact on the layout of a mechanical room because HVAC units can often be held up in the air above other equipment.
More accurate dimensions for the mechanical equipment will be updated by teams as they revise their designs. The exact specification of the equipment sets a lower bound on the size of the mechanical room. However there is not a huge difference between the available sizes of devices. Rather the final layout of the mechanical room is more dependent on ensuring that the equipment is readily accessible for installation, maintenance, and replacement.

As a part of a modular and transportable house, size and weight restrictions must be considered as well as the ease of assembly and disassembly. Lastly it is important to remember that the solar decathlon is meant to be a show room. The mechanical systems are on display and the room should be kept tidy. Architectural concepts should also make their way into the housing of our mechanical systems.

# Objectives

## Statement of Goals

### Engineering Team Leadership

The Solar Decathlon project is one whose goals are moving targets. As engineering leaders, it is our role to make sure that everything is running smoothly so those goals can be met. First and foremost this means managing the project timeline and assuring that the engineering team deadlines are understood and met by everyone. Secondly it is our objective to communicate both inside and outside our discipline to ensure that all majors see eye to eye and that our efforts are coordinated. No one discipline can fully design the house and all our decisions have effects on other parts of the project. Lastly it is our goal to assign goals to the other engineers and delegate tasks to the most appropriate teams.

### Appliances

The Project Engineers' goals for the appliances are to balance affordability and performance by selecting all (or almost all that apply) with an Energy Star rating and filtering them based on the optimal low energy use and water consumption as well as environmental impact. We also want to ensure that we meet the Solar Decathlon 2015 competition criteria for various tasks that require appliance use, such as washing laundry, a dinner party, and shower use.

### Passive Design for Thermal Regulation

A major goal for the Solar Decathlon 2015 was to incorporate passive elements of design in order to reduce the active cooling load on the house while also providing a comfortable environment for the customer/client. We also want to implement new and innovative technology, as this competition is about designing new techniques and approaches for net zero housing. Since passive design mainly has to do with the placement of the passive elements, we also want to determine the optimal size and locations of the passive elements by using energy modeling software such as DesignBuilder.

### Energy Usage

Since the Solar Cal Poly house is only allotted 175 kWh for the nine days of competition, the Solar Cal Poly Project Engineers plan to accurately measure and carefully analyze how much each appliance and device needing electrical power to make sure that each device is at its maximum use for minimal energy usage. We aim to select products to minimize usage in order that we do not go over the energy budget. We plan to carefully understand the rules in order to comply with the standards set up in each contest in order to use the least amount of energy in each contest.

### Mechanical Room

Due to the multidisciplinary nature of the project, it is essential to integrate all components of the mechanical room such as the electrical panels and water heaters into the architectural design without any conflict of interests. We also want to ensure that the proper codes and regulations are met by ensuring the proper clearances and safety criteria. For the ease of the customer, we also require that there is easy accessibility to the different mechanical elements for maintenance.

## Customer Objectives

The four customers that the Project Engineers are design their specifications around are the Society (the people of the USA and world), Department of Energy, a Potential Client, and Cal Poly San Luis Obispo. These four clients each have different goals and requirements for the Solar Decathlon project. When the QFDs were performed and the requirements of each of the customers were stated, each customer had different weights of importance on each requirement. Society and the Potential Client are more interested in the affordability and livability of the appliances, passive thermal regulation, and mechanical room, while the requirements of the Department of Energy and Cal Poly San Luis Obispo tend to be more about the competition requirements and tests and overall safety and efficiency of the three main areas that the Project Engineers are in charge of. The QFDs for the appliances, passive thermal regulation design, and mechanical room are in Appendix C and show in greater detail the requirements, weightings, and specifications laid down by the customers and Project Engineers.

## Engineering Specifications

### Appliances

Each role of the Project Engineers was individually tailored to match customer requirements and engineering specifications. The Project Engineers looked at the requirements from all customers and evaluated which requirements would be most pertinent.

Society: The top three requirements from Society were affordability of the appliances, the ease of use, and the overall energy efficiency of the appliances.

Department of Energy: The top three requirements from the DOE were the rules specified by the competition, the energy and water usage, and the innovative way of achieving those ends.

Potential Client: These requirements almost mirror the societal requirements, but differ slightly. In the appliance section, the Potential Client mirrors Society and the top customer requirements are affordability, ease of use, and the overall energy efficiency.

Cal Poly, San Luis Obispo: The requirements from Cal Poly were affordability, the DOE rules, and the innovation of the appliances.

A QFD was created for the appliances in Appendix D.

Table 1. Appliance Engineering Specifications Table.

| Spec # 1 | Parameter Description | Requirements or Target | Risk | Compliance |
|---|---|---|---|---|
| 1 | Long Life | >10 years | L | S |
| 2 | Number of Settings | <$20,000 | L | S, I |
| 3 | Water Usage | <100 gallons per week | M | T, S |
| 4 | Energy Usage | <50 kWh per week | M | T, S |
| 5 | Cost | <$20,000 | M | S |
| 6 | Dimensions | Fits inside specified areas | L | I, S |
| 7 | Schedule of Repair | Follows code regulations | L | S, I |

## Passive Design for Thermal Regulation

For the Passive Design section, the main requirement was to lower the active energy usage of the home. This is important, because it is the principle goal of this project.

Society: The top three requirements from Society as the customer was affordability of the passive design mechanisms, an appreciable decrease in the reliance of the active HVAC systems, and environmentally friendly solutions for the passive systems.

Department of Energy: The main goals for the Solar Decathlon 2015 is to reduce energy usage in innovative ways, so it is no surprise that the top three requirements are reduce active energy usage, use innovative passive HVAC systems, and ensure affordability.

Potential Client: The top three requirements for the Potential Client were affordability of the passive design systems, the aesthetic value of the systems, and the reduction of active HVAC energy usage.

Cal Poly San Luis Obispo: Cal Poly, as a customer, was most interested in the affordability of the passive systems, the innovative designs, and the reduced energy usage.

A QFD was created for the passive design considerations in Appendix D.

Table 2. Passive Design for Thermal Regulation Engineering Specifications Table.

| Spec # 1 | Parameter Description | Requirements or Target | Risk | Compliance |
|---|---|---|---|---|
| 1 | Thermal Insulation Value | <15 | M | A, T |
| 2 | Cost of Materials | <$100,000 | L | I |
| 3 | Solar Heat Gain Reduction | <10 °F | M | A, T |
| 4 | Heat Storage Capacity | 10 °F | M | T |
| 5 | Space Requirements | Follows code regulations | L | I |
| 6 | Temperature Difference | 70°F<Temperature<76 °F | M | T |
| 7 | Schedule of Repair | Follows code regulations | L | S, I |

**Mechanical Room**

In the mechanical room of the house, the main focus was of the safety, operability, and placement of the different systems in the enclosed space.

Society: The three main requirements for the Society were operability, the comfort level of the space while it is being occupied, and the efficiency of the different systems.

Department of Energy: The DOE is more concerned about the different regulations that the mechanical room must follow, so the top three requirements were following the DOE rules, the safety of the mechanical room, and the efficiency of the different systems.

Potential Client: In this case, the Potential Client mirrored the requirements as Society. The top three were operability, the comfort level of the space while it is being occupied, and the efficiency of the different systems.

Cal Poly San Luis Obispo: In the mechanical room, the requirements of Cal Poly as the customer mirrored the requirements of the DOE. In this case, the top three requirements were following the DOE rules, codes, and standards, the safety of the mechanical room, and the efficiency of the different systems.

A QFD was created for the mechanical room in Appendix D.

Table 3. Mechanical Room Engineering Specifications Table.

| Spec # 1 | Parameter Description | Requirements or Target | Risk | Compliance |
|---|---|---|---|---|
| 1 | Temperature Levels | 50°F<Temperature<90°F | H | A, T |
| 2 | Safety Codes and Standards | Follows code regulations | M | I, T |
| 3 | Schedule of Repair | Follows code regulations | L | I, S |
| 4 | Space Requirements | Follows code regulations | L | I, S |
| 5 | Size of Instruments | Follows code regulations | L | I, S |

# Design Development

## Engineering Team Leadership

Most cost effective measures towards efficiency and performance take place in the design phase. As project engineers it is our responsibility to ensure that adequate steps are taken from the beginning. This starts from Architectural design. We believe that it is essential to combine passive solar technology and methods that can be integrated with on-site assets. The goal is to achieve optimum lighting, stable indoor temperatures and water heating with minimum mechanical systems. This is what creates a true Net-Zero home. Once the architectural design is complete, energy models may be constructed in order to further reduce the power consumption in the developmental phase.

As the Project Engineers, we attended the architecture studio twice every week to consult the architects in various decisions such as placement and orientation of the three mechanically intensive rooms such as the bathroom, kitchen and mechanical room. We advised them to put all these three components together in order to reduce the amount of wiring, plumbing, heat-loss due to pipes and various other reasons. Some students required us to help them analyze their grey water filtration systems and thermal mass systems. A major area for correction was the integration of the HVAC system along with the architectural design since many architectural students were making their design consisting of two separate modules of conditioned space with an unconditioned space in the middle, something that would require more energy to perform.

From research and help from a graduate ME student working on the project, the HVAC system that was recommended for the solar decathlon house was a split system. This is due to the effective performance of split systems for small houses as well as efficient energy consumption. In order to push for mechanical efficiency in the architectural design, the ME team created an architectural model on Google-SketchUp and created scaled model out of basswood. This design was then presented in the weekly architectural review. From the feedback given from the panel of judges, the design was changed by a significant amount and reconstructed on SketchUp and another scaled model was made. This final model along with a poster was then submitted for an architectural competition at the end of the quarter.

This process not only helped us understand various concepts and principles of architectural design but also helped us explain things better to the architects which worked out pretty well as reflected by the final architectural designs of the architects.

## Appliances

Careful consideration went into the choosing of each appliance. In the Spring 2014 quarter, our team did a preliminary study on the appliance choices, but when the house layout changed in the Fall of 2014, and because we gained a better understanding of the project as a whole, the appliance list was deemed outdated and needed to be revised. For those appliances that had Energy Star criteria, the different information was organized and compared to arrive at the best conclusion. For those appliances that did not have Energy Star criteria, the decisions were made based on the energy usage (and water usage if applicable), size, and cost. Those appliances were then chosen and a new list was created. As this project is ever-changing and evolving, a third pass was started in early Winter 2015. This pass took appliances from one main manufacturer, Whirlpool, because it is possible that we could more easily get the appliances donated if they all came from one manufacturer. Although ease of obtaining the appliances is important, energy usage of the appliances is the most important, so all the appliances analyzed throughout the quarters are still being considered based on energy usage.

### Fall 2014

The following criteria was applied for each appliance in order to determine the best model according to the specifications.

Refrigerator: This appliance did have Energy Star criteria, so to choose this appliance, we used the spreadsheet of all the models that were Energy Star compliant. The energy use per week and storage capacity were the two factors that went into choosing a refrigerator for the house. We organized the refrigerators based on their capacity and energy use to try to maximize them both. As a rule of thumb, for each person living in a house, there should be 4-6 cubic feet of space in the refrigerator [x]. Assuming that there will be two people living in the house, the appliances were organized so that refrigerators with an interior capacity of 12-18 cubic feet were the best choice. The weekly energy use ranged between 5.7 and 12.8 kWh per week, and the less energy used, the better. We then maximized the two criteria in order to achieve the best in both of the categories. The last step was to find the top three choices using the Energy Star criteria on the internet to compare pricing, as we wanted to minimize cost because we want the home to be affordable as possible.

Dishwasher: Dishwashers are also evaluated by Energy Star, so we were able to determine a dishwasher based off of the criteria set by Energy Star. For dishwashers, the two criteria that are the most important to remember are the energy use and water use. Although there is no measured contest for water usage, we wanted to conserve water to represent the California drought problems, as well as demonstrate a conservative approach. The team only receives as much water as we specify, and we wanted to limit waste and extra space taken up by water tanks on the limited property given. Like in the refrigerator case, the different dishwasher options were organized by energy use and water use in order to find the best case solution. As can be shown in Figure 8 below, the best solutions were from Bosch, but many of the models on the Energy Star website, where this data comes from, was outdated and many of the Bosch models are no longer in production. That is why the top choice for dishwashers was the Viking Range LLC FDW300. It was the best choice in availability, cost, energy use, and water use.

| Brand Name | Model Number | Annual Energy Use (kWh/yr) | | US Federal S | % Better t | Water Use (gallons/cycle) | US Federal Stan | % Better than US |
|---|---|---|---|---|---|---|---|---|
| Bosch | SHX8ER5*UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Bosch | SHE8ER5#UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Gaggenau | DF260760 | 180 | 3.461538462 | 307 | 41 | 2.46 | 5 | 51 |
| Bosch | SHV68E13UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Bosch | SHX68E15UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Bosch | SHX68E05UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Bosch | SHE68E05UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Bosch | SHE8ER5*UC | 180 | 3.461538462 | 307 | 41 | 2.22 | 5 | 56 |
| Asko | D5894A | 187 | 3.596153846 | 307 | 39 | 4.2 | 5 | 16 |
| Bosch | SHX98M0#UC | 190 | 3.653846154 | 307 | 38 | 2.9 | 5 | 42 |
| Bosch | SHX9ER5*UC | 200 | 3.846153846 | 307 | 35 | 2.9 | 5 | 42 |
| Bosch | SHE9ER5#UC | 200 | 3.846153846 | 307 | 35 | 2.22 | 5 | 56 |
| Bosch | SHE9ER5*UC | 200 | 3.846153846 | 307 | 35 | 2.9 | 5 | 42 |
| Bosch | SHV9ER5*UC | 200 | 3.846153846 | 307 | 35 | 2.9 | 5 | 42 |
| Blomberg | DWS 54100 * | 210 | 4.038461538 | 307 | 32 | 3.08 | 5 | 38 |
| Summit Professi | DW18* | 210 | 4.038461538 | 307 | 32 | 3.08 | 5 | 38 |
| Asko | D5644 | 212 | 4.076923077 | 307 | 31 | 3.8 | 5 | 24 |
| Blomberg | DWT 25500* | 214 | 4.115384615 | 307 | 30 | 2.54 | 5 | 49 |
| VIKING RANGE | FDW300 | 214 | 4.115384615 | 307 | 30 | 2.54 | 5 | 49 |
| Asko | D5654 | 218 | 4.192307692 | 307 | 29 | 3.7 | 5 | 26 |
| Asko | D5554 | 218 | 4.192307692 | 307 | 29 | 3.7 | 5 | 26 |

Figure 8. Analysis table for deciding on the best dishwasher.

Combination Washer and Dryer: For this appliance, there was no Energy Star rating, so we researched the best reviewed combination washer and dryers and compared the top seven based on cost, energy use, and water use. A combination washer and dryer was chosen instead of the standard washer and dryer for a few reasons. Since the Solar Decathlon states that the house must have less than 1000 square feet of space, availability of space was a big factor. The combination washer and dryer is a better choice in this case because of the space it saves. Most combination washer and dryers are also ventless, which means that the warm, moist air is condensed in an outer drum and the water is drained through the drainage pipe system. Because it is ventless, there is no need for an additional vent specifically for the dryer going to the outside air. This eliminates extra material costs and helps reduce the energy and heat loss by not having holes puncturing through the walls, roof, and floors. The criteria that factored into the choosing of the product were energy use, water use, and capacity. Cost was also a factor, but a minor one in the overall decision. The top three choices were about the same in energy use, so the factors that impacted the decision the most were the capacity and water usage. The top choice was the largest, at 4.3 cubic feet, but it had a water factor of 2.5, which means that it uses 13.76 gallons per cycle. Another model had a capacity of 1.9 cubic feet with a water factor of 7.2, which meant that it uses just about as much water, but does not have the same capacity. Our top choice is therefore uses water more efficiently.

Microwave Oven: The microwave oven may not be a part of any measured contest, but in the Home Life contest [25], two meals must be cooked for a group of people during the competition. A microwave oven was chosen, again to save on space. The microwave oven combines both the oven and microwave so it can have the capabilities of both, but is able to take up a lot less space. Microwaves are much smaller than standard ovens, so an important consideration while comparing microwave ovens was the capacity as well as the energy use. The average weekly hourly use of a microwave oven is 2.48 hours per week [26], but our team overestimated to 3 hours. The best choice microwave oven had a capacity of 1.9 cubic feet and an energy use of 3.3 kWh per week based on our set criteria.

Stovetop: The stovetop will most likely be the appliance that evaporates the 5 pounds of water required in one of the appliance contest tests. The criteria that went into the study of which stovetop to choose was based on the wattage and the price. It was assumed that the stovetop had an average use of 9 kWh, which translates to a use of one burner turned on fully for 4.3 hours per week. Since most of the stovetops that were analyzed had the same energy use, more emphasis was placed on the cost, and that is why the first choice stovetop cost less than the second and third choices.

Table 4. Recommended appliance list for the Fall 2014 iteration of the design.

| **#1 Appliance Choices (Fall 2014)** | | | | |
|---|---|---|---|---|
| **Appliance** | **Brand Name** | **Model #** | **kWh/week** | **Price** |
| **Dishwasher** | VIKING RANGE LLC | FDW300 | 4.11 | $1,099 |
| **Refrigerator** | Frigidaire | FFHT1514Q* | 6.5 | $578 |
| **Microwave Oven** | Whirlpool | WMH76719CS | 3.3* | $549 |
| **Stovetop** | Whirlpool | G9CE3065XS | 9 | $1,199 |
| **Washer/Dryer** | LG | WM3997HWA | 2.4 | $1,899 |
| TOTAL | | | 25.31 kWh/week | $5,324 |

The table above show the top choice of appliances selected by using the algorithms and criteria stated in the above paragraphs. Unfortunately, all these calculations were done on a weekly basis, and the competition dates were not taken into account. The appliances will be judged in a nine day competition, not a week, so more analysis was needed to be done.

## Winter 2015

In the Solar Decathlon 2005 Cal Poly house, all appliances were from the same manufacturer, KitchenAid, except f0r the combination washing machine and dryer. This made it easier for the past team went to acquire the appliances because they only had to go to two companies to ask for donated appliances. In the Solar Decathlon 2015 case, we did another appliance pass like this in order to also make it easier to ask companies for donated appliances.

Whirlpool was the top appliance choice for us because many of its appliances were Energy Star rated, which means that many of the appliances picks would use less energy than the average appliance. Whirlpool does not manufacture washing machines and dryers, so another manufacturer was needed in order to find one. It was found that the best combination washer and dryer was still the LG model chosen in the Fall 2014 quarter because of its superior capacity and minimal energy and water use.

Each appliance was chosen with two factors in mind. Each model has an energy use manual to see how much power the appliance would approximately use per year. Since the competition is only for eight days, the energy use per hour or per use, depending on the appliance, was calculated in order to find the specific amount of energy used. This was important because of the scarcity of power in the energy budget. The other consideration that weighed into the final decision was cost. Cost has always been part of the decision process because if this was a real household, cost would factor in the buying of appliances. Many appliances, like the refrigerator and dishwasher had good energy ratings, but the cost became too high. A balance was therefore needed in order to find the best energy efficient, cost-effective appliances.

Based on those two factors mentioned above, a new appliance list was chosen for the architect's consideration [Table 5].

Table 5. Winter 2015 pass on appliances from only two manufacturers.

| Appliance | Brand | Model # | kW use per hour/use | Energy Usage (best) | Cost ($) |
|---|---|---|---|---|---|
| **Refrigerator** | Whirlpool | WRT134TFDW | 0.04 kWh | 7.66 kWh | 699 |
| **Microwave Oven** | Whirlpool | WMH76719CS | 1.6 kWh | 4.8 kWh | 569 |
| **Stovetop** | Whirlpool | W5CE3024XS | 2.5 kWh | 10 kWh | 649 |
| **Dishwasher** | Whirlpool | WDF320PADW | 1.25 kW per use | 6.25 kWh | 549 |
| **Washer/Dryer** | LG | WM3997HWA | 0.3 kW per use | 2.4 kWh | 1709 |
| **Total** | | | | 31.11 kWh | $4,175 |

Although these appliances do not have a terrible energy draw, it is possible that these appliances do not have the best energy efficiency in each of its individual fields. Because most of the appliances were taken from the same manufacturer, there was a limited amount of products to choose among. If the appliances were researched and chosen based only on best energy efficiency, somewhat like the last appliance pass, it is possible that the energy usage could have been even lower. It is possible that we might do another analysis on the appliances, this time combining the analysis we have done before and understanding which appliance from all the ones analyzed has the best energy efficiency, no matter the manufacturer.

Moving forward with these products, we as the engineering team must collaborate with the architects to confirm that these appliances will be chosen. It is also possible that the architects may want their own appliance selections, but those appliance selections must be carefully analyzed in order to confirm that they are better in some way than the appliances chosen here. There must be a viable reason for the change because of the careful analysis that was put into each appliance choice to confirm that they each had the best energy efficiency and cost.

## Energy Use

For the first time in the DOE Solar Decathlon history, there will be an energy budget placed on the house as well as the energy balance, and it serves as one of the ten contests in the competition. This was put in place because the Solar Decathlon 2015 is not just about net zero homes and using renewable energy to power homes, but to reduce energy use in the first place. The best way to conserve energy is to use none at all. In the past Solar Decathlons, teams would oversize their Photovoltaic panels on their roofs to offset their high energy usage during the competition. Since this competition is about reducing energy, even renewable energy, a cap of 175 kWh was placed on the teams' designs. This means that the house must only use 175 kWh during the 8 days of competition in October. In order for Solar Cal Poly to stay within that small budget, we must carefully monitor and evaluate each appliance and object that will need power during the competition.

In the above section, the appliance selections were chosen in careful consideration of energy usage, but that is only part of the energy usage in the house. The house will also find energy draws from the vehicle that must be driven around, lighting, the heating, ventilation, and air conditioning systems (HVAC), home electronics, and other products.

The Solar Decathlon 2015 has many different contests that the Solar Cal Poly house must perform in. Contest 6-10 have to do with the energy use of the house, so each contest was carefully analyzed and researched in order to achieve a complete understanding in what Solar Cal Poly needs to do in order to complete the tasks assigned.

Contest 6 is about the comfort zone of the house, which applies to the heating, ventilation, and air conditioning systems. The Solar Cal Poly Project Engineers, as part of our senior project, worked with phase change material and other passive designs, as can be seen in other sections of this report, to minimize the use of the active HVAC systems. We worked in collaboration with the Active HVAC team to determine the cooling loads on the house, and how large the active system must be in order to keep the house in the required temperature range. The team estimated how long the active systems have to run for the eight days of competition to arrive at an estimation of total energy use of 45 kWh for the active systems. This would be a best case scenario in which the passive HVAC systems worked perfectly and all other systems worked in conjunction with the active HVAC systems. If more cooling is needed than expected, then the active systems team estimated a use of 55 kWh.

Contest 7 has to do with the appliances in the house. The contest measures the refrigerator and freezer temperature, the dishwasher and clothes washing capabilities, and a cooking simulation. The dishwasher will be tested five times during the competition, and according to national standards which assumes that a normal dishwasher is used four times per week so this part of the contest does accurately simulate a standard home life usage. We were then able to find the kWh usage of the dishwasher per use to find an assumption for the energy use during the competition. The same was also stated for the washing machine, except national standards dictated that an average household uses a washing machine eight times per week. The combination washer and dryer that we have is very efficient, so it only uses 0.3 kWh per use. In the cooking simulation, our team must vaporize five pounds of water in a specified amount of time six times throughout the competition. To do that, as of right now, we will be using the stovetop to complete that task. In order to use the least amount of energy possible, calculations were done to estimate how long it takes to vaporize water. The time limit for the task is two hours, so the power of the stovetop could not be below 0.9 kW because it would not have enough time to evaporate all the water needed to complete the task. From the calculations, it was found that the power that the stovetop is set as only affects the time it takes to vaporize the water. No matter what power setting the stove is set to, the energy usage will stay the same. This was a confirmation of our hypothesis, because the water amount and the constants of water do not change, and it takes the same amount of energy to vaporize the same amount of water; changing the time and power input has no effect on the energy used.

Table 6. Constants for Water (liquid).

| Mass (kg) | Specific Heat (kJ/kgC) | Temperature Difference (C) | Heat of Vaporization (kJ/kg) |
|---|---|---|---|
| 2.26 | 4.179 | 78 | 2257 |

Table 7. Energy calculations from evaporating 5 lbs of water.

| Power (kW) | Time (min) | Time (hours) | Energy for 6 uses (kWh) |
|---|---|---|---|
| | | | |
| 1 | 97.29 | 1.62 | 9.729 |
| 1.5 | 64.86 | 1.08 | 9.729 |
| 2 | 48.65 | 0.81 | 9.729 |
| 2.5 | 38.92 | 0.65 | 9.729 |
| 3 | 32.43 | 0.54 | 9.729 |
| 3.5 | 27.80 | 0.46 | 9.729 |

Contest 8 simulates the home life of the house. This contest measures the ability of the house to use all of its lights and home electronics like the TV and a personal computer. All of the lights in the house must be on for 26 hours during the competition, but the lights will also be on during other times in the competition as well, so an assumption of four extra hours was also added in the energy budget, but this number might go up or down depending on further testing. As of now, the lighting design team has a count of 33 LED bulbs that will be used in the house. From this, an estimation of 9.9 kWh was calculated as the energy load from the lighting. Home electronics manifests into the operation of a laptop and TV for 34 hours throughout the competition. At first, it was assumed that the home electronics used little power, but when researched further, it was found that the electronics took more up of the budget than earlier anticipated.

Contest 9 is mainly in the electrical engineering realm, because it has to do with the charging and commuting of the vehicle. Initially, the vehicle was estimated to take up 75kWh of the energy budget, but with careful analysis and specific calculations based on the times of the competition and the exact contest rules, it was determine by the electrical engineers that a best case scenario of the vehicle energy draw would be 49.2 kWh. This is a major reduction from the initial estimate, and this helps the energy budget by allowing space for other systems to use a bit more energy than before.

Contest 10 is the overall energy budget and energy balance competition. It states that the overall energy usage of the house must not exceed 175 kWh during the eight days of competition. In our best case scenario analysis, our energy usage estimation amounts to 145.68 kWh, which is 29.32 kWh under the limit. This is good because when we start testing we will most likely realized that the appliances, products, and systems do not act perfectly, which would close the gap between our estimated usage and the allowed budget. This is what our overestimation of the energy use is trying to get at, but even with that overestimation, we would still only use 168.5 kWh, leaving a small margin of error.

Table 8. Energy usage for each appliance, system, and device.

| Power Draw | Total Available Hours to Complete Task | Hours/# of Times Used in Competition | kW use per hour/use | ENERGY USE (kWh) (nominal) | ENERGY USE (kWh) (overestimation) |
|---|---|---|---|---|---|
| refrigerator | 191.5 hrs | 191.5 hrs | 0.04 kWh | 7.66 | 8.00 |
| stovetop | 12 hrs | 4 hrs | 2.5 kWh | 10.00 | 11.00 |
| dishwasher | 12.5 hours | 5 times | 1.25 kWh per use | 6.25 | 6.50 |
| oven | (dinner party use) | 3 hours | 1.6 kWh | 4.80 | 5.00 |
| washing machine | 24 hrs | 8 times | 0.3 kWh per use | 2.40 | 3.00 |
| HVAC | | | | 48.00 | 55.00 |
| PCM Inline Fan | | 40 hrs | | 6.00 | 9.00 |
| Mechanical Room Fan | | 40 min | 0.3 kWh | 0.20 | 0.50 |
| blackwater pump | | 10 min | | 0.21 | 0.25 |
| greywater pump | | 10 min | | 0.21 | 0.25 |
| lighting (350 W) | 25 hrs | 25 hrs + 15 extra | 0.350 kWh | 14.00 | 17.00 |
| Laptop (assumption) | 32 hrs | 32 hrs | 0.05 kWh | 1.60 | 2.00 |
| TV (30") | 35 hrs | 32 hrs +3 hrs | 0.15 kWh | 5.25 | 6.00 |
| controls system | | | | 4.00 | 6.70 |
| vehicle | 16 hrs | | | 64.00 | 70.00 |
| **TOTAL** | | | | 174.58 | 200.20 |
| **LEFT OVER** | | | | 0.42 | -25.20 |

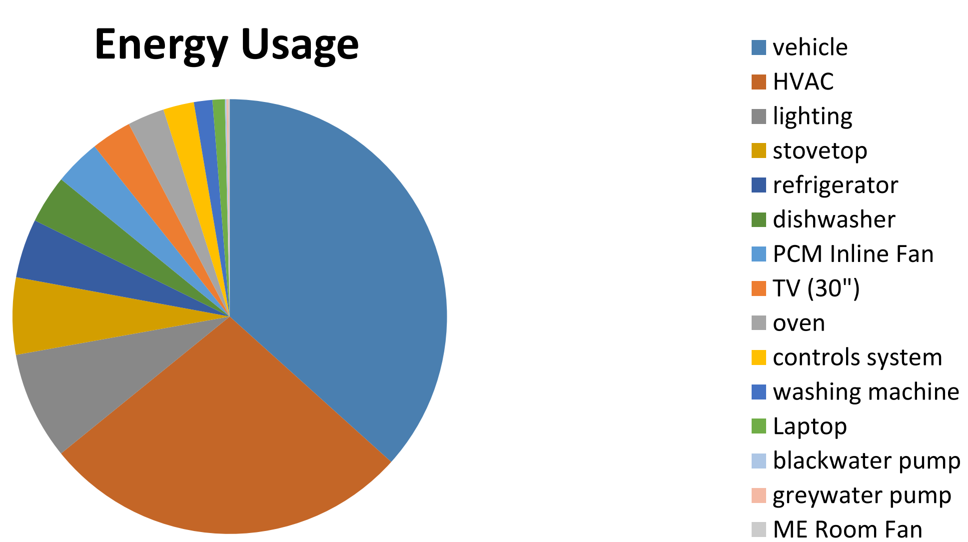



Figure 9. Pie Chart showing the different power draws of the energy budget.

This above chart shows the energy usage of the home. A large part of the 175 kWh allotted per week will go to the active HVAC system and vehicle charging, and the rest goes to the appliances, lighting, and other, smaller uses. If everything performs as it should, there will be little worry about going over the allotted budget, but we will have to monitor and test the systems more thoroughly once the systems are built or installed to see if this energy use prediction is accurate.

The energy budget is still in flex, and different systems or devices will be changing, but not by much. The estimations and analysis made are very close to the actual energy usage of the house, barring any major changes or disasters. Moving forward, we will just need to keep in mind the power draw of each device and system to confirm that there is little or no increase power consumption.

## Passive Thermal Regulation

The passive means of thermally regulating a house are outlined in the background section of this report. These methods can be summarized as preventing heat from entering the house, through effective insulation, shading, or glazing and preventing heat from accumulating in the house by using heat evacuation with ventilation or heat storage with thermal mass.

