Experiments in Energy Efficient Building Design for Extreme Hot Climates

ABSTRACT

This paper reviews results of approximately six months of monitoring of four houses located in the extreme hot climate of Borrego Springs, California. Four houses were constructed using identical floor plans but differing wall materials, and each house incorporated unique prototype cooling and heating systems designed to reduce energy use and demand. Detailed monitoring and field obersvations revealed the advantages and disadvantages of the various designs.

INTRODUCTION

The southern desert areas of California, Nevada, and Arizona experience extreme climate conditions characterized by mostly very hot, dry summers. In some areas, including Borrego Springs, California, the dry conditions are occasionally interrupted by monsoons that pump moisture into the region from the gulf. Summer daytime highs commonly exceed 110°F and nighttime lows frequently do not drop below 80°F. Most air conditioner operating hours occur at outdoor temperatures above the 95°F EER rating point, contributing to high energy consumption and electrical demand during utility peak periods.

Clarum Homes, a leading California builder and participant in the US Department of Energy's Building America Program (BAP), had several projects planned for very hot climates, and desired to develop house designs that would perform well under these conditions. Clarum secured building sites near the town of Borrego Springs, California, and assembled a team to design, construct, and evaluate four advanced prototype houses. The houses have identical floor plans, but each incorporate unique design characteristics that address the need for improved hot climate performance in different ways. Clarum's goals were to reduce cooling energy use by 90% and to determine the most cost-effective, and production compatible means of achieving high levels of cooling efficiency. This paper describes the design strategies and methods used to evaluate them, and provides preliminary results from summer and winter testing.

The wealth of data being gathered at these sites could be used for many detailed studies. The topics of greatest interest to the authors and the focus of the research described in this paper include:

- Comparative heating and cooling energy use for the building-system combinations
- The role of thermal mass in limiting peak cooling demand
- The effectiveness of floor cooling and risk of condensation
- The relative efficiency and comfort consequences of evaporative cooling
- The effectiveness of using evaporatively cooled water to cool slab floors
- The comparative hot climate performance of a high SEER air conditioner and an evaporative condenser

Cost data are presented, but since the technologies applied are not "main stream" and many are prototypical, the actual costs experienced should not be used for a mature-market assessment of the potential success of the technologies.

Location and Climate

The Borrego Springs community of about 2,500 people is located in the middle of the Anza-Borrego State Park, between the Salton Sea and Escondido and about 60 miles northeast of San Diego. Table 1 lists normals and ranges for the months of July and December, measured at the local airport[1].

The data in Figure 1, from a seven-day weather sequence measured at the site during 2006, provide an illustration of monsoon weather conditions that typically occur in July and August. Under these conditions the daytime dry bulb temperature usually exceeds 100°F while the relative humidity and wet bulb temperatures can exceed 40% and 80°F, respectively. This is a condition that makes evaporative coolers perform extremely poorly; a cooler with an evaporative effectiveness of over 100% would not be able to maintain comfort. However, during the dryer conditions that prevail a good part of the summer, the lower wet bulb temperatures make evaporative cooling an attractive alternative for reducing cooling energy use.

Table 1: Borrego Springs Winter and Summer Temperatures

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[1] Source: www.wunderground.com

	July	December
Normal High	109°F	70°F
Normal Low	77°F	38°F
2006 High	105-120°F	60-81°F
2006 Low	75-90°F	23-46°F

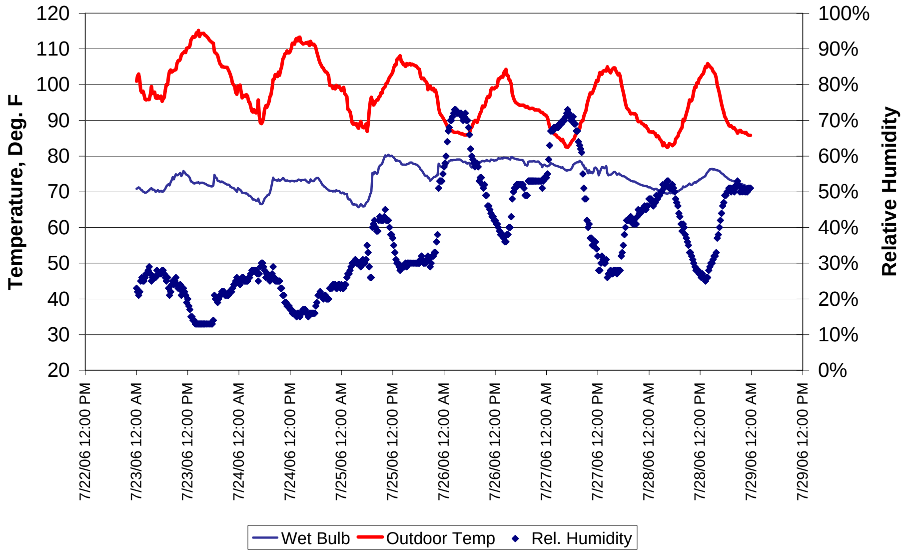

Figure 1: July Weather Sequence Illustrating Monsoon Conditions

HOUSE AND SYSTEM DESCRIPTIONS

House Designs

Four advanced prototype houses were built to different specifications, but using the same floor plan as shown in Figure 3. One of the houses is pictured in Figure 2. Each has a conditioned floor area of about 2,000 ft^2. Foundations are slab-on-grade, and the edges of the slabs are insulated.

Energy use, peak load reduction, thermal comfort, construction cost, and production compatibility were the key performance criteria considered in the design, but it was recognized that the cost for prototype experimental houses could be much higher than would be acceptable in full production. The designers felt that high mass construction would provide energy and comfort benefits in this climate, so two of the houses were built using a precast concrete-foam-concrete “sandwich panel” product, shown in Figure 4. This product has two inches of concrete on the exterior side, four inches of extruded polystyrene, and four inches of concrete on the interior side. One of the remaining houses was built using structural insulated panels (SIPs), and the other using 2x6 wood framing.

The houses have low-slope roofs with mineral roofing and minimal non-vented attics. The original architectural program assumed that all heating and cooling could be supplied from the floor (no ducts). Weather data obtained during the summer of 2004 showed that forced-air cooling would be needed during monsoon conditions to maintain indoor relative humidity. Also, since two of the houses were to employ advanced evaporative coolers, some ducting was required to adequately deliver the evaporativly cooled air. All ducting was installed in soffits within the conditioned space.

Figure 2: One of Four Borrego Springs Prototype Houses

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Figure 3: Floor Plan Used by All Four Houses

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Figure 4: Cut-away View of High Mass Wall Panel (With 2 Inches of Extruded Polystyrene)

Mechanical Systems - Cooling

To test their comparative performance, different mechanical systems were selected for each house. Since outdoor wet bulb temperatures are low during much of the summer, advanced, 2 stage, evaporative coolers were selected for two of the houses. To explore the value of using evaporative cooling to cool building mass, evaporative coolers were used on one of the high mass houses (DiGiorgio) and on the SIP house (Arrow), which serves as a low mass control[2].

The evaporative cooler used in both houses is a prototype that was developed by Davis Energy Group (DEG) under a grant from the California Energy Commission's Public Interest Energy Research (PIER) program. The two-stage direct-indirect coolers utilize a single down-flow variable speed blower that moves air both through the wet side of the indirect cooling module (heat exchanger) as well as supply air to the house through the dry side of the heat exchanger and the direct cooling module (cellulose media), as shown in Figure 5. To eliminate corrosion, the blower housing, air passages, and water reservoir are made of a single rotationally molded plastic part.

