TEAM ASU-UNM DOE SOLAR DECATHLON 2013 SHADE HOUSE: COMBINING PASSIVE AND ACTIVE SOLAR DESIGNS WITH ARCHITECTURE

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ABSTRACT:

Team ASUNM will present current results of the design of the SHADE house- team's entry into the DOE Solar Decathlon 2013 competition. The work is concentrated on finding the right balance between passive building technologies and photovoltaics utilization, while at the same time incorporating home energy automation, controls, energy consumption monitoring and demand reduction techniques. The designed house incorporates state of the art thermal technologies – such as radiant cooling and thermal storage with phase-change materials. An important feature of the house is the SHADE canopy structure which not only serves as an area for photovoltaic power production, but provides shade – a much needed element in the arid southwest. Appliances and electronics inside the house are networked through a centralized home automation system which can be controlled through smart phone applications.

1. INTRODUCTION.

The U.S. Department of Energy Solar Decathlon 2013 competition challenges collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and appealing to the consumer base. The winner of the competition is the team that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency.

Team ASUNM is a joint team between ASU and UNM, and therefore, we are specifically focusing our building as a home for the urban sprawl of the Southwest cities, such as Phoenix or Albuquerque. The main working points of the project are to effectively integrate architecture, ecology, community and technology.

Figure 1. Artists vision of SHADE in a typical urban neighborhood setting.

But at the same time, our teams goals are far greater than just building a house. We want to contribute to the solution of the sustainable future of the Southwest urban areas. SHADE house is a way to show how solar can be integrated into the existing urban housing conditio and how to revitalize communities left after urban sprawl. Our mission is to promote affordable and adaptable sustainable living.

Figure 1 shows artist's vision of how SHADE house can seamlessly fit into the current urban landscape. SHADE house takes its inspiration from the ecosystem, and from the idea of bio-mimicry: plants and organisms need to take advantage of shade to allow them to flourish, but they also take advantage of the sun and grow further. We wanted to incorporate this idea into our house. Our solar array structure is placed on the south side of the façade , but is liberated from the house itself. By liberating the solar canopy from a typical location of the roof of the house we can demonstrate that such design is adaptable to both new construction and to retrofits. At the same time, much needed shade promotes outdoor living and enjoyment of the often pleasant Southwest weather.

2. SHADE HOUSE DESCRIPTION

Team ASUNM's house is inspired by the Southwest region. Historical house designs used passive heating and cooling before the advent and widespread use of mechanical systems. The use of massive building materials and South-facing orientation were common features of regional design long before modern interest in solar building became popular. Team ASUNM has chosen these strategies for integrating architecture and engineering and for many situations the architecture is the engineering.

Team ASUNM's house is designed for the Phoenix climate, which is characterized by high average air temperatures year-round, very high summer temperatures, low relative humidity, and high insolation. Major constraints on the design include finding a balance between affordable construction, low energy demands for cooling and heating, and appropriate use of daylight for tasks and ambiance.

As previously mentioned, the inspiration for this strategy comes from the observation of the Southwest ecosystems and living organisms. Different systems work together to create and sustain life. The structure of the house is akin to the trunk of a cactus, or the skeleton of an animal, providing support for the living systems and pathways for circulation. The windows and glazed areas of the house are like the sensory organs of an animal, giving house occupants information about the surroundings; they are also part of the skin of the house. The house envelope, including windows, serves the same purpose as the skin of an animal, or the outer layer of a cactus: tempering the exchange of heat and cool and protecting the insides from damage. Operable passive design features mimic behaviors of animals to outside conditions, seeking shade to avoid heat or basking in the sun for warmth. Stationary design features mimic the thorns on a cactus that provide shade and windbreaks to the trunk. Heating and cooling systems within the house mimic respiratory and circulatory systems. Specifically designed thermal storage system recharges at night – akin to living organisms recharging during sleep.

While the abundant solar resource has a long history of use in the Southwest, the desert sunlight can also be harsh. Desert organisms and humans occupying the desert protect themselves from the sun as much as they harness its power. Another obvious limitation to life in the desert is the lack of abundant water. Desert ecosystems thrive by minimizing water loss, and maximizing water storage, among other strategies.

These tendencies will play a major role in the strategies used for our house in the Solar Decathlon competition. The primary goal is to utilize passive systems which are backed up by active systems. Well-designed passive systems are the most energy efficient systems, especially when the lifetime energy use of the house is considered. There is a strategic element to the use of passive systems: in order for many passive systems to function optimally, the house occupants must sometimes activate them and therefore interact with the house. Occupants therefore have a more engaging experience with the house.