### House Shading Devices

It was decided early on that the decathlon house would implement some sort of envelope to provide shading for the building. This stemmed from our precedent studies which showed how such construction had been used by several successful teams in the past. The trick however, was to balance the engineering and architectural implications of a whole house shading device. Iterations involved using deployable canvas sheets, perforated fiber reinforced polymer screens, and green walls. Ultimately the design steered towards the use of a lattice wood structure. This approach was simpler, cheaper, and more effective than many of the alternatives explored. Designing the spacing and placement of the screen was important because it needed to protect areas sensitive to overheating from the sun. Ensuring proper opacity was also important to avoid the screen from becoming a prison like wall which blocked views and further confined the already small scale house.

Figure 10. View of the wooden envelope with alternating screen direction to effectively cut down on sunlight.

Additional shading devices could also be implemented later in the project which were not crucial to the overall design of the building. These include blinds or screens placed on windows for control over light penetration. The specifics of these elements however would be best addressed by the interior design team working under our recommendations.

## Effective Glazing

Choosing the right windows is an important design consideration because of their effect on the heat gain by the house. Ideally a home would require no windows and could thus perform very well thermally. This is obviously impractical and ignores the upsides of natural lighting which can greatly reduce the dependence on active lighting. The architecture team also favored a higher proportion of glazing to make the 1000 square foot house seem larger. It was therefore imperative that a balance be struck to fine tune windows which provided enough natural lighting and sense of space without significantly damaging the thermal integrity of the design. The main means of achieving this was to follow the recommendations outlined in the background section of the report. Sensitivity analysis on these factors will be discussed in the final design section.

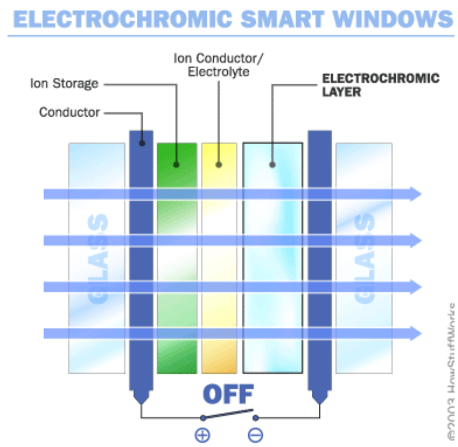



Figure 11. SMART window with the ability to change translucence with an applied current or voltage.

An alternative method was also explored which involved the use of Smart Windows. These devices had the ability to provide the lighting and views when needed but could be altered to block light at other times. This had the prospect of being able to serve both the engineering and architectural needs of a window. A possible solution analyzed was the use of electro-chromic windows coupled with a thermocouple to generate the required voltage for the window to change its opacity. This was based on the inherent property of a thermocouple according to which a voltage is induced when a temperature difference is achieved across its two ends. However it was determined that thermocouples could not achieve the required amount of voltage based on the differential temperatures between the interior and exterior of the house.

## Insulation

The thermal seal of the house is a key factor to its performance. Our team explored the conventional avenues for insulating a home but determined that the use of continuous SIP walls and ceilings would be best. The analysis and specification of this insulation system was delegated to another team.

## Ventilation

The ability to ventilate a home is important for cooling purposes. Our team worked with the architects to place operable windows so that cross ventilation through the house was possible. To achieve this we made sure that openings had access to areas with different temperatures to induce natural air flow across the thermal gradient whilst ensuring that there were minimal obstructions to said flow between rooms.

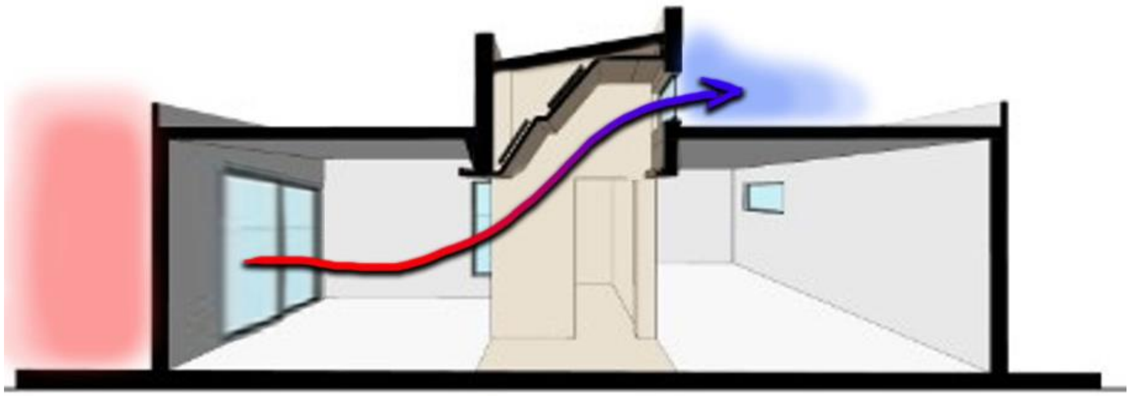


Figure 12. Section view of the elevated core section to provide natural stacked ventilation.

Natural ventilation was also explored for flow in the vertical direction. The idea was to use pressure differences driven by thermal buoyancy to force air flow. The greater the height and temperature differences, the greater the effect. The main core stands fourteen feet tall and has high and low openings on both the cooler north side and warmer south side. Both of these factors help increase the efficacy of stacked ventilation. The flow of air passing horizontally and vertically through the house help cool it off and increase occupant comfort with a slight breeze.

## Thermal Mass

Heat will inevitably enter the house. This heat could be exhausted out through the passive ventilation or active air conditioning system but doing so is wasteful waste. Instead the heat should be stored for later use at night. The background section of this report outlined the main ways to achieve this through solid, liquid, or phase change thermal mass. Relying on solid thermal mass was quickly ruled out because it is too heavy for the equivalent amount of heat storage capacity compared to liquid or phase change.

Initial ideas for design included a transparent tank of water as a thermal mass in the middle of the house. Above the tank was a solar tube which brought in light and dispersed it into the house. Calculations were performed in order to assess the temperature regulation performance of this system. Various types of glass were also analyzed to determine their effect on the heat transfer. In the end this model was abandoned as it could not be incorporated with the architectural design of the house.

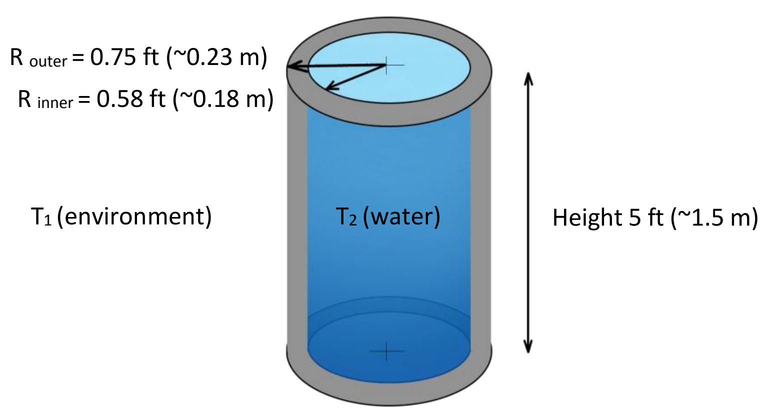



Figure 13. Model of water tank used as thermal mass to regular temperature.

Liquid thermal mass continued to be explored but increasingly we turned an eye towards phase change material which could store the same amount of heat but with a much lower profile. Commercially available products were researched to determine what products were market ready. We settled on products from the company BioPCM which had already developed phase change sheets for easy installation in construction projects. Energy Builder was used to model the phase change material and its effect on the cooling loads of the house. Architectural limitations and energy modelling were used to fine tune the selection, amount, and placement of phase change material in the house.


Figure 14. Phase change products sold by BioPCM to be used for heat storage applications.

It was determined that the standard phase change material would not provide enough heat regulation for the house and so we began to develop a more robust heat sink using phase change material tubes known as Thermastix.

## Energy Builder Modeling

Initially, the architectural Revit model was opened with design builder and analyzed. However, there were many errors encountered due to the software integration. This led design builder to display cooling loads that were much higher to the expected values. Thus, a simpler model was then built to run the energy analysis. Once the engineering officers completed the design-builder model, it was then passed on to the SIP and HVAC teams for analysis. Through coordination, the model was continually updated until the optimal thermal insulation with SIPs was reached and the proper HVAC settings were put in place. The latest iterations of the design had an impact on the cooling load of the house which affected the energy requirement for air conditioning which was then fed back into the total house energy use.

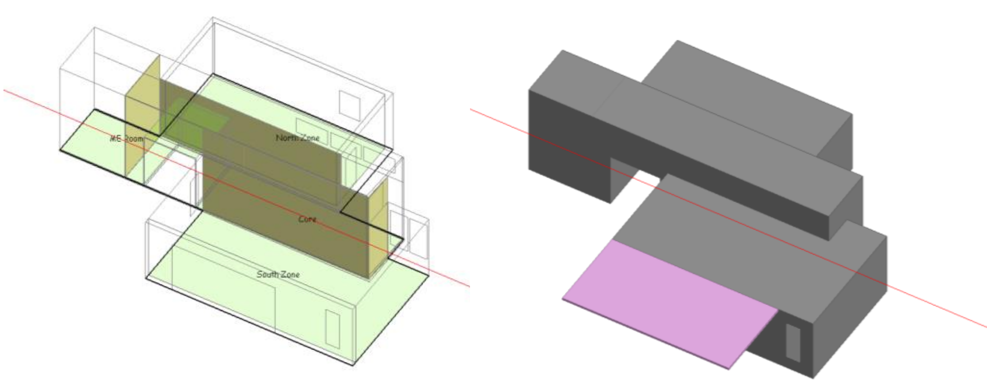


Figure 15. Design Builder model of the house with the internal partitions, windows, doors, and awnings.

## Mechanical Room

The mechanical room is a part of the house that architects include in all of their concepts. The problem however is that they do not always know what an effective mechanical room is. At the beginning the house design was very conceptual and it was our role to serve as consultants to the architects and provide ball park estimates for a functioning mechanical space. The basic parameters for a mechanical room without specified appliances came from our background research listed previously. As the architectural design process focused in on one design, we were able to get a better sense of what would actually be going into the space.

The first clear concept of the mechanical room came out of the design from the summer studio. The house concept was centered around having a compact, concentrated module in the center of the house with all the mechanical equipment. This was a result of our insistence on efficiency through proximity which also helped add clarity to the concept of an architectural life support system in the center of the house.

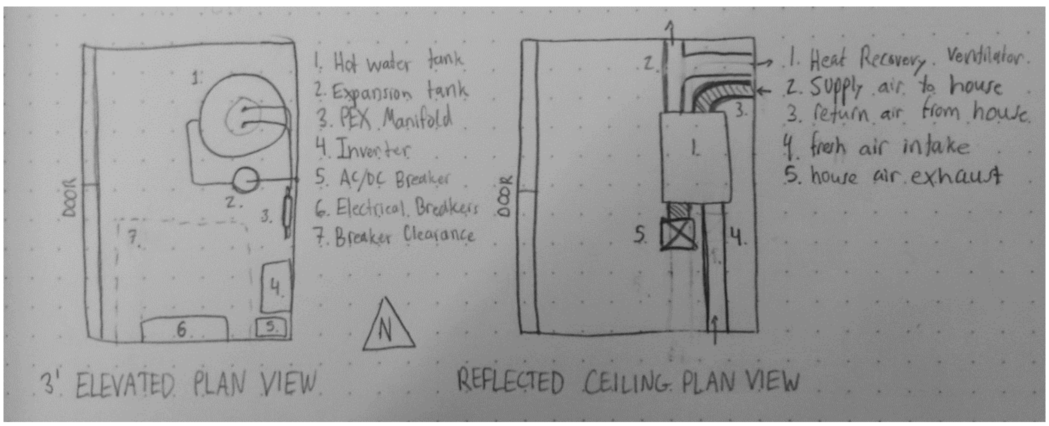



Figure 16. Sketch of the summer studio mechanical room with the left view showing most of the equipment in the room and a separate view on the right showing the elevated ventilation equipment.

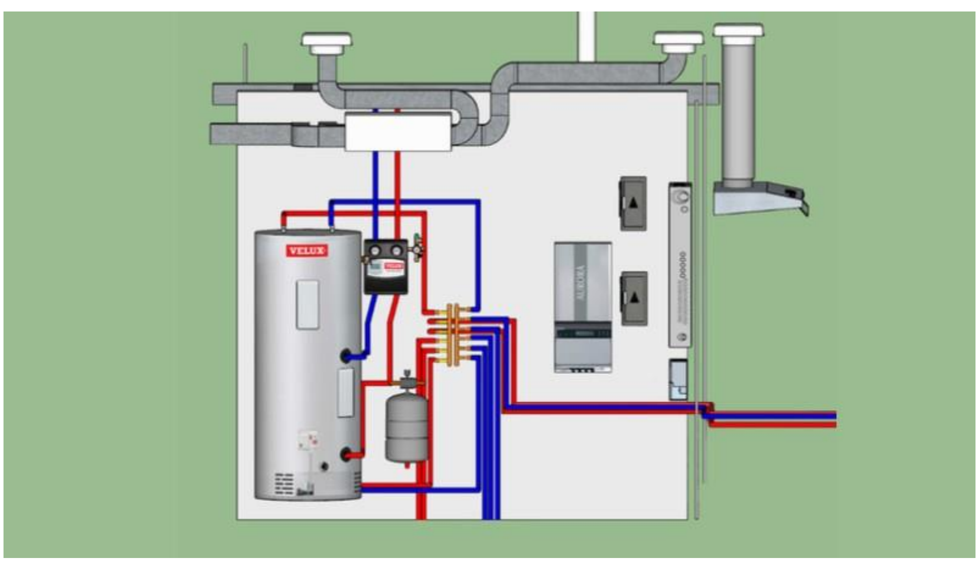



Figure 17. Section view of the summer studio mechanical room taken from the Sketchup model. The water tank is on the left, plumbing lines are in blue and red, electrical components are on the right, and HVAC is suspended above.

The mechanical room for this house was extremely compact. Bay doors opened from the east and gave access to a wall of equipment. While the design fit and met the bare requirements it was starting to sacrifice some of our design goals. For starters the cramped space in the room was starting to push the limits of equipment clearances. This would have a detrimental effect on the ease of installation and maintenance. Another concern was that the room would not end up looking very tidy. The largest contributor to this was the centrally located PEX manifold. This system of plumbing lines extended out from the center of the room in all directions and would likely look much messier than what is shown in our diagrams.

Architects went through another round of redesigns which drastically changed the house design. They kept the idea of a centralized mechanical space but stretched it out into a bar module. This helped place more emphasis on the mechanical room and greatly increased its size from around 30 square feet to 64 square feet. The increased size of the layout gave all the equipment more breathing room and largely resolved many of the issues with the previous design. Most of the ground level equipment has been concentrated to the left to make room for a potential storage space on the right. The ventilation units are still suspended from the ceiling but now have a much simpler circulation route than before. Previously the intake and exhaust vents were too close to one another due to the cramped space and had to be extended past the confines of the restrictive mechanical room. With the new design, supply air was simply drawn from the south of the mechanical room and later exhausted out of the house through the north side. This ensured efficiency and prevented the system from rebreathing vented air which was now separated by the room itself.

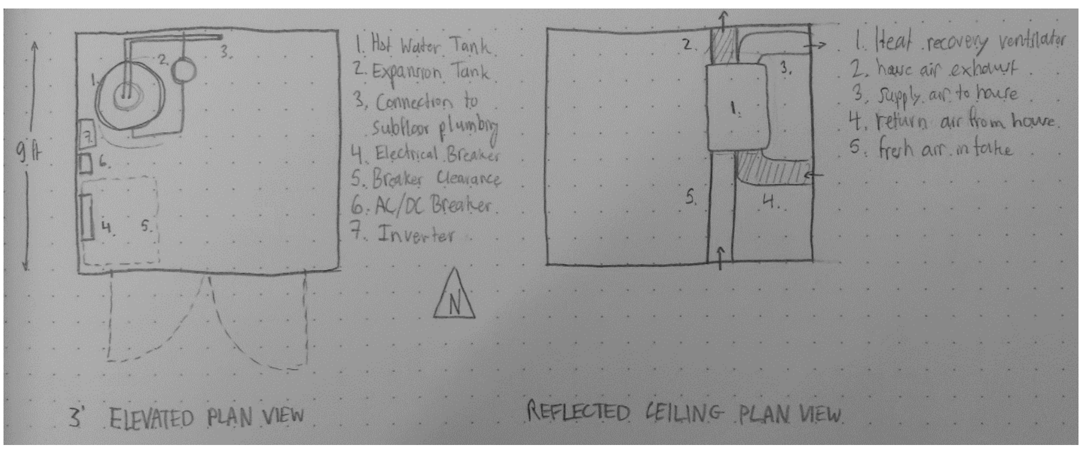



Figure 18. Sketch of the first iteration of the mechanical room for the house design with an extended mechanical bar.

The mechanical room however did still have some issues. The main concern was that the doors were located to the south and would therefore receive excessive solar irradiation causing the entire space to heat up to uncomfortable levels. An initial fix to this was to add extra insulation to the room to prevent heat from leaking in through the door and walls. A protective rain screen and shading device would then be wrapped around the perimeter of the mechanical room to provide some defense against the sun. These measures however would prove to be relatively costly and also began to interfere with the clean exterior look the architects wanted.

After coordinating with the other teams, it was decided that the simplest fix would be to move the door. With help from the architect we were able to alter the design such that the mechanical room door was now on the east side. This move took it out of the direct sunlight and also placed the door in a recessed portion of the main mechanical bar which helped provide additional shading. Further alterations to the mechanical room layout were a response to changes from other engineering teams. The HVAC team decided that the house would now be using ducted systems for both ventilation and conditioning. This meant that an air handler now had to be added to the space. Adding new equipment however was not much of a concern because the mechanical room already had space to spare, especially near the ceiling. A sketch of the mechanical room is in figure 19. There is ample space for ease of access and also storage. All mechanical systems can be seen superimposed on the house layout in figure 20. This image, taken from Revit, helps to demonstrate the organized and linear connection of all systems which will greatly improve efficiency and installation time during the competition.

More changes to the mechanical room were anticipated due to the implementation of a Scheffler dish for the house. This solar concentrating dish will focus light onto a receiver plate integrated into the southern wall of the mechanical room. On the inside a container of phase change material will then store thermal energy to be used for water heating and cooking. The dimensions of this system will be detailed in the future but for now there is enough extra space in the mechanical room to allow for design flexibility. This is no longer in effect as the Scheffler dish proved too costly to work into the final design.

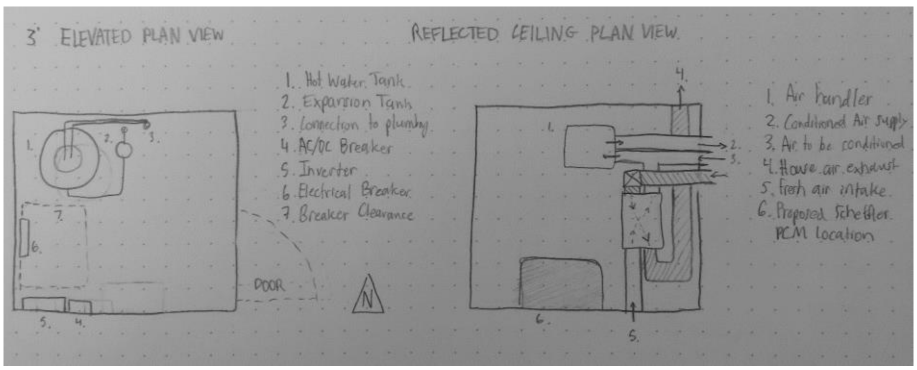



Figure 19. Sketch of the mechanical room with east facing doors and the added Scheffler thermal storage unit.

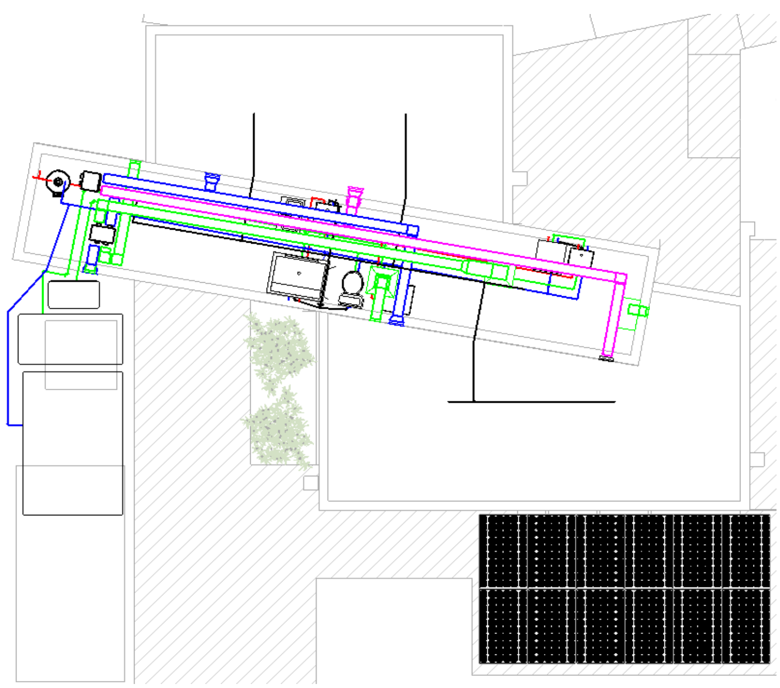


Figure 20. Revit layout of the tilted core house design with all mechanical systems.

# Final Design

## Appliance

The appliance choices are below, but these are still subject to change. It is possible that there will be more than two manufacturers because there might be another appliance pass based on the appliances analyzed so far to get the minimal energy use possible.

Table 9. Appliance selection for Winter 2015 analysis.

| **Appliance** | **Brand** | **Model #** | **kW use per hour/use** | **Energy Usage (best)** | **Cost ($)** |
|---|---|---|---|---|---|
| **Refrigerator** | Whirlpool | WRT134TFDW | 0.04 kWh | 7.66 kWh | 699 |
| **Microwave Oven** | Whirlpool | WMH76719CS | 1.6 kWh | 4.8 kWh | 569 |
| **Stovetop** | Whirlpool | W5CE3024XS | 2.5 kWh | 10 kWh | 649 |
| **Dishwasher** | Whirlpool | WDF320PADW | 1.25 kW per use | 6.25 kWh | 549 |
| **Washer/Dryer** | LG | WM3997HWA | 0.3 kW per use | 2.4 kWh | 1709 |
| **Total** | | | | 31.11 kWh | $4,175 |

## House Shading Devices

The final design for shading the house is a marriage of engineering and architectural concepts. Broadly speaking the shading plan seeks to shade the house in three ways. The first two are the awnings and the wooden lattice screen which have the largest effects on the cooling load. The third shading feature includes the use of blinds or shades on the windows but due to the relatively negligible effect of these compared to the first two features, they do not figure into our analysis.

### Awnings

The architectural plan called for two large, south facing windows to provide proper daylighting and a sense of openness. Both of these risked overheating the house and required shading.

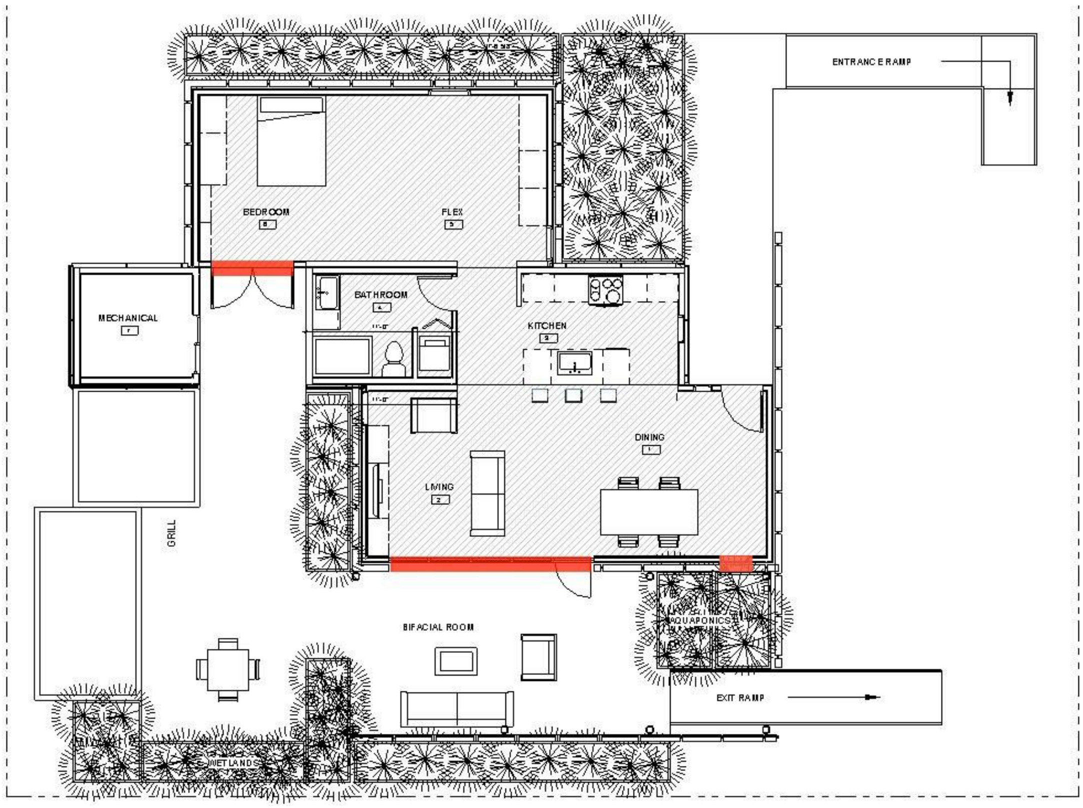



Figure 21. Overhead view of the house design with the two largest, south facing windows highlighted in red.

Figure 22. Side view of the south of the house with the two largest, south facing windows highlighted in red.

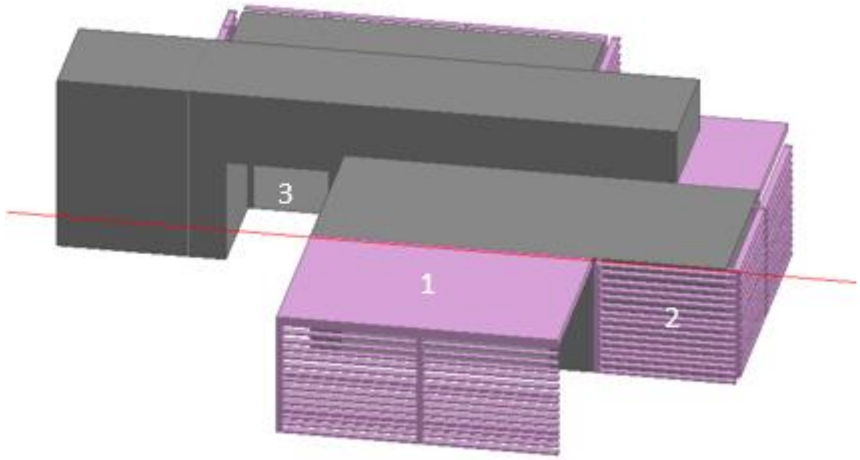



Figure 23: Awnings and shading elements used for analysis. (1) Bifacial panels, (2) south east living room window, and (3) receded bedroom access doors

Sun-Path charts were configured for both San Luis Obispo (35.28° N, 120.65° W) and Irvine (33.66° N, 117.82° W) in California using the Sun Path Chart program for EES. These two locations were considered as they represent the house location both during and after the competition. Three key south facing windows of the house were then designated as collector surfaces and analyzed to determine their shading conditions.

The first location chosen was the glass Nana wall indicated with a "1" in figure 23. Dimensions for the awning in front of it were used from the latest architectural house model. The awning perimeter was then described in azimuth and altitude angles from several reference points. Three reference points were chosen at the center of the window at 0, 2, and 4 ft off the ground to better describe partial shading on the Nana wall. The three pairs of angles were then superimposed on sun path charts to create a shading chart which describes at what month of the year and time of day the window will be shielded from the sun.

Since Irvine and San Luis Obispo are relatively close to each other based on latitude and longitude, their sun path charts are almost identical. The largest windows of the entire house are in the south wall of the living room. These are Nanawalls which are clear glass sliding doors made from three panels 5 ft wide and 8 ft tall. An awning of bifacial photovoltaics were placed in front to offer protection. A shading map was generated (Figure 23). It appears that the window is completely shaded from 9 am to 3 pm during the summer and is only half shaded from 8:30 am to 3:30 pm during the winter in Irvine.

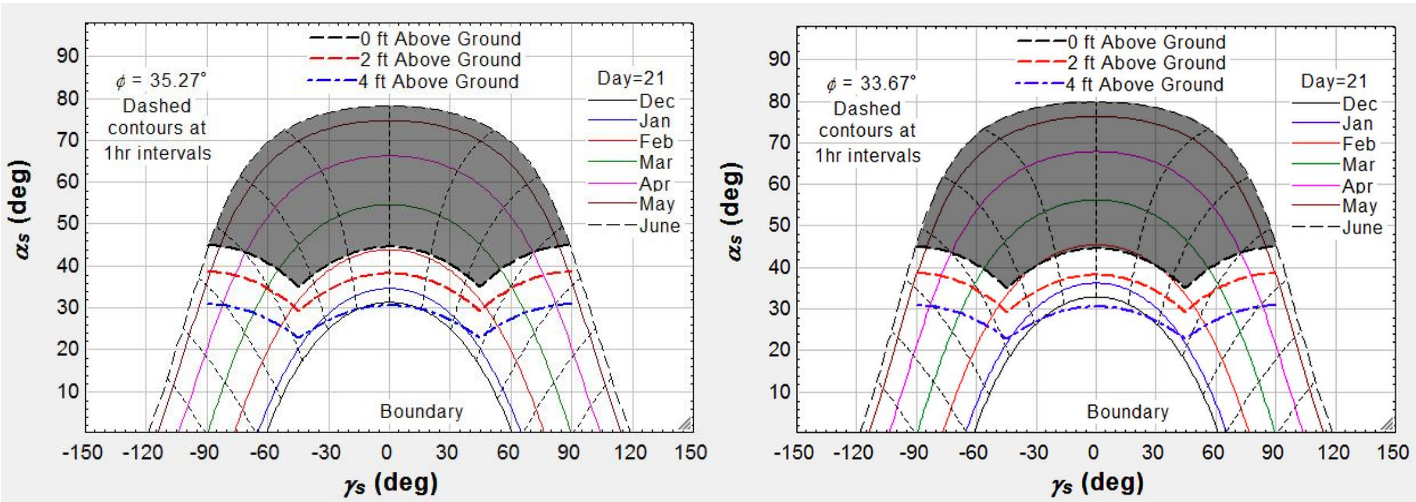



Figure 24: Irvine (right) and San Luis Obispo (left) shading chart for the large, south living room window(nana-wall). The darkened region represents complete shading during those time periods.

