CRETE house

ENGINEERING

BUILDING COMPONENTS

Concrete is the building material of the future. It is affordable, customizable, and, as the Washington University team will demonstrate, can be quite sustainable. The CRETE house derives its name from the re-innovated material, concrete. Because of concrete's strength, thermal properties, and resiliency, Washington University has chosen to build the CRETE house almost entirely of pre-cast concrete.

With the help of countless entities across the concrete industry, the CRETE house team has designed concrete panels for the walls, floor, ceiling, gutters, and other interior components of the building. The walls are made of six concrete sandwich panels. Combined, the three wall layers have a total R-value of 25.2 hr °F ft2 / BTU once thermal bridging and air film resistances are considered. Five inches of FOAMULAR® 250 rigid extruded polystyrene insulation (R-25) fill the middle. Thermomass Wythe tie connections limit the thermal bridging across the insulation layer.

The exterior layer is made from an Ultra-High Performance Concrete (UHPC) known as Ductal. Ductal's high strength allows the exterior layer to be just 1.25", as compared to the industry standard of 3" to 4". By reducing the thickness of the concrete, the overall amount of cement is reduced, ultimately lowering carbon emissions from the concrete production process as well as lowering the cost and environmental impact due to transportation. Washington University's CRETE house is the world's first example using UHPC as an architectural feature in a concrete sandwich panel. Figure 1 shows a section view of a CRETE house wall panel.

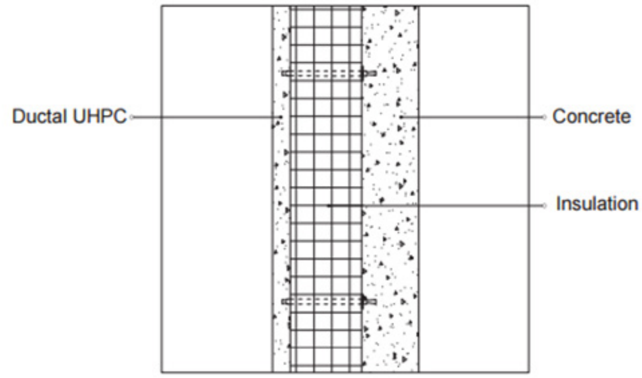


FIGURE 1: SECTION OF CRETE WALL PANEL

The floor of the CRETE house, set on pre-cast footings, consists of five panels. Each panel is comprised of three layers to make a 12" double-wall floor. The top layer is 4" of pre-cast concrete; beneath is 5" of EPS (expanded polystyrene) insulation with steel support trusses. Then, a 3" layer of pre-stressed pre-cast concrete. The total R-value is 21 once thermal bridging and air film resistances are considered. Radiant tubing is buried 2.5" from the surface of the top layer of concrete. This depth allows for a more uniform temperature on the surface of the concrete. Due to the nature of pre-cast concrete, the tubing is set into the rebar supports before the concrete is poured. During use, hot water runs through the tubing in the floor, providing heating for the home.

Architectural panels in the floor and roof cover the connections between concrete panels and the radiant tubing and electrical connections. These strips align with the locations of the floor-to-ceiling windows and overhanging gutters, creating a linear visual effect throughout the entire project. The detailed integration of function and design is a common theme throughout the mechanical systems, architectural design, and ambiance within the CRETE house.

Figures 2a and 2b below show section views of a standard floor and ceiling panel, respectively.

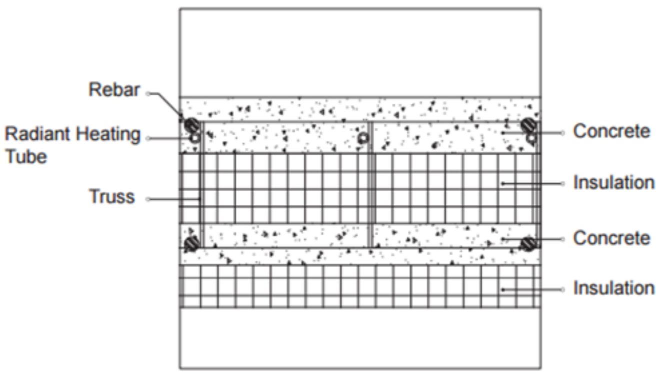


FIGURE 2a: SECTION VIEW OF FLOOR PANEL WITH RADIANT HEATING TUBES

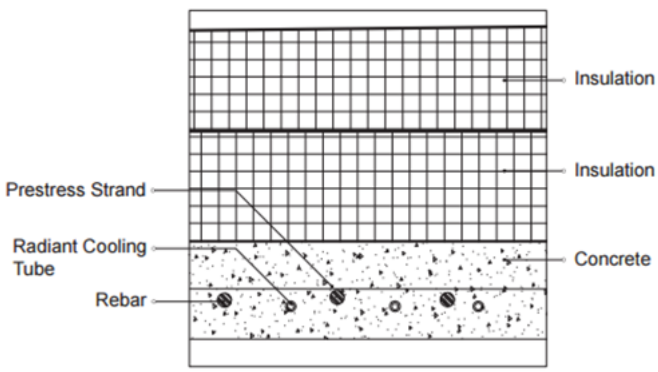
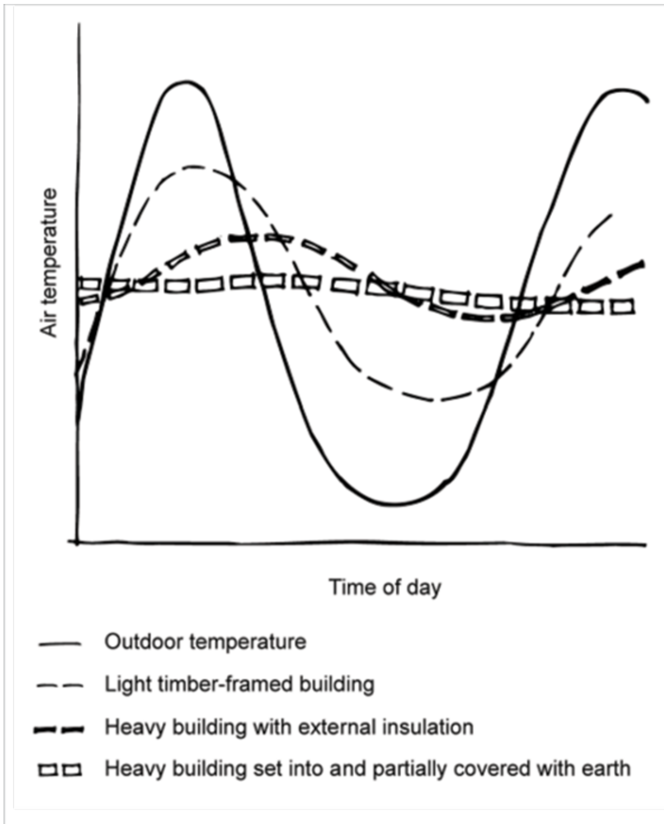


FIGURE 2b: SECTION VIEW OF CEILING PANEL WITH RADIANT COOLING TUBES

The pre-cast ceiling is similar to the floors. Radiant cooling tubing is embedded 3" into the 7" of pre-cast concrete. A 13" layer EPS lies on top of the concrete, covered by a tapered layer of Polyisocyanurate with an average depth of 2" on top of the EPS. A rubber membrane provides a waterproof seal. The shape of the insulation drives rainwater to the edges of the roof and down the gutters. Like the floor panels, the ceiling panels connect at the same lines as the windows and gutters, with a thin strip of perforated metal covering the connections. Figures 2a and 2b below show section views of a standard floor and ceiling panel, respectively.



In addition to strength and design flexibility, concrete gives the CRETE house a high thermal mass. The high heat capacity allows the house to act as a thermal battery, mitigating diurnal temperature variations thus reducing energy consumption. Figure 3 shows interior air temperature of concrete buildings, compared to other types of construction.

The sandwich panels, and inherent material compositions, prevent mold growth by limiting moisture diffusion and keeping interior surface temperatures warmer due to a small temperature gradient throughout the assembly. Temperature sensors are embedded in the floors and ceilings to ensure radiant tubing does not cause condensation on the slab surface. Moisture, durability issues, and mold growth are avoided using these techniques.

LIFE CYCLE AND EMBODIED ENERGY

In addition to reducing operational energy consumption, concrete buildings are resilient, reducing total embodied energy and environmental harm. The frame of a wooden house is commonly composed of softwood 2x4's with a minimum average life expectancy of 30 years.[1] However, concrete buildings have an estimated lifetime of 100 years or more, about three times longer than that of a wooden house.[2] This constitutes a major advantage to both the CRETE house and the environment alike, while demonstrating the viability and the environmentally friendly benefits from the materials design.

Embodied CO2 of the CRETE house was quantified through a life cycle analysis. This primarily included the structural aspects of the house including the concrete, insulation, steel, doors, windows, and plaster. Other aspects were not quantified because they are similar between the houses. CRETE house in the end tallied a total of 49,000 kg of CO2, with over 50% from concrete. A wooden house of the same size only emits 32,000 kg of embodied CO2. CRETE house despite its higher embodied CO2, only takes around 1.5 years to start becoming more environmentally friendly than a wooden house. This is due to the extremely low operational carbon footprint CRETE house. When considering that CRETE house lasts at least three times as long as a typical wooden house, the environmental benefits of concrete as a building material truly come to light.[3]

[1] Seiders, David , Dr., et al. "Study of Life expectancy of Home componentS." Lafarge.com. February 2007. Accessed July 13, 2017. http://www.hbact.org/Resources/Documents/Files%20L-Z/Life%20Expectancy%20of%20Home%20Components%20-%20NAHB.pdf., 4.