The two evaporatively cooled houses also are equipped with 13 SEER air conditioners, both to provide supplemental cooling during the monsoon season, and to provide a backup in the event the prototype coolers fail. One of the houses uses a conventional fan coil and evaporator coil to distribute the cool air and shares ducts shared with the evaporative cooler (with appropriate back-draft dampers). Both houses are also provided with "up-ducts" to automatically vent relief air to outside.

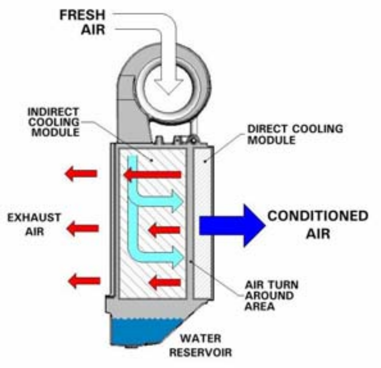

Figure 5: Schematic of 2-Stage Evaporative Cooler

In keeping with the goal to minimize ducting, the design for the second house substituted a refrigerant-to-water plate heat exchanger for the cooling coil, turning the air conditioner into a water chiller. Chilled water is first routed to an air handler that provides latent as well as sensible cooling, and then through tubing in the floor. The air handler coil was sized to

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[2] For ease of reference, the four houses are assigned abbreviated names for the streets on which they are located.

meet about one third of the cooling load. A schematic of the system is shown in Figure 6. The air handler has minimal ducting.

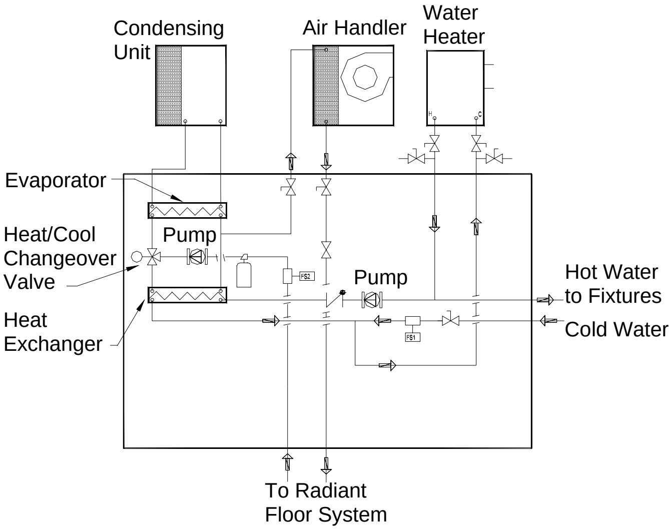

Figure 6: Schematic of "Wagon" Heating & Cooling System

The third house (DiGiorgio) uses an evaporative condenser for cooling, connected to a variable speed air handler. In addition to providing vapor compression cooling, the cooling tower of the evaporative condenser is operated at night to cool water that is circulated through tubing embedded in the slab floor. Controls enable operation the floor cooling system to operate at outdoor temperatures above 90°F, disable operation at temperatures below 60°F, and activate floor cooling when the outdoor dry-bulb temperature is below 80°F. This temperature was used as a proxy for wet-bulb temperature to simplify controls, and assumes a 10-15°F wet bulb depression. The return-air side of the air handler is also connected to an outside air damper, and the air handler operates to provide nighttime ventilation cooling using proprietary controls. The fourth house (East Star) is equipped with a comparatively standard, two-speed high performance cooling system (manufacturer's rating of SEER 21). A standard ducting system was installed in this house.

To facilitate installation and integration of monitoring components, hydronic modules were custom-assembled for each of the houses. The modules contained pumps, heat exchangers, valving, controls, temperature sensors, flow meters, and other components. One of these modules is pictured in Figure 7. These modules were mounted on the exterior walls of the houses near the tankless water heaters and other mechanical equipment.

Figure 7: Typical Hydronics Module

To prevent concurrent operation of the moisture-adding evaporative coolers and the moisture-removing vapor compression cooling systems, controls included an interlock that disabled the vapor compression systems whenever the evaporative coolers are operating. However, occupants are free to choose whichever system best meets their comfort needs and addresses their energy use concerns. This control approach adds a sociological component to the study that is not evaluated in this paper because the evaporatively cooled houses were not occupied.

Mechanical Systems - Heating

Three of the houses (all except DiGiorgio) are heated by radiant floor systems consisting of cross-linked polyethylene tubing embedded in the slab floors, 12” on center. Hot water for the systems is generated by 180,000 Btuh tankless water heaters that also provide hot water for domestic use (domestic water heating is given priority). A plate heat exchanger isolates the domestic water from the water used for radiant heating.

DiGiorgio is heated by a variable speed air handler that is also used for cooling. The air handler incorporates a heating coil that is connected to the tankless water heater. As with the radiant heating systems, domestic water heating receives priority over space heating.

Ventilation Systems

All of the houses except DiGiorgio rely on bathroom fans for fresh air ventilation. DiGiorgio utilizes the variable speed air handler and outside air damper for fresh air ventilation. The air handler fan operates at a very low speed to deliver outside air at the rate of about 200 cfm for a fraction of each hour.

Integration of House and Mechanical System Features

Table 2 identifies the combination of building envelope types and system types. All houses use a tankless water heater to provide heat for both domestic hot water and space conditioning. These were also mounted on the exterior of the houses.

Table 2: Building Envelope and System Type Combinations

Site Name	Envelope Type	Cooling Source	Distribution	Other
“East Star”	Advanced frame	21 SEER 2-speed	Radiant heating;	Ventilation via bath fans

	2x6	condenser with var. speed fan coil	forced air cooling	
“Arrow”	Structural Insulated Panels	Two-stage evap. cooler and 13 SEER air conditioner	Radiant heating; forced air cooling	Ducting shared by evap cooler and air conditioner. Ventilation via bath fans.
“Wagon”	“T-Mass” concrete sandwich wall	Two-stage evap. cooler and 13 SEER “water chiller”	Radiant heating; radiant and forced air cooling	Minimal ducting. Ventilation via bath fans.
“DiGiorgio”	“T-Mass” concrete sandwich wall	Evaporative condenser and variable speed air handler with heating and cooling coils	Forced air heating and cooling; tubing in slab for partial cooling	Nighttime ventilation cooling; slab cooling using evap. condenser cooling tower. Ventilation via air handler and outside air damper.

MONITORING AND TESTING APPROACH

General Approach

Data loggers were installed at each house to collect data from the more than 220 sensing points. Sensors are scanned on 15 second intervals and data are reported on 15 minute intervals. Calculations of energy flows are completed every 15 seconds and summed or averaged over 15 minutes. Data loggers are polled each day, and data were transferred to a server. Macros are used to automatically review data and to report any out-of-range data.

Weather Data

The National Renewable Energy Laboratory (NREL), who has been conducting detailed monitoring of the Borrego Springs cooling systems in their technical leadership role in BAP, also installed a weather station to measure outdoor temperature, relative humidity, outdoor wet bulb temperature, wind direction and velocity, and horizontal solar radiation. The weather station was installed at the East Star site, but because of the close proximity to the other sites, these data can be applied to all four sites.