The double doors leading to the master bed room were recessed into the central core to protect it. A shading map was then generated for the window to assess its exposure (Figure 24). The calculations determined that direct sunlight will never reach the top half of the window at any point during the year in Irvine. The bottom half of the window will only receive direct sunlight between 10:30 am and 1:30 pm during the winter. These results show that the window is well protected from direct sunlight throughout the year.

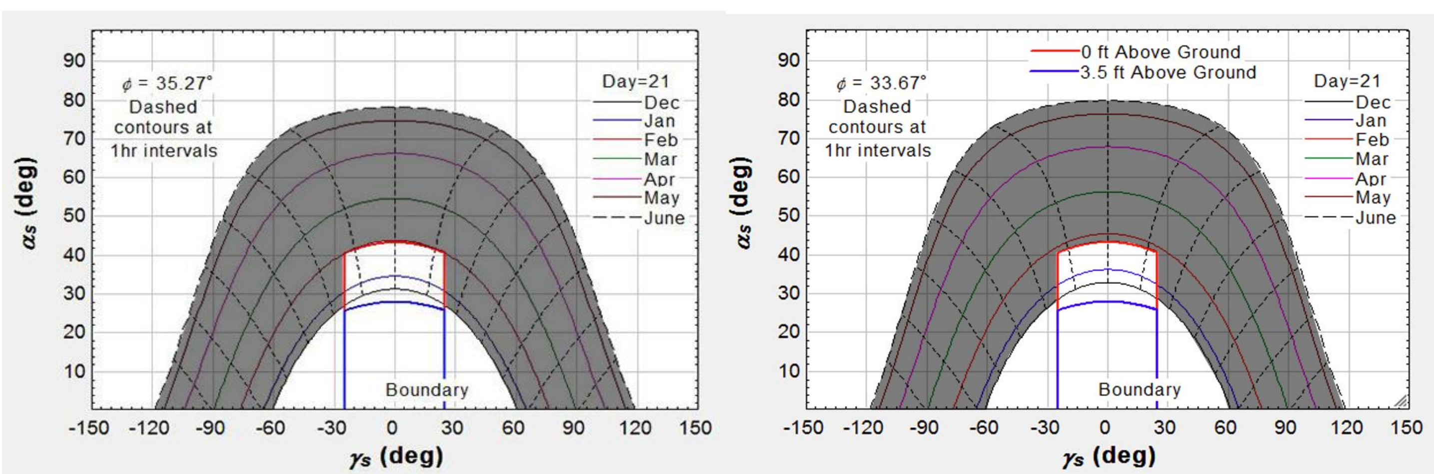



Figure 25. Irvine (right) and San Luis Obispo (left) shading chart for the south bedroom window. The darkened region represents complete shading during those time periods.

The south east window of the living room is important for providing illumination in an otherwise dark corner of the house. A shading diagram was once again constructed but this time with the goal of determining if there was enough sunlight passing through the opening (Figure 25). The shading features include the main bifacial awning along with a small addition being considered by the architects. Without the addition, the window will only be shaded between 3 and 6 pm throughout the year. Implementing the addition however, will mean that shading occurs from 11am to 6 pm during winter months.

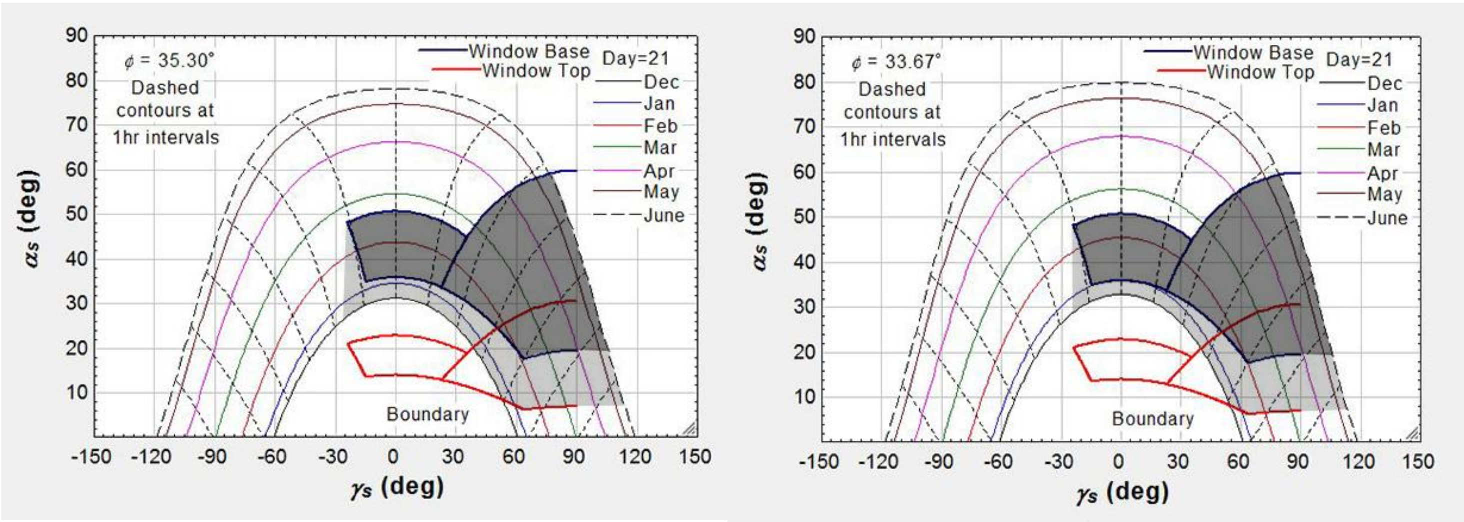



Figure 26. Irvine (right) and San Luis Obispo (left) shading chart for the shading element next to the south eastern living room window. The darkened region represents complete shading during those time periods.

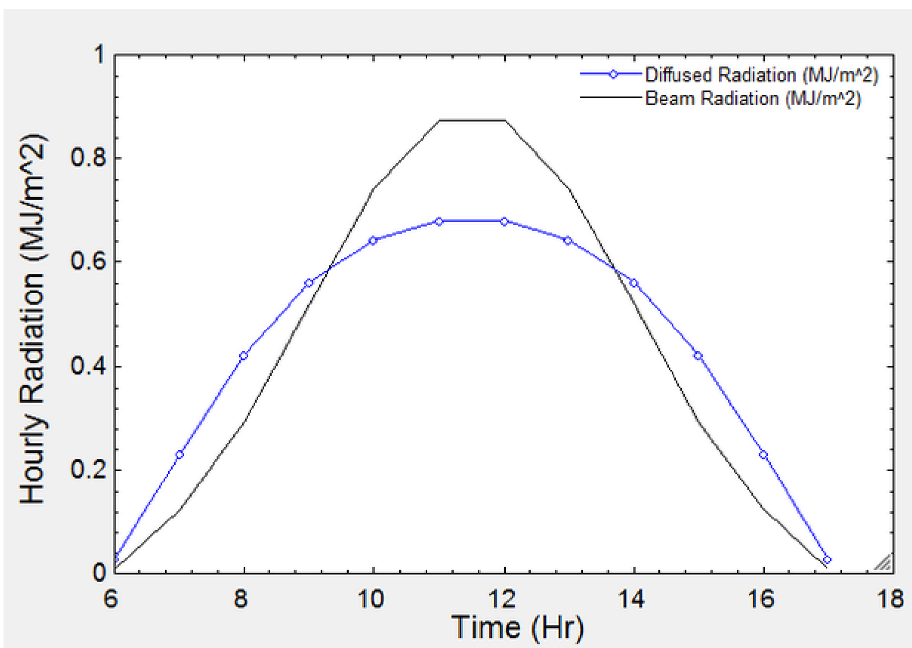



Figure 27. Diffuse and beam radiation on a vertical surface on a typical October day in Irvine.

## Wooden Lattice Screen

The house is further protected by a wooden screen. This structure does not completely surround the house to reduce expenses. From an architectural standpoint the application of the wood on just the northern and southern modules helps differentiate the mechanical core visually. This structure stands off from the house several inches to allow natural convection to take place.

Figure 28. View of the northeast side of the house with the surrounding screen system.

An additional wooden screen was added to the southern and eastern sides to form a comfortable, semi-private outside deck. This has the benefit of further shading the southern side of the house, particularly the large Nanawall. The spacing of the vertical and horizontal beams vary from location to location. Fine tuning of this particular arrangement is still in progress and awaits further analysis.

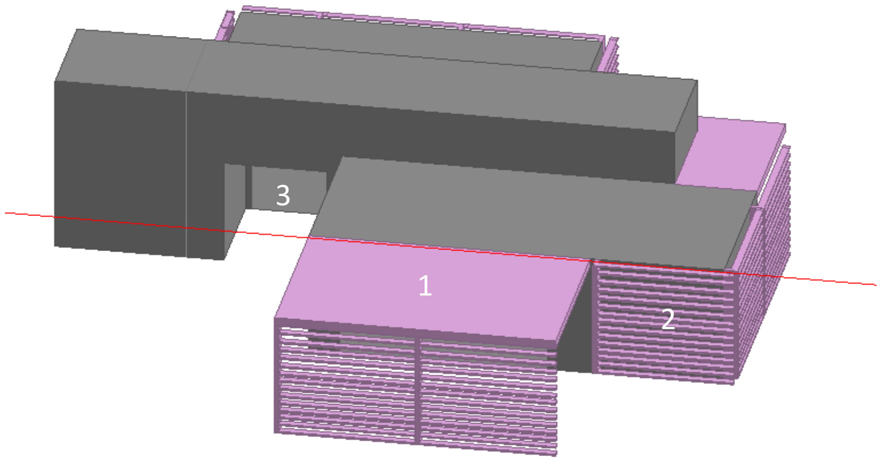
Figure 29. A closer view of the outdoor bifacial room with the second layer of screen for shading and privacy.

All cooling load calculations were run without the addition of the wooden lattice screen. This was in part due to the difficulty of modelling the intricacies of the screen in Design Builder but was also done as a way to provide an extra factor of safety to our cooling load estimates.

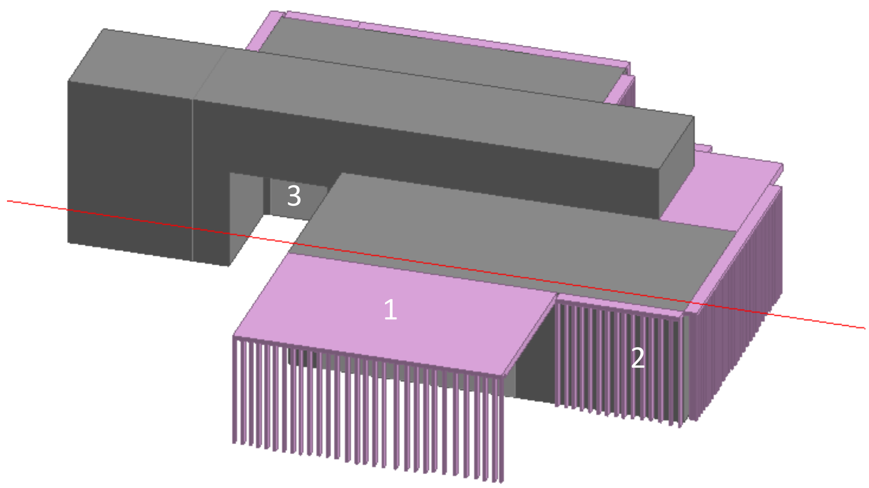
## Design-Builder Analysis – Screens

The shading the screen was analyzed using Design-Builder. In this case, we modified a preexisting version of the Solar Decathlon house which was already tuned for thermal analysis. The current architectural design for the screen calls for a pattern of vertical and horizontal wooden beams wrapped around the exterior of the public and private modules. Dimensions were gathered from the architects and used to construct a version of the house with vertical slats and one with horizontal slats. The screens consisted of

2in x 6in wooden slats aligned vertically or horizontally. Both orientations were analyzed in the study. According to the Architecture model, a 12in gap was input between the screen and the house wall. The windows used in the model had a SHGC of 0.3 (Solar Heat Gain Coefficient) and a U-factor of 0.3. Both of these were run through cooling load calculations to determine whether one orientation was more effective than the other. The screen with the most optimal orientation would then be compared to a house without a screen to see what the actual benefits of this passive element amount to.




(a)




(b)

Figure 30. Design Builder models with horizontal (a) and vertical (b) screen orientation shown as pink members attached to the house modules shown in grey.

The effect of the screen was analyzed by constructing a screen on each wall one at a time and analyzing their effect on the house. The two types of screens analyzed (horizontal and vertical) show that there is no difference between them and have the same effect on the house.

Table 10. Cooling Load reduction with the addition of screens

| | | Vertical/Horizontal (kbtu) | | | |
|---|---|---|---|---|---|
| | No Screen | South wall | Entire South zone | South Zone + North Wall | South Zone+ North Zone |
| South Zone | 4.3 | 4.3 | 4.1 | 4.1 | 4 |
| ME Room | 1 | 1 | 1 | 1 | 1 |
| Core | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 |
| North Zone | 2.2 | 2.2 | 2.2 | 2.1 | 2 |
| Total | 10.8 | 10.8 | 10.6 | 10.5 | 10.3 |
| Percent Difference | - | 0 | 2% | 3% | 4% |

It can be seen from the Table 10 that there was a 4% reduction of cooling loads with the help of the screen. The thickness of the slats in the screen would be directly proportional to reduction in cooling loads and their spacing is inversely proportional to the reduction in cooling loads.

## Solar Resource – Tilt Angles

Three different angles were analyzed for sun exposure. 0, 10, and 30 degrees were chosen because of how the house is built and the optimal tilt for the solar collectors. 0 degrees is the current tilt of the solar collectors, and where the architects want to keep the tilt because of its symmetry with the house. A tilt of 30 degrees was analyzed because, usually, the best tilt angle for sun exposure is the latitude at which the panels are placed. Irvine has a latitude of 33° and San Luis Obispo has a latitude of 35°, so 30° was a good estimate. If it is proven to the architects that a tilt would be beneficial, then they said that they would be willing to tilt the panels 10 degrees, in order to do minimal damage to their concept of straight lines and modern designs. That is why 10 degrees was also analyzed, to see if the difference between 0 and degrees was substantial enough to promote a change in the tilt angle.

The EES code was used to vary tilt angles and months in order to receive results on which angle has the most solar radiation associated with it. Once the tilt angle and month were programmed into the EES code, it ran and gave a range of vales for the hourly radiation normal to a tilted surface at different hours of an average day in a month, 7AM-5PM. These hours were used because the sun exposure during the other parts of the day would be minimal to none and negligible amounts of radiation would reach the solar collectors.

The three angles were tested for the month in October, because that is when the competition is being held, using two different clear sky models, HDKR and LJ, in order to see how different each model performed. These graphs may be found in the Results section. January was also analyzed with the varying tilt angles for the hours of 7AM-5PM using the HDKR model in order to see how the solar collector would perform in the winter months. Four months, January, March, July, and October, were analyzed and their average day hourly radiation values were added up to get a value for the average day total radiation that hit the solar collectors. Months throughout the year were analyzed because the house is not just built for the 2015 Solar Decathlon. It is also built to be a year-round house for either future clients to live in or future students to learn about. In order to achieve an optimal compromise, the best angle for the most year-round sun exposure should be used.

From the EES code, the hourly normal radiation on a tilted surface for an average day in October was found for the time between 7AM and 5PM. Table X shows the data for each hour with the three different angles that were analyzed.

Table 11. Hourly radiation values for an average day in October with different tilt angles of the solar collector.

| Time | 30 degrees | 0 degrees | 10 degrees |
|---|---|---|---|
| 7 | 0.91 | 0.52 | 0.66 |
| 8 | 2.09 | 1.45 | 1.70 |
| 9 | 3.32 | 2.43 | 2.79 |
| 10 | 4.41 | 3.29 | 3.75 |
| 11 | 5.15 | 3.88 | 4.41 |
| 12 | 5.42 | 4.09 | 4.64 |
| 1 | 5.15 | 3.88 | 4.41 |
| 2 | 4.41 | 3.29 | 3.75 |
| 3 | 3.32 | 2.43 | 2.79 |
| 4 | 2.09 | 1.45 | 1.70 |
| 5 | 0.91 | 0.52 | 0.66 |
| Total | 37.18 | 27.23 | 31.27 |

In order to help the architects understand the numbers generated from the analysis, the percent difference, Table X, was calculated. This shows how much improved the hourly radiation would be if the solar collectors were tilted. In October, over the course of an average day, the average improvement for a 10 degree tilt versus no tilt would be around 14.5%. This may not seem like a lot in the grand scheme of things, but a 14.5% difference can mean the difference between procuring enough hot water for the contests, and not.

Table 12. Percent difference between the different tilt angles for an average day in October.

| Time | % difference (0&30 degrees) | % difference (10&30 degrees) | % difference (0&10 degrees) |
|---|---|---|---|
| 7 | 42.90 | 26.84 | 21.96 |
| 8 | 30.62 | 18.52 | 14.86 |
| 9 | 26.91 | 16.01 | 12.97 |
| 10 | 25.35 | 14.93 | 12.24 |
| 11 | 24.65 | 14.46 | 11.91 |
| 12 | 24.46 | 14.33 | 11.83 |
| 1 | 24.65 | 14.46 | 11.91 |
| 2 | 25.35 | 14.93 | 12.24 |
| 3 | 26.91 | 16.01 | 12.97 |
| 4 | 30.62 | 18.52 | 14.86 |
| 5 | 42.90 | 26.84 | 21.96 |
| Average | 29.58 | 17.80 | 14.52 |

Below, in Figures 31 and 32, shows the results of the HDKR and LJ models for the month of October in graphical form. Both models show about the same results, which is as it should be, and the both show that tilting the solar collectors even 10 degrees would increase the performance.

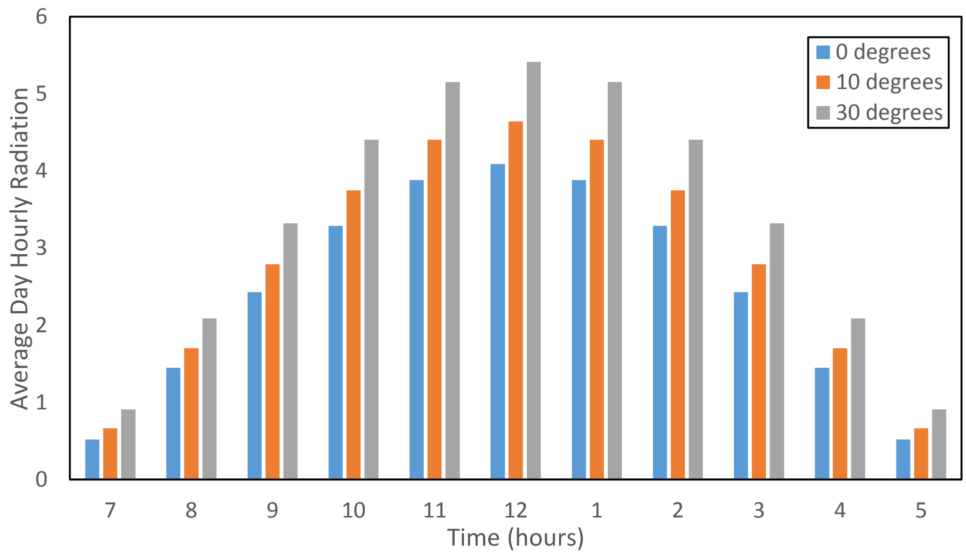


Figure 31. October average day hourly radiation with varying tilt angles – HDKR model.

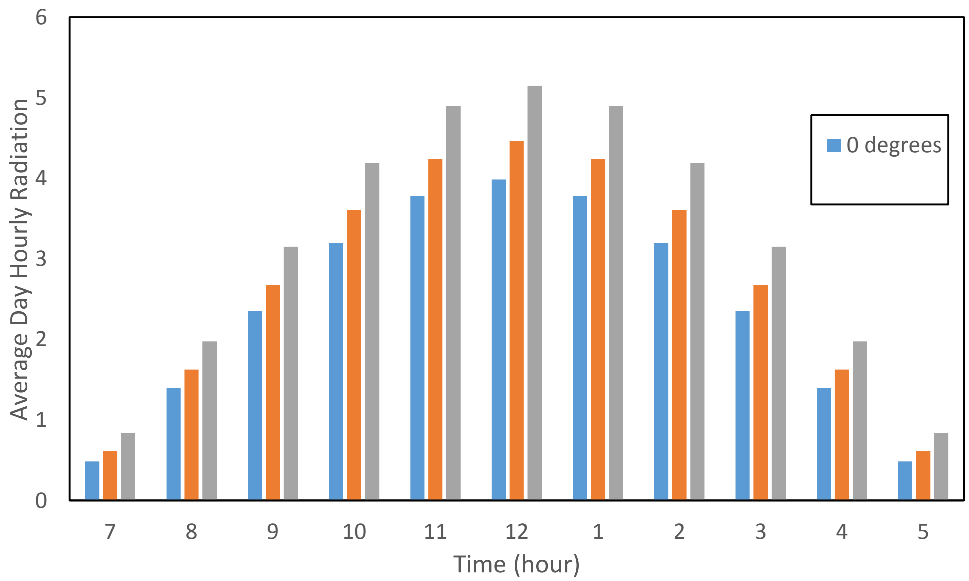


Figure 32. October average day hourly radiation with varying tilt angles – LJ model.

Since this house will hopefully be used year-round, it was crucial to analyze the tilt of the solar panels for other months as well as October. Usually, hot water is used in the winter months, so that is when production of hot water should be the most efficient and largest. The month of January was analyzed in order to see how much the average day hourly radiation would be improved if the panels were tilted. As can be seen in Figure 33, the tilted surfaces have a better ability of collecting radiation because the sun is in the lower, southern part of the sky and the tilted surfaces are more normal to it than a flat panel. The percent difference is also larger in January, and an increase from 0 to 10 degrees would improve the performance by 23.5%.

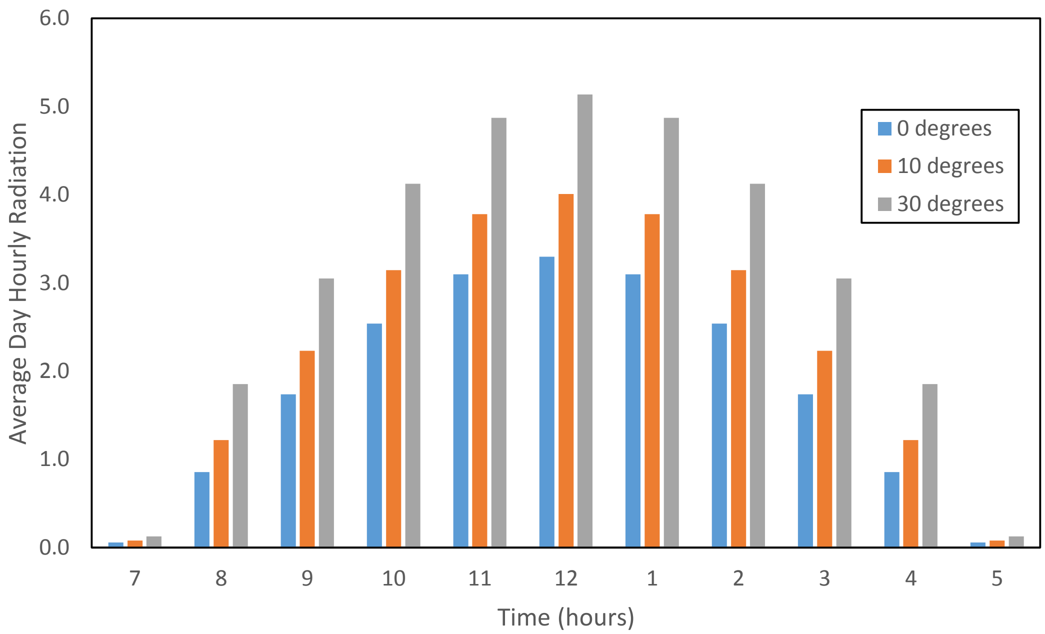



Figure 33. January average day hourly radiation with varying tilt angles – HDKR model.

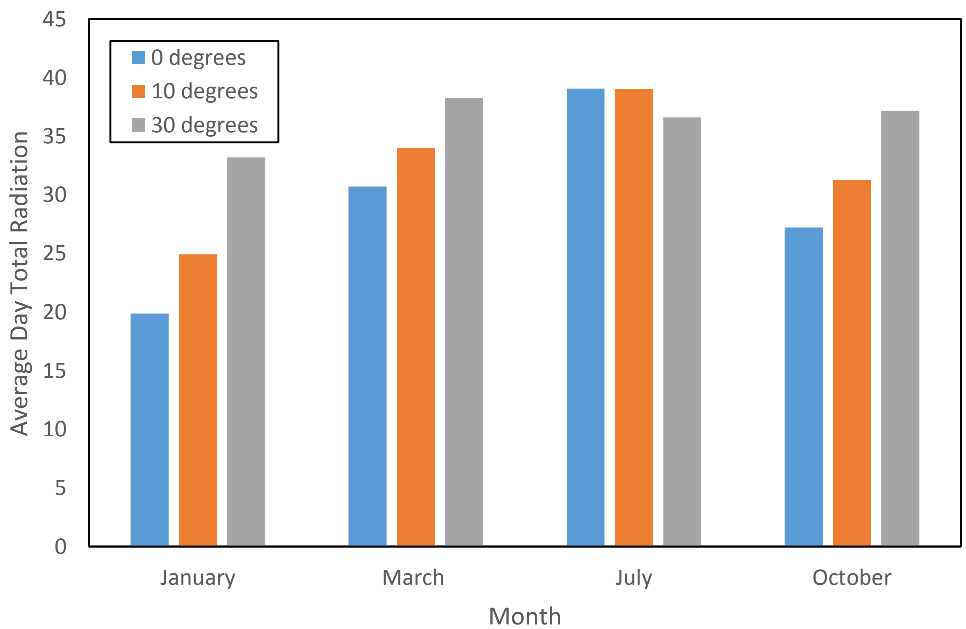



Figure 34. Total average day hourly radiation with varying tilt angles for different months throughout the year.

As stated above, this house will hopefully be used year-round, so it was important to see how the solar collectors performed throughout different parts of the year. In Figure 34, it shows the total radiation for an average day for four different months. In January, March, and October, it is much better to have a tilted solar collector than to have a flat one. In the summer months, however, the radiation on the collectors is about the same, and even lower if the tilt was 30 degrees. Although in the summer months the tilt of the collector might not matter, in an overall year, it is better for the solar collectors to be tilted in order to receive the maximum amount of radiation possible in order to produce hot water for the house.

## Effective Glazing

The next line of defense against heat gain in the house is the windows. As was discussed, the amount and the placement of the glazing in the house has been an ongoing compromise between the architectural and engineering needs. The total amount of glazing has been kept to a minimum. Traditionally it is recommended that energy efficient homes keep glazing down to about 20% of the total square footage of the house and that windows have a U factor and SHGC of 0.3. It is clear that these broad generalizations were merely guidelines and further research had to be conducted to determine what was best for our house.

The current glazing is 27.5% of the total square footage of the house. While this is higher than recommended, we have made sure that all of the windows either face north or that the house shading features protect them. The next step involves determining what the actual U factor and SHGC have to be. Many iterations of Design Builder cooling calculations were run as a way to measure sensitivity. The figure below demonstrates how the house performance is more greatly influenced by the SHGC. This means that we should focus our efforts on tuning this factor.

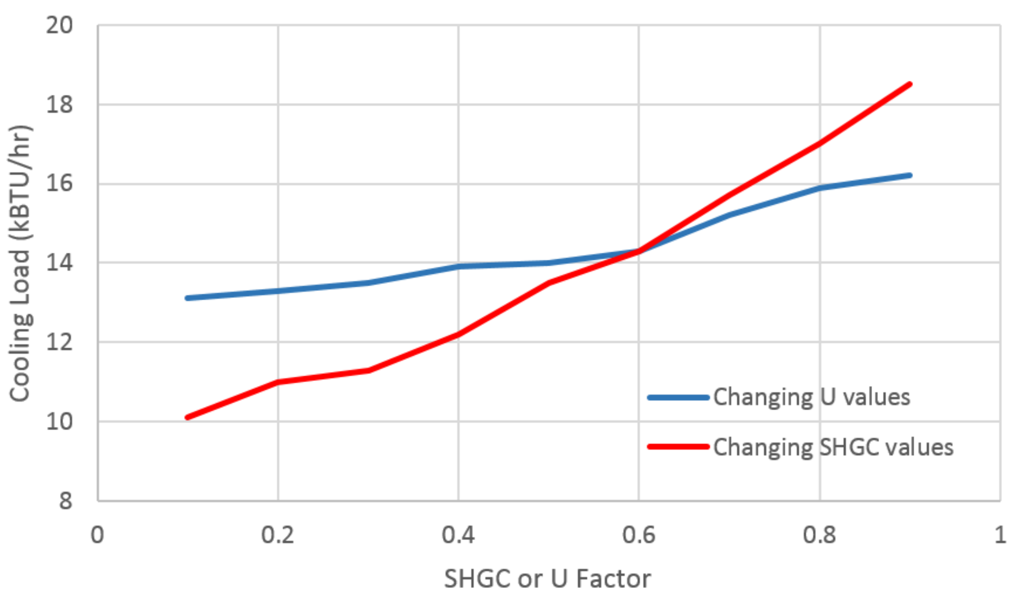



Figure 35. Sensitivity analysis for the effects of cooling loads versus window characteristics. The analysis was run by setting both the U factor and SHGC for all windows in the house at 0.6 and then holding one variable constant while the other was varied from 0.1 to 1.

The SHGC has to do with the amount of heat that enters the house due to solar radiation. It stands to reason therefore that windows exposed to the most sunlight on the south side of the house should have better SHGC while those in the north should not. This was tested again through a series of Design Builder calculations. The iterations were focused around determining how the investment in south facing windows would affect the performance of the house when the rest of the windows had non recommended U factors and SHGCs.