The active systems will achieve a high level of comfort while consuming a minimal amount of energy and water. The comfort systems will take advantage of the sun, stored water, sensory devices and well-timed operations to demonstrate a novel and healthier approach to an indoor lifestyle.

The energy systems of the house are designed as well to be innovative and efficient. First, AC and DC electricity will be distributed throughout the house, which will minimize power losses to some loads Total power consumption will be monitored by an automation system which will also control other aspects of the house. Acting like a nervous system, the home automation will be adaptable and configurable to the user. House occupants will be able to interact with the automated systems using a digital interface. The objective of this interface is to create a sense of connectedness between the occupants and the engineered systems.

3. ENGINEERING APPROACH:

Team ASUNM's engineering strategy is based on the goal of seamless integration between the architecture, engineered systems, and the house occupants. Our design has a number of inspirations, ranging from the ecosystem of the desert environment to the cultural and regional practices prevalent to the area. From this, we are able to develop engineering strategies that will utilize innovative yet intuitive approaches to comfort, water management, and energy systems.

3.1 Modeling

Our team used several modeling tools to calculate accurate energy balance of the SHADE house. Three of such novel software packages are TRNSY, eQuest and EnergyPlus.

TRNSYS is a building energy modeling application capable of evaluating transient effects. It offers a great degree of user control, and can evaluate highly complex building systems. While this software is capable of carrying out complex analyses, learning to use its full capabilities is also complex. To date, team ASUNM has used TRNSYS to evaluate the contribution of building envelope elements and shading features to heating and cooling loads. Future work with TRNSYS will include annual energy use analyses comparing the energy use of the engineered systems with a typical household's energy use in Phoenix. TRNSYS is one of the only building energy modeling applications that can easily accommodate a radiant ceiling for cooling. It also has the ability to simulate the effects of the proposed thermal storage, which are transient and not easily modeled by steady-state software.

eQuest: This application is available as a free download from the US Department of Energy. It is a valuable tool for quickly and easily estimating cooling and heating loads, as well as evaluating the effects of changing envelope parameters such as size and placement of windows, and R-values of walls. However, eQuest does not currently easily incorporate radiant cooling into its simulations. eQuest will continue to be used in parallel with TRNSYS to compare/validate results.

EnergyPlus: This building energy simulation engine is available as a free download from the US Department of Energy. It includes modules for radiantly cooled ceilings, and will be used to simulate operating conditions of a typical year in Phoenix. Simulation results will also help to optimize HVAC controls algorithms.

3.2. Household Systems

3.2.1 Heating, ventilation, and cooling:

Capillary mats made of plastic are laid underneath the ceiling plaster (and part of the walls in the bathroom). Chilled or heated water is pumped through these mats; this radiant delivery system provides the primary heating and cooling needs of the house. Humidity control and additional peak cooling are provided by a minimal air system consisting of a fan coil unit with a chilled water coil, an energy-recovery ventilation unit, and air ducts. Heating is also provided via the ceiling, with additional capacity via the air system; however, additional heating is not projected to be necessary for typical operation.

3.2.2. Thermal storage:

Energy storage in the form of latent energy, or phase change energy, will be implemented to satisfy the cooling load. A thermal storage system consisting of an insulated box, internal energy storage containers that hold water for freezing/ice, a circulating pump, and a 20% - 30% mixture of propylene glycol will be used to store energy and offset the peak cooling load. During the cooling season, a heat-pump will operate at night to circulate very cold working fluid to the ice bags, freezing them and storing the day's cooling requirement. This nightly cycle will allow the chiller to operate at a lower ambient temperature, increasing its efficiency.

While thermal storage systems are in use for commercial systems, the residential market for this product remains under-served. Team ASUNM is constructing and intends to showcase its solution for residential thermal storage. This form of energy storage will help to reduce peak electricity demand in regions such as Phoenix, where air-conditioning makes up a dominant part of the electricity demand. Shifting some of the cooling load to thermal storage smoothes peak electricity demand, and allows consumers to take more advantage of off-peak electricity rates

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3.2.3 Solar Energy Systems:

Photovoltaic panels will be mounted on the South-facing detached shade structure and will convert sunlight into electricity while shading the South-facing windows from most direct summer sunlight. The current PV system size is 8.8 kW DC.

3.3 Control system:

A combination of wired and wireless equipment will be used to coordinate the controls of the indoor and outdoor lighting, home entertainment and security system, HVAC equipment, and household appliances. The goal of the integrated control system is to maximize the usability of the controls system for the home occupant while providing opportunities for energy conservation.