Ground Coupling, Mass, and Building Envelope

In an effort to identify ground heat transfer, a total of twelve temperature sensors were installed in and under the slab of each of the four houses to measure temperatures at various depths and locations. Data from these sensors will also be valuable for future calibration of building models. An additional eight sensors were placed in the mass walls of the Wagon and DiGiorgio houses, and six sensors were placed in the walls of the SIP and frame houses (Arrow and East Star). The wall sensors are useful for evaluating conducted heat flow through the walls, mass effects, and interior wall surface temperatures, which affects the mean radiant or “operative” temperature of the interior spaces.

Mechanical Systems

To facilitate calculations of HVAC system efficiency, the monitoring systems were configured to gather data on energy delivery and system energy consumption. Cooling delivery was calculated from airflow and temperature differences at 15 second intervals. Measurement of evaporative cooler airflow was complicated by the fact that the fan speed varies with cooling demand. An airflow station installed in the ducting was used at the Wagon site to continuously measure airflow, and fan power data calibrated to manual airflow measurements were used to determine cooling delivery for the Arrow site. For the evaporative coolers, the temperature difference measurement was based on supply air temperature vs. indoor air temperature. Water consumption of the coolers was also measured.

One-time measurements were used in the calculation of cooling delivery for the constant volume forced-air systems. For the high efficiency two-speed air conditioner installed at the East Star site, condensing unit power was used to select the appropriate airflow in the calculation of cooling delivery. Relative humidity and temperature sensors located in the supply and return ducting were used to measure total as well as sensible cooling. For the evaporative condenser, pump, fan, and compressor energy were separately measured.

Energy transfers were also measured on the “wet” side of those systems that use chilled water for cooling, including the floor cooling systems at Arrow and DiGiorgio, and all of the heating systems. Immersion thermocouples and flow meters were built into the hydronics modules to obtain the appropriate measurements (see Figure 6). Sensors were placed so as to allow energy applied to domestic uses to be separated from energy applied to space heating.

Monitoring Schedule, Operation, and Building Occupancy

Monitoring systems were installed and commissioned in May 2006. Due to the unfinished condition of the houses, HVAC equipment problems, power outages, and problems with monitoring sensors, a small portion of the initial data collected was invalid inaccurate. Improvements to systems through the summer and fall of 2006 have been improving data reliability. Monitoring will be continuing through 2007 so that a full year of valid data can be obtained.

Only one of the houses, DiGiorgio, was sold at the time of completion. This house has been occupied since monitoring began. A second house, Wagon, sold in September 2006 but has been occupied sporadically.

It is usually desirable to monitor unoccupied rather than occupied houses so that temperatures can be controlled to obtain valid comparative data, particularly in this case, where the houses are nearly identical. However, due to the remote location it has been difficult to control conditions. Sales personnel and others have randomly modified thermostat settings and system operation, making data more difficult to interpret.

Some examples of problems with systems that affected monitoring data should be noted. All of the houses were to have been equipped with photovoltaic arrays, but the arrays were not fully operational until December, due to issues with county approval of the mounting method. Controls issues were encountered with the evaporative condenser and the Wagon house's cooling control interlock. Water was not supplied to one of the houses until mid-2006, preventing operation of the evaporative cooler. Water pressure regulators were installed to limit house pressure, but were placed such that they only lowered hot water pressure. As a result, hot water was being delivered to all of the cold water fixtures in two of the houses. Debris in the piping clogged a flow switch at one of the sites, preventing the heating system from operating. All of these problems have been resolved.

Probably due to moisture and/or corrosive soils affecting the thermocouples, only eighteen of the original fifty-two ground and slab sensors are working as of this writing. All of the wall sensors are still operational.

Peak Cooling Demand Tests

Pre-cooling of houses has been under investigation as a means to reduce peak load (SMUD 2006). To evaluate the impact of high mass construction on the effectiveness of pre-cooling, NREL conducted a test during August of 2006 on three of the unoccupied houses, including one of the high mass houses (Wagon), the SIP house (Arrow), and the frame house (East Star).

To conduct the tests the houses' vapor compression cooling systems were used to adjust indoor temperatures according to the schedule shown in Table 3. The August 15th and 16th tests were based on an assumed utility peak period beginning at 12 noon. The August 17th test evaluated a peak period starting at 12 noon and a "super-peak" period beginning at 4 PM. The remaining days were used to establish control conditions, and maintained a fixed 78°F setpoint. As shown in Figure 8, outdoor temperatures did not vary greatly over the days the tests were conducted.

Table 3: Thermostat Settings Used for Pre-Cooling Experiment

Date	Time	Set Point (°F)
Aug. 15	12 AM – 12 PM	72
	12 PM -12 AM	85
Aug. 16	12 AM – 12 PM	72
	12 PM -12 AM	85
Aug. 17	12 AM – 12 PM	72
	12 PM – 4 PM	74
	4 PM -12 AM	85
Aug. 18	12 AM -12 AM	78
Aug. 19	12 AM -12 AM	78
Aug. 20	12 AM -12 AM	78

Date	Time	Set Point (°F)
Aug. 21	12 AM -12 AM	78

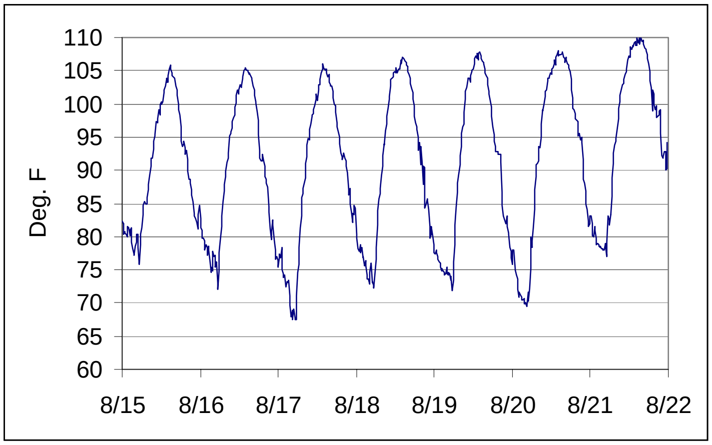

Figure 8: Outdoor Temperatures During Pre-Cooling Experiment

RESULTS OF TESTING

Leakage Test Results

House leakage was measured using standard blower door methods. While the air leakage goal was 2.0, initial tests yielded Specific Leakage Area (SLA) values of close to 5. It was subsequently determined that all the houses were leaking air through custom built skylights and windows, as well as through interior walls. Table 4 lists the results of leakage measurements before and after remedial measures were taken to seal the custom fenestrations and interior wall baseboards.

Table 4: Specific Leakage Area (SLA) Measurements

House	Initial	Final
DiGiorgio (Mass Wall)	5.0	3.3
East Star (Frame)	5.3	3.3
Arrow (SIP)	5.0	3.3
Wagon (Mass Wall)	6.6	2.9

Duct leakage at DiGiorgio was measured to be 4.5% of total airflow. Duct testing of other houses was not completed because ducts are within conditioned space.

Pre-Cooling Test Results

The results presented below are for the Wagon house for Wednesday, August 16. The house was in the third week of the experimental cooling cycle and had completed one super-cooling cycle.