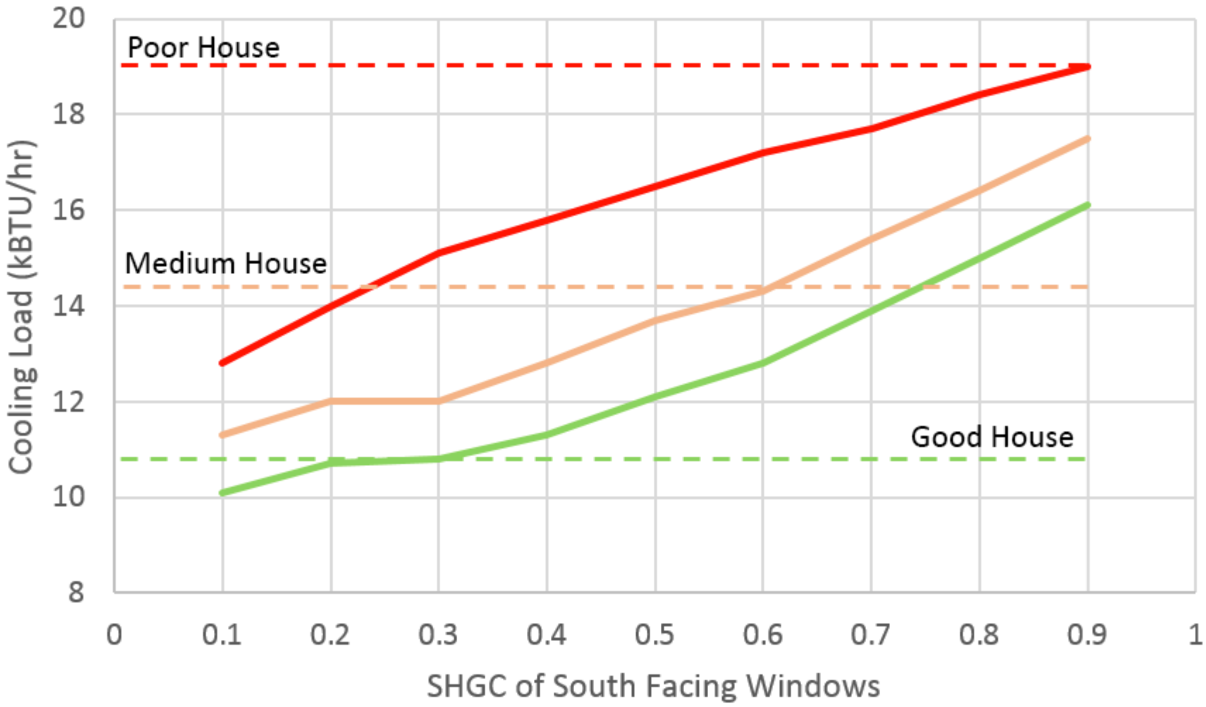



Figure 36. Sensitivity analysis for the effects of cooling loads versus south facing window characteristics. The analysis was run by setting both the U factor and SHGC for all windows at varying levels to represent a poor design (U=0.9, SHGC=1) a medium design (U=0.6, SHGC=0.6) and a good design (U=0.3, SHGC=0.3) which are marked as dashed horizontal lines as the resulting cooling load. From these tiers of house designs, just the southern windows were subjected to a range of changes to their SHGC from 0.1 to 1 and their resulting cooling loads calculated.

The results of the iterations are listed in the figure above. It appears that we do not necessarily need to have all the windows at the recommended values where U=0.3 and SHGC=0.3 which results in a cooling load of about 11 kBTU/hr. A poorly designed house (U=0.9, SHGC=1) with an initial cooling load of 19 kBTU/hr could go all the way down to about 13 kBTU/hr with a SHGC set to 0.1. Getting a value that low might be expensive but it could be offset by the fact that all other windows could be much cheaper. A house with a medium design (U=0.6, SHGC=0.6) could drop its cooling load from 14.5 kBTU/hr to 12kBTU/hr just by making sure the south facing windows have a reasonable U factor of 0.3. Alternatively it can be seen that a good design (U=0.3, SHGC=0.3) quickly degrades in performance if the south facing window values are increased.

The conclusion of these results are that we could save money by using windows of only medium quality (U=0.6, SHGC=0.6) and only having the south facing windows at the recommended SHGC value of 0.3. Doing so will result in a cheaper house which performs comparably to the recommended window design.

## Mechanical Room

The design of the mechanical room has been continuously refined to make room for the changing mechanical systems. The latest design can be seen below which has been neatly organized to make room for all required devices. The final space has more than the recommended clearance required by manufacturers and allows for ample space for ease of access as well as potential storage room.

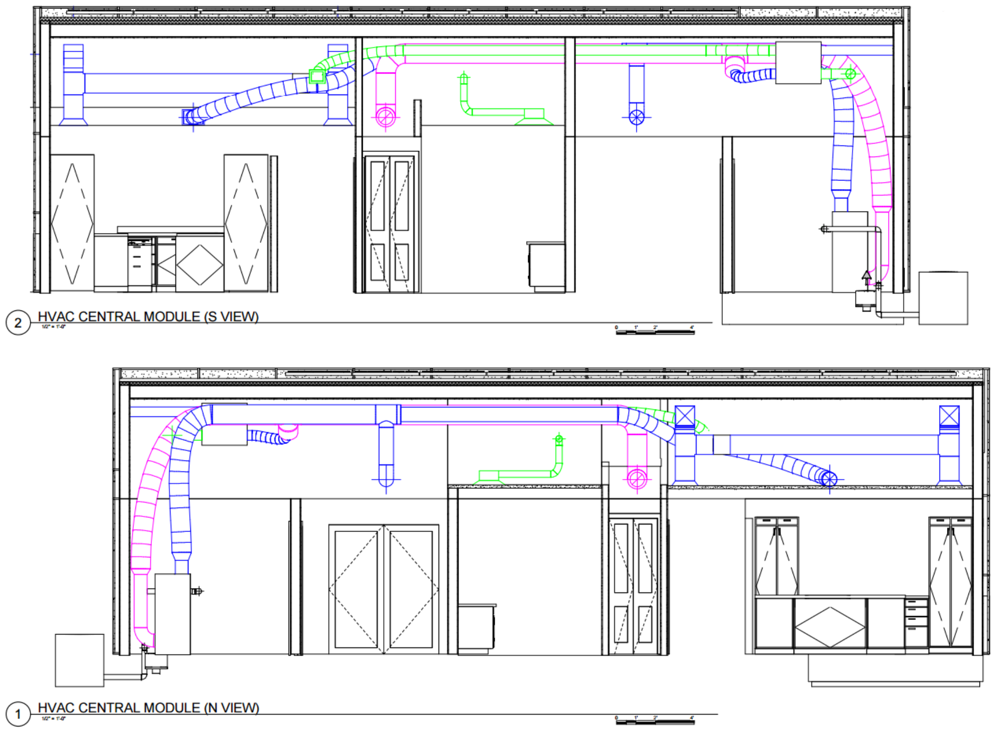



Figure 37. (Bottom) East-West cross section of the central module looking north. (Top) Ease-West cross section of the mechanical module looking south.

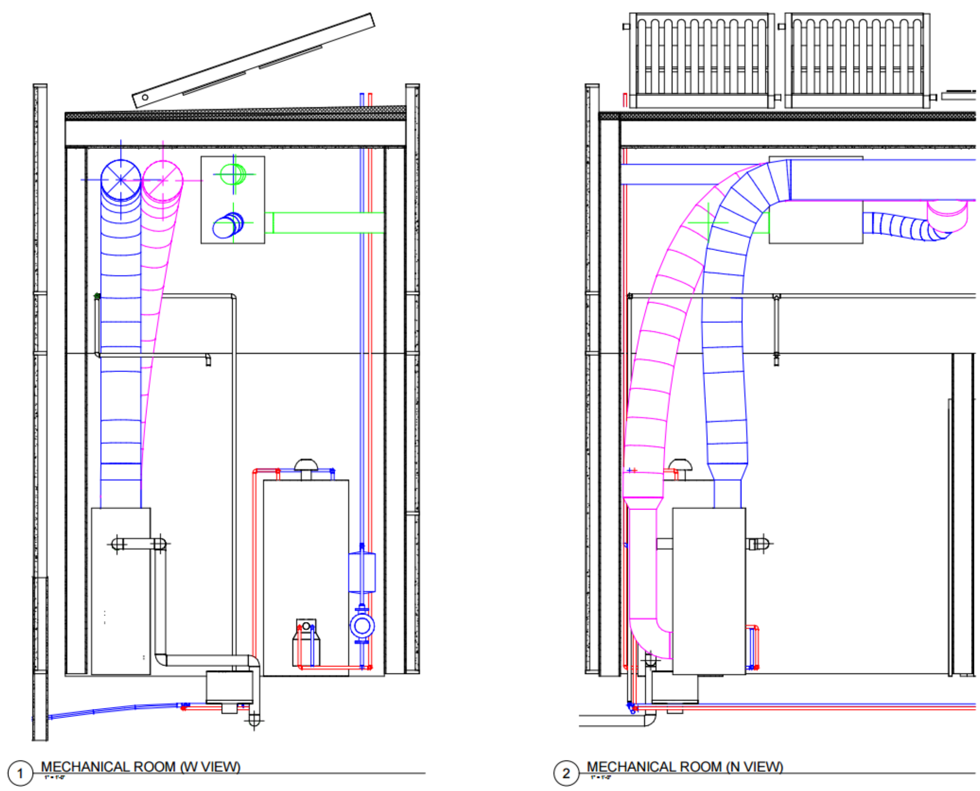



Figure 38. (Left) North-South cross section of the mechanical room facing west. (Right) East-West cross section of the mechanical room facing north.

## Thermal Mass (Phase Change Material)

A large part of the passive design was achieved with the use of Phase change materials (PCM) in 2 different applications. Weather Underground was used to determine the historical weather data for Irvine for the month of October. The average highs of the month was determined to be approximately 72 F (23 C) and average lows was 68F (18 C). Thus, 72F was chosen as the set-point temperature of the PCM used.

### Standard BioPCM Sheets

The first application was to use PCM in the walls or ceilings embedded between the OSB and Gypsum on the innermost layer of the both the walls and ceilings. The restraint on this application was the space available in the walls/ceilings, which was determined to be 2 in based on architectural and structural concerns.

Amongst the available bio-PCM sheets given by Phase Change Solutions, the only available sheets are designated as M91/Q23 (1.46 in thick) and M51/Q23 (0.82in thick). The first part of the designation M91 or M51 is the normalized latent heat of fusion and Q23 is the set-point temperature (23C or 72F) as stated above. The thickness of M51/Q23, thus one sheet of M91/Q23 or two sheets of M51/Q23 would be used. This application would be entirely passive and thus it was essential to determine its contribution to the reduction on the HVAC load of the building.

Design-Builder was used to determine the appropriate PCM location and its corresponding contribution to the reduction of HVAC load.

When modeling PCMs or other materials that have variable thermal properties in Energy-Plus, one cannot use the default, Conduction Transfer Function (CTF) Heat Balance Algorithm, as the thermal properties cannot be updated at every time-step with this method. Thus, we used the Conduction Finite Difference (CFD) Heat Balance Algorithm to account for the dynamic properties of the PCM.

A parametric study was conducted to determine the location and type of PCM and optimize its corresponding heat load contribution. The following table shows the results of the design-builder analysis to analyze the sensitivity of PCM in the walls/ceilings.

Table 13. Results of two types of PCM sensitivity on the house based on location.

| | | ME Room | North Zone | Core | South Zone | Total |
|---|---|---|---|---|---|---|
| | No PCM | 1 | 2.3 | 3.1 | 8.1 | 14.5 |
| M91/Q23 | All Wall and Roofs | 0.8 | 2 | 2.8 | 7.5 | 13.1 |
| | All Walls | 0.8 | 2.1 | 2.9 | 7.7 | 13.5 |
| | All Roofs | 0.9 | 2.1 | 3 | 7.9 | 13.9 |
| | | | | | | |
| | South Wall | 1 | 2.3 | 3.1 | 7.7 | 14.1 |
| | South Roof | 1 | 2.3 | 3.1 | 7.9 | 14.3 |
| | South Wall+Roof | 1 | 2.3 | 3.1 | 7.5 | 13.9 |
| 2 X M51/Q23 | All Wall and Roofs | 0.8 | 2 | 2.7 | 7.5 | 13 |
| | All Walls | 0.8 | 2.1 | 2.9 | 7.7 | 13.5 |
| | All Roofs | 0.9 | 2.1 | 3 | 7.9 | 13.9 |
| | | | | | | |
| | South Wall | 1 | 2.3 | 3.1 | 7.7 | 14.1 |
| | South Roof | 1 | 2.3 | 3.1 | 7.9 | 14.3 |
| | South Wall+Roof | 1 | 2.3 | 3.1 | 7.5 | 13.9 |

As expected, the results on Table 10 indicate that the ideal placement of the PCM is the south wall and ceiling. PCM in the south wall + south ceiling reduce the cooling load of the house by 4.14% (6 kBTU/hr). Both PCM types give approximately the same results even though the PCM volume in the two sheets of M51/Q23 is more than that of one sheet of M91/Q23. Thus, M91/Q23 should be used. This analysis is however limited by the shading screen that could not be modelled on design builder.

## Active PCM Heat Sink Duct

The second application of PCM analyzed was an independent system which comprises of a duct containing different ways arrangements of PCM and a fan to conduct heat exchange with forced convection. The diameter of the duct was 1.5ft.

The two arrangements of PCM analyzed were:

1) Rectangular sheets of PCM that are 0.5in thick, 16.5in wide and 96in long(0.5in x 16.5in x 96in) in parallel flow (Volume = 0.46 ft^3)

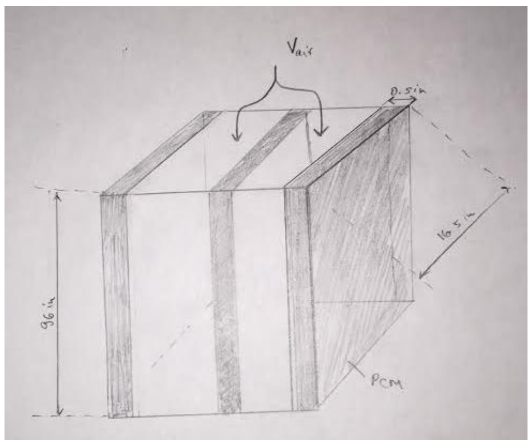



Figure 39. Flat plate heat exchange model for PCM

2) Cylinders of PCM (also called Therma-Sticks) with a hydraulic diameter of 2in and 6in length in cross-flow (Volume = 0.011 ft^3)

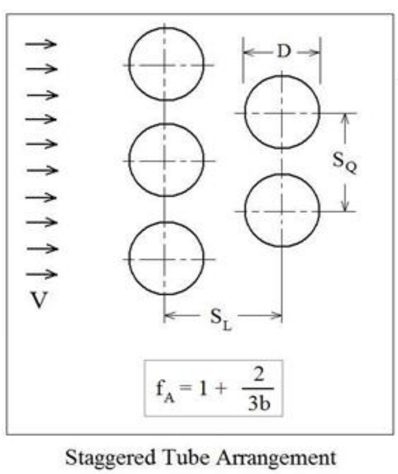



Figure 40. Staggered cylinders heat exchange model for PCM using Zurkhausius correlations

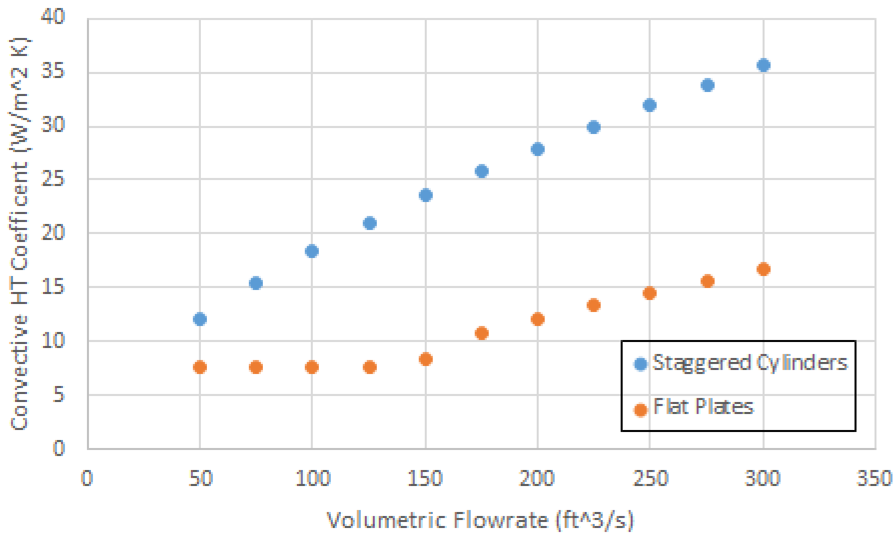



Figure 41. Comparing the convective heat transfer coefficient for flat plates and staggered cylinder arrangement. Note - The volume of PCM enclosed in the two arrangements is taken to be the same.

This graph shows that convection through staggered cylinders is significantly larger than that of flat plates. It also shows that the staggered cylinder in cross-flow is more sensitive to change in flow-rate.

Various parameters were varied to optimize the heat transfer in the staggered cylinder model. Each tube contained a PCM volume of 0.011 $ft^3$ and were subjected to cross flow in the duct.

Table 14. Parametric study varying the # sticks to determine the effective heat transfer coefficient. (1 row = 2 sticks)

| Rows -> | N = 5 | N = 10 | N = 15 | N = 21 | N = 30 |
|---|---|---|---|---|---|
| cfm | h (W/m^2K) | h (W/m^2K) | h (W/m^2K) | h (W/m^2K) | h (W/m^2K) |
| 50 | 11.19 | 11.8 | 12 | 12.16 | 12.16 |
| 75 | 14.27 | 15.05 | 15.31 | 15.51 | 15.51 |
| 100 | 16.96 | 17.88 | 18.19 | 18.43 | 18.43 |
| 125 | 19.39 | 20.44 | 20.8 | 21.07 | 21.07 |
| 150 | 21.63 | 22.81 | 23.2 | 23.51 | 23.51 |
| 175 | 23.73 | 25.02 | 25.45 | 25.79 | 25.79 |
| 200 | 25.7 | 27.1 | 27.57 | 27.94 | 27.94 |
| 225 | 27.59 | 29.09 | 29.59 | 29.99 | 29.99 |
| 250 | 29.39 | 30.98 | 31.52 | 31.94 | 31.94 |
| 275 | 31.12 | 32.81 | 33.38 | 33.82 | 33.82 |
| 300 | 32.78 | 34.57 | 35.16 | 35.64 | 35.64 |

Table 14 shows that the effective heat transfer coefficient is constant from 21 and above rows of cylinders. This suggests that adding more cylinders does not affect the heat transfer through the duct. The percent difference in the heat transfer coefficient from N=15 and N=21 is 1.33%. Thus, it can be concluded that 15 staggered cylinders may be ideal for the system.

Table 15. Parametric study varying the distance between the cylinders (SL and ST)

| SL=ST -> | SL = ST = 3 in | SL = ST = 4 in | SL = ST = 5 in |
|---|---|---|---|
| cfm | h (W/m^2K) | h (W/m^2K) | h (W/m^2K) |
| 50 | 12.16 | 7.857 | 7.169 |
| 75 | 15.51 | 12.16 | 10.9 |
| 100 | 18.43 | 14.45 | 12.96 |
| 125 | 21.07 | 16.52 | 14.81 |
| 150 | 23.51 | 18.43 | 16.52 |
| 175 | 25.79 | 20.22 | 18.12 |
| 200 | 27.94 | 21.91 | 19.64 |
| 225 | 29.99 | 23.51 | 21.07 |
| 250 | 31.94 | 25.04 | 22.45 |
| 275 | 33.82 | 26.52 | 23.77 |
| 300 | 35.64 | 27.94 | 25.04 |

Table 15 shows that the heat transfer coefficient for convection is inversely proportional to the distance between the cylinders. This is expected as each molecule of air would go through more obstructions and surface area leading to more heat transfer. Thus, 3in spacing was chosen.

Final design characteristics:

Table 16. PCM analysis.

| Model: | Number of rows: | Spacing: | Material |
|---|---|---|---|
| Staggered Cylinders | 75 (150 sticks) | ST = SL = 3in | Aluminum |

In the Mechanical Core, there is a 15’ 6” long space provided for the PCM duct to fit into. Each mechanical duct element took away from that space, and so whatever length was left determined how long the duct with the PCM in it would be. There was also a height constraint on the dampers and tee ducting joint because of the limited height in the core. Initially, it was planned that 12” ducting would be used for all ducts, but once the dampers and tee duct dimensions were combined, it was too close of a fit in the space provided. Now, all the ducting, not including the PCM duct, has a 10” round diameter in order for it to fit inside the core with enough clearance.

Table 17. Length of each ducting part.

| Part | Length (in) |
|---|---|
| Tee Ducting | 13 (x2) |
| Inline Fan | 10 |
| Round to Square Transition | 12 (x2) |
| **TOTAL LENGTH** | 60” (5’) |

With these final dimensions, the maximum length of the PCM duct could be was 10’ 6”. In order for clearance around the duct and room for mistakes to be made, a length of 9’ 6” was set for the PCM duct. Even with this very conservative length, it is still longer than 7’, the originally proposed duct length.

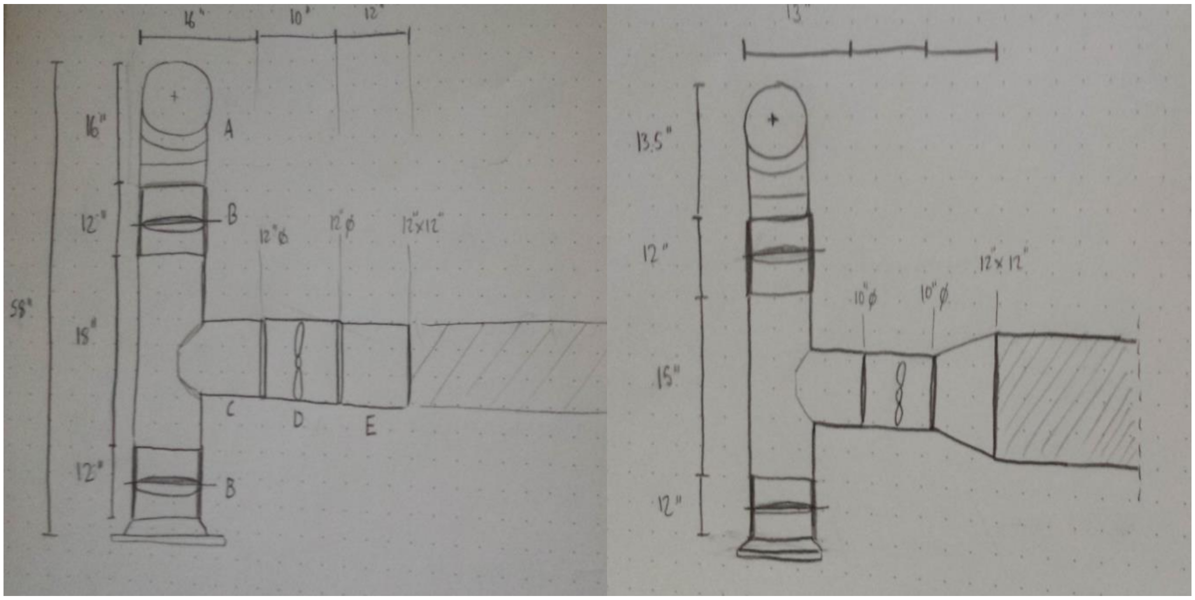



Figure 42. Preliminary PCM duct assembly indicating duct size changes and their effect on the total height.

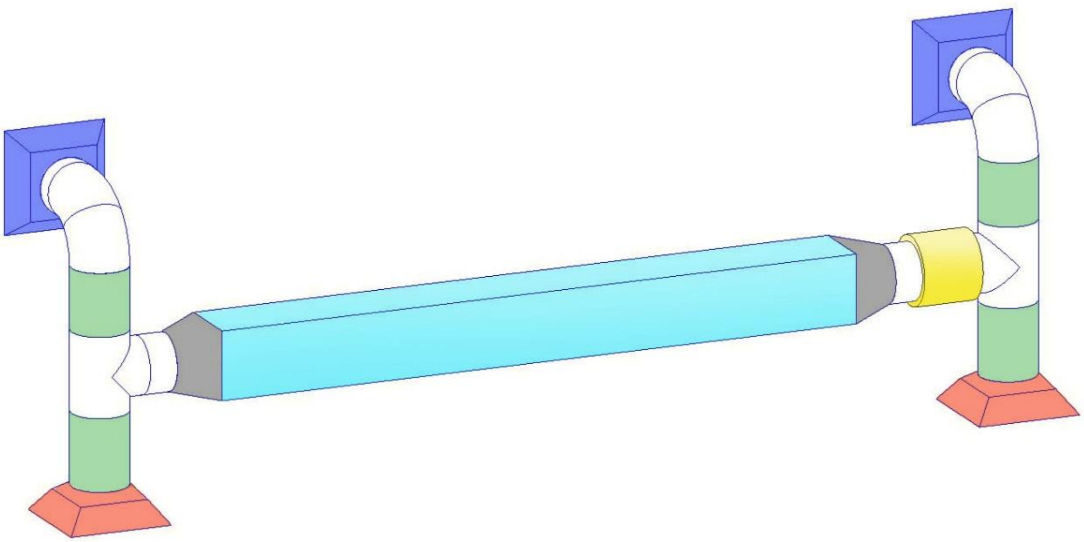


Figure 43. Latest PCM duct assembly. The phase change material (light blue) is a 1ft by 1 ft rectangular duct. Either side is then attached to transition fittings (grey) which neck down to a 10 inch round duct. An in line fan (yellow) is placed to one side of the duct assembly. Next the horizontal duct run is attached to 10 inch round tees. Either side of the tees are then connected to dampers (green) which can be opened or closed to control the mode of operation. Lastly the registers are attached to the duct ends. The interior registers (red) allow for air exchange with the house during the day while the exterior registers (blue) allow for air exchange with the environment at night.

Table 18. Part List for PCM duct

| Description | Quantity | Supplier | Brand | Model | Specifications |
|---|---|---|---|---|---|
| In-line fan | 1 | Home Depot | hurricane-fans | #736140 | 10 in dia; 10 in length |
| Round to Square transition | 2 | Home Depot | SPEEDI-BOOT | SBH-121210 SRA | 12x12" square to 10" round |
| Back Draft Damper | 4 | Home Depot | Speedie-Products | # AC-BD 08 | 10 in dia |
| Speed Control | 1 | Home Depot | DAYTON | #G5287764 | 4-1/2 X 2-3/4 |
| PCM - Thermastix | 150 | Phase Change Solutions | Phase Change Solutions | M91/Q23 | 2in dia x 6ft |
| Square Ducting | | | | | 12"x12" square by 9'6" long |
| Programmable Thermostat | 1 | Home Depot | LUX | PSP511C | 4-1/2" x 3-1/4" x 1-1/4" |

## PCM Duct Fan

In order for enough heat transfer to and from the Thermastix to happen, a minimum flow rate of 100 CFM must be provided. There would not be enough air flow over the PCM sticks in the duct without an inline duct fan. Once this was recognized in our design, three main concerns arose:

- Noise problems
- Fan stall problems
- Energy usage problems

This PCM duct is being placed inside a house, and no homeowner wants to hear the mechanical systems running. Especially because the PCM duct is placed over the kitchen space, it was crucial that the fan would run quietly and have a Reynolds number less than 10000 in order to minimize the fain noise.

Another problem that arose while designing the fan was the possibility of the fan stalling because the pressure head is very high since it is a long duct, it has obstructions (the Thermastix), and the air flow has two 90 degree bends that it must undertake. Different inline fans were researched and analysis was completed on each fan by taking the fan speed and flow rate given on the specification sheets and using an EES code to calculate the Reynold's number and pressure drop. From these values, the specific speed could be calculated:

$$N_{SD} = \frac{\omega(RPM) * \sqrt{Q(GPM)}}{[ha(ft)]^{3/4}}$$

Four fans were tested at variable flow rates in order to see which ones would work in the PCM duct system (Table 19).

Table 19. Data for each fan tested based on fan speed and flow rate given in fan specification sheets.

| Fan | Fan Speed (RPM) | Flow Rate (CFM) | Pressure Head (ft) | Specific Speed | Reynold's Number | Power Required (W) |
|---|---|---|---|---|---|---|
| **Max Fan** | 2990 | 1019 | 234 | 4363 | 18349 | 413 |
| | 1470 | 500 | 66 | 3882 | 9003 | 56.8 |
| **Mach10 Fan** | 3100 | 1050 | 247 | 4410 | 18907 | 449 |
| | 886 | 300 | 26 | 3646 | 5402 | 13.2 |
| **Hurricane Centrifugal Fan** | 2480 | 780 | 148 | 4464 | 14045 | 198 |
| | 1590 | 500 | 66 | 4199 | 9003 | 56.8 |
| **Hurricane Mixed-Flow Fan** | 3030 | 1000 | 226 | 4496 | 18006 | 392 |
| | 1515 | 500 | 66 | 4004 | 9003 | 56.8 |

Based on the findings in the table above the specific speeds were all in the 3000-4000 range. Using the chart in Figure 44 below, a mixed flow fan would be the best option for the ducting system. The Hurricane centrifugal fan is a mixed flow fan, somewhat because it works like an axial fan because the flow come out in the same direction it went in. Because it has enough power to run at different speeds, this fan was chosen as the one that we will install in the PCM ducting system.

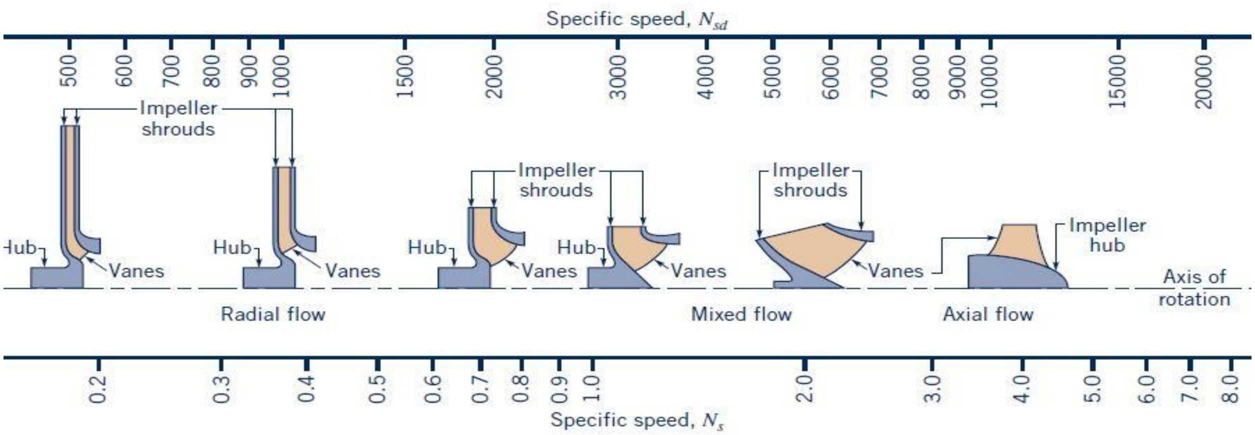


Figure 44. PCM duct basic construction indicating duct size changes

In order for the use of the fan to make sense, the fan must use less energy than the Thermastix capture. In initial calculations, the PCM duct will capture about 10% of the cooling load on the house. Assuming the cooling load per a day is 1 ton, which would mean that the fan must use less than 3.51 kW per day. If the fan was run at full speed for seven hours, the fan would use 1.66 kW, leaving a positive reduction on the energy use of 1.85 kW per day, which is 14.8 kW for the total competition.