[2] "High-performance precast concrete for 100-year life span in Kansas City." Lafarge.com. December 03, 2015. Accessed July 13, 2017. http://www.lafarge.com/en/high-performance-precast-concrete-100-year-life-span-kansas-city.

[3] Monahan, J., and J.c. Powell. "An Embodied Carbon and Energy Analysis of Modern Methods of Construction in Housing: A Case Study Using a Lifecycle Assessment Framework." Energy and Buildings 43.1 (2011): 179-88. Web.

	CRETE House	Wooden House
Area (m2)	92.9	92.9
Embodied CO2 (kg)	49,000	32,000
kgCO2/m2/yr (Estimated)	30	150
Years of Use	Total kg CO2	
1 yr	51,787	45,935
1.5 yrs	53,180.5	52,902.5

Although concrete is often perceived as environmentally harmful, a thorough life cycle analysis reveals that concrete is more friendly than wood for ranch style residences. The modular pre-cast panel construction makes CRETE house a competitive alternative to a traditional wood frame home.

Due to its inherent strength and material properties, the CRETE house can withstand tornados, heavy storms, floods, wind, fire, insects, moisture, and mold. Missouri annually averages 30 or more tornados; as such, a resilient and tornado resistant house was a necessary feature.[4] Tornadoes that pass through the area of Missouri can cause millions of dollars of damage, destroy dozens of houses, and injure or even kill inhabitants. To simulate an F1 tornado with wind speeds of 100 mph, a 15 pound 2x4 piece of lumber was shot at each wall at a speed of 60 mph, the speed of flying debris. The 1.25" UHPC was not damaged; results can be seen in figure 4. A second test to simulate an F5 tornado with 250 mph wind speeds was conducted; the 2x4 was shot at 100 mph and penetrated the UHPC but not the inner pre-cast wall.

[4] http://climate.missouri.edu/news/arc/apr2011.php

A final assembly was tested with the UHPC layer thickness increased to 2.5". This assembly was struck by a 2x4 at around 130 mph (the max of the machine) five times with only slight surface marking as a result. Resiliency to tornadoes is of the utmost importance as the final destination of the CRETE house, is St. Louis, in the heart of tornado alley. Figures 4a, 4b, and 4c show sections of a wood frame wall, brick wall, and the CRETE house walls.

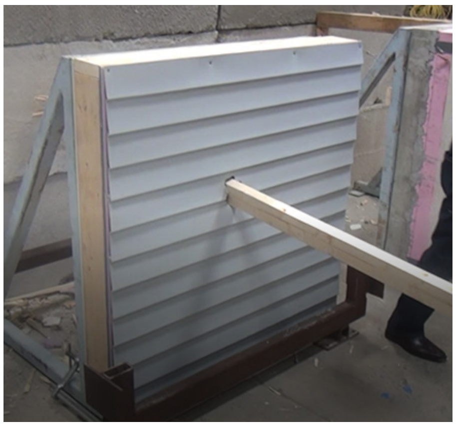


FIGURE 4a: AT 60MPH, A 2x4 PENETRATES THROUGH A WOODFRAME WALL SECTION

FIGURE 4c: AT 60MPH, A 2x4 LEAVES A SURFACE MARK ON THE EXTERIOR FACADE OF THE CRETE WALL SECTION

FIGURE 4b: AT 60MPH, A 2x4 PENETRATES THROUGH A BRICK WALL SECTION

Complementing the resilient concrete perimeter are nine windows and four doors, which provide protection from noise, wind, and storms. The windows and doors are made of double pane, PPG laminated floor-to-ceiling glass, providing natural light in the home and reducing the amount of artificial light necessary reducing energy consumption. The windows are thermally broken, minimizing the conduction losses through the frame. The majority of these openings are on the North and South faces of the building, minimizing heat gain from the East and West. The windows are operable, allowing occupants to open them during pleasant weather.

Motorized Venetian blinds reflect direct UV rays and radiant energy while allowing light to pass through. The exterior blinds prevent light from penetrating the building envelope, reducing the heat gain into the building. Blinds are controlled by the building automation system to manage solar heat gain, even when the house is not occupied. The blinds also function as part of a resilient building system to further protect the laminated glass from impacts during extreme weather events.

Within the perimeter, the steel frame core is the heart of the building. The core contains all the mechanical, electrical, and plumbing systems. It is integral to the modular design and quick erection of the building. After the floor panels are placed, the core is simply lowered into the house and systems can be quickly connected.

MECHANICAL SYSTEM

The mechanical system, located entirely in the house's core, uses two different modes for heating and cooling. The majority of the sensible heating and cooling loads are handled with the radiant tubing in the ceiling and floor, while a dedicated outdoor air system (DOAS) is used to handle the latent loads, ventilation, and any excess sensible heating and cooling loads. An Energy Recovery Ventilator (ERV) uses exhaust air to precondition fresh outdoor air before it enters the DOAS, capturing or releasing both sensible and latent heat. Figure 4 shows a simplified flow diagram of the heating and cooling hydronic system, while Figure 5 shows a 3D model of the air side.

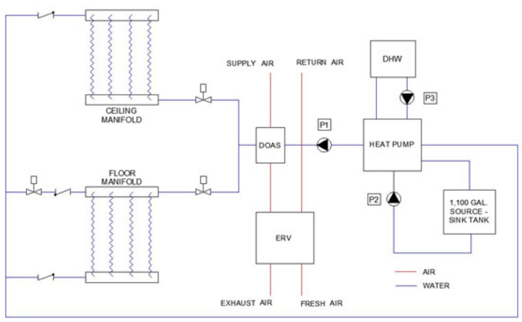
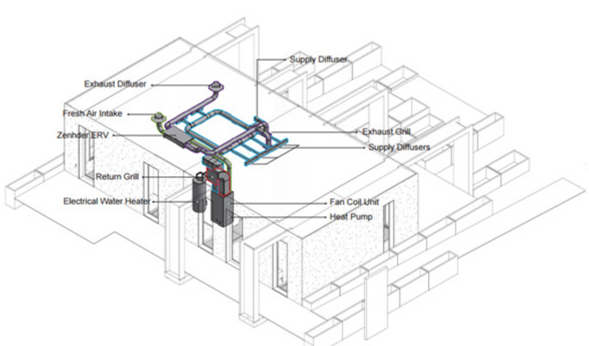


FIGURE 4: SIMPLIFIED AIR AND WATER FLOW DIAGRAM



`FIGURE 5: 3D RENDERING OF THE MECHANICAL SYSTEM

The mechanical heating and cooling system is designed to meet peak cooling loads of 22,000 BTU/H (95°DB/ 76°WB) and peak heating loads of 14,100 BTU/H (5°F)*.

These loads are met with a Hydro-Temp water source heat pump with a variable speed compressor that can provide 30,200 BTU/H of chilled water and 20,500 BTU/H of hot water at design conditions.

In Denver, the Hydro-Temp water source heat pump uses an 1100 gal storage tank as the heat sink/source to generate chilled/hot water for the hydronic system. Upon arrival at its final destination in Eureka, Missouri, the CRETE house will connect to ground source wells.

The oversized system has the ability to recover heat for domestic hot water from the heat rejected during cooling. In the heating season, it operates to provide DHW on a priority basis. This means that the water source heat pump, coupled with a 60 gallon hot water storage tank, can provide 100% of the annual DHW energy requirements at much lower energy costs than all other methods available. With advanced, high performance buildings, the domestic hot water loads often outstrip the annual heating loads.

With a six-row coil, the two-pipe fan coil unit (FCU), coupled with chilled water from the heat pump, has real coil depth to aggressively dehumidify the air and better manage space relative humidity. The FCU has an electrically commutated motor (ECM) for variable speed operation. This allows for a fine degree of control over airflow. The system can ramp from 150 CFM, providing the minimum airflow required by ASHRAE 62.2 (based on square footage and occupancy) up to 1000 CFM. This provides over 1 CFM/SF for economizer operation that can also be used for nighttime mass charging (pre-cooling) when appropriate.

All pumps and fans within the mechanical system have an electronically commutated motor (ECM), which allows for adjustable motor speeds. For a majority of the time, these pumps operate at low speeds, reducing energy consumption significantly. The house uses a sophisticated building automation system (BAS) to control the thermal comfort of the interior environment, tying together all of the systems and adaptively learning the most efficient way to utilize energy.