Figure 9 shows the interior temperature of the Master Bedroom and Kitchen along with condenser energy use. Note that when the HVAC system is set to 85°F from 12 PM to 12 AM, which includes the afternoon peak hours, the interior temperature rises only 5°F. The HVAC system does not run during this period when the thermostat is set at 85°F even though the outside air temperatures climbs to 105°F.

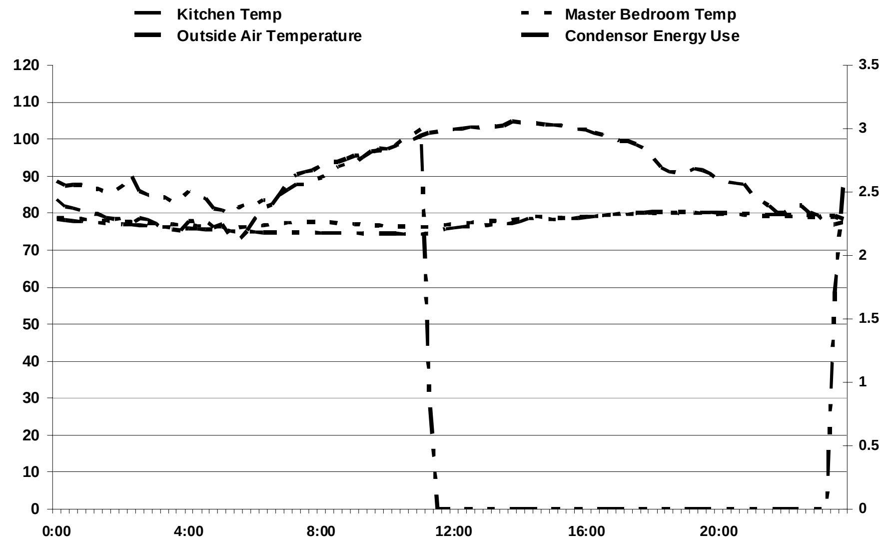

Figure 9: Pre-cooling Test Results for August 16th, Wagon High Mass House

Figure 10 shows other interior and exterior wall temperatures during this same period. Both the NE and SW external walls reach peak temperatures of 115° and 122°, even though the outside air temperature peaks at 105°.

For comparison, the following two figures show the wall temperature data from the SIP and 2x6 frame houses. Figure 10 shows that the SIP house never reaches the 85°F set point and exhibits a temperature rise of 8°F during the afternoon coast period. The interior wall temperatures are also less stable than was seen in the T-Mass walls indicating that the mean radiant temperature would be higher than in the T-Mass house, providing less comfort. The 2x6 frame house, however, reaches the 85°F set point in 4.5 hours and experiences a temperature change of 9°F over the 11 hour interval (see Figure 11). Note that the exterior surface of the Northeast exterior walls also reach a temperature of 140°F. The house with the T-Mass walls, in comparison, never reaches the 85°F set point and experiences a temperature rise of only 3.5°F.

It should be noted that at the time these tests were conducted not all of the remedial air sealing of the 2x6 frame house (East Star) had not been completed. If the house had been sealed as well as the other houses, it may have performed more similarly to the SIP house in that they both have similar amounts of thermal mass in the walls and floors.

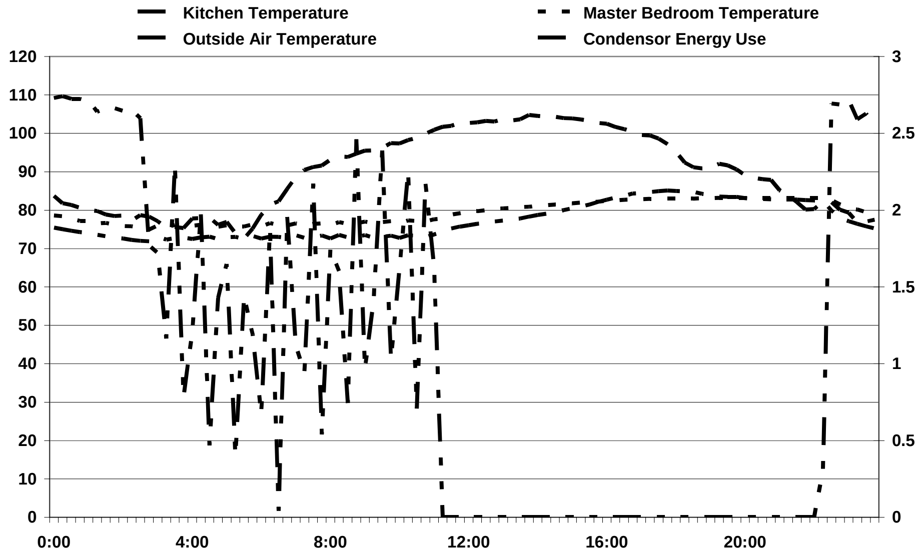

Figure 10: Pre-cooling Test Results for SIP House (Arrow), August 16th

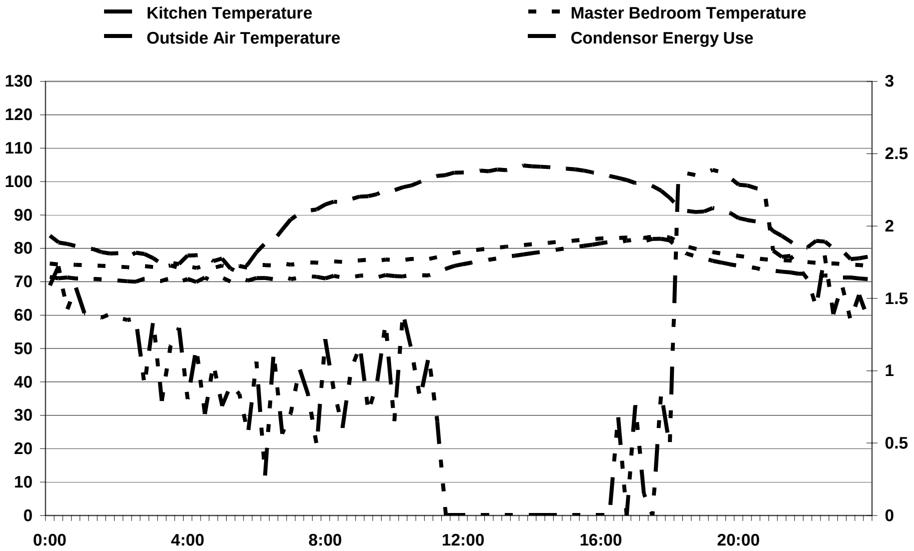

Figure 11: Pre-cooling Test Results for Frame House (EastStar), August 16th

INTERIM MONITORING RESULTS

As noted previously, the houses were in a continual state of improvement over the summer of 2006, indoor temperatures were not well controlled due to the remote location and lack of occupancy, and there were several problems that affected the reliability of some of the data being collected. Preliminary results presented in this paper will be verified by monitoring the houses through 2007.

Comparative Heating Energy Use

The evaluation of space heating energy use is simplified by the fact that all houses use the same model of tankless water heater to provide heat for space conditioning (as well as water heating. A single day (January 11) was selected to compare heating system performance because it was the only day when all four heating systems were active. The energy delivered to the houses, based on water flow and temperature differences, was normalized using indoor-outdoor temperature difference. Actual and normalized energy use is shown in Figure 12.