A schematic diagram showing the major aspects of the controls system is shown in Figure 1.

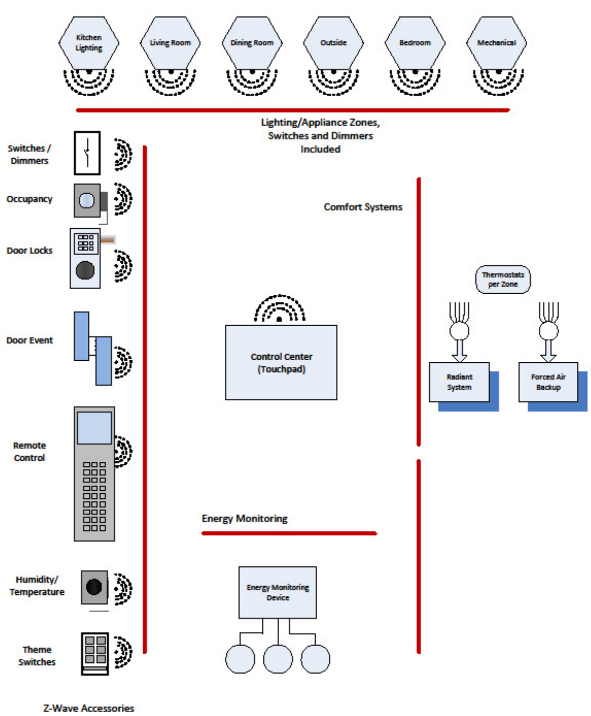


Figure 2: Schematic showing proposed logical connections between control and other house systems

4. ENVELOPE, ELECTRICAL LOADS, AND INTERNAL GAINS ANALYSIS

4.1. Heating and cooling loads

The main contribution to the cooling load was found to be the size, placement, and shading of windows. Samples of results can be seen in Figure 3, showing the influence of window area and shading structures.

The results of this energy modeling helped guide the architectural design team in the placement and sizing of glazing and shading features.

In addition to software energy modeling, analyses of building cooling loads were carried out using the ASHRAE method for residential heating and cooling load calculations. A comparison was made of peak cooling load based on varying the R-values of the walls and roof. This analysis compared the cooling loads for R-values ranging from the minimum of 13 required by the IRC to 60, a high R-value. It can be seen from Figure 4 that there is a large reduction in cooling load going from a wall R-value of 13 to 19 or 30; however, the slope of the curve flattens out above thirty, indicating a diminishing thermal return. For a wall R-value of 30, there is a fairly small decrease in cooling load moving from a roof R-value of 38 to 45.

The walls of SHADE have an R-value of 40 in the walls and R-50 to R-60 in the roof. While a site-built house may not have insulation underneath a poured slab, team ASUNM's competition prototype will benefit from insulating the subfloor to prevent excessive heat gain from the tarmac.

4.2 HVAC system sizing and operation

The radiant delivery system was chosen to maximize thermal comfort while minimizing energy use for HVAC. Radiant cooling provides superior thermal comfort compared to forced air systems, even at higher indoor ambient temperatures. This effect is primarily due to the mean radiant temperature of the room being lower than that of an air-cooled space. Since water has a much higher heat capacity than air, it is more efficient to move heat around a living space using water than air. This efficiency translates to less energy required for both the circulating pump and the fan for the supplementary air system than for the fan alone for an all-air system.

The thermal storage system is sized to store the full cooling load of a day. By producing ice at night, the compressor of the chiller runs when ambient temperatures are lower, giving a better efficiency to remove the same heat.

Both the radiant and thermal storage systems are sized for the nominal peak cooling load, of between 1.5 and 2 tons of sensible cooling. Figure 4 shows estimated heating and cooling loads generated using eQuest. Calculations using the ASHRAE residential cooling load resulted in slightly higher cooling load calculations, including both sensible and latent loads. An energy recovery ventilation unit will be combined with a chilled water cooling coil to meet the latent cooling load, and supply additional cooling not met by the overhead radiant panels, which have a nominal heat transfer rate of 27 Btu/sq. ft. hr. The latent load calculations are being completed for both Phoenix and the more humid conditions during the contest.