All these calculations are only estimates, the only way to be certain of the designs is through testing. The different tests that will be performed on the PCM duct will be described in the Future Testing section later in this report.

## Visible PCM

A shading analysis was conducted to determine whether there will be sufficient heat on the glass door for the PCM to change phase and contribute to the reduction in HVAC loads. Figure 22 describes the shading analysis (Sun-Path chart) and shows that the glass door doesn't get enough light in the winter. Thus, awning on the south face needs to be shortened. It is assumed that if the PCM does change phase in the day, it would go back to solid phase at night since the south glass is in contact with the outside atmosphere which is at 18 C (below its melting temperature) and undergoes natural convection at night.

The results of this study should be used as a guideline when considering using PCM in a Passive House. It is very important to consider the climate that the Passive House will be located in. Climates with warm to hot and dry summers are ideal for the utilizing PCM. Also, the benefits are increased when the temperature fluctuations are large as this allows the PCM to discharge at night.

# Design Verification Plan (Safety and Testing)

## Appliances

The selection of proper appliances plays an important role in placing well in the home comfort and energy contests of the Solar Decathlon. The main driving criteria for appliance selection are cost, efficiency, and size. Moving forward we will want to perform additional steps to ensure that these are met. In order to optimize for the three criteria we will design a refined spreadsheet of all devices with an algorithm in place to select from the best of the available appliances. This data has already been assembled from sources such as Energy Star which have already pre-filtered devices on the market for efficiency. Our next step is to add more detailed information for each of our devices and perform an additional selection pass for refined appliance selection.

Once a set of appliances has been selected we will have to quantify their impact on the key criteria mentioned previously. Checking for cost will be a matter of referring to manufacturers and retailers for capital costs and then using software such as Cost Works to approximate typical installation costs for similar devices. The operating costs will be a function of the power and water draw of the appliances. This is linked to our planned calculations for efficiency.

The water and electricity demand of the selected appliances claimed by manufacturers will be crosschecked with the testing performed by Energy Star. The final estimation for the rate of consumption of both electricity and water will then be run through models for expected use. We will develop models that simulate best and worst case scenarios for Decathlon conditions as well as a typical family's use. The results of these simulations will help define ranges for our expected energy and water budgets. These can then be used to determine the operating costs of the appliances based on expected energy and water costs.

Lastly comes testing for the size of the selected appliances. The nominal sizes of the devices are not expected to differ from manufacturer claims but the clearances required for both installation and operation will have to be cross checked. We will determine an acceptable amount of space based customer reviews, safety officer recommendations, and our own inspection of the devices. All relevant outcomes of the testing for appliances will be shared with other disciplines to ensure that all requirements are met.

## Mechanical Room

The mechanical room is a crucial part of the project. It houses many of the major components needed to operate the house and also serves as the main connection point for many devices. As a result the major criteria for the mechanical room are size, clearance, and operability. The dimensions of the mechanical room are largely an architectural decision with mechanical engineering suggestions. Early work helped ensure that the current mechanical room is large enough to ensure we can meet the three criteria.

Meeting the size requirement is a matter of making sure that all the equipment located in the room will in fact fit within the maximum size limits established by the architectural design. We will continue to test this in Revit by placing all the equipment in the mechanical room. Accuracy will require communication with other teams to be certain that every component is up to date. Once an updated virtual mechanical room has been designed, it will be important to visually inspect that everything fits. More accurate measurements taken in the space will help us determine that the proper clearances have been met.

We will further test clearance and operability by “plugging” everything in. Doing so will help us determine visually whether elements such as duct work or plumbing does not have any interference. Considerations such as ergonomics will be taken into account to make sure that the placement of all equipment not only fits and has proper clearance but can also be accessed comfortably. Actual testing of this will take place once the house has been built at Cal Poly. Early mock ups of the mechanical room may also be built before actual construction is complete to get an idea of how everything fits together in real life. This could be done using properly scaled plywood and cardboard representations of the mechanical room and its components.

## Passive HVAC

Various parameters need to be considered while performing analysis on the Phase Change materials used. First was to ensure that the set point temperature of the PCM is consistent with the environmental conditions, mainly temperature data, for the Solar Decathlon site in Irvine. Using this, the correct PCM will be purchased that works in that temperature range so that the PCM completely changes phase from solid to liquid in the day and then from liquid to solid at night. We are using historical temperature for Irvine but the exact weather conditions cannot be predicted. That being said, if the temperature in Irvine is a few degrees higher than what we designed all PCM applications for, then the PCM may not change phase and won’t work.

### Active Heat Sink Duct

An essential PCM application was the independent active system where aluminum cylinders filled with PCM were placed in cross flow in a duct. As stated in the previous section, if the temperature at night is equal to or higher than the set point temperature of PCM, then the night flush to solidify the PCM would not work and the PCM would be highly ineffective.
The correct size fan is required so that enough heat transfer can be done through convection, keeping in mind the energy budget for the house. This would be done by constantly increasing the complexity on the energy calculations to determine the losses and dynamics of the system. A mockup of the design will be built to check for visual and spacial impacts of the duct when placed in the house.

### Leakages

As a safety concern, it is important to ensure that PCM material is not leaking as it may drastically affect the insulation and degrade the SIPs over time. This would be done by following manufacturer's safety guidelines for installations and performing safety checks before transportation and before installation by visual and physical inspection.

### Natural Ventilation

Another aspect of our design was to model the effects of natural ventilation in the house. This was done by visual inspection of the Revit model provided by the architects to ensure that the windows are operable. Natural ventilation was then modelled in Revit as well as design builder to analyze its effectiveness in regulating temperature. This and active ventilation was helpful in cooling down PCM at night so that it is ready for use in the morning in its solid form.

### Timeline

A Gantt chart was created to organize and plan out the different deadlines, tests, and reports that take place throughout the Mechanical Engineering senior project and the Cal Poly Solar Cal Poly decathlon process. The Gantt chart in Appendix C is a rough estimate of the process and order of events from September 2014 to June 2014. The senior project was started in March 2014 with background research done on the Solar Decathlon and appliance selection, but much of the engineering analysis started in September. Although the Solar Decathlon will be taking place in October 2015, two of the Project Engineers will be graduating in June 2015, so the senior project will effectively end when the Final Project Report is submitted in June 2015.

As of now, the Gantt chart is just a rough estimate of the plans for future months; this is not a plan to be set in stone, it is an ever-changing model that will evolve throughout the next few weeks based on changing deadlines, additional knowledge, and so forth.

Throughout the next few months, there will be many different deadlines because of the two projects, the senior project and the Solar Cal Poly project. Although these are working towards the same outcome, Solar Cal Poly has a longer timeline and different goals, hence, the different deadlines.

The building and testing of the house is slated to start taking place in March 2015, but after that date, there is no official dates to set in stone. This chart will be continually updated as more information from the architects and other teams finalize their designs.

## Future Tests

### Appliances

Once the house is built and finished, which will be in late summer, a mock competition will be set up in order to test the different systems in the house to make sure that they work as projected and specified by the manufacturers. This applies to the appliances in that the manufacturer has given an estimation of the energy usage in their specification sheets, but we need to confirm the exact kWh usage of each appliance to update the energy budget of the house. Once this testing is complete, we can compare the projected versus the actual amount of energy used during the competition to confirm that house did not go over the allotted amount. If it does go over, appliance cannot really be re-ordered, but other parts of the energy budget can possibly be reduced in order to stay under the 175 kWh mark.

### Phase Change Material Duct

The PCM duct has the most unknowns, as this has not really been implemented in houses before. Thus, after the duct is built, many tests need to be performed to test if this duct actually helps reduce the cooling load on the house. The main reason why this duct was design was to reduce cooling load on the house so that the active HVAC system would not have to work as much. We will be testing the duct to make sure that it does help reduce the cooling load needed, and not use more energy than a house without it. Also, because this system will be going inside a home, the fan and duct system will be tested to confirm that there is as little fan noise as possible heard in the lower portions of the house, especially in the kitchen.

### Testing Fan Noise

If the fan runs at its required speed, and no noise is heard, then there will be no further testing or analysis required. But, as the estimated Reynold's numbers of the different fans showed, the fan noise might be a problem. If the fan is audible to the average human listening, there are two different ways to minimize the noise. The fan chosen will also be paired with a variable fan speed controller, in order to test different flow rates. Reducing the speed will also reduce the Reynold's number, which correlates to the noise production. If the minimal speed that the fan must operate at still produces an audible noise, there is one other option. Sound dampers or insulation can be placed around the fan and ducting system in order to dampen the noise. These two factors will hopefully reduce the noise levels to where the average human cannot hear the sound that the PCM ducting system makes.

### Testing Pressure Losses

To maximize the flowrate, which in turn maximizes the energy transfer to and from the phase change material, minimal pressure losses are preferred. We plan on using the variable speed controller to set the fan at different speeds to measure the air flow through the duct. We can then use that information to calculate the pressure losses to determine an optimal speed for the fan to run at. We will also experiment with the number of Thermastix rows, columns, and the spacing between the two. If there are less Thermastix in the duct, there will be less obstructions, and therefore less pressure losses. As of right now, the tee parts of the duct are 90 degree bends. But if we smooth out the curves instead of having the air slam into a sharp corner, this will reduce both the pressure head and the noise of the air and fan. There is a delicate balance, though, of how much the pressure losses can be reduced. If the fan speed is reduced too much, the Thermastix will not have enough air flow for complete phase change to happen, which is needed for maximum energy transfer. If too many of the Thermastix are taken out, then there will not be much heat transfer, and the cooling loads will not reduce as much. If the phase change material does not help reduce the cooling loads, then there is no point in adding the expensive system to the house.

### Testing Energy Savings

In order for the PCM duct to be a profitable endeavor in the house, it must reduce the cooling load and therefore the energy used more than what the fan uses. Once the system is set up and running, we will measure the inlet and outlet temperatures of the ducts to calculate the heat transfer to the phase change material. From this, the energy saved by the Thermastix can be calculated. Based on how long the duct system runs each day, the energy usage of the fan can also be calculated. If the energy saved by the Thermastix is more than the energy used by the fan, then this PCM duct system is profitable. If it does not, other options like reducing the pressure losses, can be tried in order to reduce how hard the fan must work in order to supply a specific flow rate over the phase change material.

## Management Plan

This section describes the responsibilities of the team members. For example, it identifies who will have primary responsibility for information gathering, documentation of project progress, manufacturing considerations, prototype fabrications, testing plans, etc. Where appropriate, also identify who is primarily responsible for particular subsystems of the design. The management plan at this point should include a timetable of milestones relevant to the sponsor. (In the next report we will include a software generated Gantt chart). Look at the syllabus and include the milestones that will require the sponsor's participation (Design Reviews, Reports, prototype testing and Design Expo).

The various responsibilities for the project have been laid out based on each team member's strengths in order to make the best of this team. A major part of the project till now has been research on various net-zero building techniques, modeling of mechanical layouts of the house on Revit, communication and consulting to architecture team and specifying the appliances used for the house.

Julien Blarel is the point of contact for the mechanical engineering team and is responsible for all communication to and from the multidisciplinary teams and faculty involved in the project. He is in charge of specifying all the appliances used for the house and converting them into CAD format required by the U.S. Department of Energy for the construction documents. He conducts the necessary research required new technologies and compiles them for team research and development.

Sanchit Joshi is responsible for modeling all mechanical layouts on Revit and conducting all mathematical analysis required for heat transfer and passive HVAC technologies. He is also the go to person for ensuring that all mechanical layouts are built according to California code and don't conflict with the layouts of any other discipline such as electrical or architectural. He is also responsible for organizing and maintaining communication within the mechanical engineering team.

Cristina Paquin's primary responsibility is to execute all the data prepared by the team. She compiles all the data gathered by the team and puts it in format and conducts the necessary steps for submission. She handles the team schedules and meetings and ensures that the team is on track. An important role undertaken by her is identifying manufacturing consideration for various potential passive HVAC systems used in the house and their interaction and integration with other systems such as electrical control systems.

A 100% construction document submittal was due Tuesday, March 17, for one last submittal to the DOE. This means that all the mechanical systems throughout the house will be completely specified out and models will be finished by this date. The construction documents for the different mechanical systems are complete, and now only small changed will be made based on whatever may come up. A global materials list has also been completed and should be updated a final time so that Solar Cal Poly can acquire every part it needs, down to the last screw, in order for construction to occur. As of now, hired contractors will be building the house, so student work will only be done on constructing the phase change material duct.

# Conclusion

From working on the Solar Decathlon as project engineering officers for 4 consecutive quarters (Spring2014, Summer2014, Fall2014 and Winter2015), the mechanical engineering team has successfully met all design criteria and submittals to the department of energy. Most mechanical engineering senior project teams on Solar Decathlon have almost completed their designs that will be forwarded to contractors to build the house. Our key roles for the house include appliance selection, energy balance, PCM duct construction and Revit construction documents and managing/delegating the mechanical subsystems for various senior project teams for solar decathlon.

The total energy budget was 175 Kwh/week from which appliances (refrigerator, stovetop, dishwasher, oven and washing machine) constitute 32 Kwh/week (18 of total) and all mechanical equipment (HVAC, PCM Inline Fan, Mechanical Room Fan, Blackwater Pump, Gray-water pump) contribute to 86.15 Kwh/week (50% of total).

The PCM duct contributes approximately 0.1 tons of cooling load to the house with the use of 150

Thermastix (aluminum tubes filled with phase change material). The duct parts have been specified which will be then handed over to the current ME senior project teams for construction and testing.

All Revit documents have been completed and will be sent to department of energy and contractors for house construction. Minor changer will still be made to fix last minute construction issues.

Even though, our senior project sequence is complete, we will still honor our roles as engineering officers and communicate with other disciplines involved on the project and help the ME teams in their designs.

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# Appendix B: Team Contract

## Team Contract – Solar Cal Poly Project Engineers

Mission:
The mission of the Solar Cal Poly Project Engineers is to collaborate with the multidisciplinary team of students at California Polytechnic State University San Luis Obispo to design and build the Solar Cal Poly house for the U.S. Department of Energy Solar Decathlon 2015 competition. This team is specifically in charge of reducing energy use and heat gain on the home in order to maintain a net-zero house. The team also oversees the Mechanical Engineering teams working on the project and serves as the liaison between the Mechanical Engineering teams and the rest of Solar Cal Poly.

Section 1—Name

A. This organization shall be known as "Solar Cal Poly Project Engineers". The three members of this team are the Lead Project Engineers for the Solar Cal Poly house in the U.S. Department of Energy Solar Decathlon 2015 competition.

Section 2—Membership

A. Members of the team include:
   1. Julien Blarel – 4$^{th}$ year, Mechanical Engineering major
   2. Cristina Paquin – 4$^{th}$ year, Mechanical Engineering major
   3. Sanchit Joshi – 4$^{th}$ year, Mechanical Engineering major
B. No member shall purport to represent the team unless so authorized by the team. Julien Blarel is the main team contact for reporting to Solar Cal Poly. He will be the team member that reaches out to, contacts, and answers questions for those not part of Solar Cal Poly Project Engineers. This statement is only for meetings that only the Team Contact is required to go to, and if all three Project Engineers are present or available, they shall all represent the team, unless otherwise stated and agreed upon by the Project Engineers in that specific instance.
C. Each member shall be provided a digital and paper copy of the team contract. This contract should be accessed at any time on the google drive, Senior Project – Solar Decathlon ME. Request of a contract shall always be approved.
D. Officers of the team include those listed below with their designated responsibilities.
   1. Team Contact (Julien Blarel)
      a. Serve as the main point of communication with the sponsor as well as extra disciplinary teams, and interdisciplinary teams.
      b. Organize and facilitate meetings with outside groups
      c. Represent our team in cases where all members cannot be present
   2. Design and Implementation (Sanchit Joshi)
      a. Maintain team's travel and material budget
      b. Primary expert on 3D programs and mechanical layouts
      c. Knowledgeable of all relevant code
   3. Secretary/Recorder (Cristina Paquin)
      a. Maintain information repository for team (e.g. team binder, google documents site, etc...)
      b. Compiling and assimilating research
      c. Responsible for moving systems from design to documentation

## Section 3—Decision Making

A. Decisions within the team shall be made by consensus. All Project Engineers must be present and have some knowledge or understanding about the outcomes of the different options for each decision. If the Team Contact is at a meeting without the other Project Engineers and an immediate decision must be made, he has the power to make a decision without contacting the rest of the team. The other Project Engineers must be contacted as soon as possible about the new decision and allowed to share concern about the decision made. If the concern is viable, steps will be taken to communicate the concern to others involved with the made decision.
B. Voting on decisions made by the Solar Cal Poly Project Engineers shall be oral, unless the situation calls for another method in which the team will decide unanimously on how to best vote for the decision needing to be made.
C. All decisions made will be made unanimously. All Project Engineers must come to a consensus on every decision made. If there is dissent, the Project Engineers must confront the issue and reach a compromise. If needed, the Technical Advisor, Professor Shollenberger, can step in and advise the Project Engineers on the different decision options.

## Section 4—Team Interactions

A. Meetings will be held throughout the week. No specific time shall be stated beyond the required hours of Tuesday and Thursday so that schedules can be kept flexible as the work load for the Project Engineers varies from week to week.
B. Meeting locations will be decided by all Project Engineers when meetings come up, unless otherwise stated. Location depends on what materials are needed for the meeting.
C. Meetings may be called by any member of the Project Engineers. The Project Engineer setting up the meeting must contact all Project Engineers to confirm availability.
D. Attendance is mandatory unless the team member has a time conflict (class, study time, or club), any emergency, or special event (must be confirmed with other Project Engineers). The team member must inform all Project Engineers before the meeting commences.
E. Meeting discussions will be conducted in a conversational format with special regard for a dialogue that is respectful and considerate of all members in attendance.
F. If a Project Engineer is organizing a meeting for a specific reason, the Project Engineer must convey that reason to the other team members so that the others can be prepared and ready for meaningful discussion.
G. All team members are expected to be punctual to all meetings. The Project Engineers know that problems and emergencies do come up, and lenience will be provided, if not done in excess.

## Section 5—Conflict Resolution

If a conflict or problem arises in the team, this is the information and procedure that will be followed.

A. The team member(s) with the conflict will set up a conflict/resolution
B. A mediator will be chosen, either the other Project Engineer, or the Technical Advisor if the conflict involves all Project Engineers.
C. The team member with the conflict will state what they see as the problem, referring to the guidelines in the Student Success Handbook.
D. The other party of the conflict will then have the opportunity to respond and explain where they are coming from.
E. A resolution will be made by both parties to the conflict, and will be agreed upon by all.
D. A follow-up meeting will be scheduled no more than a week later, to confirm that all conflicts have been resolved.

Section 6—Amendments

A. Amendments to the Team Charter will only be passed if all Project Engineers agree upon it.
B. It will then be written into the Team Charter, and new digital and paper copies will be distributed to all Project Engineers.

Section 7—Effective Date (10/13/2014)

A. This contract of the Solar Cal Poly Project Engineers shall become effective on October 20, 2014 to ensure that the Charter has been agreed upon by all Project Engineers and that no additional changes need to be made to the Charter.
B. Dates of amendment must be recorded in minutes of meetings at which amendments were approved, together with a revised set of bylaws.

Section 8—Signatures

_________________________ Date: 10/10/14

Cristina Paquin

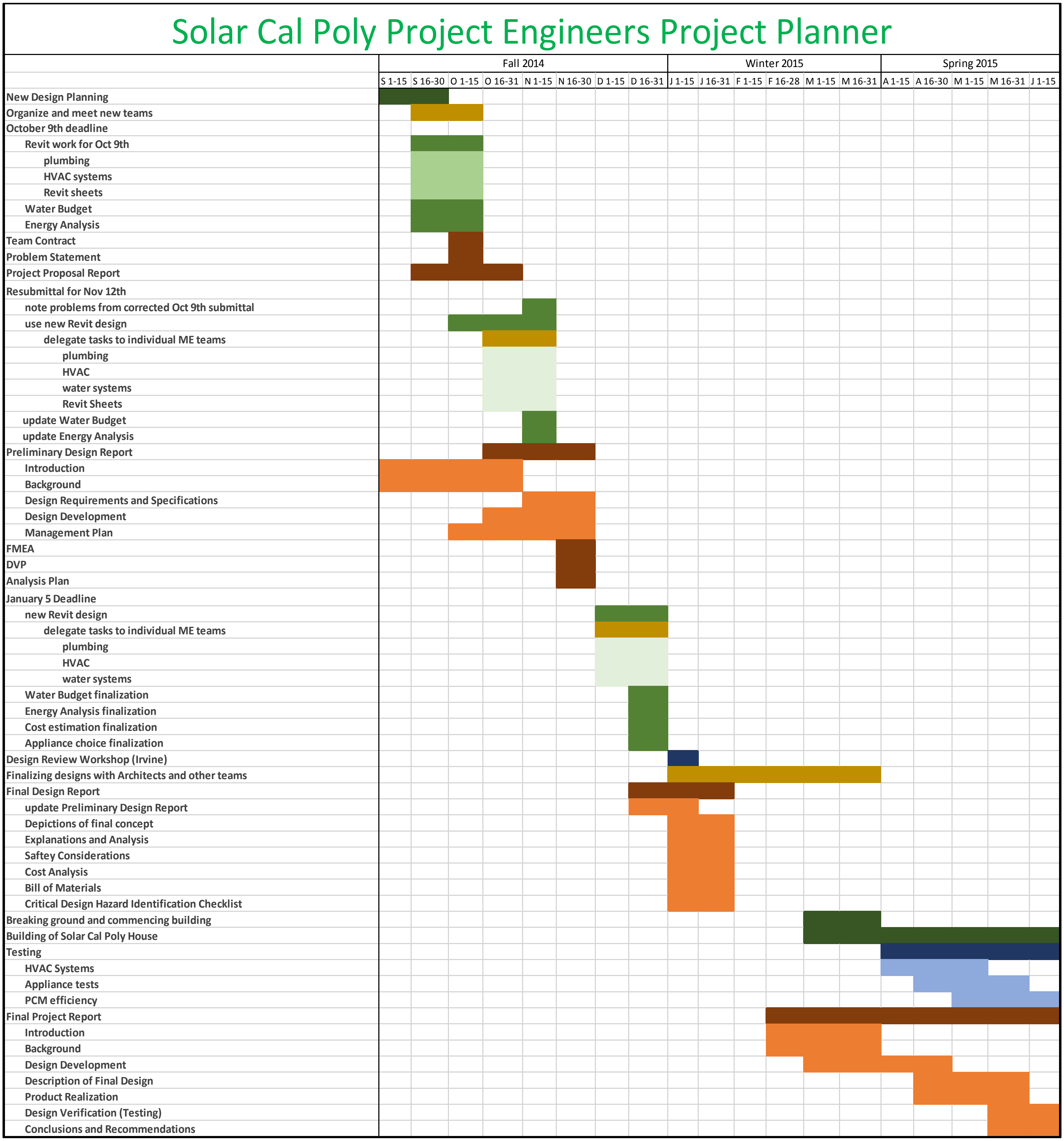
_________________________ Date: 10/10/14

Julien Blarel

_________________________ Date: 10/10/14

Sanchit Joshi

## Appendix C. Gantt Chart



# Appendix D. QFD

## Appliances QFD

| Relationships | |
|---|---|
| Strong | ● |
| Moderate | ○ |
| Weak | ▽ |

| | | | WHO: Customers | | | | | Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Direction of Improvement | | | | | | | |
| | | | | | | | | WHAT: Customer Requirements (explicit & implicit) | | | | | | | |
| 1 | | 9% | 12 | 6 | 12 | 12 | 9 | Affordable | ○ | ○ | ▽ | ▽ | ● | ○ | |
| 2 | | 7% | 8 | 3 | 1 | 8 | 9 | Aesthetic | ▽ | ▽ | ▽ | ▽ | ● | ▽ | ▽ |
| 3 | | 9% | 4 | 9 | 4 | 5 | 3 | Innovative | ▽ | ▽ | ○ | ○ | ▽ | ▽ | ▽ |
| 4 | | 7% | 5 | 5 | 6 | 4 | 9 | Safe to Use | ▽ | ▽ | ▽ | ▽ | ▽ | ▽ | ● |
| 5 | | 7% | 1 | 12 | 11 | 1 | 3 | Abides by DOE rules | ▽ | ▽ | ○ | ○ | ▽ | ▽ | ▽ |
| 6 | | 8% | 2 | 8 | 2 | 3 | 3 | Creative | ▽ | ▽ | ○ | ○ | ▽ | ▽ | ▽ |
| 7 | | 10% | 6 | 10 | 7 | 6 | 9 | Reduces Waste | ▽ | ○ | ● | ○ | ▽ | ▽ | ▽ |
| 8 | | 13% | 10 | 11 | 10 | 11 | 9 | Saves Energy | ▽ | ○ | ○ | ● | ▽ | ▽ | ▽ |
| 9 | | 9% | 9 | 7 | 9 | 9 | 9 | Endurable | ● | ○ | ▽ | ○ | ▽ | ▽ | ▽ |
| 10 | | 6% | 3 | 1 | 8 | 2 | 3 | Increases home resale | ○ | ▽ | ▽ | ▽ | ▽ | ▽ | ▽ |
| 11 | | 8% | 7 | 2 | 3 | 7 | 9 | Fits in home | ▽ | ○ | ▽ | ▽ | ○ | ● | ▽ |
| 12 | | 7% | 11 | 4 | 5 | 10 | 9 | Easy Install/Maintenance/Use | ○ | ● | ▽ | ▽ | ○ | ○ | ▽ |
| | | | | | | | | HOW MUCH: Target | | | | | | | |

# Passive Design QFD

| | | | | | | | | Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WHO: Customers | | | | | | | Direction of Improvement | | | | | | | |
| Row # | Weight Chart | Relative Weight | Society | Department of Energy | Cal Poly San Luis Obispo | Potential Client | Maximum Relationship | WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications | Thermal Insulation Value | Cost of Materials | Solar Heat Gain Reduction | Heat Storage Capacity | Space Requirement | Temperature Difference | Schedule of Repair |
| 1 | | 9% | 11 | 10 | 10 | 10 | 9 | Affordable | ● | ● | ▽ | ▽ | ▽ | ▽ | ▽ |
| 2 | | 9% | 8 | 8 | 6 | 11 | 3 | Aesthetic | ▽ | ○ | ▽ | ▽ | ○ | ▽ | ▽ |
| 3 | | 9% | 2 | 9 | 11 | 2 | 3 | Innovative | ○ | ▽ | ▽ | ▽ | ▽ | ▽ | ▽ |
| 4 | | 9% | 3 | 6 | 2 | 5 | 9 | Safe | ▽ | ▽ | ▽ | ▽ | ○ | ○ | ● |
| 5 | | 9% | 6 | 4 | 5 | 4 | 3 | Robust | ▽ | ▽ | ▽ | ○ | ▽ | ▽ | ▽ |
| 6 | | 9% | 4 | 5 | 7 | 1 | 9 | Manufacturable | ● | ○ | ▽ | ▽ | ○ | ▽ | ▽ |
| 7 | | 9% | 1 | 3 | 1 | 3 | 3 | Operable | ▽ | ▽ | ▽ | ▽ | ○ | ▽ | ▽ |
| 8 | | 9% | 9 | 7 | 8 | 6 | 3 | Environmentally Friendly | ▽ | ▽ | ▽ | ▽ | ▽ | ○ | ▽ |
| 9 | | 9% | 5 | 1 | 3 | 8 | 9 | Convenient | ▽ | ▽ | ▽ | ▽ | ● | ▽ | ▽ |
| 10 | | 9% | 7 | 2 | 4 | 7 | 9 | Comfort | ▽ | ▽ | ○ | ○ | ▽ | ● | ▽ |
| 11 | | 10% | 10 | 11 | 9 | 9 | 9 | Lower Active Energy Use | ● | ▽ | ● | ● | ▽ | ○ | ▽ |
| | | | | | | | | HOW MUCH: Target | <15 | <$250,000 | | | | 70>Temperature<76 | 2 years |

Mechanical Room QFD

| | | | WHO: Customers | | | | | Column # | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Direction of Improvement | | | | | |
| Row # | Weight Chart | Relative Weight | Society | Department of Energy | Cal Poly San Luis Obispo | Potential Client | Maximum Relationship | WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications | Temperature Levels | Safety Code Standards | Schedule of Repair | Space Requirement | Size of Instruments |
| 1 | | 9% | 2 | 5 | 5 | 2 | 9 | Safe | ▽ | ● | ● | ● | ○ |
| 2 | | 7% | 3 | 7 | 7 | 1 | 9 | Follows Rules and Regulations | ● | ● | ▽ | ○ | ○ |
| 3 | | 9% | 5 | 6 | 6 | 5 | 9 | Efficient | ● | ○ | ● | ▽ | ▽ |
| 4 | | 7% | 7 | 2 | 2 | 7 | 9 | Ease of Use | ○ | ▽ | ▽ | ● | ● |
| 5 | | 7% | 4 | 4 | 4 | 4 | 9 | Ease of Installation/Maintenance Access | ▽ | ▽ | ● | ▽ | ● |
| 6 | | 8% | 6 | 3 | 1 | 6 | 9 | Comfortable | ● | ▽ | ▽ | ○ | ▽ |
| 7 | | 10% | 1 | 1 | 3 | 3 | 9 | Longevity of Machinery | ○ | ○ | ● | ▽ | ▽ |
| | | | | | | | | HOW MUCH: Target | 60<Temperature<90 | Code Standards | Code Standards | Code Standards | Code Standards |

## Appendix E. Calculations

# Phase Change Material Calculations
# Staggered Alignment and Flat Plate

"Operating pressures and temperatures:"

P_air = 14.696 [psia] "Average air pressure"
T_air = (T_m_i + T_m_o)/2 "Average air temperature"
T_m_i = ConvertTEMP(C,F,18) "Mean cold temperature of outside air at inlet"
T|star = ConvertTEMP(C,F,23) "Melting temperature of phase change material"
T_m_o = ConvertTEMP(C,F,23)
"Properties for air:"

rho_air = Density(Air,T=T_air,P=P_air) "Density of cold air"
c_p_air = Cp(Air,T=T_air) "Specific heat of cold air"
mu_air = Viscosity(Air,T=T_air) "Viscosity of cold air"
k_air = Conductivity(Air,T=T_air) "Thermal conductivity of air"
Pr=Prandtl(Air,T=T_air)

"Overall calculation for night-time cooling potential"