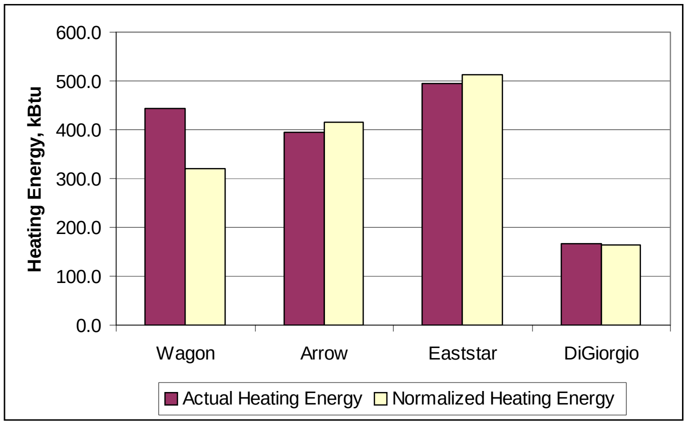

Figure 12: Comparison of Heating Energy Use on January 11, 2007

Keeping in mind that the Wagon and DiGiorgio houses employ the same high mass wall systems, the difference in normalized energy use for these houses must be attributable to the efficiency of the distribution system. DiGiorgio uses an air handler with ducts in conditioned space, and the other three houses employ radiant floor heat distribution. The data suggest that over 50%, of the heating energy for the radiant heated houses was lost to the ground through the underside of the uninsulated slabs. Considering other comparative evaluations of radiant and forced air heating (Baskin 2003), this is a surprising result. An explanation for the large observed ground losses is that the radiant heating systems at all houses except DiGiorgio were started on January 8th. Once the soil temperatures under the house reach equilibrium, heating energy is likely to subside. Longer term monitoring is needed to determine the comparative performance of the forced-air and radiant heated houses.

Comparative Cooling Energy Use

Cooling energy use for all systems (air conditioners and evaporative coolers), and all components (condensing units, fans, and pumps) were totaled to obtain the energy usage shown in Figure 13. Because there were differences in thermostat settings and system operation between the houses, energy use was normalized using average weekly indoor and outdoor temperature differences to develop the energy use values shown in Figure 14.

Referring to Figure 14, energy use in July, the hottest month, varies little for the four houses. The East Star high SEER air conditioner appears to have performed well, despite the higher expected cooling loads of the frame construction. Even during July, 71% of the high SEER unit’s energy use was at low speed operation. The evaporative coolers were operated during about half of June at Arrow and Wagon, accounting for their comparatively low energy use in that month, but were operated minimally the rest of the summer.

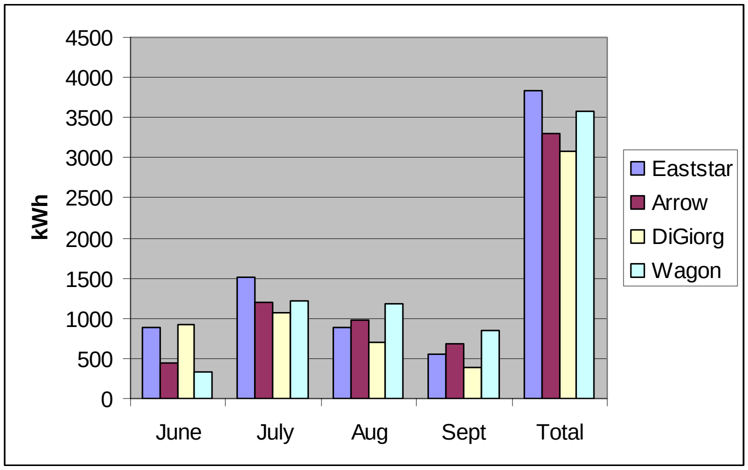

Figure 13: Actual Cooling Energy Use, Summer 2006

The total energy use values are skewed by June data; differences in house operation during that month may have accounted for the larger differences in cooling energy use. If June data are ignored, Wagon had the most energy use, followed by Arrow, DiGiorgio, and East Star. The standard deviation is less than 10%. Optimal use of the evaporative coolers would have probably swung the results in favor of Arrow and Wagon.

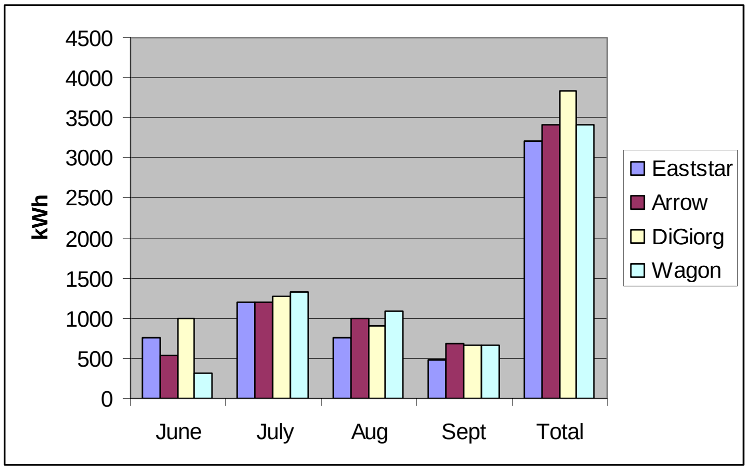

Figure 14: Normalized Cooling Energy Use, Summer 2006

Floor Cooling Evaluation

As shown in Figure 6, the system used for the Wagon house delivers chilled water to the air handler to accomplish some latent cooling, and then to the radiant floor tubing. Of primary interest was the effect on condenser EER of using a refrigerant-to-water cooling coil in lieu of a conventional refrigerant-to-air evaporator coil. There was also a concern was that the floor would approach the dewpoint temperature, causing moisture to condense during humid conditions. Figures 15 and 16 show the EER's of the Wagon and Arrow systems respectively, both of which use the same 13 SEER condensing units. These figures show the efficiency of the water-based system to be about two to four points higher than the air-based system.

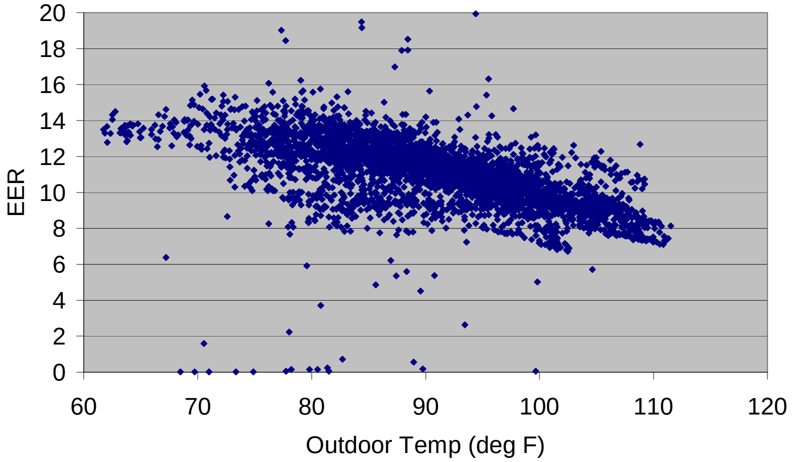

Figure 15: EER of 13 SEER Condensing Unit Used as a Water Chiller (Wagon)