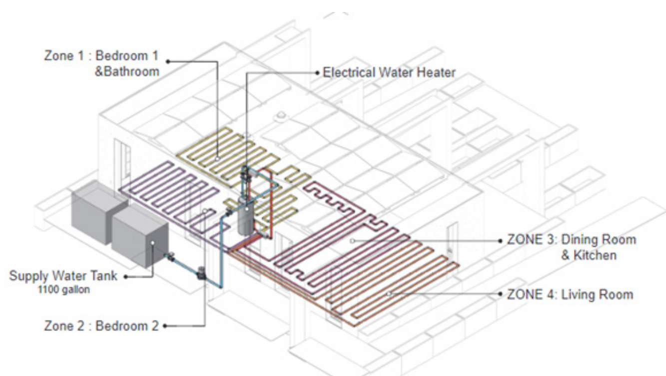


FIGURE 6: HYDRONIC FLOOR LAYOUT (3D RENDERING)

The thermal capacitance of the concrete mass is 34,500 BTU/°F, providing a thermal flywheel advantage. For example, if the concrete is pre-cooled to 60 degrees in the summer and allowed to coast until 70 degrees, this is equivalent to 16 hours of peak cooling loads. Similarly, pre-heating the concrete slabs to 85 degrees and letting it drop 10 degrees is equivalent to 22 hours of peak heating loads. A predictive energy model was developed in DesignBuilder to estimate the optimal preheating and precooling times. This can take advantage of lower electrical costs at night. This capacitance provides resilience, survivability, and sustainability in the face of future power outages.

The radiant heating and cooling system is divided into four zones, each with independent control of water flow rates, and therefore, the load distributed to that zone. Figure 6, above, shows the radiant tubing layout for the floor, which is mirrored in the ceiling. The hydronic floor is primarily used for heating, while the hydronic ceiling is primarily used for cooling. However, both surfaces can be used for heating or cooling if necessary.

Since condensation is a common issue with radiant cooling systems, the CRETE house's BAS uses several measures to ensure no surfaces will reach the dew point inside the house. During the cooling season, hot and humid outdoor air first enters the ERV where the exhaust air from the building is used to precondition the outdoor air. The preconditioned air is mixed with the return air and sent to the DOAS, where the BAS controls the chilled water temperature and flow rate in order to deliver the minimum energy to cool down and dehumidify the air. The supply air temperature and humidity are calculated to produce space temperatures of 75°F and 50% relative humidity. At these conditions, the dew point is 55°F.

Additionally, the CRETE house has 27 total slab temperature sensors that feed information directly to the BAS. Based on the outdoor temperature and relative humidity, the BAS calculates the current dew point and ensures that the slab surface does not reach this temperature, in the event that the building changes from natural ventilation to mechanical environmental control, the fan coils unit operates to first bring the space humidity below any surface dew point prior to hydronically cooling the radiant panels. If the floor is used for heating or cooling, the temperature sensors also ensure that the slab surface is within the comfortable temperature ranges according to the ASHRAE 55-2004 standard of 66.2°F-84.2°F

The performance of the CRETE house's innovative mechanical system is dependent on an advanced BAS. The systems described have very detailed sequences of operation that carefully and efficiently manage the interior environment.

ELECTRICAL SYSTEM

Electricity for the home is provided by a solar array, mounted on the roof. There are 30 Sunpower E20-327-COM photovoltaic (PV) panels, each panel consisting of 96 Monocrystalline Maxeon Gen II solar cells. Under standard test conditions, they produce 327 W peak power per panel with 20.3% efficiency. To increase power density, an East-West racking system was designed for the PV panels, with each panel tilted at 10 degrees. An entirely South facing array allows for maximum solar production per panel, for a total system peak power of 7,848 kW. However, an East-West racking system allows for 6 more panels for a total of 9,810 kW, which more than accounts for the slight decrease in output per panel due to the orientation. Energy produced by the PV system is either used directly by the home or stored using a Tesla Powerwall 2 DC Battery. Figure 7 shows an overall schematic of the electrical system.

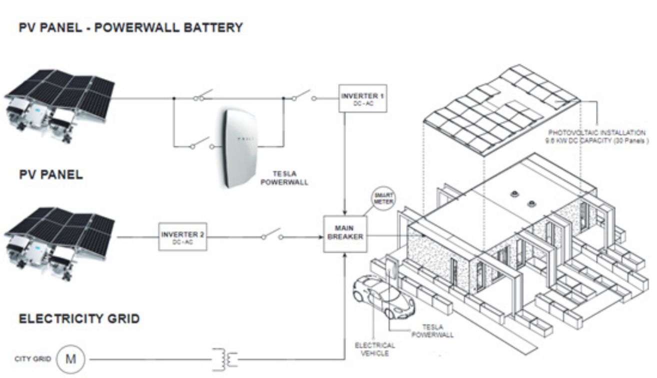


FIGURE 7: OVERALL ELECTRICAL SCHEMATIC

The East-facing panels and the West-facing panels each have their own maximum power point tracker (MPPT). The MPPTs eliminate any issues with multi directional arrays and increase panel efficiency by 10-15% in the winter and up to 20-45% in the summer, by matching the voltage coming out of the panels with that of the battery.

Each Sunpower panel is connected to a SolarEdge P400 power optimizer, which increases the energy output of the panel by constantly tracking the maximum power point of each PV module individually. Using these power optimizers, the performance of each module can also be tracked and monitored. These combinations of inverter savings and efficiency of the overall system, including complex conditions, help to offset the extra nominal cost of power optimizers for each panel over the system's lifecycle.

The solar array is split into 3 strings. One string feeds an inverter (SolarEdge 3000A-U) that is a grid tied through the load center, while the other strings feed an inverter (SolarEdge 7600A-USS) that controls battery charging and smart feeding into and out of the grid. The battery specified is the Tesla Powerwall 2, which is mounted outside due to interior space demands and heat gain considerations.

The system uses a smart meter with current transformer (CT) monitoring of the main load center. Additionally, the inverter communicates with the battery. These two systems work together to maximize PV production and self-consumption. Battery storage allows CRETE house to utilize on-site PV production and eliminate the use of grid power completely, or to shift demand to off peak hours in the rate schedule.

Since all components of the system can communicate with one another and to the web, each panel's output can be tracked in real time, along with real time monitoring of the battery status and self-consumption data. This connection also allows for remote access of the system for monitoring and maintenance.

During emergency situations, the system requires rapid shutdown. When either the inverter or the grid power is shut down, the DC voltage of the PV modules is shut down by the SafeDC feature of the P400 power optimizers. To shut down grid power, there is an AC disconnect switch next to the electrical meter outdoors. Furthermore, the SolarEdge inverters contain an integral DC disconnect that also triggers rapid shutdown when flipped. Efficient and safe distribution of power through the electrical system is of utmost importance. Electricity consumption is limited wherever possible. The house's electrical system is all AC power without any DC specific appliances or lights, which represents a conventional approach to help cost effectiveness and market adoption.

COMFORT AND PRODUCTIVITY

The CRETE house is designed to not only maximize energy efficiency, but also human health, comfort, and productivity. Though these factors are usually not the primary focus in building design, they are integrally associated with the buildings we work and live in. Productivity is defined as the amount of progress an individual can complete for a specific task within a set time limit; for example, the number of emails someone can write in an hour.

Optimized habitat conditions can save money and time, as well as improve occupants' health in the long run. Individual productivity is increased and health incidences are decreased when ventilation rates are higher, sunlight and nature views are maximized, light level and temperature are customizable, and ambient noise is minimal.[5]

The CRETE house provides between 80 cfm to 1000 cfm of fresh air, depending on the number of occupants. [In a study involving school children, standardized math performance was increased 14.4% when airflow was increased from 4.77cfm/person to 9.53 cfm/person.]** More air flow and increased outdoor air reduces the amount of CO_2 inside the building. Large windows allow for increased daylight and natural landscape views, which is correlated with increased productivity[6] and mental health.[7] The large windows and dimmable interior LEDs contribute to decreased electricity consumption and increased human attentiveness.[8]

Radiant heating/cooling systems are a more comfortable method for controlling thermal comfort than forced air systems. Radiant heat transfer is highly sensitive to temperature changes, and with the CRETE house building automation system, controlling comfort can be done quickly and does not require forced air draft, which is a source of discomfort.[9]

5 Loftness, Vivian, et. al. "Health, Productivity and the Triple Bottom Line." December 2007. Accessed July 13, 2017. http://www.cmu.edu/iwess/workshops/absic_dec_2007/BIDS%20ABSIC_FINAL%202007.pdf.
6 Loftness, Vivian, et. al. "Health, Productivity and the Triple Bottom Line."
7 Berman, Marc G., John Jonides, and Stephen Kaplan. "The Cognitive Benefits of Interacting With Nature." Psychological Science 19, no. 12 (2008): 1207-212. doi:10.1111/j.1467-9280.2008.02225.x.
8 Loftness, Vivian, et. al. "Health, Productivity and the Triple Bottom Line."
9 Rhee, Kyu-Nam, and Kwang Woo Kim. "A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment." Building and Environment 91 (2015): 166-90. doi:10.1016/j.buildenv.2015.03.040.

Further research on the CRETE house will study thermal comfort resulting from the radiative heating and cooling system. A wireless sensor network was developed in order to test and refine a predictive thermal control model. This project uses multiple motes; small, battery operated circuit boards containing a radio, light sensor, humidity sensor, and temperature sensor. The motes collect data at 5 minute intervals and transmit the data to a Raspberry Pi (RPI), a small computer. Temperature sensors on the radiant tubing also provide temperature data. Sensor data are uploaded offsite and combined to generate a point by point thermal surface map, which can then be used to calculate radiative temperature at any point in the house.