V_dot = (100 [ft^3/min])*Convert(h,min) "Volumetric flowrate of cold air"
DELTAt_cold = 10 [h] "Time cold air flows through system"
m_air = rho_air*V_dot*DELTAt_cold "Mass of cold air"
DELTAE = m_air*c_p_air*(T|star - T_m_i) "Total amount of energy in cold air"

"Amount of phase change material (PCM) to store energy:"

DELTAt_hot = 3 [h] "Time air flows through PCM system into hot room"
Q_dot = (DELTAE/DELTAt_hot)/Convert(ton,BTU/h) "Power for air conditioning in hot room during operation"

lambda = 90 [BTU/lbm] "Heat of fusion of PCM"
m_PCM = DELTAE/lambda "Mass of PCM"
rho_PCM = (235 [kg/m^3])*Convert(kg/m^3,lbm/ft^3) "Density of PCM"
rho_prime_PCM = 1 [lbm/ft^2] "Density times thickness of PCM for standard sheet"
L_PCM = Convert(ft,in)*(rho_prime_PCM/rho_PCM) "Thickness of PCM sheet"
A_PCM = m_PCM/rho_prime_PCM "Area of PCM"

"Heat transfer between multiple sticks"

V_PCM = A_PCM*(L_PCM*Convert(in,ft)) "Volume of PCM used in Sheets"
D = (2/12) [ft] "Diameter of ThemaStick"
L2 = (6/12) [ft] " Length of Thermastick"
N_Sticks = V_PCM / (pi*((D/2)^2)*L) "Number of Thermasticks"
A_C2 = pi*D*L2 "Surface area of each Thermastick"
D_duct = 1.5 [ft]

H = (0.5/12) [ft] "Height of one air channel"
W = (16.5/12) [ft] "Width of air channels"
L = 8 [ft] "Length of air channels"

```
N_chan = 10                                  "Number of air channels"

A_c = H*W                                    "Cross-sectional area of one air channel"
P = 2*(W+H)                                  "Perimeter of one air channel"
D_h = 4*A_c/P                                "Hydraulic diameter of one air channel"
A_s = 2*W*L                                  "Sufrace area between air and PCM for one
channel"
m_dot = rho_air*V_dot                        "Mass flowrate in duct"
V_air = V_dot/(pi*((D_duct/2)^2))            "Mean air velocity in channels"

"Nusselt number correlation for fully-developed flow through staggered Alignment"

Re_D = (rho_air*V_air*D_duct)/mu_air         "Reynolds number for air flow in channels"
NuD = IF(Re_D, 2300,7.54,7.54,
0.023*Re_D^0.8*Pr^0.4)
NuD = (h_bar*D)/k_air
h_bar_SI = h_bar*Convert(BTU/h,W)*Convert(m^2,ft^2)*Convert(C,F)
```

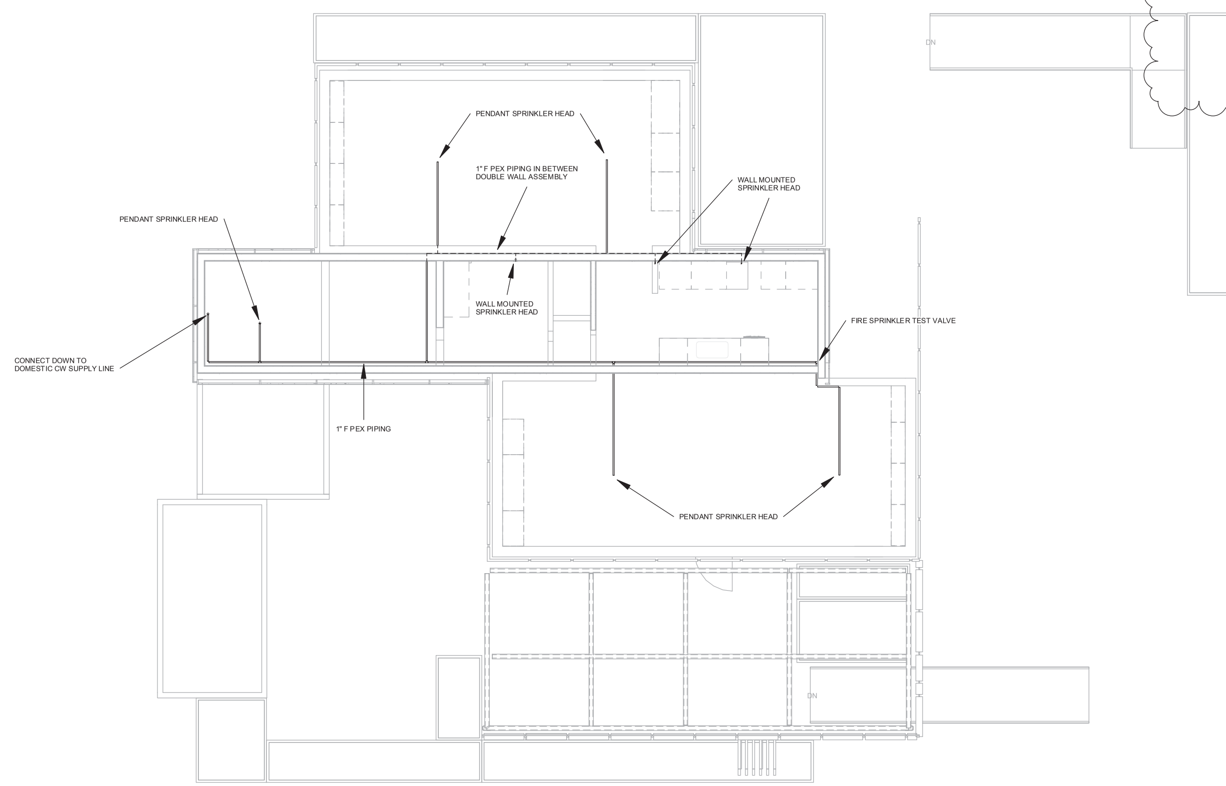
# EES Function for Staggered Arrangement

```
Fluid$='air'

P=101.300 [KPa]
V_dot = 100*convert(ft^3/min,m^3/s)          "Volumetric Flowrate"
D_duct = 1.5*convert(ft,m)                   "Diameter of Duct "
u_inf=V_dot/(pi*((D_duct/2)^2))
D=2*convert(in,m)                            "Diameter of PCM cylinders"
T_in=18 [C]                                  "Inlet Air Temperature"
T_out=23 [C]                                 "Outlet Air Temperature"
N_L=21                                       "Number of Rows"
S_T=4*convert(in,m)                          "Spacing"
S_L=4*convert(in,m)

Call External_Flow_Staggered_Bank(Fluid$, T_in, T_out, T_s,  P, u_inf, N_L, D,S_T,S_L: h, DELTAp,
Nusselt, Re)
```

# Shading EES code

```
"Coordinate lengths for the awning geometry"
G= 2 [ft]
H= 8[ft]
W= 20.8[ft]
P= 10.17[ft]
E_L= 1 [ft]
E_R= 1 [ft]
"Let x = distance to the east, y = distance to the south, z = distance up"
z=H/2+G
"Calculating the solar azimuth and solar altitude angle from the point to the object edge"
    Gamma_s=arctan(x/y)
    Alpha_s=arctan(z/(x^2+y^2)^(1/2))

"The receiver plate faces due south and is symmetric so we can assume that the solar conditions will be
symmetric"
    Gamma_s_reflected=-Gamma_s
```

# Appendix F. Construction Documents




1 FIRE SUPPRESSION SITE PLAN
1/4" = 1'-0"

GENERAL SHEET NOTES:

SCOPE: MULTIPURPOSE RESIDENTIAL FIRE SUPPRESSION SYSTEM INTEGRATED WITH THE POTABLE COLD WATER DISTRIBUTION SYSTEM

1. SUPPRESSION SYSTEM INTEGRATED WITH THE POTABLE COLD WATER DISTRIBUTION SYSTEM.
2. 1" F PEX PIPE FOR ALL FIRE SUPPRESSION LINES SPECIFICATION:
1. INSTALL PEX TUBING AS INDICATED ON THE DRAWINGS.
2. INSTALL SPRINKLER HEADS IN ACCORDANCE WITH THE PEX TUBING MANUFACTURER'S SPECIFICATIONS.
3. ENSURE SPRINKLERS ARE POSITIONED SO THAT DISCHARGE WILL NOT BE AFFECTED BY OBSTRUCTIONS SUCH AS BEAMS OR LIGHT FIXTURES.
4. ENSURE SPRINKLER HEADS MAINTAIN MINIMUM DISTANCES FROM HEAT SOURCES AS SPECIFIED IN THE PEX TUBING MANUFACTURER'S INSTALLATION MANUAL.
5. A SPRINKLER SHALL NOT BE WITHIN THE RADIUS IF A MOUNTED CEILING FAN.
6. REFER TO SHEET P-103 FOR DOMESTIC COLD WATER CONNECTIONS.

NOTE:
F - FIRE PROTECT, PEX PIPING, REFER TO MANUFACTURER RECOMMENDATION

SOLAR CAL POLY

| | |
|---|---|
| TEAM NAME: | SOLAR CAL POLY |
| ADDRESS: | CALIFORNIA POLYTECHNIC STATE UNIVERSITY<br>SAN LUIS OBISPO, CA 93410 |
| CONTACT: | SOLARCALPOLY@GMAIL.COM<br>WWW.CALPOLYSOLARDECATHLON.ORG |

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Revision Schedule

| Revision Number | Revision Description | Revision Date |
|---|---|---|
| 1 | DESIGN REVISIONS AND DETAILING | 2/12/2015 |

| | |
|---|---|
| LOT NUMBER: | 107 |
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| CHECKED BY: | |
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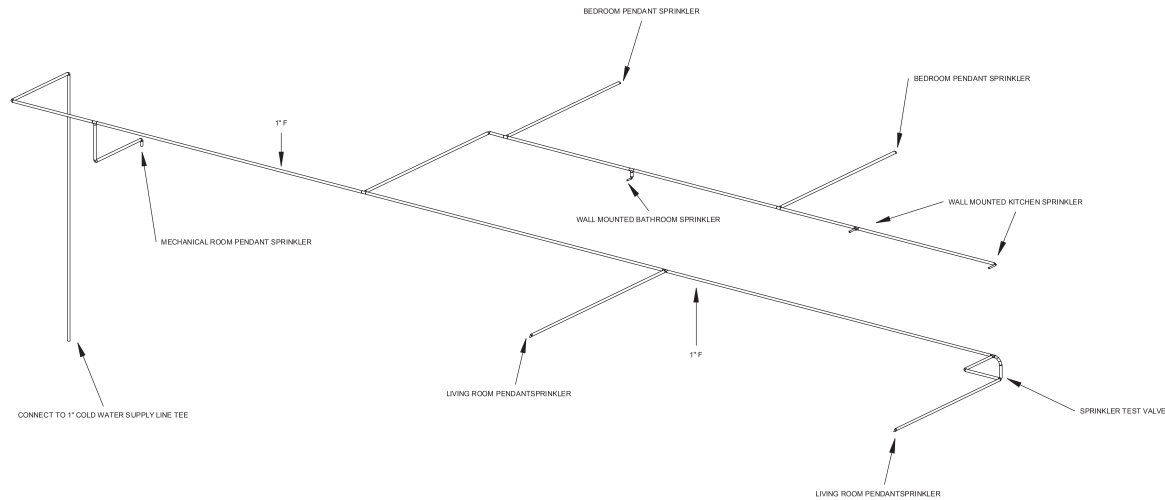
SHEET TITLE

FIRE SUPPRESSION SITE PLAN

F-102




1 FIRE SUPPRESSION ISOMETRIC

0 1' 2' 4'

SOLAR CAL POLY

| | |
|---|---|
| TEAM NAME: | SOLAR CAL POLY |
| ADDRESS: | CALIFORNIA POLYTECHNIC STATE UNIVERSITY<br>SAN LUIS OBISPO, CA 93410 |
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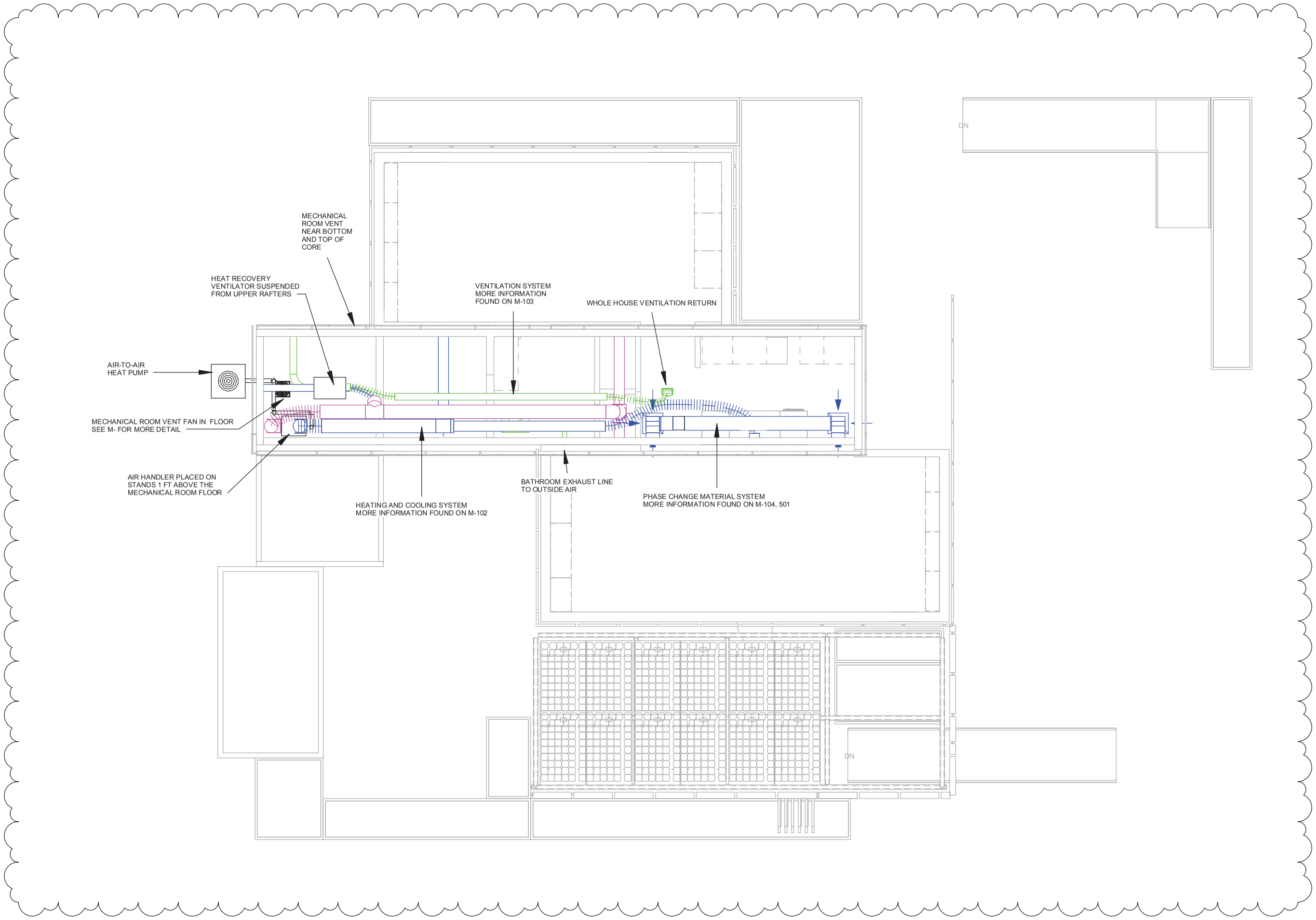
SHEET TITLE

FIRE SUPPRESSION DETAILS

F-501

GENERAL SHEET NOTES

1. GENERAL NOTES SHALL APPLY TO ALL WORK SHOWN.
2. VERIFY ALL MESUREMENTS TO PROPERLY LOCATE COMPONENTS.
3. ALL NOTES COINCIDE WITH SIMILAR DRAWINGS.
4. COORDINATE ALL WORK AND PLACEMENT OF COMPONENTS WITH OTHER TRADES.
5. CONTRACTOR SHALL FOLLOW EQUIPMENT MANUFACTURERS INSTRUCTIONS FOR HANDLING AND INSTALLATION.




1 HVAC SITE PLAN
1/4" = 1'-0"

0 2' 4' 8'

SOLAR CAL POLY

| | |
|---|---|
| TEAM NAME: | SOLAR CAL POLY |
| ADDRESS: | CALIFORNIA POLYTECHNIC STATE UNIVERSITY<br>SAN LUIS OBISPO, CA 93410 |
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Revision Schedule

| Revision Number | Revision Description | Revision Date |
|---|---|---|
| 1 | DESIGN REVISIONS AND DETAILING | 2/12/2015 |

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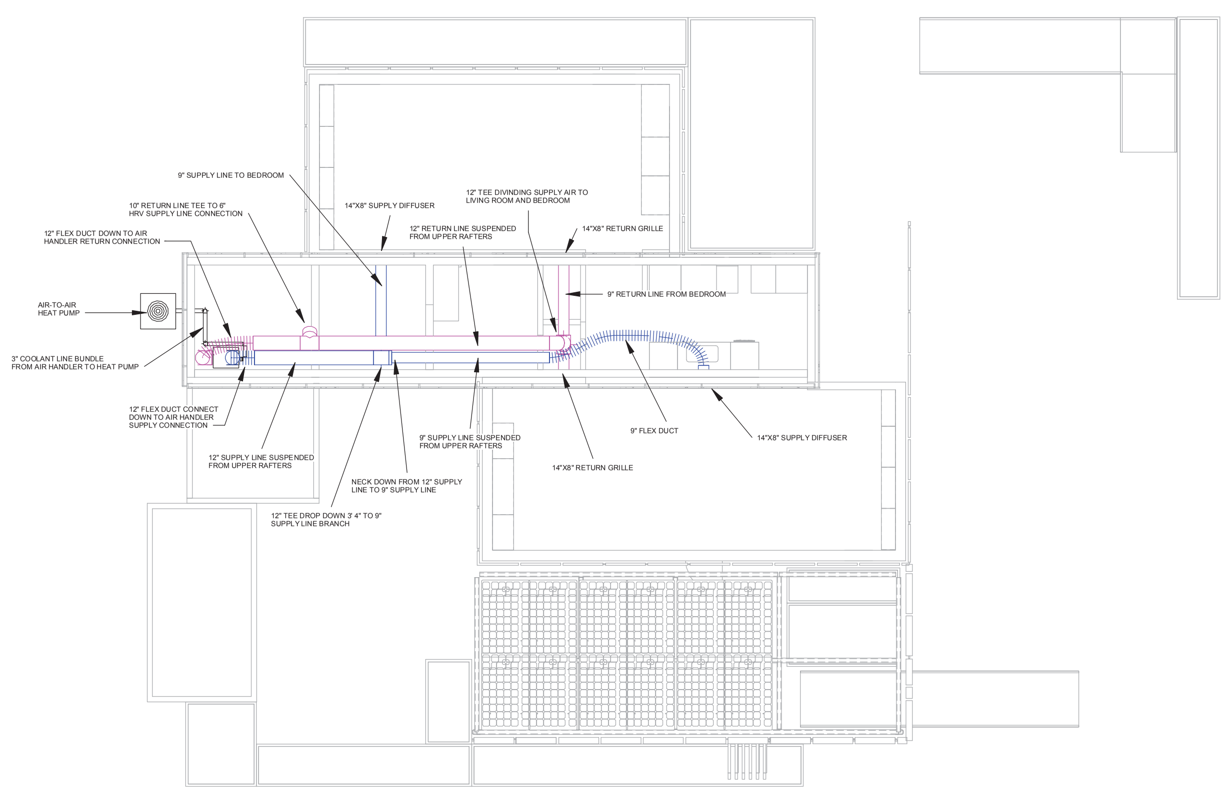
SHEET TITLE

HVAC EQUIPMENT AND DISTRIBUTION PLAN

M-101

GENERAL SHEET NOTES

1. ALL DUCTWORK IS ROUND




1 HEATING AND COOLING SITE PLAN

1/4" = 1'-0"

0 2' 4' 8'

SOLAR CAL POLY


TEAM NAME: SOLAR CAL POLY

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|---|---|---|

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SHEET TITLE

HEATING AND COOLING SITE PLAN

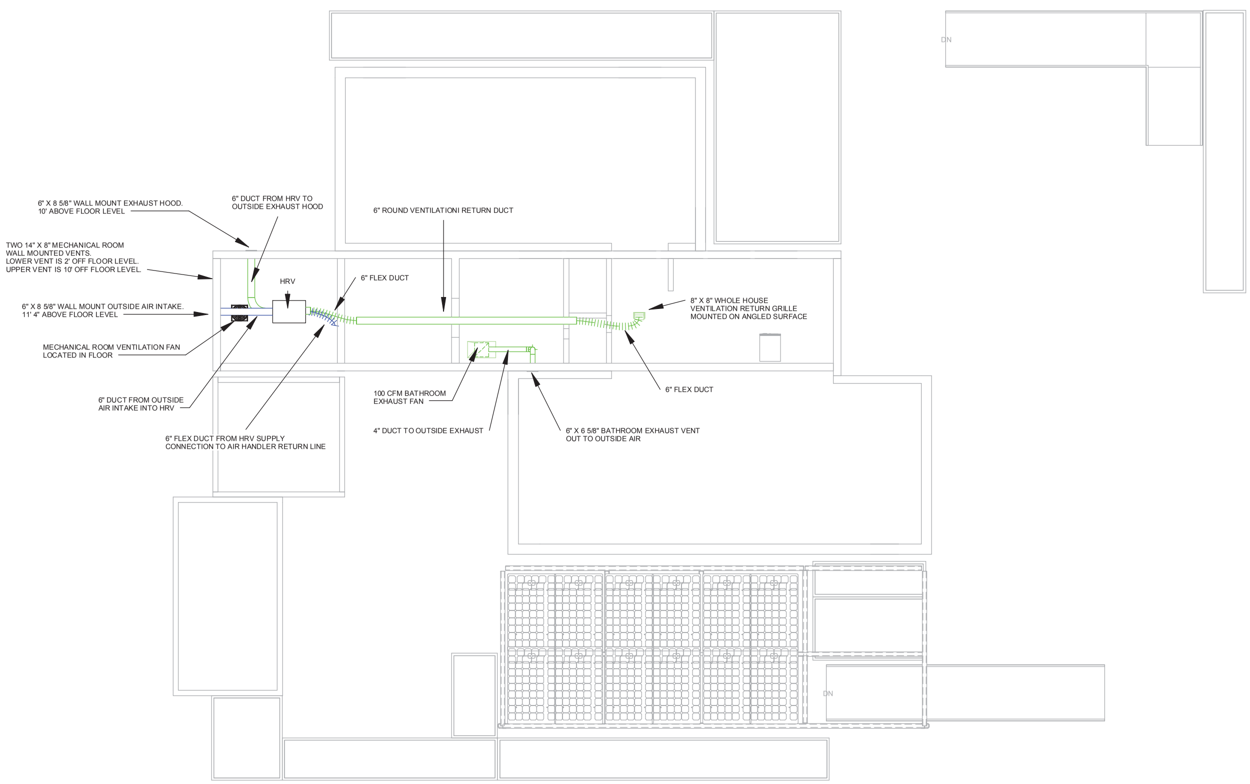
M-102

GENERAL SHEET NOTES

1. ALL DUCTWORK IS ROUND

NOTE

HRV - HEAT RECOVERY VENTILATOR




1 VENTILATION SITE PLAN

1/4" = 1'-0"

SOLAR CAL POLY

TEAM NAME: SOLAR CAL POLY

ADDRESS: CALIFORNIA POLYTECHNIC STATE UNIVERSITY SAN LUIS OBISPO, CA 93410

CONTACT: SOLARCALPOLY@GMAIL.COM WWW.CALPOLYSOLARDECATHLON.ORG

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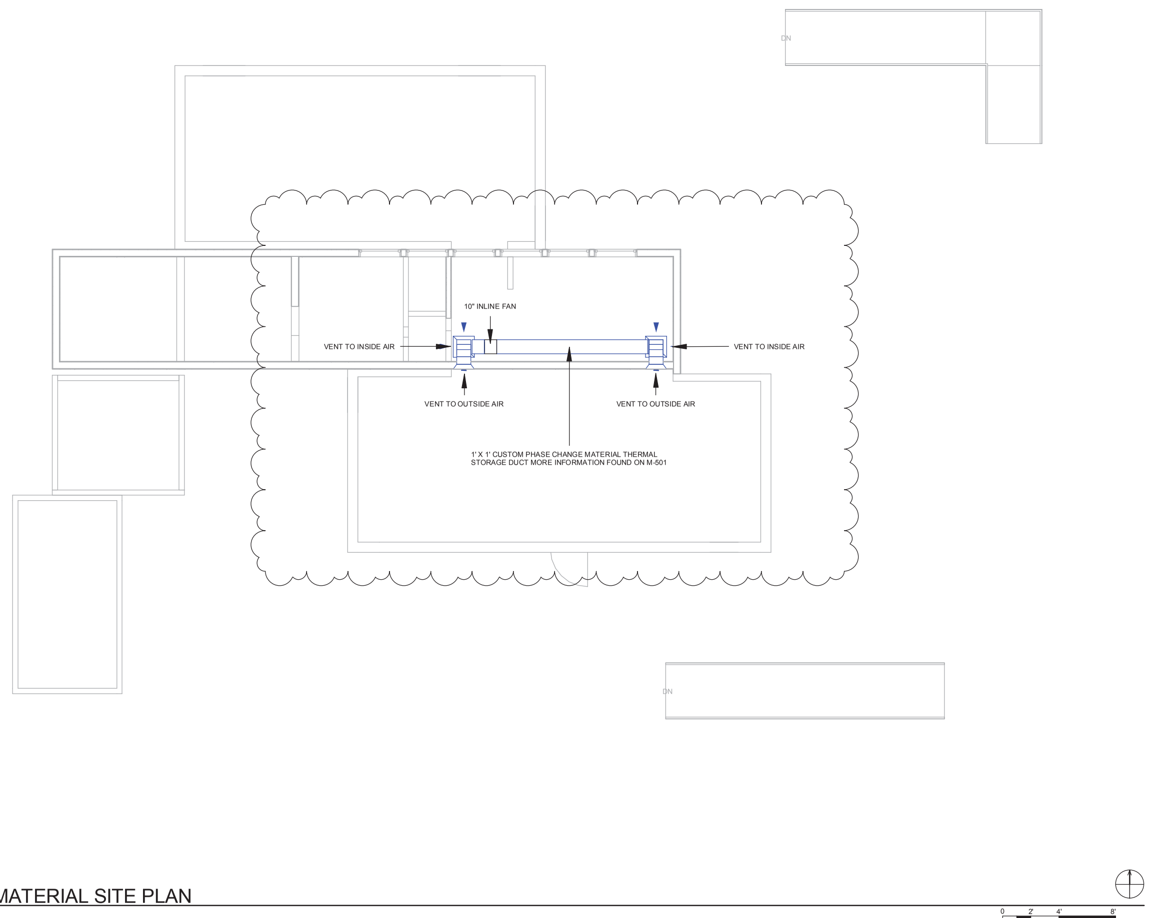
VENTILATION SITE PLAN

M-103




1 PHASE CHANGE MATERIAL SITE PLAN
1/4" = 1'-0"

SOLAR CAL POLY

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| 1 | DESIGN REVISIONS AND DETAILING | 2/12/2015 |

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SHEET TITLE
PHASE CHANGE MATERIAL SITE PLAN

M-104

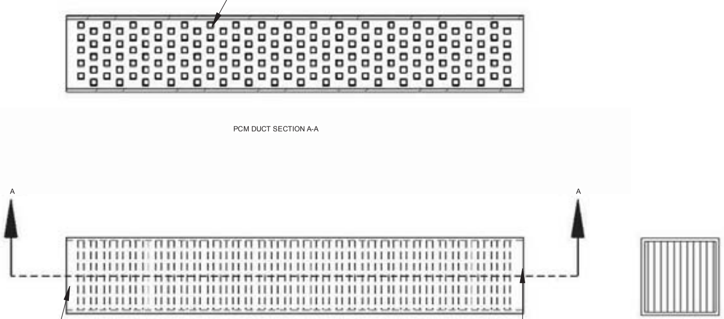
GENERAL SHEET NOTES

PCM - PHASE CHANGE MATERIAL

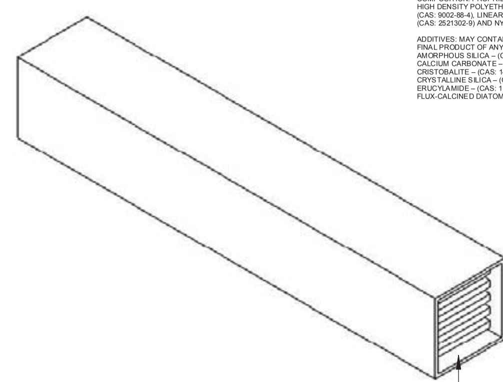
BioPCM CHEMICAL COMPOSITION:

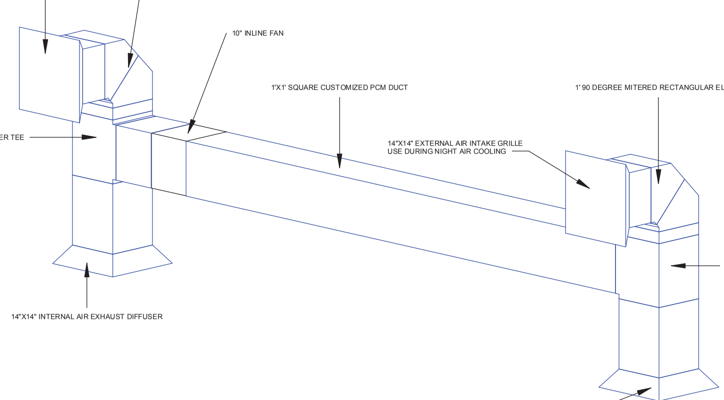
CHEMICAL FAMILY: THERMOPLASTIC OLEFIN POLYMERS
COMPOSITION: PROPRIETARY BLEND CONTAINING LOW AND HIGH DENSITY POLYETHYLENE
(CAS: 9002-88-4), LINEAR LOW DENSITY POLYETHYLENE
(CAS: 2521302-9) AND NYLON 6 (CAS: 25038-54-4)

ADDITIVES: MAY CONTAIN UP TO 0.03% BY WEIGHT OF THE FINAL PRODUCT OF ANY OF THE FOLLOWING:
AMORPHOUS SILICA – (CAS: 60676-86-0)
CALCIUM CARBONATE – (CAS: 471-34-1)
CRISTOBALITE – (CAS: 14464-46-1)
CRYSTALLINE SILICA – (CAS: 15468-32-3)
ERUCYLAMIDE – (CAS: 112-84-5)
FLUX-CALCINED DIATOMACEOUS EARTH – (CAS: 68855-54-9)