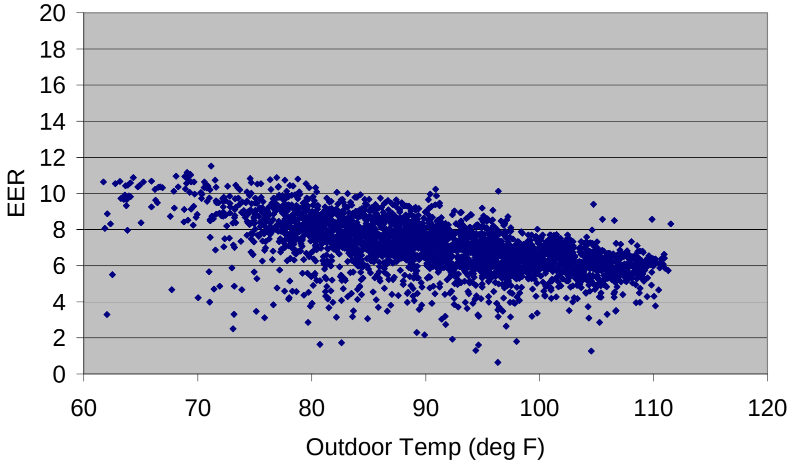

Figure 16: EER of 13 SEER Condensing Unit with Conventional Cooling Coil (Arrow)

Figure 17 compares floor surface temperatures for the Wagon and Arrow houses, and plots the dewpoint temperature over one week of typical hot weather. The cooled floor at Wagon averaged 71.9ºF surface temperature compared to 77.1ºF for the non-cooled floor. The cooled floor never came closer than 11ºF to the dewpoint, and averaged 22.8º above dewpoint.

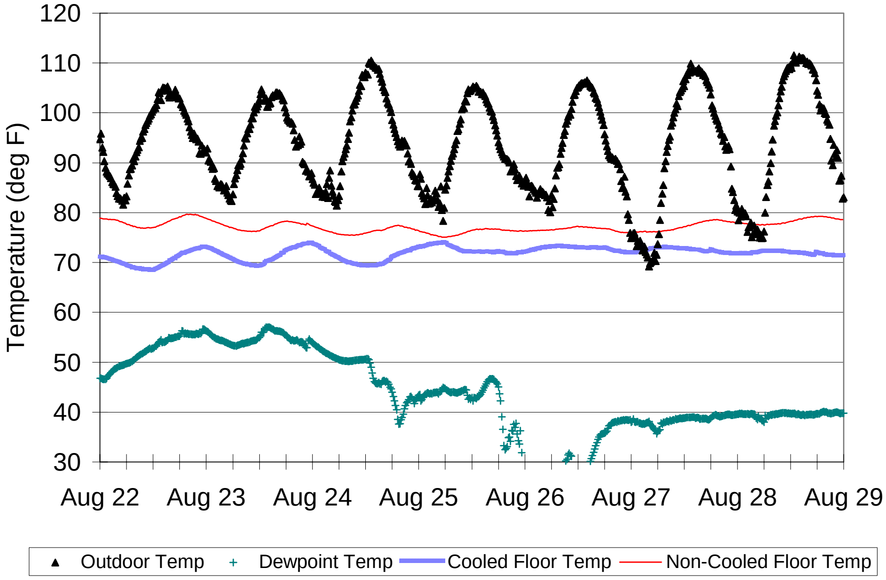

Figure 17: Comparison of Cooled and Non-Cooled Floor Surface Temperatures and Dewpoint

If the distribution efficiency of the conventional ducted and radiant cooling systems were the same, the radiant cooling system would appear superior. However, as shown in Table 4, the radiantly cooled Wagon house used twice the cooling energy of the conventionally cooled Arrow house over a 65 day period. The net result is the loss of energy to the ground caused the radiant cooling system to use 30% more electrical energy than the conventional cooling system. Under-slab insulation might have reversed this outcome.

Table 5: Floor Cooling Energy Use and EER

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House	System	Cooling Energy KBtu	kWh	Average EER	Average Air Temperature
Wagon	Radiant Cooling	21,059	1,977	10.7	77.7
Arrow	Ducted Cooling	10,798	1,519	7.1	78.5

Evaporative Cooling Evaluation

The evaporative cooler at the Wagon site was operated through most of June. A maximum airflow of 1,426 cfm was measured. Water use averaged about 170 gallons per day. The Arrow cooler was operated for 17 days in June. Water use averaged 91 gallons per day. The maximum airflow measured at Arrow was only 730 cfm. The explanation for the lower airflow is that Arrow has much more ducting and higher supply side static pressures, which diverts more air to the secondary heat exchanger (and exhaust). Hoods with dampers were retrofitted to the secondary air discharges of the coolers late in the summer to allow the secondary air volume to be throttled, but this occurred too late in the year to obtain meaningful data.

Figures 18 and 19 plot the EER for the Wagon evaporative cooler vs. the outdoor dry bulb and wet bulb temperatures, respectively. The trend lines illustrate the greater dependence of performance on wet bulb than dry bulb temperature. The large amount of scatter is a result of the cooler's periodic purge cycles, during which the pump shuts off, the reservoir drains, and the fan falls to a low speed setting. While the evaporative media is still wet the efficiency rises because of low fan and no pump energy. As it dries the efficiency falls.

Figure 20 plots the EER for the Arrow site, compared to wet bulb temperature. It is not immediately understood why there is so much less scatter than for the Wagon site; it is possible a different purge setting was used. The higher secondary airflow and lower primary airflow probably contributed to increase the performance at lower wet bulb temperatures. The cooler may also have been running at a lower speed due to control settings.