LONG TERM IMPACT

Nearly every aspect of the CRETE house involves research in one form or another. The most notable efforts include; modular design with concrete and the core, quick erection time, development of thin UHPC as a facade material, thermal properties of concrete, radiant cooling in a humid climate and developing an academic channel through which industry partners can communicate.

It will be a lasting fixture in its final installation location of Tyson Research Center for decades to come. Here the CRETE house will serve as a living quarters for the many scientists that visit and work at the center. At Tyson, further studies can be done on the efficiency and comfort of the CRETE house

The CRETE house highlights the advantages of concrete as a future building innovation, such as durability, affordability, and resiliency. The integrated systems and materials design of the house allow for minimal daily carbon emissions, which compared to a traditional wood house, leads to an ultimately more environmentally friendly and safe structure. The CRETE house is a product of creative solutions to the prevalent problems regarding environmental impact, as well as human health and safety.

CRETE house

ENERGY MODEL & ANALYSIS

1. INTRODUCTION

Washington University's Solar Decathlon home aims to integrate passive and active mechanical strategies to optimize the interception of comfort and energy use in a home. In addition to meeting competition and standards, Crete aims to elevate expectations for energy efficiency. To achieve this, we believe structural design and HVAC system design must marry with the home's exterior environmental conditions to reduce demand for heating and cooling.

We used Climate Consultant 6.0 to understand Denver's climate relative to comfort conditions in a home. We see from fig. 1, mean temperature is primarily at or below comfort zone temperature. Even considering the design high, the temperature range only ever exceeds comfort conditions during June through September months. Based on Denver's climate narrative, the primary demand is concentrated towards heating. Throughout the diagrams provided by Climate Consultant, the climate in Saint Louis, MO is very comparable to Denver, CO. Therefore, making the prototyping of the house in Saint Louis much more effective in gauging how it will truly perform in competition.

ST. LOUIS DENVER

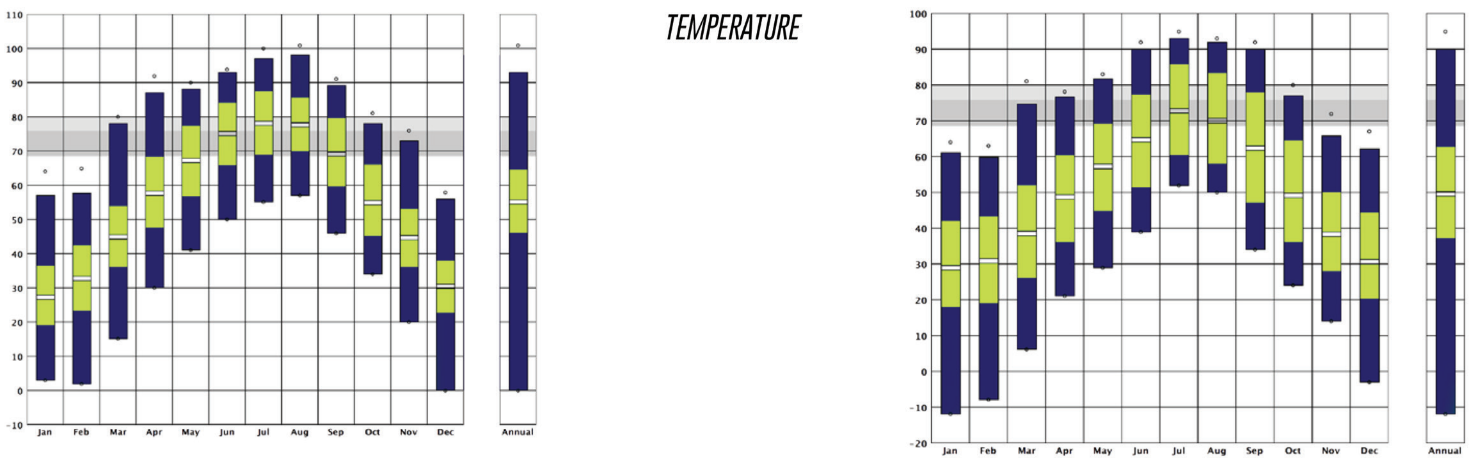
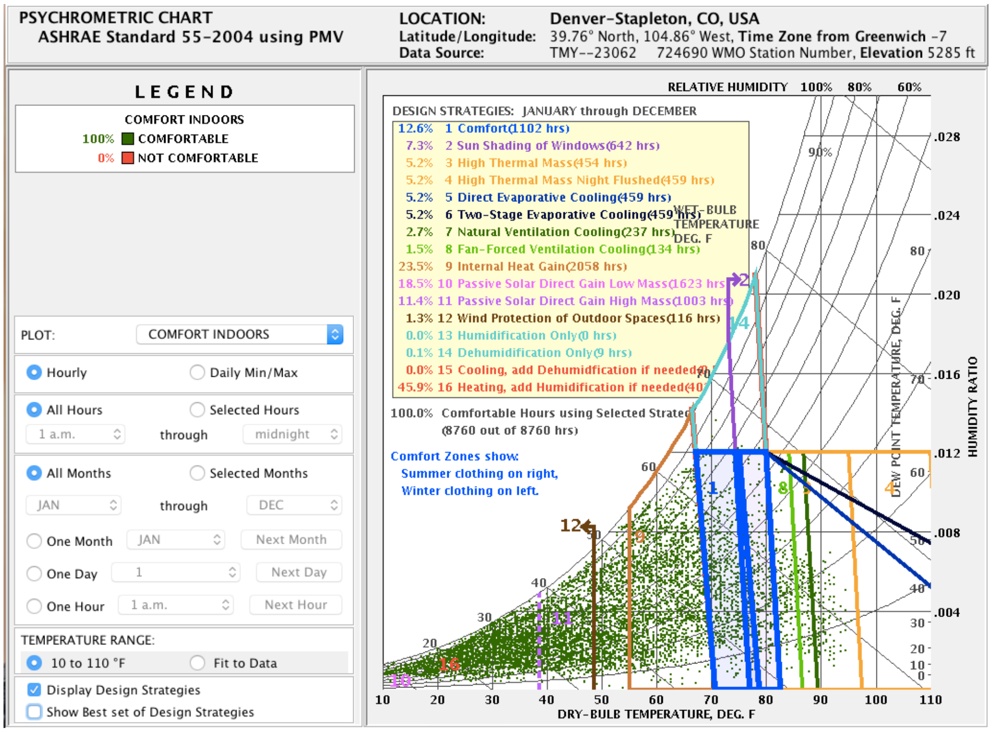


Figure 1

Climate Consultant predicts heating will account for nearly fifty percent of an effective design strategy, as shown fig. 2a. Fig. 2b specifies the best set of design strategies, which only result in a one percent decrease (from 100% to 99%) in comfortable hours. This set of strategies does not call for mechanical or even passive cooling.



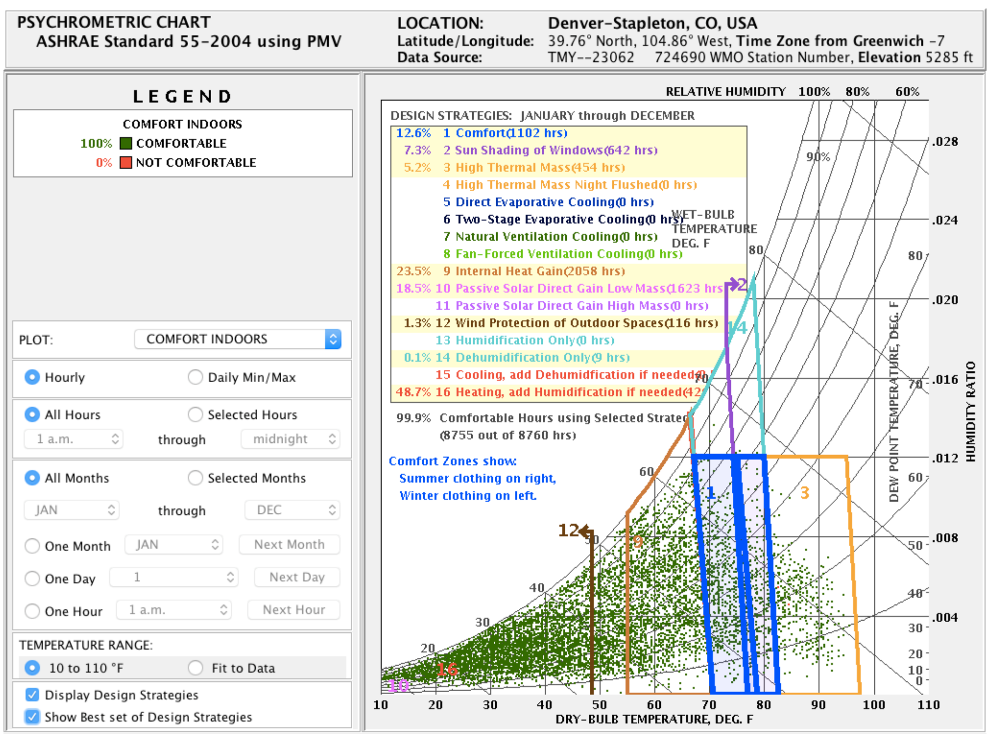


Figure 2
A) Design strategies for Denver-Stapleton, CO, USA
B) Best set of design strategies for Denver-Stapleton, CO, USA