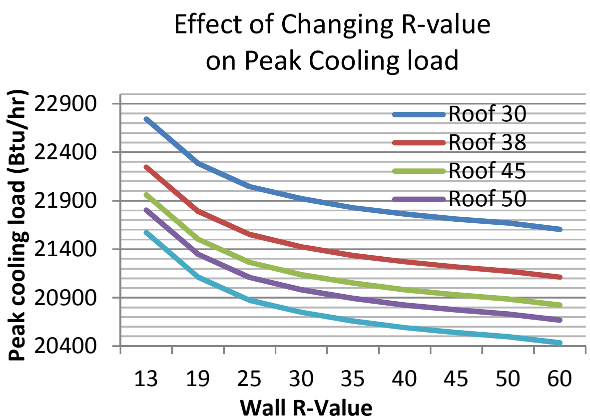
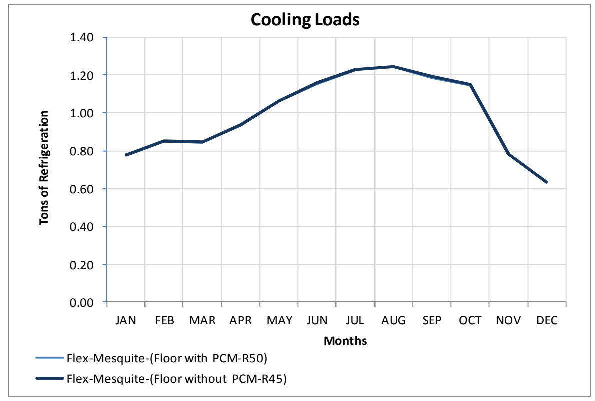


Figure 3: Parametric analysis of effect of R-value for wall and roof on peak cooling load.



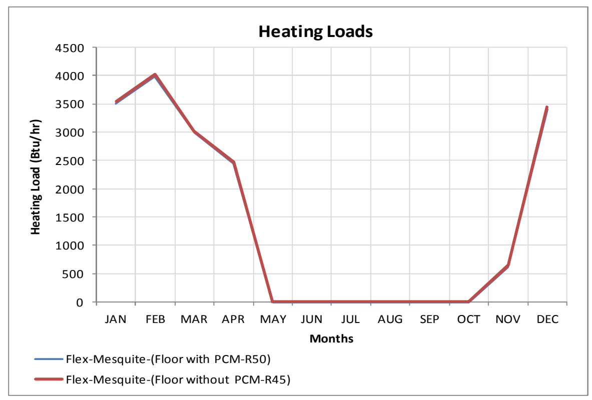


Figure 4: Example calculations of heating and cooling loads, obtained with eQuest.

4.3 Electrical loads

An estimate was made of yearly electrical loads based on typical electrical consumption of household appliances and systems, including domestic hot water production and HVAC. The HVAC system dominates the annual electrical demand, which is typical for many residential applications; this is also definitely the case in Phoenix. This large fraction of the load dedicated for HVAC is one of the primary considerations for implementing thermal storage. If the chiller can run at times when the ambient temperature is lower, the energy consumed for cooling will be much lower than typical daily load profiles.

5. THERMAL STORAGE SYSTEM

The Thermal Storage system, also called the Ice Cube, is being designed, fabricated, and tested by senior Mechanical Engineering students at the University of New Mexico. The Ice Cube is based on simple ideas whose execution has eluded the thermal storage industry. The main idea of the Ice Cube is that a 20% propylene glycol 80% water mixture circulates through the main storage box, to the delivery system, through a liquid-refrigerant heat exchanger, back through the storage box, via a centrifugal pump. Inside the thermal storage box there are 74 thick polypropylene bags filled with a water-graphite mixture.

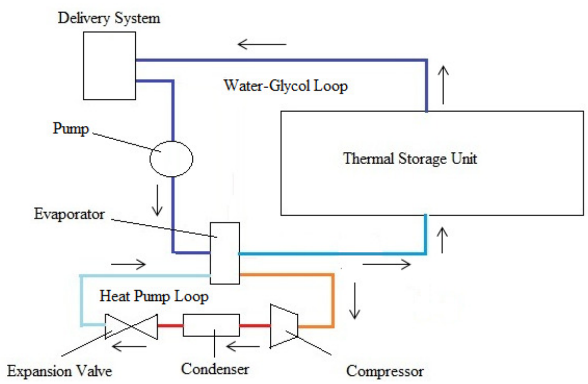


Figure 5: Charging State of the Ice Cube

Thin corrugated plastic separates the plates, which allows the glycol-water mixture to flow in-between the plates. The circulating glycol-water mixture serves two purposes depending on the state of Ice Cube unit: charging and discharging mode. In addition to this propylene glycol-water loop there is a heat pump, cycling refrigerant.