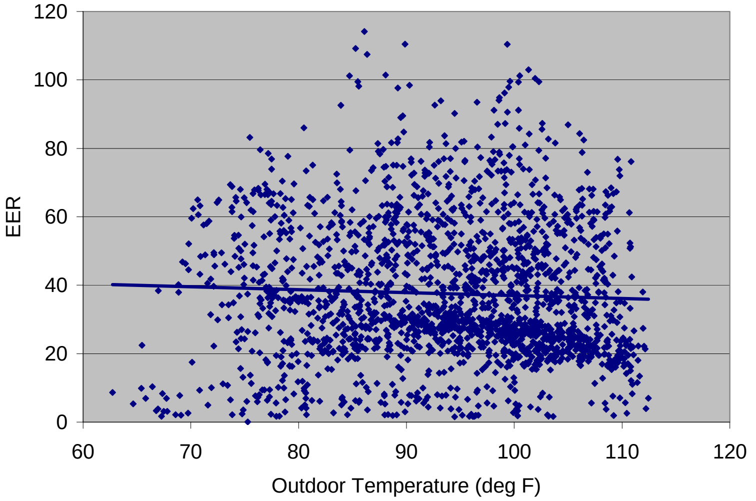

Figure 18: Evaporative Cooler EER vs. Outdoor Dry Bulb Temperature, Wagon

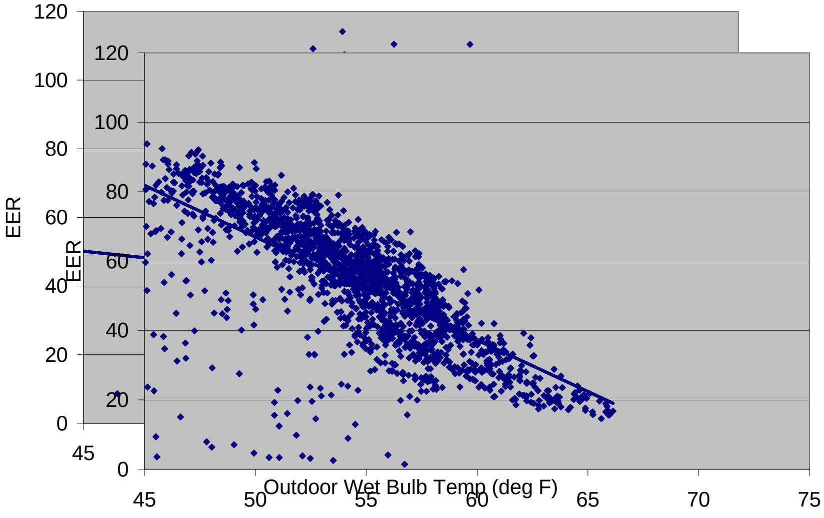

Figure 19: Evaporative Cooler EER vs. Outdoor Wet Bulb Temperature, Wagon

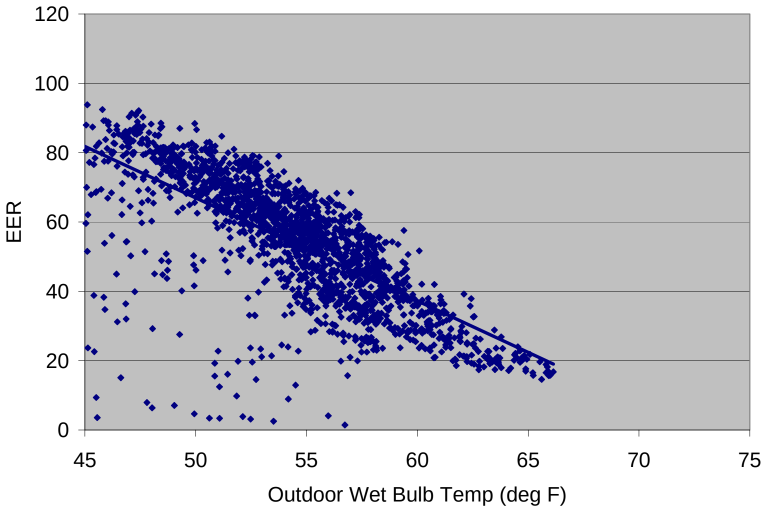

Figure 20: Evaporative Cooler EER vs. Outdoor Wet Bulb Temperature, Arrow

The EER of the evaporative coolers only tells part of the story. The overriding question is, can they provide comfort? Figure 21 shows representative temperature and humidity conditions for the Wagon house during a week containing both mild and hot weather. On June 8 the highest coincident temperature and relative humidity were 79.2°F and 66% respectively. On June 11 the highest coincident conditions were 76.5°F and 51%. These points are noted on Figure 21 and plotted on the psychrometric chart in Figure 22. The boxed area in Figure 22 is the ASHRAE Standard 55 summer comfort zone.

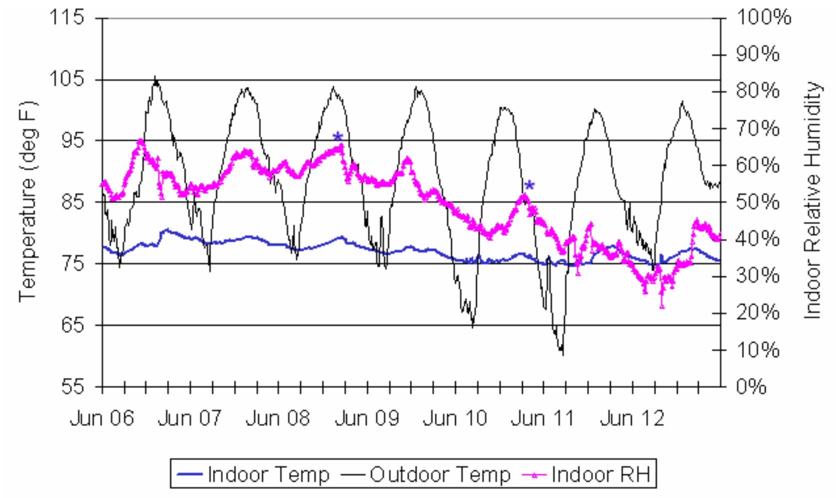

Figure 21: Indoor Conditions with Evaporative Cooling, Wagon Site

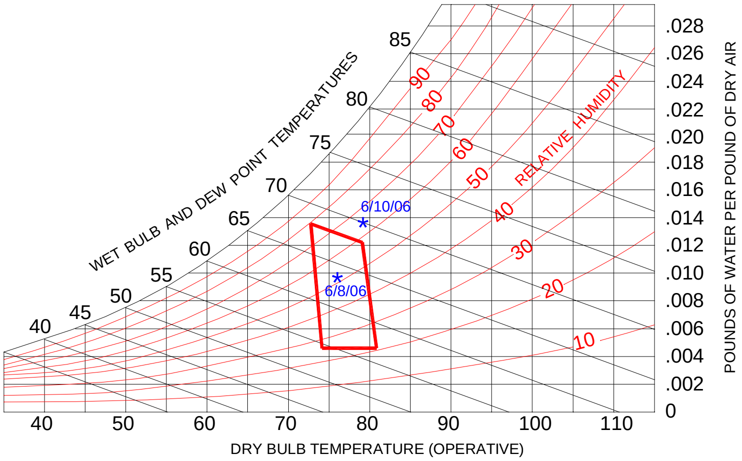

Figure 22: ASHRAE Standard 55 Comfort Zones in Relation to Indoor Conditions, Wagon Site

Though they have not been tabulated, a large number of evaporative cooler operating hours fell within the comfort zone over the period of time that the Wagon and Arrow houses were monitored. However, most peak conditions during the month of July and part of August would fall outside the comfort zone. Homeowners would be ill advised to operate evaporative cooling during night and morning hours and switch to vapor compression cooling during the afternoon and evening because of the increased latent load on the air conditioners. However, relying on evaporative cooling most of the time and switching to vapor compression cooling during a sequence of hot days would be a reasonable energy saving strategy. In order to identify the savings contribution of the evaporative coolers it will be necessary to optimally control the systems, either by having an occupant perform the switching, or by controlling them remotely. To capture possible operative temperature benefits of the high mass house, the former approach might yield better results. Collection of data from the Wagon house with occupants will continue in 2007.

Evaporative Under-floor Cooling Evaluation

As noted, the DiGiorgio house uses an evaporative condenser for cooling, but vapor compression cooling is augmented by circulating water that is cooled by the unit's cooling tower through plastic tubing embedded in the slab floor. Controls were retrofitted to the evaporative condenser to operate the spray pump, condenser fan, and an additional pump that circulates water through the slab when outdoor dry bulb temperatures are below 80°F. This set point anticipates a 10-15°F wet bulb depression and assumes the slab temperatures would typically be higher than 70°F during the cooling season if not cooled.

The floor cooling energy efficiency ratio (EER), defined as the total electrical use by the fan and pumps divided by the cooling delivered to the slab is shown in Figure 23 as a function of outdoor wet bulb temperature. The EER averaged 20.5 over the monitoring period. The loss of some of the slab and ground cooling to the environment will degrade the efficiency, but the quantity of degradation has not been determined.