ST. LOUIS

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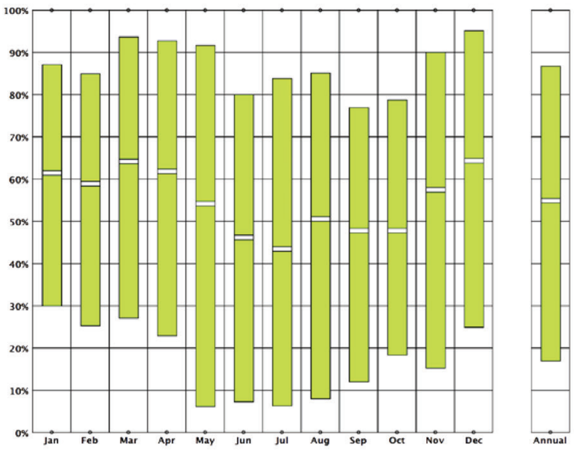
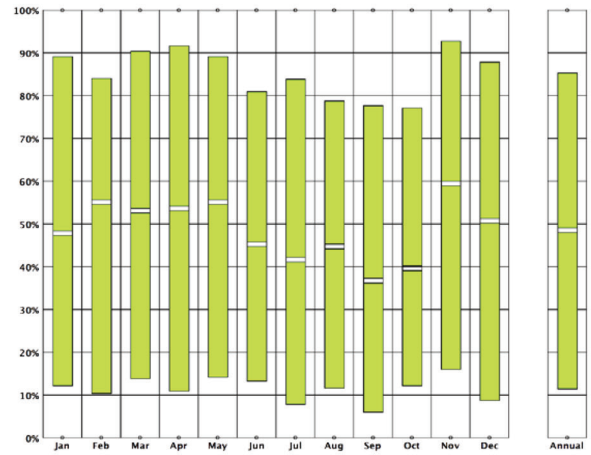
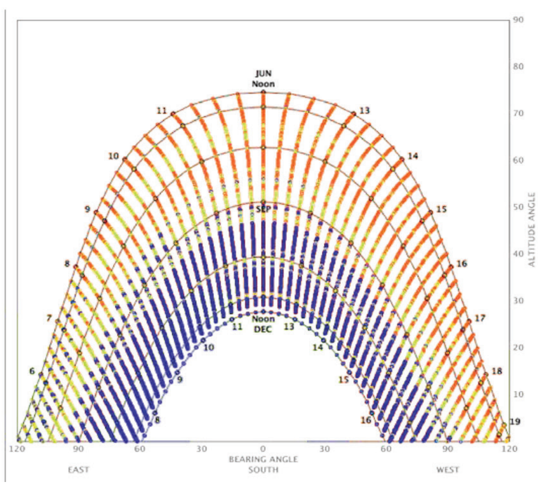
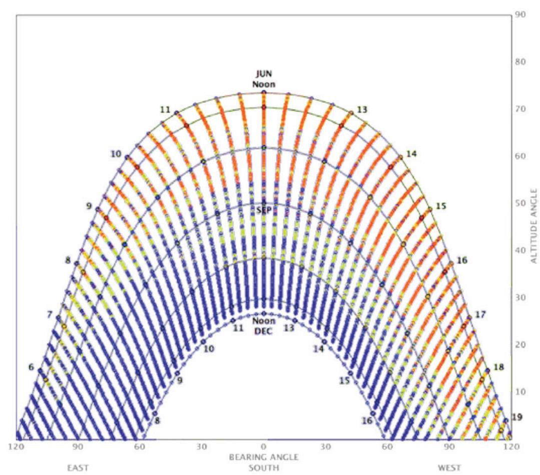
SKY COVER



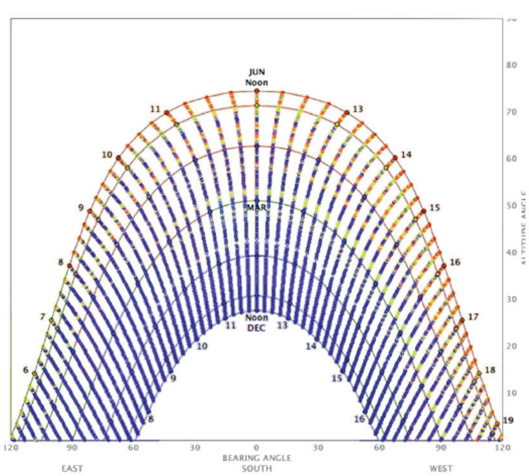


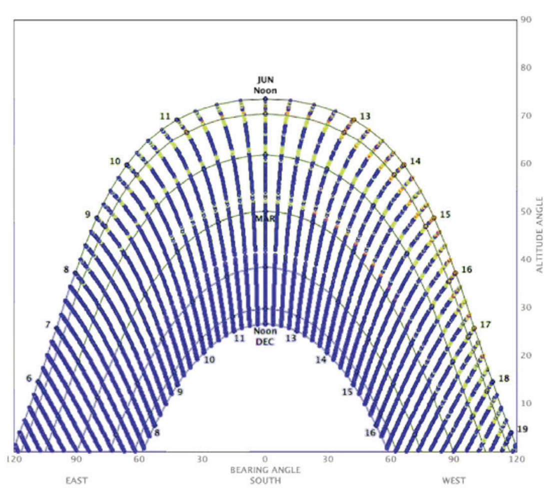
SUN SHADING SUMMER





SUN SHADING WINTER





Using Climate Consultant while considering comfort conditions based on the psychometric chart, we were able to grasp a baseline of the HVAC needs in our space. Passive strategies and mechanical ventilation should be used to address most cooling needs. Optimizing the thermal envelope is one of the most important passive strategy for energy efficiency in the home. The prefabricated concrete sandwich, composed of expanded polystyrene insulation compounded between standard concrete and an Ultra-High Performance Concrete (UHPC) exterior is an aesthetic design feature. However, the material also absorbs and retains heat well. This slows the rate at which the sun heats up the space as well as the rate at which the space loses heat when the sun is gone.

Essentially high thermal mass helps cool our space during the summer day hours from cold air buildup during the night. Alternatively, high thermal mass structures help heat our space during night from heat buildup occurring during the day. If the heat buildup is too great, controlled natural ventilation can purge and regulate the internal temperature. In addition, other features such as triple glazed Zola Windows with high R-value (R-11), careful shading, and reduced thermal bridging all prevent fluctuations in the internal dry bulb temperature and relative humidity of the home. Additively, internal heat gains from occupants, lighting, and equipment further reduce the heating load.

1.1 DAYLIGHTING, OVERCAST DAY

DesignBuilder is a good tool for monitoring design decisions while targeting standards determined by IECC or ASHRAE. Heating and cooling design allow the user to size their mechanical equipment according to thermal simulations. We are able to simulate performance at predetermined time-step intervals over any time period up to one year. The advantage of dynamic simulations, for example with an hourly time-step, is we are able to define summer and winter peak load. From the peak load, we can size heating and cooling equipment of determine strategies to offset peaks if results aren't as expected.

Alternatively, steady state heating and cooling design calculations are also performed by the software to determine equipment sizes needed to ensure comfort based on the most extreme weather conditions in recent years. Outside dry-bulb temperature and co-incident wind speed/direction are utilized in heating design calculations. Solar gains and internal gains are not considered, but zones are convectively heated constantly to ensure temperature set-points are maintained. Total heat loss is calculated as a function of glazing, walls, partitions, solid floors, roofs, external infiltration, and internal natural ventilation. These assemblies are determined as simulation inputs under "Construction" and "Openings." For our model, we specified the envelope for the walls, ground floor, and flat roof as shown in fig. 3.

Wall Roof Floor

Figure 3
A) Wall Section
B) Roof Section
C) Floor Section

Also, we programmed a glazing template to account for the resistance and solar heat gain coefficient (SHGC) of the Zola windows selected for the design. In addition to these, shading assemblies, window sizes, and natural ventilation all contribute to heat loss calculations. For cooling design calculations maximum and minimum outside dry-bulb temperatures and wet-bulb temperature corresponding to maximum dry-bulb temperature are used. The daily temperature profile is organized as a sinusoidal curve assuming max temperature occurs three hours behind max solar elevation. Wind is not considered, but solar gains through windows, scheduled natural ventilation, internal gains, and heat conduction and convection between zones are all factors when determining the capacity of mechanical cooling equipment.

Moreover, DesignBuilder is capable of simulating total site and source energy. Site energy is the energy consumed by a building as reflected in utility bills. This energy can be in the form of raw fuel (primary energy) or energy created from raw fuel (secondary energy). However, source energy accounts for losses in energy sustained from storage, transport, and delivery of primary or secondary energy to the building site. DesignBuilder helps us determine the buildings yearly usage so that we can size our photovoltaic system. In addition, by understanding the source of energy use, we can effectively reduce consumption to result at "net-zero" without installing an oversized PV system.

Currently, we have created an initial model of Crete House in DesignBuilder. However, determining how each design decision, especially within the HVAC specifications, effects the final results has proved to be an ongoing and demanding stage. The HVAC heating system relies on a high performance coefficient for the desuperheater, so it is important we ensure the simulation takes this into account. In addition, we are working on determining the source for expectantly high infiltration and similarly high heat loss results. Once we fully understand the behavior of DesignBuilder, we can proceed with an array of design alternatives.