The refrigerant loop is the means of cooling the working fluid when the Ice Cube is in the charging state.

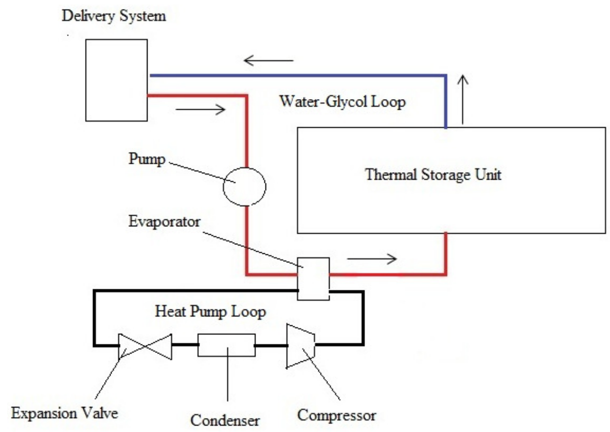


Figure 6: Discharging State of the Ice Cube

Figures 5 and 6 show schematically how the two loops connect. It is important to note that the evaporator in the vapor compression cycle is a condenser for the water-glycol loop and in reality a liquid to refrigerant heat exchanger. The way the heat exchanger works is a refrigerant at a temperature of T_{evap} enters one of the inlets of the heat exchanger while the water-glycol mixture enters the other inlet at $T_{mix,1}$. The refrigerant is tuned in so that while it goes through the heat exchanger it does not increase in temperature but changes phases (T_{evap} is constant across the heat exchanger). T_{evap} is less than $T_{mix,1}$ so heat is transferred from the water-glycol mixture to the refrigerant. This causes the refrigerant to change phase while the glycol-water mixture cools down. The Ice Cube is designed to deliver the water-glycol mixture at a temperature of -3°C into the thermal storage box. This chilled working fluid circulates for a 12-hour period in order to freeze the water-graphite plates and complete the thermal charge.

The discharge cycle simply circulates the water-glycol mixture through the loop. As the house begins to heat, the warmer glycol flows in-between the frozen water-graphite plates. This cools the glycol to 9°C which is then piped to the delivery system (air coil, radiant, or both). As the chilled glycol flows through the delivery system, it heats up. The warmer water-glycol mixture then goes back through the thermal storage box, causing heat transfer to occur, cooling the water-glycol and adding energy to the plates.

The delivery system can be a radiant system, air-coil, or a heat exchanger. In the case of ASUNM's Solar Decathlon house, the cold water is runs through a heat exchanger to cool water for the radiant mats, and runs directly through the fan coil unit for additional cooling and dehumidification.

7. HOME AREA NETWORK (HAN) AND COMMUNICATIONS INTERFACE DESIGN

Team ASUNM intends to have an extensive energy management and monitoring system, all integrated in one HAN. The HAN will monitor instantaneous power generation and load demands from various appliances and make optimized power management decisions based on programmable pre-settings saved by the residents. For example, HAN can handle uninterrupted service to critical loads inside the house while reducing consumption from non-critical loads, as a response to an increase in kWh/hr rate increase by a utility. This is one of the implementations of the Demand Response (DR). Appliance manufacturers, utilities and networking and communications companies are currently working to bridge this gap. Team ASUNM will use appliance monitoring devices (such as TED 5000) to implement suggested communication and interface devices and schemes to maximize the ability of the house to respond to potential utility Demand Response signals. This will lay ground to incorporate utility-interactive principals into the home design even though it is not required by the Solar Decathlon 2013 competition.

6. CONTROLS AND AUTOMATION SYSTEM:

The control system used in SHADE is designed to be a complete home automation system with ease of use in mind. The system has been designed to appeal to SHADE's target audience: an active older couple that will age with the house.

With the target audience at the forefront of the discussion, simplicity was applied to all aspects of the system. This needs to be implemented by having one central device (console) that will run all applications needed to control the home's temperature for each living area, change the lighting levels via electrical and natural lighting, control the media center, and secure the perimeters of the home. For completeness and ease of access (for the targeted age demographics), the home will also have separate local stationary controls throughout the home for each living space. Along with separate controls, the automation system will have several modes built in that will automatically set an entire living space's temperature and lighting for preferred settings, such as: winter or summer, evening or day time, away or an extended vacation setting, as well as Solar-Decathlon 2013 required event such as movie night.

8. CONCLUSIONS:

We hope that these projects will inspire the continued innovation of renewable energy sources and inspire the next generation of innovators to continue this work

9. ACKNOWLEDGEMENTS:

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