PCM DUCT SECTION A-A




1 PHASE CHANGE MATERIAL ISOMETRIC

0 1 2

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SHEET TITLE

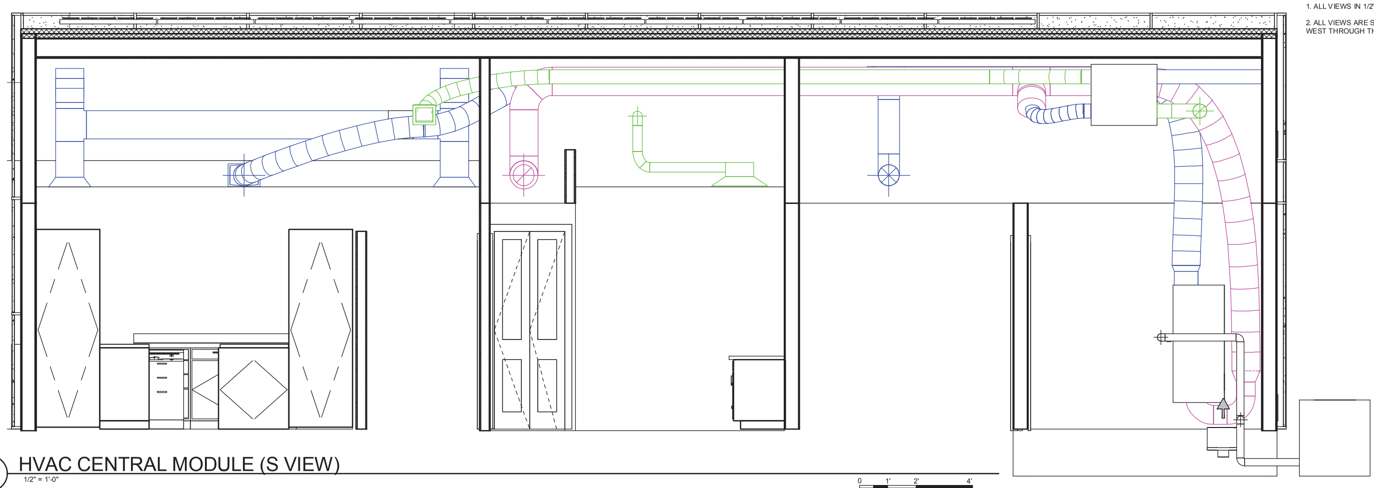
MECHANICAL DETAILS

M-501

GENERAL SHEET NOTES

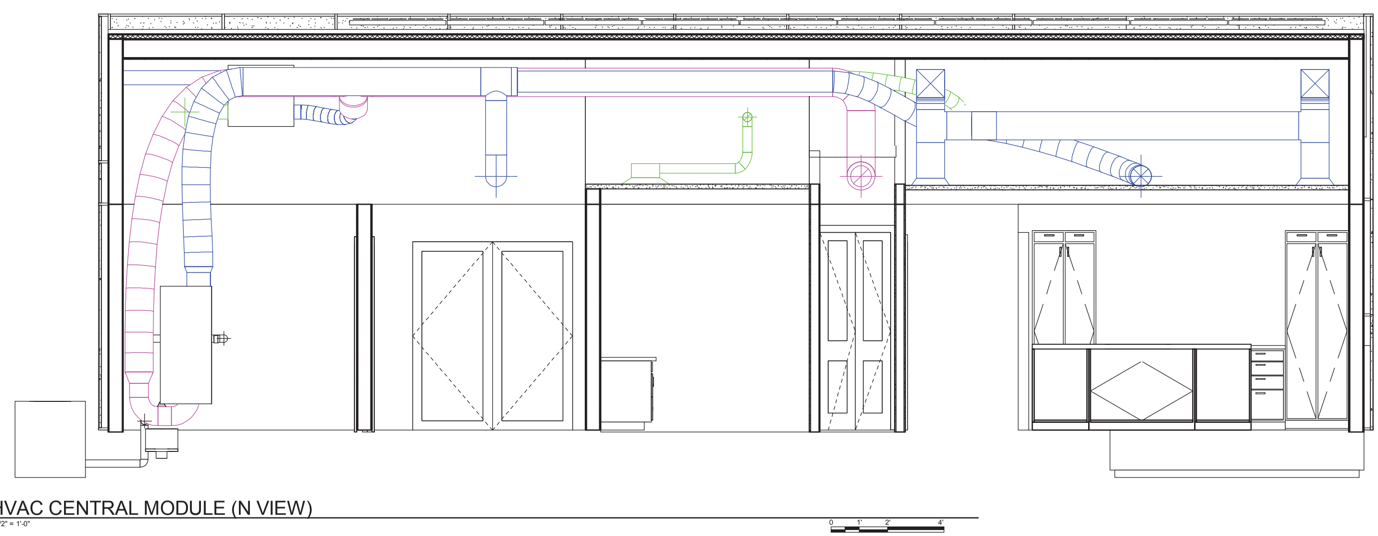
1. ALL VIEWS IN 1/2" = 1 FT

2. ALL VIEWS ARE SECTIONS CUT EAST TO WEST THROUGH THE CENTRAL HOUSE MODULE




2 HVAC CENTRAL MODULE (S VIEW)

1/2" = 1'-0"




1 HVAC CENTRAL MODULE (N VIEW)

1/2" = 1'-0"

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SHEET TITLE

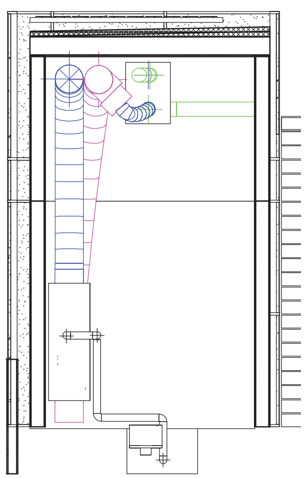
HVAC SECTIONS

M-502

GENERAL SHEET NOTES

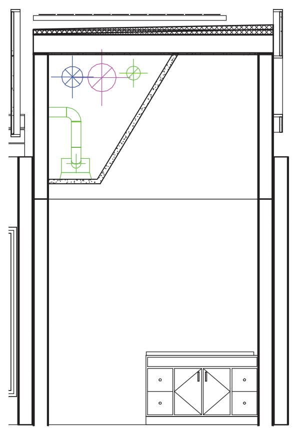
1. ALL VIEWS IN 1/2" = 1 FT

2. ALL VIEWS ARE SECTIONS CUT NORTH TO SOUTH THROUGH THE CENTRAL HOUSE MODULE



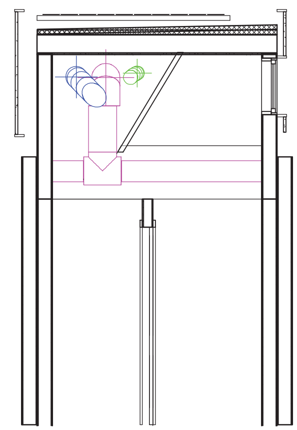
4 HVAC MECHANICAL ROOM (W VIEW)

1/2" = 1'-0"



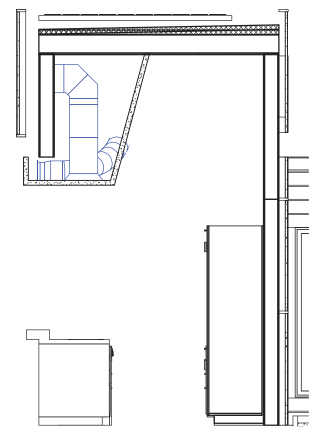
1 HVAC BATHROOM (W VIEW)

1/2" = 1'-0"



3 HVAC LAUNDRY ROOM (W VIEW)

1/2" = 1'-0"



2 HVAC KITCHEN (W VIEW)

1/2" = 1'-0"

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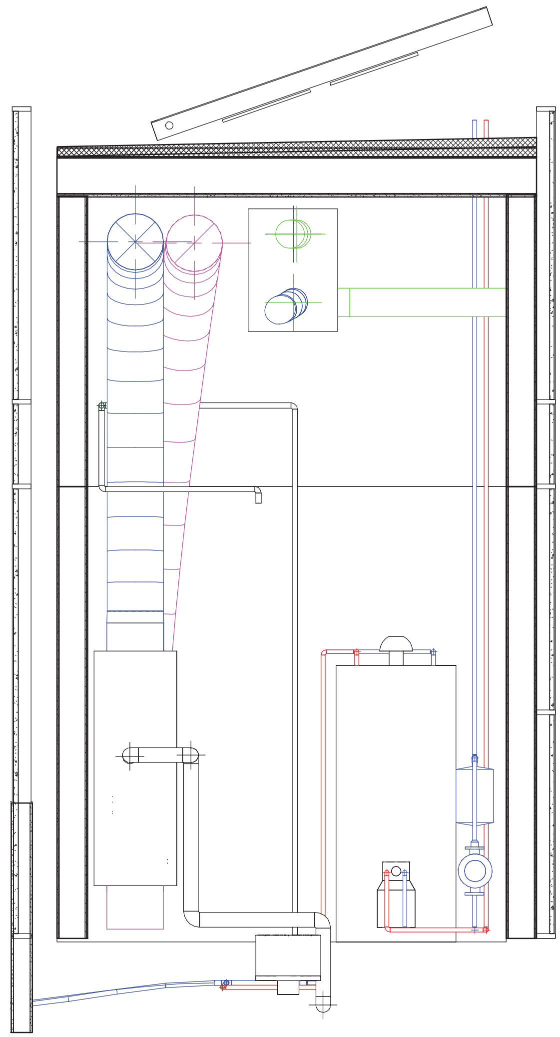
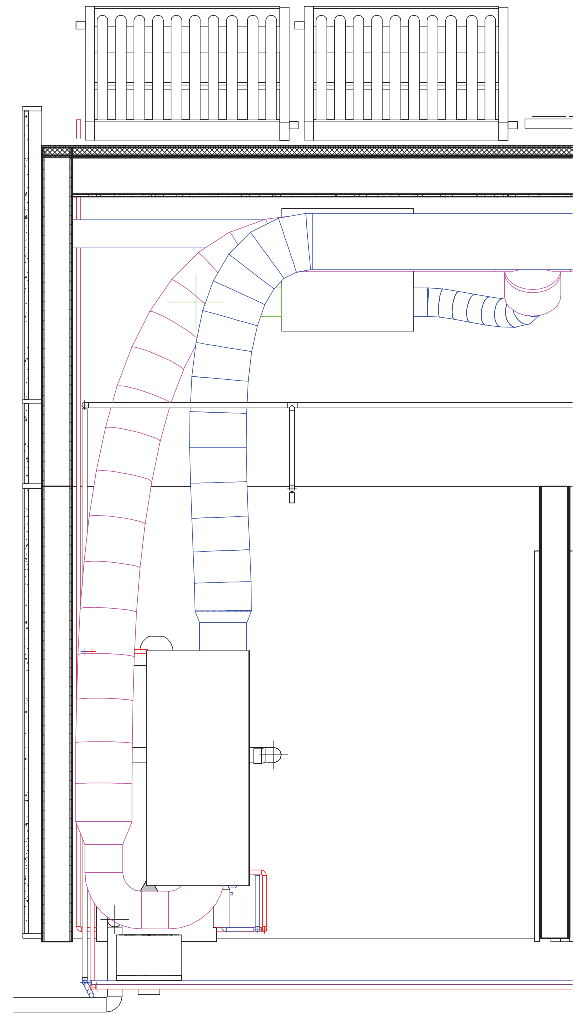
SHEET TITLE

MORE HVAC SECTIONS

M-503



1 MECHANICAL ROOM (W VIEW)
1" = 1'-0"



2 MECHANICAL ROOM (N VIEW)
1" = 1'-0"

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SHEET TITLE
MECHANICAL ROOM

M-504

GENERAL SHEET NOTES (MECAHNICAL HVAC)

| | Description | Quantity | Brand | Model | Specification |
|---|---|---|---|---|---|
| 1 | Heat Pump | 1 | XR15 | 4TWR5018 | 15 SEER (19400 Btuh, 1.5 ton(nom),600 cfm |
| 2 | Air Handler | 1 | Hyperion | GAM5A0A18 | 18,000 Btuh, 50"x22"x17" |
| 3 | SA Diffusers | 2 | | A618 | Deflection G, 14"x 8", 275 cfm @ 600 fpm |
| 4 | RA Grilles | 2 | | A650 | h = 14", w=8", 211 cfm @400 fpm, 1/3" fin spacing |
| 5 | HRV | 1 | | VNT5150H100 | 30-160 cfm, 28" x 14" x 46", 48 lbs |
| 6 | Bathroom Exhaust Fan | 1 | | QTRE100S | 100 cfm @ 0.10", 4" duct, 13" x 13-3/4" |
| 7 | Mechanical Room Fan | 1 | Ventamatic | CX1500 | 1300 cfm, 300W, Gable Mount Attic Vent Mill |
| 8 | 12" Tee | 1 | Snappy<br>Snappy | M10-136 (6-126) | 26 gauge, Crimped |
| 11 | 12" to 9" Reducer | 2 | Snappy | M80-227 (66-129) | No crimp |
| 12 | 9" 90° Elbow | 2 | Snappy | M80-034 (3-096) | 26 gauge, Crimped |
| 13 | 9" Tee | 1 | Snappy | M10-134 (6-096) | 26 gauge, Crimped |
| 14 | 6" 90° Elbow | 2 | Snappy | M80-028 (3-066) | 26 gauge, Crimped |
| 15 | 12" Flex Duct (F216) | 25' | Hart & Cooley | R94-142 (051330) | Metalized Jacket, Insulated (R=6.0) |
| 16 | 9" Flex Duct (F216) | 25' | Hart & Cooley | R94-140 (051328) | Metalized Jacket, Insulated (R=6.0) |
| 17 | 6" Flex Duct (F216) | 25' | Hart & Cooley | R94-137 (051325) | Metalized Jacket, Insulated (R=6.0) |
| 18 | 12" Round Duct | 7 | Speedi Products | SM-2860GR 12 | 60" long, Galvanized sheet metal, 28 gauge |
| 19 | 9" Round Duct | 10 | Speedi Products | SM-2860GR 09 | 60" long, Galvanized sheet metal, 28 gauge |
| 20 | 6" Round Duct | 7 | Master Flow | SM-3060GR 06 | 60" long, Galvanized sheet metal, 28 gauge |
| 21 | 6" Wall Vent (screen only) | 3 | | SWVA6 | 6" x 8.625" wall mount, Aluminum |
| 22 | 6" Wall Vent (screen&damper) | 1 | | SDWVA6 | 6" x 8.625" wall mount, Aluminum |
| 23 | 4" Wall Vent (screen&damper) | 1 | | SDWVA4 | 6.0625" x 6.625" wall mount, Aluminum |

GENERAL SHEET NOTES (MECHANICAL PCM)

| | Description | Quantity | Brand | Model | Specifications |
|---|---|---|---|---|---|
| 1 | In-line fan | 1 | hurrican-fans | #736140 | 10 in dia |
| 2 | Round to Square transition | 1 | SPEEDI-BOOT | SBH-121210 SRA | 12x12" square to 10" round |
| 3 | Back Draft Damper | 1 | Speedie-Products | # AC-BD 08 | 10 in dia |
| 4 | Speed Control | 1 | DAYTON | #G5287764 | 4-1/2 X 2-3/4 |
| 5 | PCM - Thermasticks | 40 | Phase Change Solutions | M91/Q23 | 2in dia x 6ft |
| 6 | PCM - Sheets | 10 | Phase Change Solutions | M91/Q23 | 4' x 4' x 1.46" |
| 7 | Programmable Thermostat | 1 | LUX | PSP511C | 4-1/2" x 3-1/4" x 1-1/4" |

GENERAL NOTES (MECAHNICAL SOLAR THERMAL)

| | Description | Quantity | Brand | Model | Specifcations |
|---|---|---|---|---|---|
| 1 | Expansion Tank | 1 | Caleffi | 259012 | 3 gal (capacity) |
| 2 | Automatic Air Vent | 1 | Bell & Gossett | 6ETU7 | 3/4" M NPT thread |
| 3 | Flat Plate Collector | 2 | Heliodyne | GOBI 406 001 | 26.94 sq. ft. gross area |
| 4 | Circulation Pump | 1 | Taco | 110-113 | 3/4" flanges |
| 5 | Check Valve | 2 | Grainger | 6VDT4 | 3/4" F NPT Threads |
| 6 | Isolation Valve | 5 | Caleffi | NA39589 | 3/4" F NPT Threads |
| 7 | Temperature Sensor | 3 | FLIR | 35KP94 | Dual Channel Type K Thermocouple |
| 8 | Pressure Sensor/Flowmeter | 1 | Duro | 9JEE7 | 3/4" F hose thread |
| 9 | Steel Pipe | 40' | Galvanized Pipe | GS3_410GTBE | 3/4" Galvanized Pipe MPT Threads |
| 10 | Piping Insulation | 40' | ITP Tundra | PB38078TWTU0 | 3/4" x 3/8" Rubber Piping Insulation |
| 11 | Heat Transfer Fluid | 10 gal | Greenway | | 1,3 Propanediol |
| 12 | Solar Storage Tank | 1 | Solaraide | 81V80HE-1 | 80 gallon |

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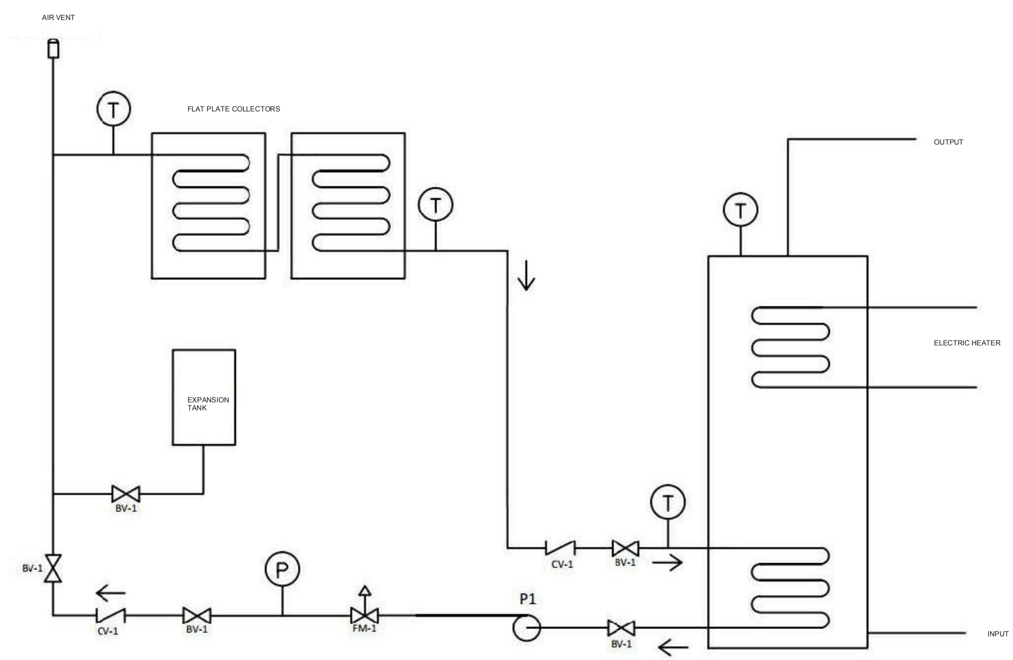
SHEET TITLE
SCHEDULES

M-601

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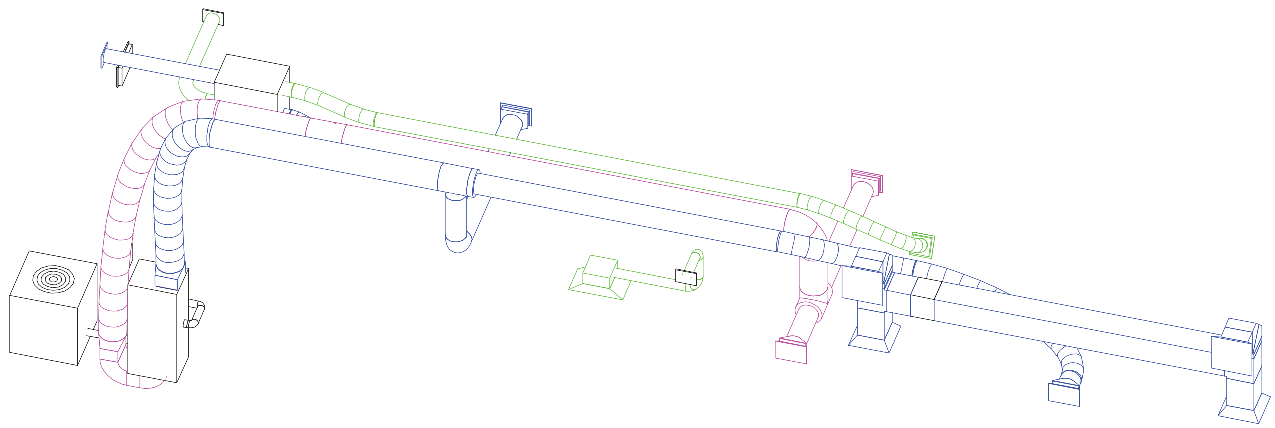
SHEET TITLE
SOLAR WATER DIAGRAMS

M-603



1 HVAC AND PCM ISOMETRIC

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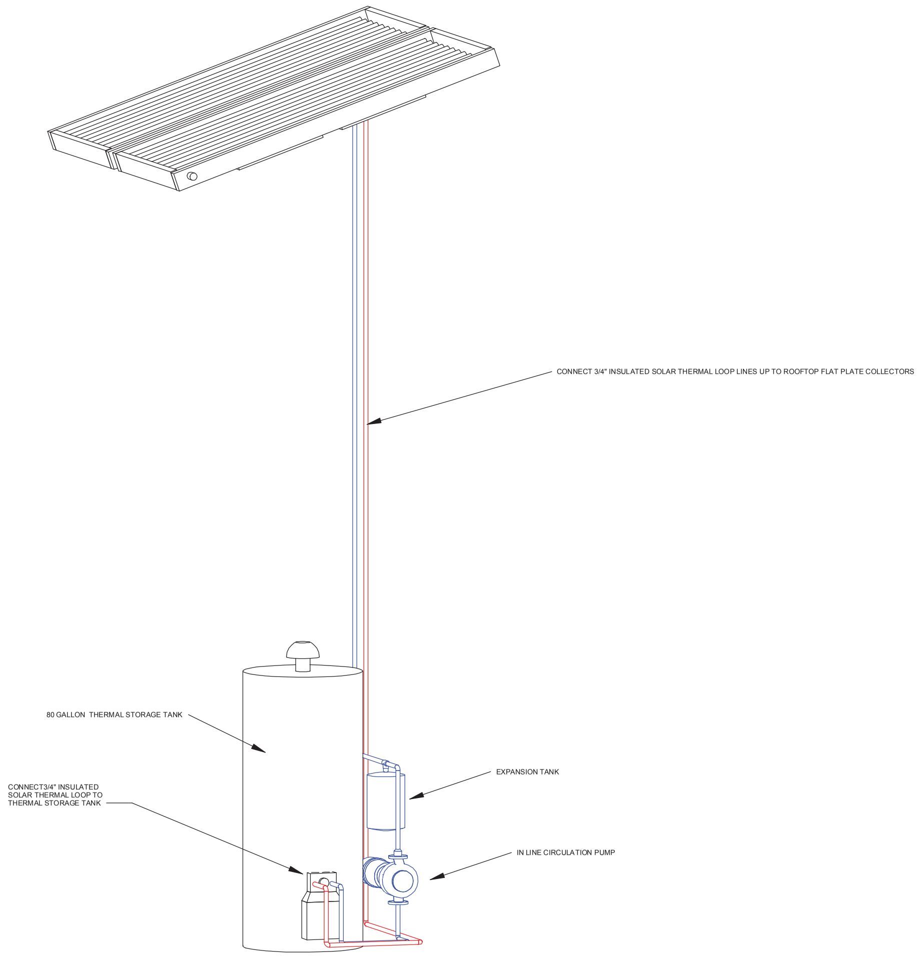
SHEET TITLE
HVAC ISOMETRICS

M-901




1 SOLAR WATER ISOMETRIC

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SHEET TITLE

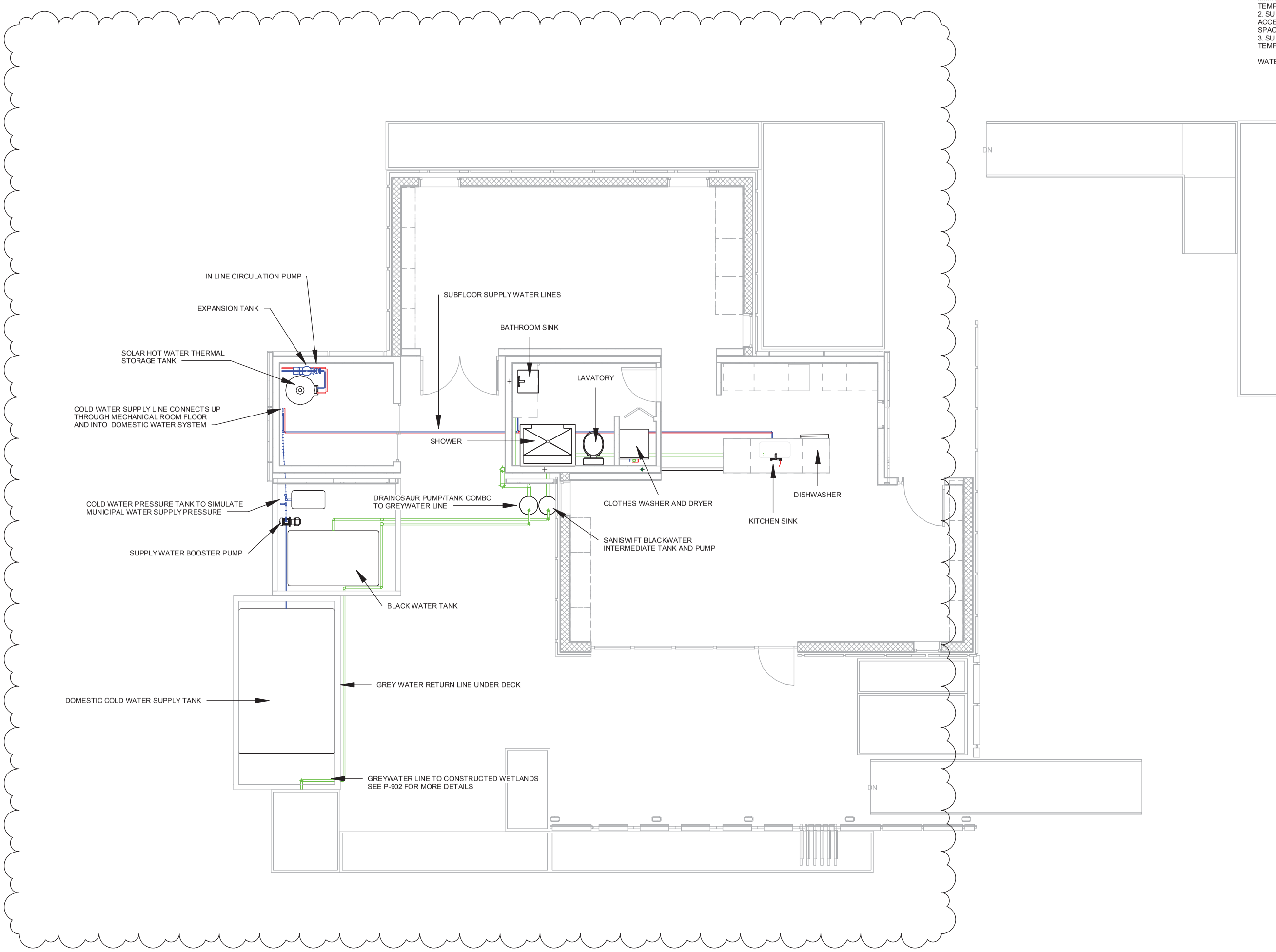
SOLAR WATER ISOMETRIC

M-902

GENERAL SHEET NOTES

1. ALL PORTABLE TANKS, PUMPS, AND VALVES INTENDED TO
MIMIC PUBLIC UTILITY WATER SUPPLY AND SEWAGE ARE TEMPORARY FOR COMPETITION PURPOSE ONLY.
2. SUPPLY TANKS MUST ALLOW FOR WATER DELIVERY ACCESS DURING COMPETITION. MUST ALLOW FOR A 12" SPACE ABOVE WATER INLET.
3. SUPPLY AND WASTE LINES FROM TANKS TO HOUSE ARE TEMPORARY.