2. ENERGY LOAD FORECASTING USING DESIGN BUILDER

DesignBuilder is a software tool useful to architects, engineers, and energy assessors featuring building performance models and EnergyPlus simulation tools based on building design and environmental conditions. DesignBuilder allows users to model their design and easily compare design alternatives to optimize energy usage.

In our case, we model the exterior bones of Crete house in a box-like form and divide the house into four zones, as shown in fig. 4.

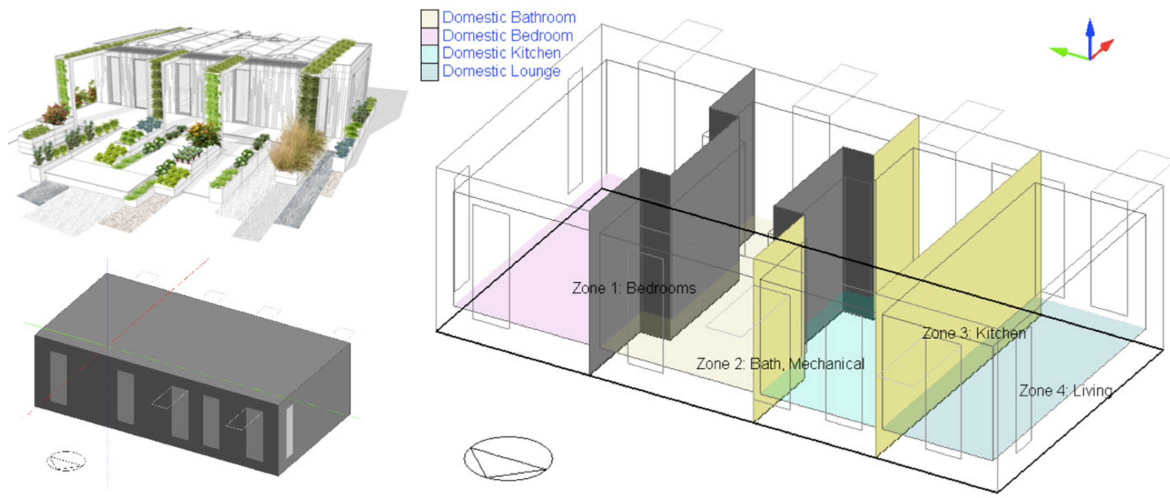


Figure 4

2,1 DESIGN BUILDER LAYOUT

In reality, our "Bedroom" zone is divided by a partition, but for modeling purposes, we treat this space as single unit. The mechanical room and bathroom spaces are treated similarly. Alternatively, the kitchen, dining, living spaces are actually have an open concept, but in order to better define occupancy in our simulations, we create an invisible partition (shown in yellow). We also insert invisible partitions in the hallways between the "Bathroom" and "Kitchen" to define the zones. DesignBuilder allows design specifications to be defined in general for the entire box or more specifically, for each zone or feature within a zone. Most specifications fall under the categories of activity, construction, openings, lighting, and HVAC. In general, the main difference across our zones lies in the activities of the occupants including the occupancy schedule, metabolic activity, DHW usage, lighting schedule, and equipment usage.

All in all, the climate data for Denver Stapleton integrated with the design decisions model the building's performance. By studying the inputs, and resulting heat loss, heat gains, peak load, and demand, we can optimize performance. Later, we include a section with inputs and outputs for a base case as well as a flow diagram indicating alternative design stages and how we arrive at a final simulation.

DesignBuilder models heating design, cooling design, construction & carbon costs, as well as a variety of other simulation options. Transient CFD simulations demonstrate the impact of supply air on temperature and velocity within a three-dimensional space. CFD analysis takes into account surface temperatures, internal heat gains, and HVAC systems when determining space conditions visualized by DesignBuilder using 3-D contours or slices. Fig. 5 shows CFD temperature distribution for our model.

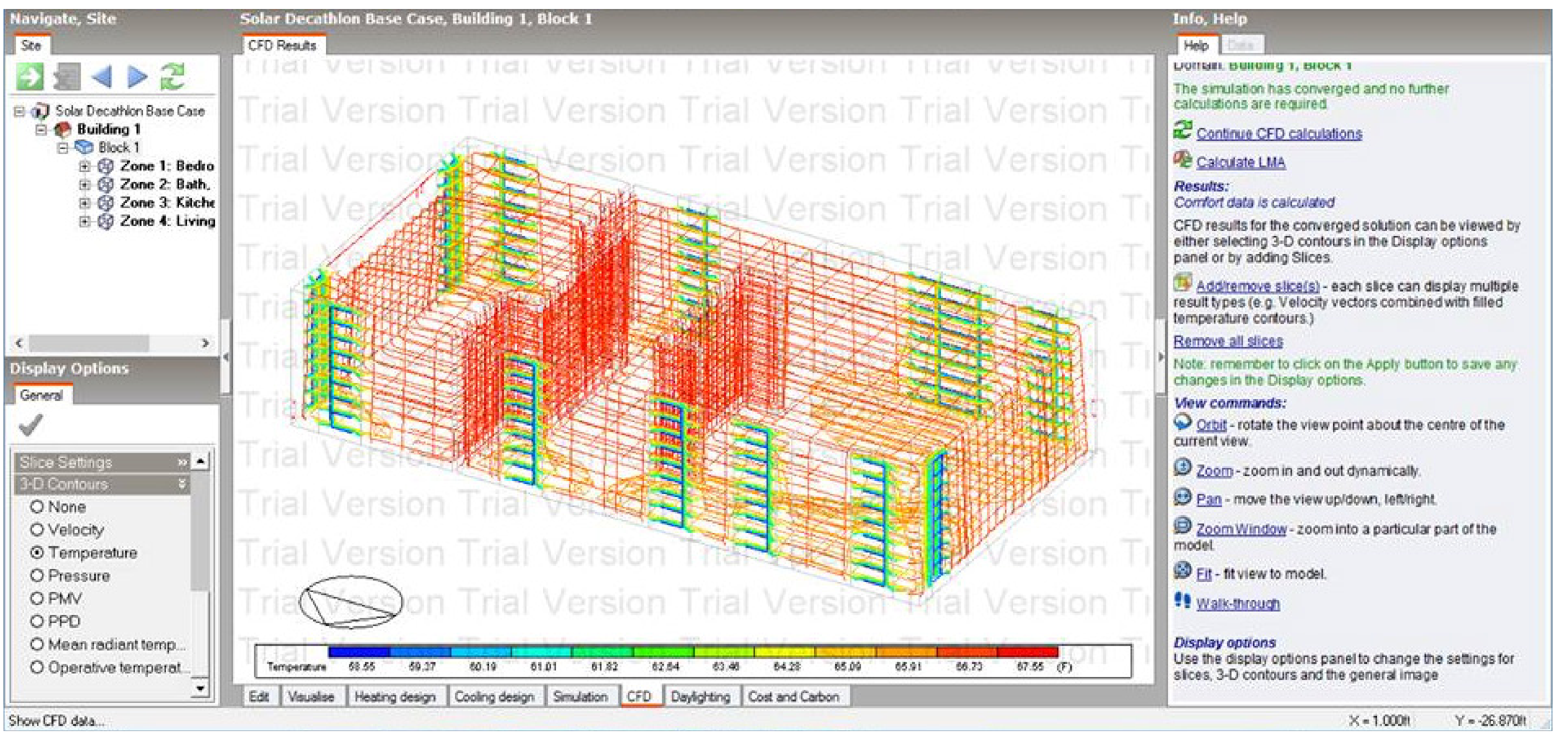


Figure 5

In addition, radiance simulations predict natural daylight distribution to help the user understand lighting needs. Fig. 6 demonstrates standard illuminance projections for our model on an overcast day determined by the International Commission on Illuminance (CIE).

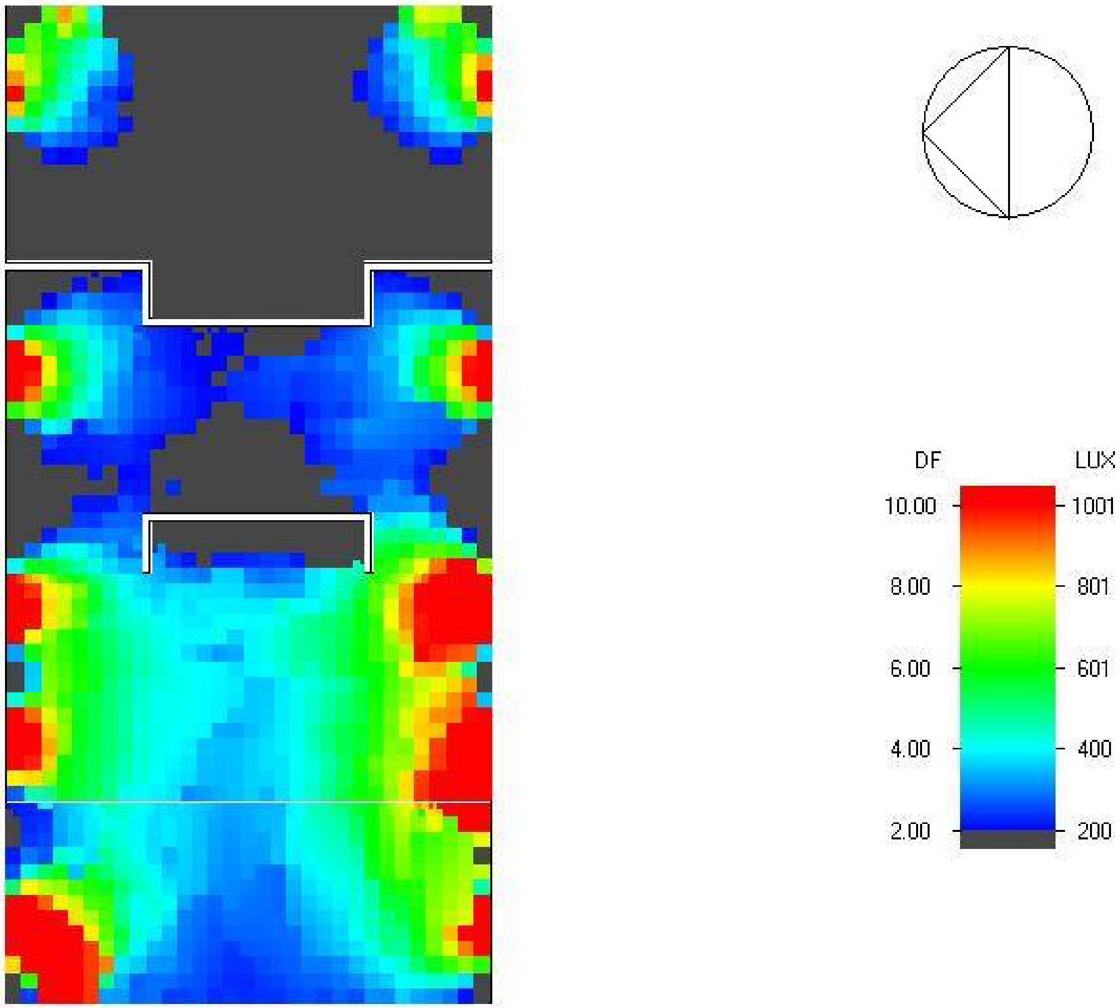


Figure 6

2.2 INFLUENCE OF THE ENERGY ANALYSIS IN THE PROJECT DESIGN: OPTIMIZATION OF THE THERMAL ENVELOPE

2.2.1 DETERMINING NECESSARY U-VALUES OF MATERIALS AND ASSEMBLIES

WUFI-Passive was one software tool used to analyze the energy flows in our house. Developed by the Fraunhofer Institute of Building Physics (Germany), with partnership from the Passive House Institute US (Chicago IL), WUFI-Passive is a modeling program that combines a static energy balance model specific to passive house construction with a dynamic modeling software, the WUFI Plus engine, to dynamically simulate the entire building for comfort and energy performance as well as hydrothermal analysis. Through an iterative process, working with architects, engineers, professional partners and the WUFI Passive software, he performance of the house was studied for both the competition site in Denver, CO and at the final destination of the house at Tyson Research Center, near St. Louis, MO. Our design ultimately relied upon a WUFI Passive scenario with climate data from Spirit of St. Louis Airport in Chesterfield, MO which is the climate data location nearest to the final project destination. The model assumed a three-person occupancy for calculating the energy demand and the latent heat and internal appliance loads from average utilization patterns that equate to 80% of the RESNET and Building America typical load profile.

A balance-based energy simulation calculates the gains and losses from the building given certain boundary conditions. WUFI Passive uses monthly average temperature and radiation values for the exterior boundary conditions and 68°F for the interior winter condition and 77°F for the interior condition in the summer. The energy losses are transmitted through building components or ventilation. The gains are due to solar radiation on the glazed facades and internal heat gains from occupants and appliances. Any difference between the gains and losses must be made up by space conditioning or the interior environment will change. We seek to keep the difference small in order to limit the need for space conditioning in the winter, therefore losses must be limited. If the house is not properly detailed, it can be problematic in the winter and in swing seasons. In the summer, the gains need to be limited to reduce the possibility of high temperature swings and overheating, since the losses will be low by design.

The home's concrete precast sandwich panel façade creates limits on the amount of insulation possible. As a team, WashU is driving the precast industry to find methods of supporting greater insulation thicknesses and eliminating thermal bridging, both of which can minimize the heat transfer in and out of the thermal envelope. It was therefore paramount that the thermal envelope was both accurately modeled and optimized. Using our WUFI Passive simulation, a critical overall heat transfer coefficient, the U-value, was determined for both the walls and the floor. To do this, WUFI was run using the following equation for transmission heat losses:

$$QT = A * U * fT * GT$$

where:

QT Transmission Heat Losses
A Area
U U-Value
fT Reduction Factor
GT Heating Degree Day (HDD) Conversion

The transmission heat loss equation shows the relationship between the Area and the U-Value, assuming that the boundary conditions are constant. To lower losses, either the U-Value or the Area need to be decreased. While the geometry of the house was influenced by energy performance, other characteristics such as usability, aesthetics, competition criteria, and its end use were also taken into account. To reduce the losses beyond the point where further reductions in area were no longer an option, we only had the U-Value left to adjust. We determined the U-Value required to limit the total heating and cooling needs of the building to below the passive house standard. We used the monthly balance method to find a critical U-Value for the wall, roof, and floor assembly. We used these values in conjunction with what was possible in a precast sandwich panel, and the insulation levels mandated in the 2015 IECC to determine the best path forward for the home.

Due to the unique construction of our house and need for efficient installation of insulation, Team WashU worked closely with our various precast manufacturers and the precast concrete institute to design g insulation strategy that worked both in manufacturing, met the thermal standards for the project and also limited the global warming potential (GWP) and ozone depletion potential (ODP) of the insulation products used. This is important because most precast manufactures prefer to use extruded polystyrene (XPS) insulation. This type of insulation has 1000 times the global warming potential of CO_2 and the energy saved to offset those emissions have paybacks that range in the decades, rather than years.

The wall assembly is precast concrete with 5" of Neopor, which is a graphite enhanced expanded polystyrene (EPS) insulation with an R-value of 4.6-4.9. The interior wythe of the concrete wall is a 4" thick structural wall, which holds the vast majority of the panels mass to the inside of the insulation where it is most useful. Lastly, the outer layer of concrete is thin and light, yet provides water resistance and some mass to the panel while reducing overall building weight. The total wall R-value is 25

The floor system was constructed in modular sections to enable the house to be easily shipped and rapidly reassembly. The floor panels are also precast sandwich panels which span between the north and south footings. They also contain 5" of Neopor EPS insulation. The topping slab is 3" thick and contains the radiant heating distribution system as well as adding additional thermal mass. The total floor R-value is 25.

The roof system is also designed as a sandwich panel. The bottom, interior, layer of concrete is the structural system, which helps add mass to the interior of the building as well as provide space for the radiant cooling distribution system to run. The total roof R-value is 49.

3. BUILDING ENERGY SYSTEM SIMULATIONS

3.1 LOAD PROFILES

Table 3.1 shows the basic building information summarizes from our solar decathlon house. The total building area indoor is about 880 ft2. The building height is 9 ft. The simulation is based on the climate data in Denver Colorado.

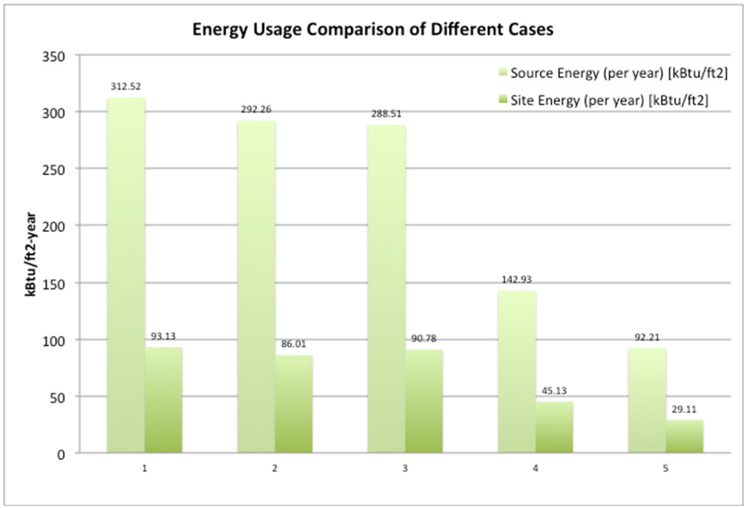
Floor Area (ft^2) - Including Envelope - Excluding Envelope	 994.072 ~880
Floor to Ceiling Height (ft)	9
Number of Occupants	3
Number of DesignBuilder Zones	4
Climate Zone	5 (Denver-Stapleton)

Table 3.1: Basic Building Information

The annual load profiles of five cases are summarized for our solar decathlon building below, using a fractional scale of full load. The site energy is converted to source energy to calculation carbon footprint. Our base case indicates the site energy consumption is 93.12 kBtu/ft2, and the best case is about 29.11 kBtu/ft2. The simulation results will be compared with the onsite operation when our building is built on Washington University campus.

Figure 3.1 the variety of energy-saving measures that have been taken achieve savings in natural gas consumption forecast 70%. Specific energy-saving measures in the SD project will be divided into two levels of discussion, the first level is a single building energy-saving measures, and the second level is the regional energy supply system. Specific energy-saving programs contain passive and active programs, detailed technical and economic evaluation of the program will be gradually raised in the following sections.