WATER TANKS ARE SHADED WITH SHADING DEVICE




1 DOMESTIC WATER SITE PLAN
1/4" = 1'-0"

0 2' 4' 8'

SOLAR CAL POLY

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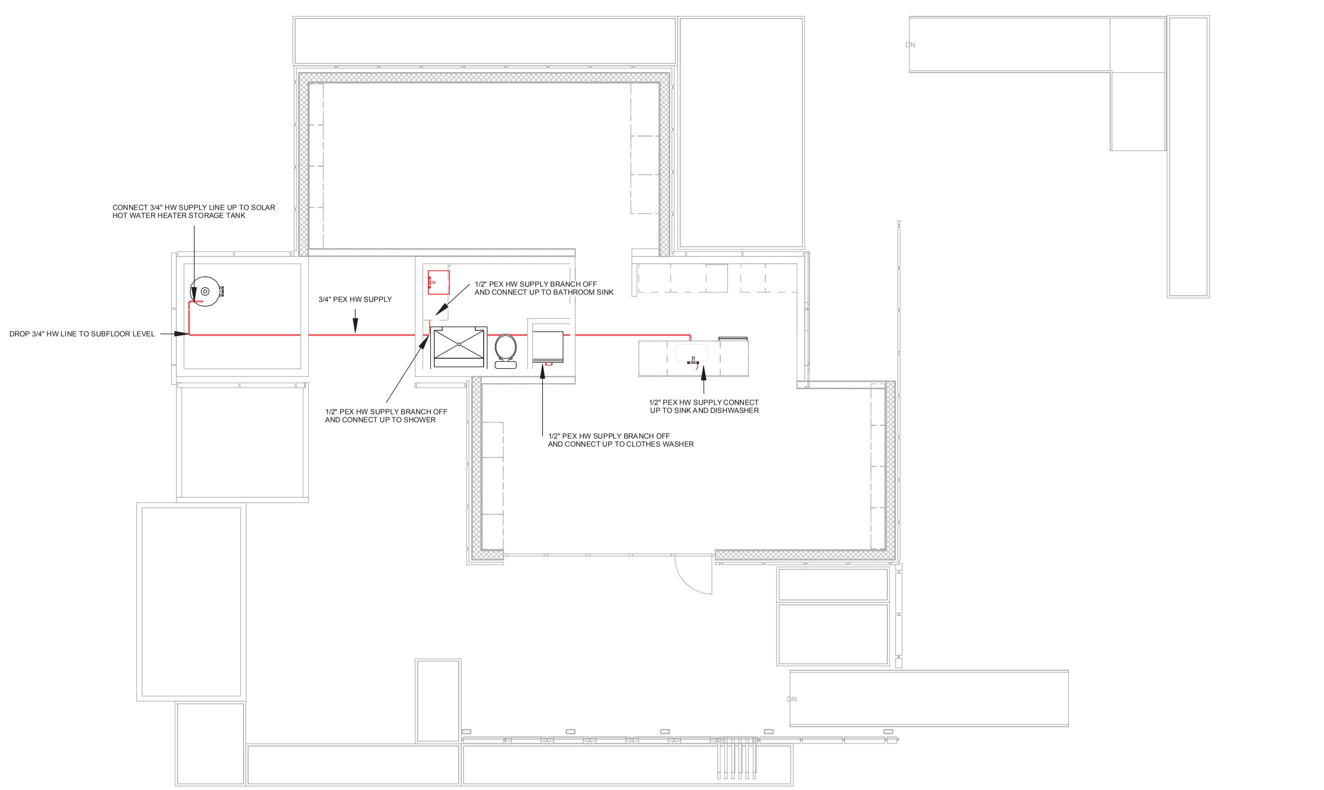
SHEET TITLE
PLUMBING SITE PLAN

P-101




1 DOMESTIC HOT WATER SITE PLAN
1/4" = 1'-0"

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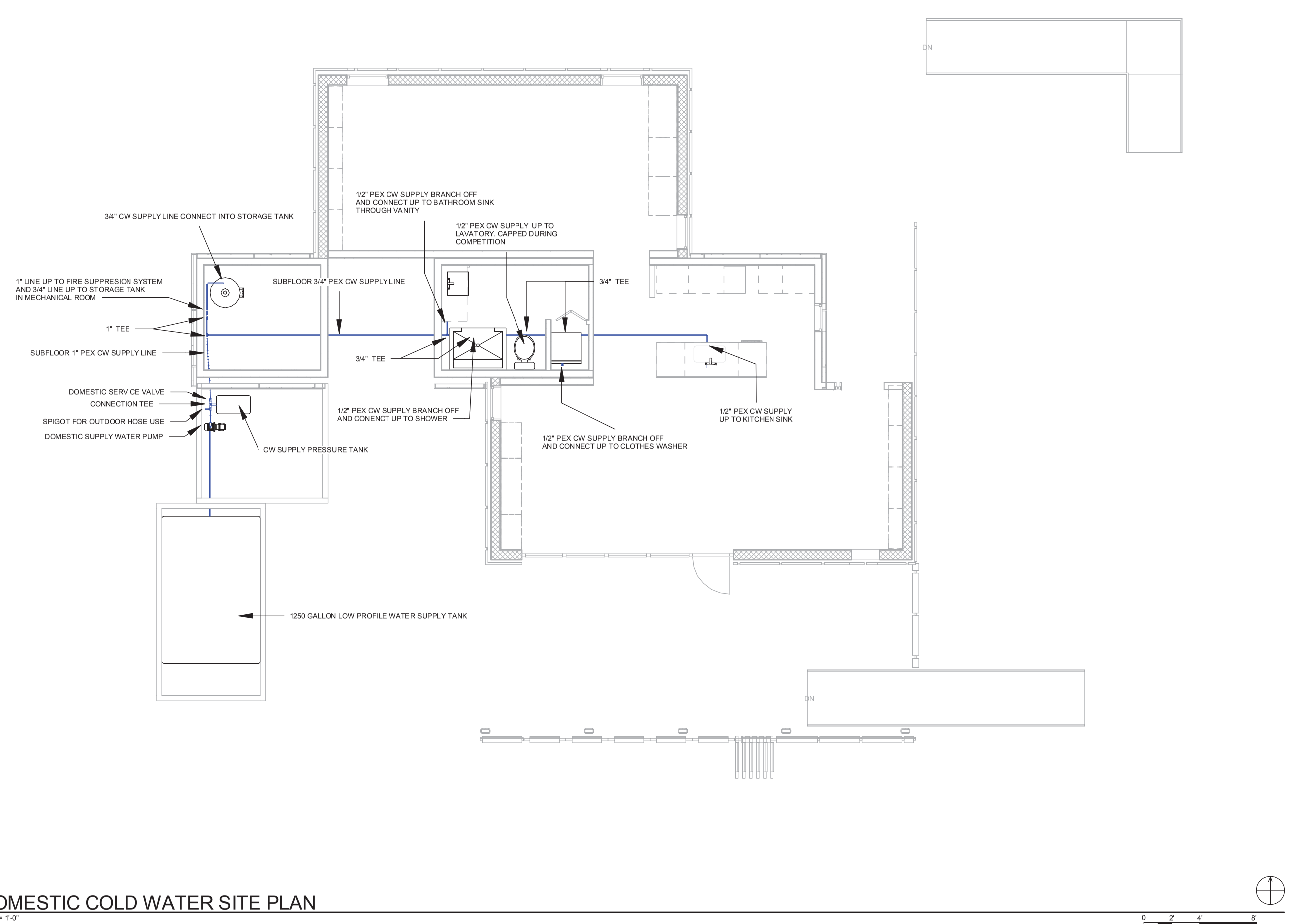
SHEET TITLE
DOMESTIC HOT WATER SUPPLY

P-102




1 DOMESTIC COLD WATER SITE PLAN
1/4" = 1'-0"

SOLAR CAL POLY

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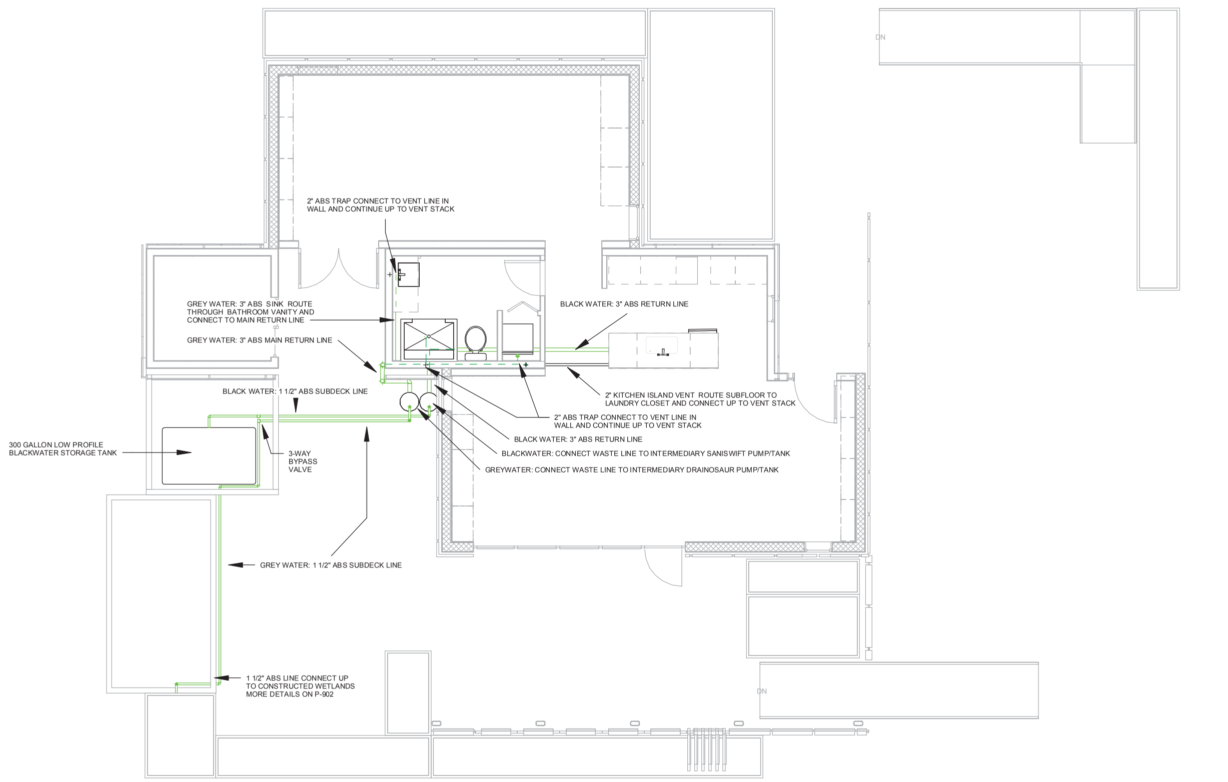
SHEET TITLE
# DOMESTIC COLD WATER SUPPLY

P-103




1 DOMESTIC WATER RETURN SITE PLAN

1/4" = 1'-0"

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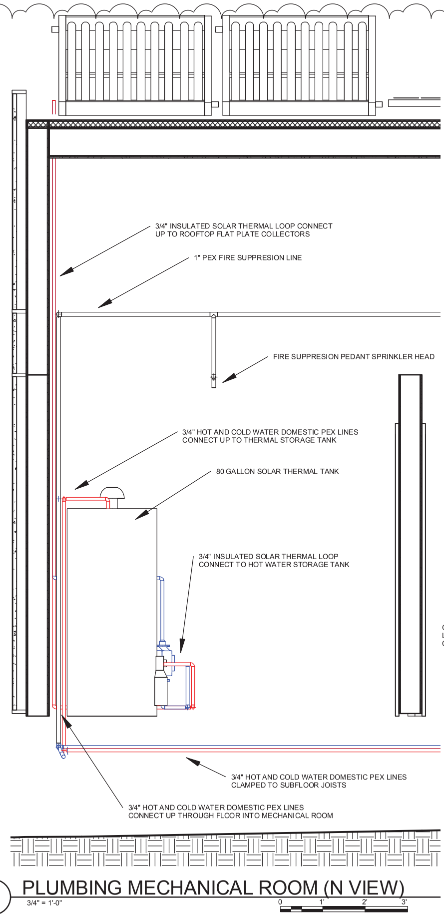
SHEET TITLE

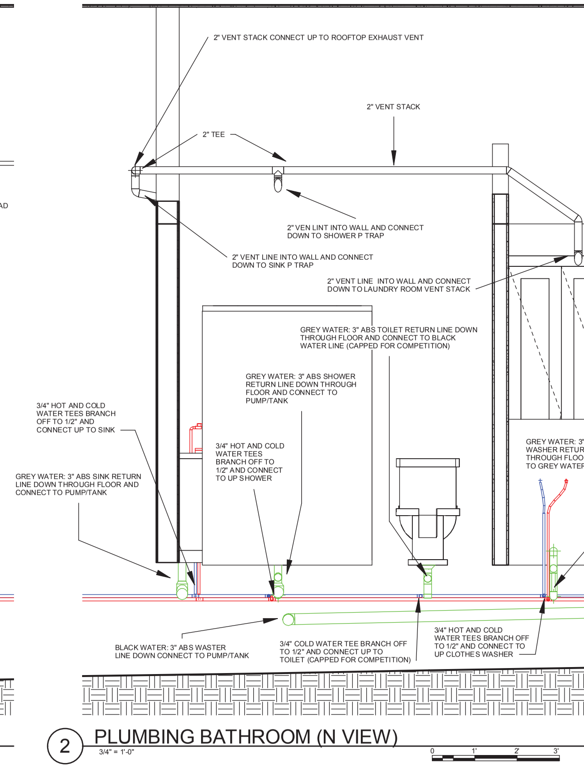
DOMESTIC RETURN

P-104



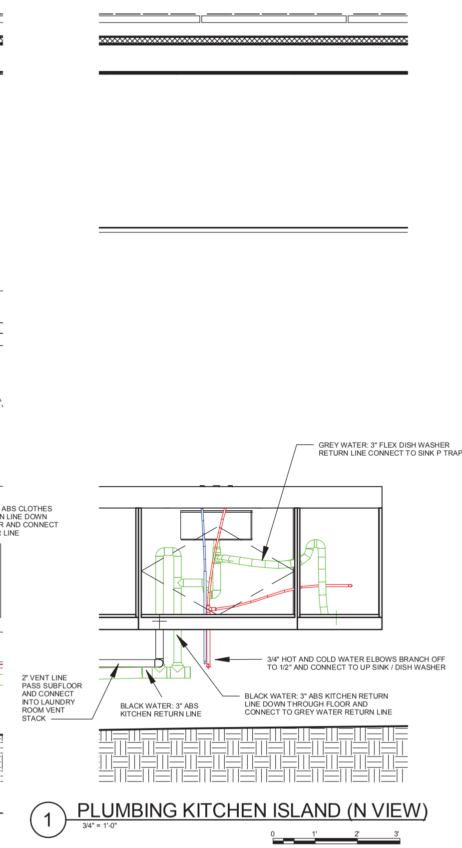

3 PLUMBING MECHANICAL ROOM (N VIEW)

3/4" = 1'-0"




2 PLUMBING BATHROOM (N VIEW)

3/4" = 1'-0"




1 PLUMBING KITCHEN ISLAND (N VIEW)

3/4" = 1'-0"

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SOLAR DECATHLON 2015
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U.S. DEPARTMENT OF ENERGY SOLAR DECATHLON

Revision Schedule

| Revision Number | Revision Description | Revision Date |
|---|---|---|
| 1 | DESIGN REVISIONS AND DETAILING | 2/12/2015 |

LOT NUMBER: 107

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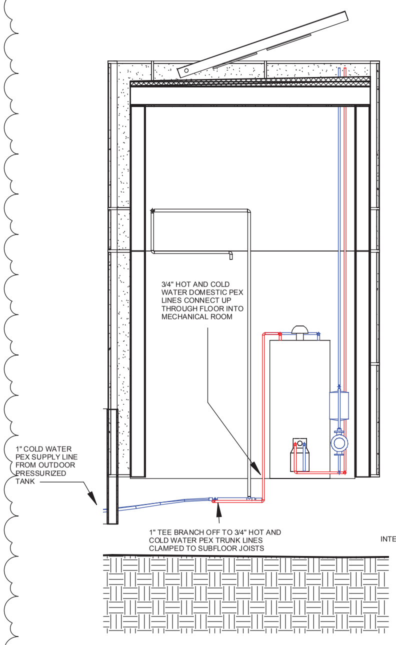
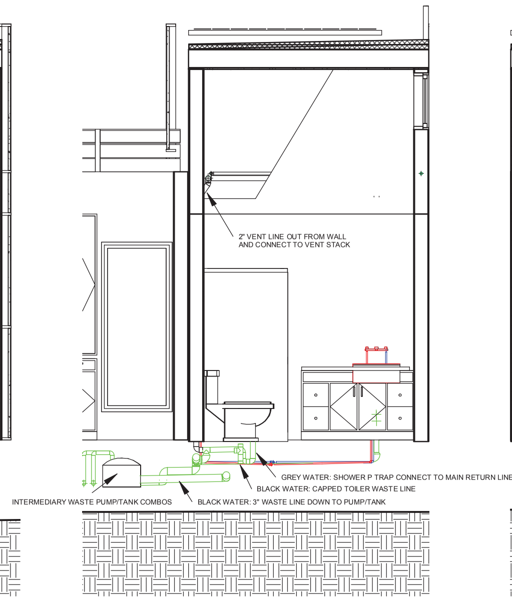
SHEET TITLE

PLUMBING DETAILS

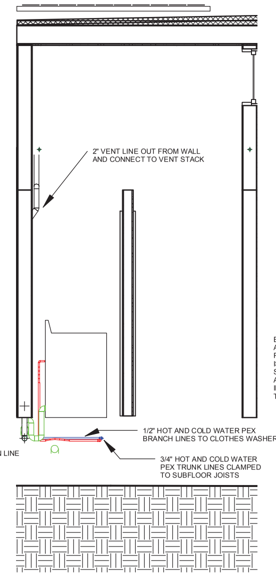
P-501



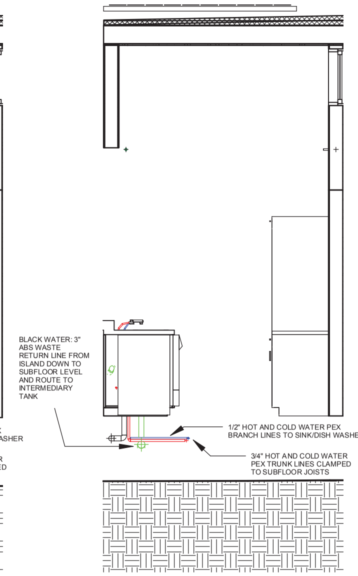

1 PLUMBING MECHANICAL ROOM (W VIEW)
1/2" = 1'-0"




2 PLUMBING BATHROOM (W VIEW)
1/2" = 1'-0"




3 PLUMBING LAUNDRY ROOM (W VIEW)
1/2" = 1'-0"




4 PLUMBING KITCHEN ISLAND (W VIEW)
1/2" = 1'-0"

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SHEET TITLE
MORE PLUMBING DETAILS

P-502

GENERAL NOTES (Mechanical Gray Water)

| Description | Quantity | Brand | Model | Specification |
|---|---|---|---|---|
| 3 Way Valve | 1 | Orbit | 38314 | 1-1/2 to 2 in |
| Supply Water Connector Kit | 1 | Boschart | TFP-2TK252UCV02NL | |
| 2x4's | 3 | Home Depot | 20496UPPS | 2" x 4" x 96" |
| Wetland Base Wood | 3 | Home Depot | 431178 | 7/32 in. x 4 ft. x 8 ft |
| Plastic Lining | 3 | Husky | RSHK3510-25C-U | 10 ft x 25 ft |
| Fasteners | 4 | GRK Fasteners | #8 x 1-1/4" | 110 per box |
| Fasteners | 2 | GRK Fasteners | #10 x 4" | 50 per box |
| Fasteners | 1 | GRK Fasteners | #10 x 3-1/8" | 70 per box |

GENERAL NOTES (Mechanical Plumbing)

| | Description | Quantity | Brand | Model | Specification |
|---|---|---|---|---|---|
| 1 | 1250 Gallon Low Profile Water Tank | 1 | Norwesco | 43011 | 1275 gal, low profile |
| 2 | 300 Gallon Low Profile Utility Tank | 1 | Ace / DenHartod | LP0300-RT | 50 gallon, low profile |
| 3 | Pressurized Well Tank | 1 | Water Worker | HT20HB | 20 gallon |
| 4 | Drainosaur Pump/Tank Combo | 1 | Little Giant | WRSC-6-506065 | 1/3 HP, 115 V |
| 5 | Supply Water Booster Pump | 1 | Walrus | TQ800 | 1 HP, 115 V |
| 6 | Black Water Pump (SaniSwift) | 1 | Saniflo | SANISWIFT | 3/10 HP |
| 7 | Fire Detection and Alarm | 5 | Home Depot | 21009992 | 10-Year Battery Operated Ionization Smoke Alarm |
| 8 | Fire Sprinkler (Viking VK468 Flush Pendent) | 1 | Viking | VK468 | 4.9 K-Factor |
| 11 | Fire Sprinkler (Viking VK476 Flush Pendent) | 5 | Viking | VK476 | 4.9 K-Factor |
| 12 | Fire Sprinkler (Tyco Flush Horizontal Sidewall) | 2 | Tyco | TY2384 | 4.9 K-Factor |
| 13 | 1 in. x 6 ft. Tubolit Self-Seal Foam Pipe Insulation | 4 | Armacell | OES11838 | 1" PEX |
| 14 | 1/2 in x 1/2 in PEX Female Thread Adapter Elbows | 7 | SharkBite | U308LFA | 1/2" PEX x 1/2" Female Thread |
| 15 | 3/4 in x 1/2 in Brass PEX Barb Reducer Coupling | 8 | SharkBite | UC058LF | 3/4" x 1/2" PEX |
| 16 | 3/4 in. Brass PEX Barb Tee | 2 | SharkBite | UC370LFA | 3/4" x 3/4" x 3/4" PEX |
| 17 | 1 in x 1 in Brass PEX Barb Elbow | 3 | SharkBite | UC260LFA | 1"x 1" PEX |
| 18 | 1 in x 1 in x 1 in Brass PEX Barb Tee | 7 | SharkBite | UC374LFA | 1" x 1" x 1" PEX |
| 19 | 1 in. x 3/4 in. Brass PEX Barb Reducer Coupling | 8 | SharkBite | UC060LFA | 1" x 3/4" PEX |
| 20 | 1 in. Brass PEX Barb x Male Pipe Thread Adapter | 1 | SharkBite | UC140LFA | 1" PEX x 1" male thread |
| 21 | 1 in. Supply PEX Piping | 120' | SharkBite | U880B100 | 1" PEX |
| 22 | 3/4 in Cold Water PEX Piping | 60' | SharkBite | U870B100 | 3/4" PEX |
| 23 | 1/2" Insulated Cold Water PEX Piping | 20' | SharkBite | U860I100 | 1/2" Insulated PEX |
| 24 | 3/4" Hot Water PEX Piping | 60' | SharkBite | U870R100 | 3/4" PEX |
| 25 | 1/2" Insulated Hot Water PEX Piping | 20' | SharkBite | U860I100 | 1/2" Insulated PEX |
| 26 | 3/4" Pipe Insulation | 120' | Pratt Retail Specialties | 419921 | 3/4" Insulation ONLY |
| 27 | 3/4 in. x 1/2 in 3-Port Open PEX Manifold | 2 | SharkBite | 22784 | 3/4" x 1/2" x 1/2" x 1/2" x 3/4" PEX |
| 28 | 1/2 in. PEX Clamps | 1 | SharkBite | UC953CPA100 | 100-Pack |
| 29 | 3/4 in. PEX Clamps | 1 | SharkBite | UC955CPA100 | 100-Pack |
| 30 | 1 in. PEX Clamps | 5 | SharkBite | UC956A | 10-Pack |
| 31 | 3/4 in. Brass PEX Barb x Female Threaded Adapter | 2 | SharkBite | UC088LFA | 3/4" PEX x 3/4" female thread |
| 32 | 3/4 in. x 1/2 in PEX reducer Tee | 1 | SharkBite | UC454LFA | 3/4" x 1/2" x 1/2" |
| 33 | 1/2 in. Brass PEX Barb x Female Threaded Adapter | 1 | SharkBite | UC072LFA | 1/2" PEX x 1/2" female thread |
| 34 | 3/4 in. Brass MPT x MHT Quarter-Turn Hose Bibb Valve | 1 | Homewerks Worldwide | VHBQTCF4B | 3/4" male thread x hose bib |
| 35 | 16 oz. ABS Cement in Black | 2 | SharkBiteOatey | 308923 | ABS Bonding Agent |
| 36 | 3 in. x 20 ft. ABS Sch. 40 Plain-End Foamcore Pipe | 6 | Nibco | 57737 | 3" straight ABS |
| 37 | 2 in. x 2 ft. Plastic ABS Pipe | 8 | Nibco | 1202 | 2" straight ABS |
| 38 | 2 in. ABS DWV Hub x Hub x Hub Sanitary Tee | 5 | Nibco | 02753H | 2" x 2" x 2" sanitary tee |
| 39 | 2 in. ABS DWV Hub x Hub Coupling | 10 | Nibco | C5801HD2 | 2" coupling |
| 40 | 3 in. Black ABS DWV H x H Coupling | 8 | Nibco | C5801HD3 | 3" coupling |
| 41 | 2 in. ABS P-Trap | 3 | Nibco | C5885HD2 | 2" P-trap |
| 42 | 2 in. ABS DWV 90 Degree Hub x Hub Elbow | 4 | Nibco | C5807HD2 | 2" 90° |
| 43 | 3 in. ABS DWV SPG x FIPT Female Street Adapter | 1 | Nibco | C58032HD3 | 3" x 3" female prep for plug |
| 44 | 3 in. ABS DWV MIPT Cleanout Plug | 1 | Nibco | C5818HD3 | 3" plug |
| 45 | 3 in. x 3 in. x 2 in. ABS DWV Hub x Hub x Hub Sanitary Tee | 4 | Nibco | C5811HD332 | 3" x 2" x 3" sanitary tee |
| 46 | 3 in. ABS DWV 90 Degree Hub x Hub Elbow | 4 | Nibco | C5807HD3 | 3" 90° |
| 47 | 1/2 in. Plastic Polymer PEX Pipe 90-Degree Bend Support with Mounting Bracket | 25 | SharkBite | 23050 | 1/2" PEX bend |
| 48 | 3/4 in. Plastic Polymer PEX Pipe 90-Degree Bend Support with Mounting Bracket | 5 | SharkBite | 23051 | 3/4" PEX bend |

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LOT NUMBER: 107
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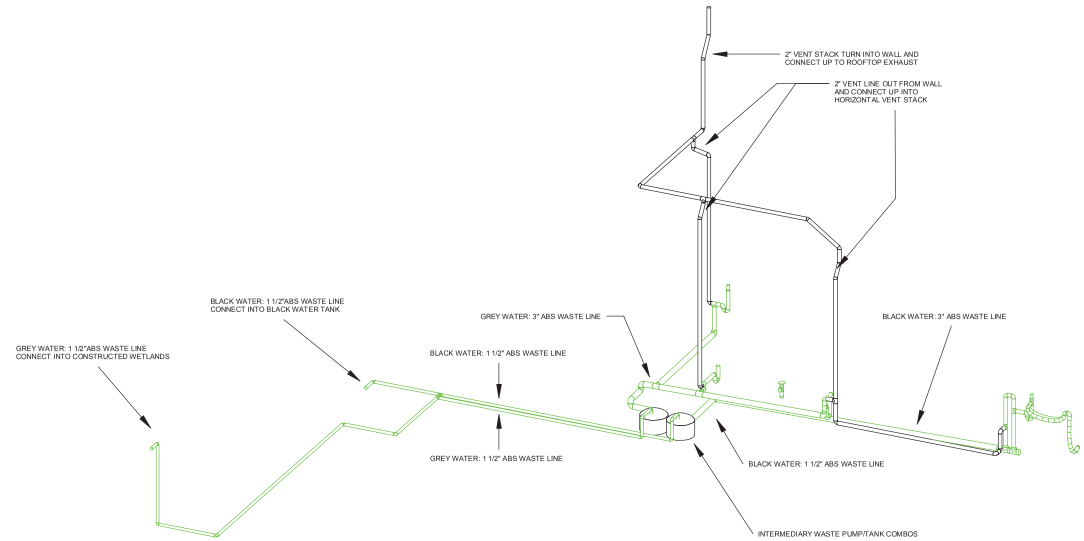
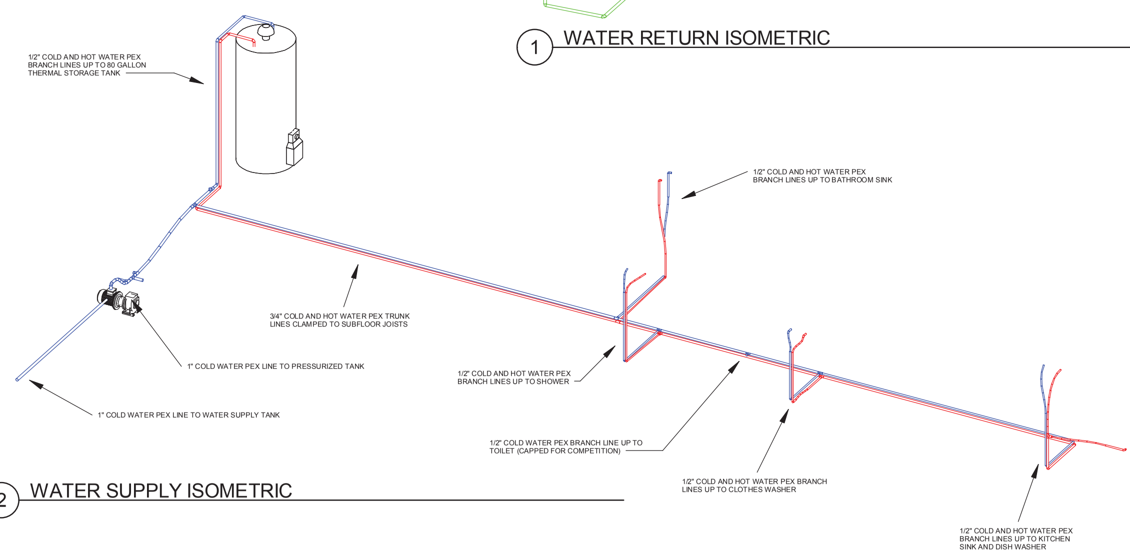
SHEET TITLE
SCHEDULES

P-601




1 WATER RETURN ISOMETRIC




2 WATER SUPPLY ISOMETRIC

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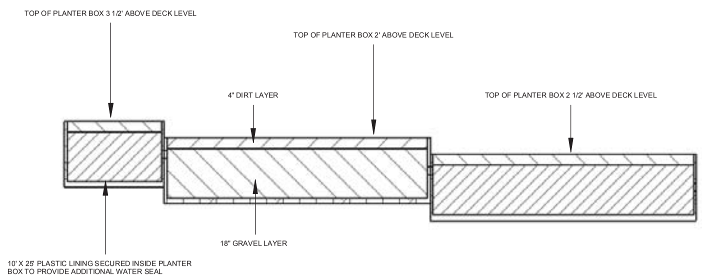
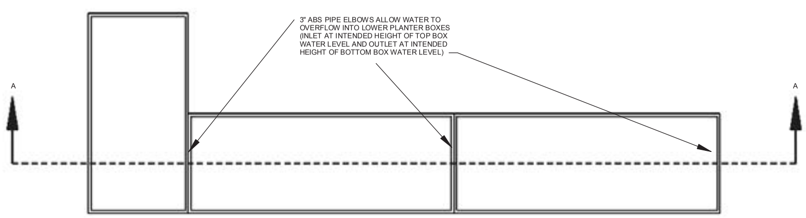
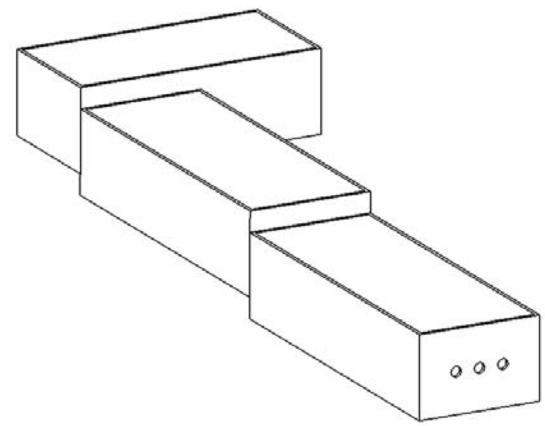
SHEET TITLE
DOMESTIC WATER ISOMETRICS AND DETAILS

P-901




CONSTRUCTED WETLANDS SECTION A-A



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SHEET TITLE

WETLANDS ISOMETRIC

P-902