Figure 3.1 Summary of Site Energy of different Scenarios



4. ENERGY LOAD FORECASTING

4.1 SPACES ENERGY LOAD FORECASTING

Designbuilder was used to model the energy performance and usage through the year of the Solar Decathlon house, using half hour increments to understand sub-hourly, hourly, monthly, and yearly trends between different construction techniques. Figure 4.1 on the left shows the basic inputs for base case (IECC 2015). Improved cases are compared with base case later.

Table 4.1: SD Base Case Standard

These standards are modified from the IECC 2015 standard to be more energy efficient, with better quality lighting, temperature control, windows, and passive design standards.

IECC 2015 Expectations Summary	
Fenestration U-Factor	0.32
Ceiling R-Value	49
Wood Frame R-Value	20 or 13 (cavity) + 5 (continuous)
Mass Wall R-Value/if 0.5 of insulation on inside	13/17
Floor R-Value	30 or R-19 (fill frame)
Ceiling U-Value	0.026
Frame Wall U-Value	0.06
Mass Wall U-Value	0.082/0.065
Floor U-Value	0.05
Area weighted alternative to U or R	Total UA <= Total UA (code)
Without Attic, Ceiling R-Value	30
Air infiltration max (windows/swinging doors)	0.3 CFM per ft2 / 0.5 CFM per ft2
Mechanical Ventilation	International Residential Code
Air leakage rate	3 ACH (According to climate zone 5)
Temperature Set-Points	Cooling (75F) - Heating (72F)

4.2 ANNUAL LOAD SIMULATION

Figure 4.1 shows the SD project annual energy consumption broken down by daily consumption. The largest consumption is in the winter season. This figure indicates Denver is heating dominated climate. Insulation becomes one of the primary strategies in passive design. Ground source heat pump is one of the primary strategies in mechanical system.

Figure 4.1: Annual Loads Profiles

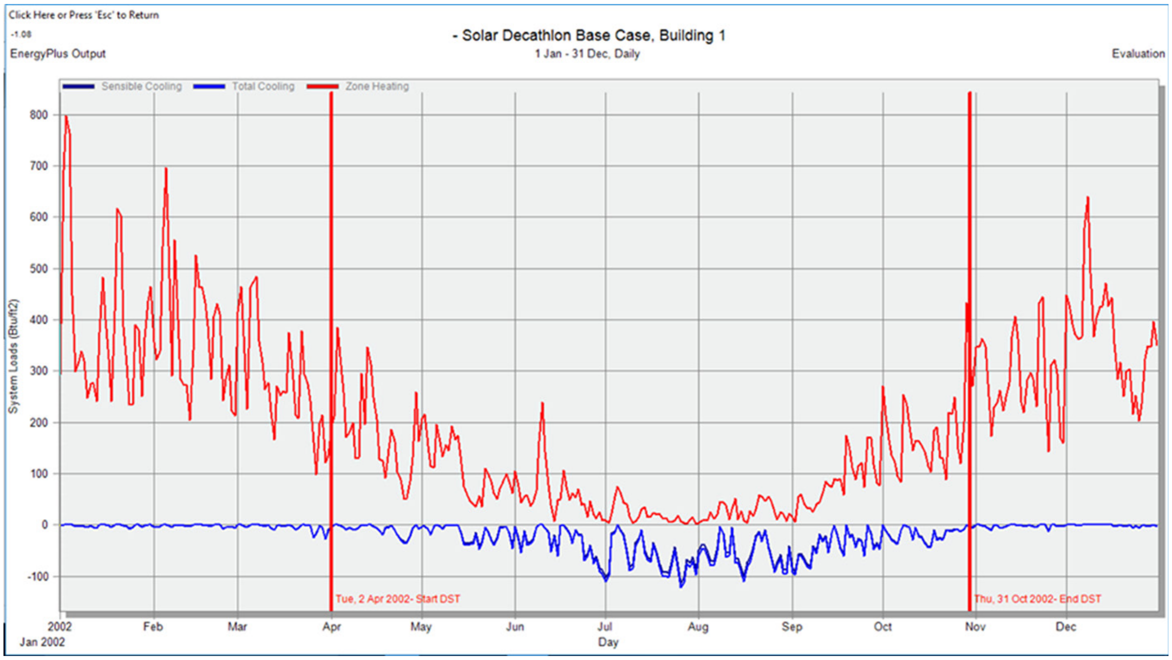


Figure 4.2 is a measure of the building energy consumption per unit area of the building. The site energy is about 93.12 kBtu/ft2 on average building area. The base case accurately reflected our base building design.

Figure 4.2: Annual total site energy consumption summary for base case

YEARLY SITE ENERGY CONSUMPTION

- 92,198.16 kBtu
- 93.12 kBtu/ft^2

4.3 ENVIRONMENTAL IMPACT

Figure 4.3 represents the value of the annual energy consumption of base case into CO2 emissions, and thus reflects the impact of different systems on the environment. As can be seen from Figure 4.3, the average carbon footprint is about 20.56 lb/ft2. The number is lower than ASHRAE 90.1 standard by about 30%.

Figure 4.2: Annual Carbon Footprint

5. PASSIVE ENERGY SAVING MEASURES

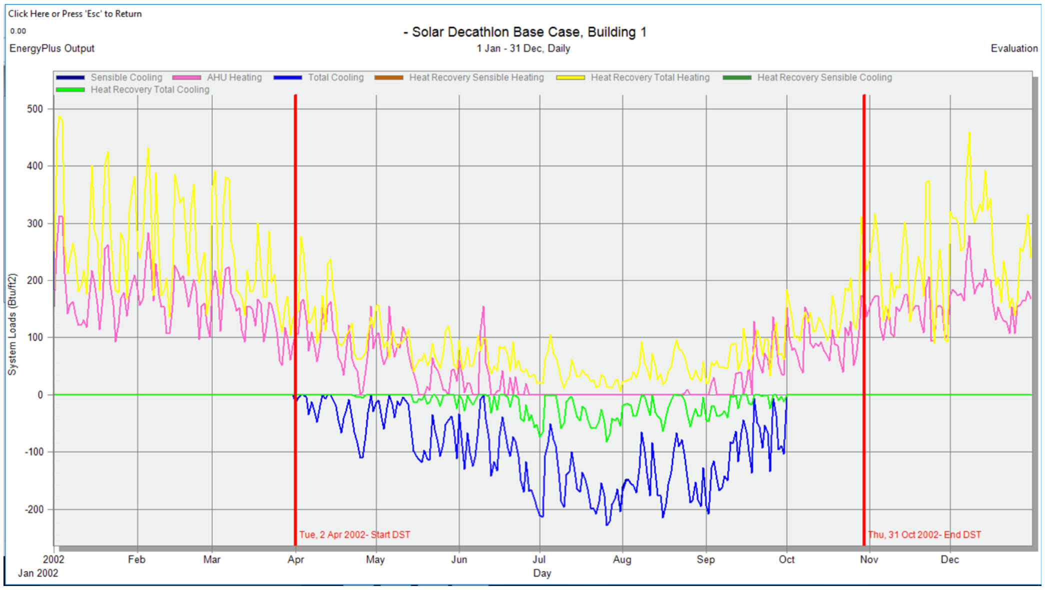
5.1 PASSIVE BUILDING ENERGY SAVING MEASURES

Now the external envelope was analyzed to select the best plan to reduce annual energy running costs. From previous research on the outer envelope, we have determined the following three aspects to have most possible impact on the structure: first, the comparison of four different glass window types, including an economic analysis, and the best cost-glass recommendations. Second, three different thicknesses of wall insulation material were compared, to select the most suitable wall insulation layer thickness for the SD project, and make recommendations for wall insulation throughout the SD project. Third, the external shading compared four different lengths, to select the shade that works best for SD projects.

5.2 COMPARISON OF GLAZING TYPES

Different translucent glass insulation effect, the choice of high-performance glass, can improve the visible light transmittance, increased indoor natural light, and infrared blocking high-calorie high-energy ultraviolet light, but it can also result in an increase of the initial investment. We use DesignBuilder to predict the building annual energy consumption for each case, with standard IECC2015, double LoE glass, triple LoE glass (air layer), and triple LoE glass (filled with argon), all with a window to wall ratio of 30%. In DesignBuilder, the mathematical model of four kinds of glass, analog SD construction project annual heating load different glass and invest economic analysis. Figure 5.1 indicates the annual simulation results of using the passive technology indicated above. Figure 5.2 is a measure of the building energy consumption per unit area of the building. The site energy is about 45.13 kBtu/ft2 on average building area. The passive design case accurately reflected our base building design.

Figure 5.1: Passive Design Annual Loads Profile



YEARLY SITE ENERGY CONSUMPTION

- 44,679 kBtu
- 45.13 kBtu/ft²

6. BEST PRACTICES

Our best case includes the optimization of operation schedule for day-lighting/lighting system, air system, MEP system, and advanced insulation for enclosure, and night cooling and thermal storage in concrete thermal mass system, etc. The estimated energy consumption is indicated in Figure 5.1. The average site energy is about 29.11 kBtu/ft2. The simulation data will compare with onsite operation when building is erected on site.

Figure 5.1: Best Case Performance