The cooling capacity averaged 6.75 ton-hours per day, and varied with wet bulb temperature as shown in Figure 24. Assuming all of the cooling was delivered to conditioned space, the system would be the equivalent to running a 2-ton air conditioner about 3 hours per day.

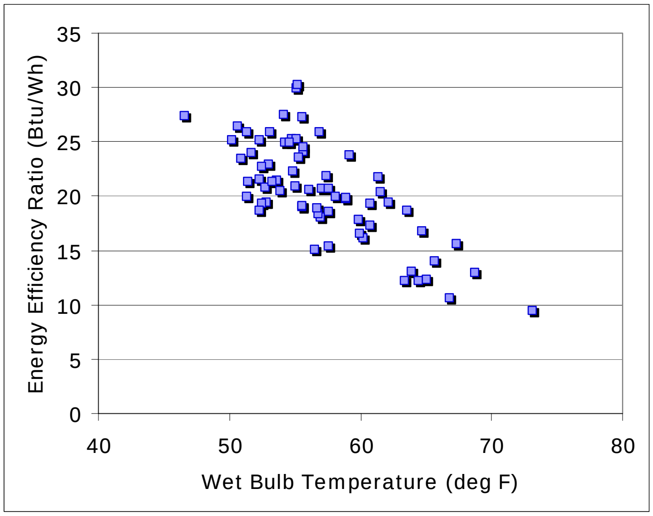

Figure 23: Daily Average Energy Efficiency Ratio of Floor Cooling System

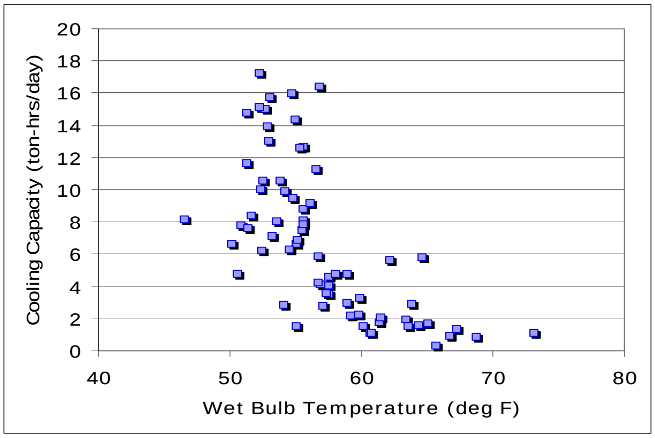

Figure 24: Daily Average Cooling Capacity of Floor Cooling System

Comparing below slab temperature profiles for cooled and non-cooled slabs shows clear evidence of the floor cooling contribution. Figure 25 plots temperatures 12" below the slab surface for DiGiorgio (cooled floor) and East Star during September 2006[3]. The soil below the East Star slab was cooler at the beginning of the month because the indoor temperature was maintained about 4°F cooler than the DiGiorgio house. However, since the normalized cooling energy use of the DiGiorgio house was nearly the same as for the East Star house (see Figure 14), cooling energy savings resulting from cooled floor cooling are not remarkable. The lower floor surface temperatures will result in a lower mean radiant temperature and improved comfort, but unfortunately this cannot be measured with the existing monitoring system.

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[3] Corresponding slab and ground temperature data from other houses are not available because of sensor failure.

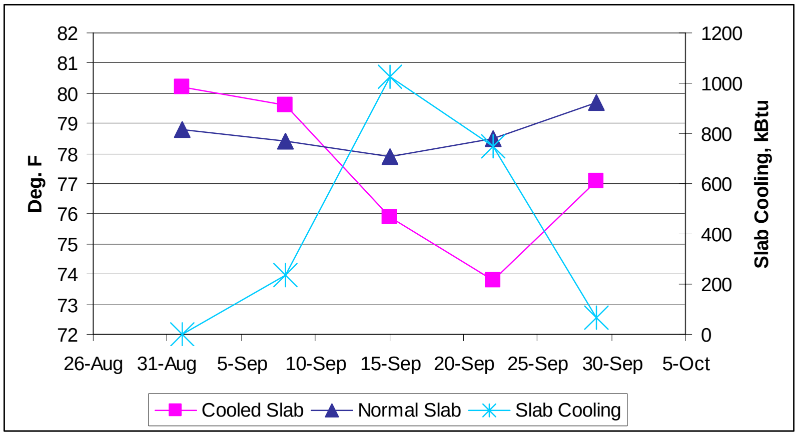

Figure 25: Comparison of Cooled and Non-Cooled Ground Temperatures

Performance Comparison of High SEER and Evaporative Condensers

NREL completed detailed monitoring of the evaporative condenser and high SEER air conditioner to determine how their performance varied with outdoor temperature. Figure 26 compares the EER of both systems to one of the 13 SEER systems[4]. The performance of the high SEER unit is superior under mild conditions because of its higher low speed efficiency. The EER of the evaporative condenser is practically flat with respect to outdoor temperature, and lower than expected.

Prior Building America monitoring of another evaporative condenser of the same model and capacity produced EER's ranging from 14-15 at 75-100°F outdoor dry bulb temperatures. Fan energy is one reason for the discrepancy; the furnace fan motor of the previously monitored system averaged about 500 Watts, whereas the fan motor at DiGiorgio averaged 813 Watts. From fan measurements obtained by the author from another variable speed air handler identical to the one used at DiGiorgio, the motor drew about 300 Watts at 1,200 cfm and 0.4" external static pressure. Further investigation is needed to identify the reason for the excessive fan energy.

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[4] Credit Mark Eastment, NREL

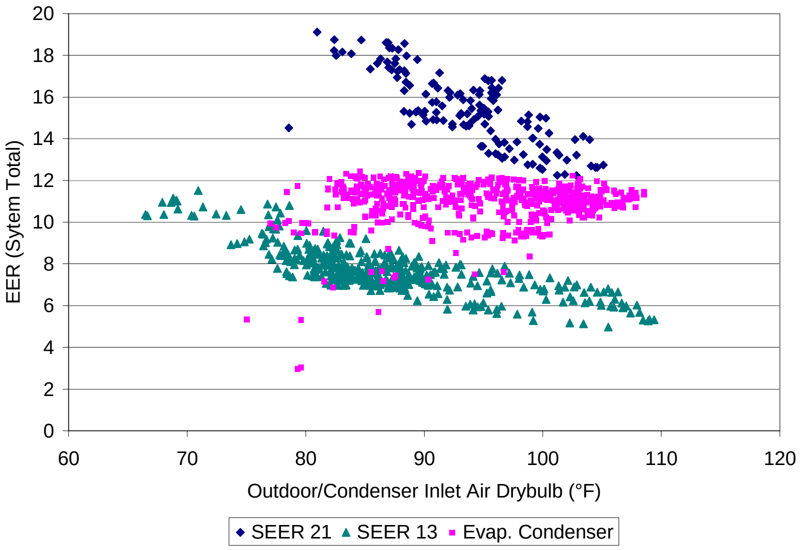

Figure 26: Comparison of Measured EERs for Three Air Conditioner Types

COSTS

Construction costs were abnormally high because of the remote location and the extreme environment. These factors, as well as the prototype nature of the houses, contributed to higher-than-normal costs that would not be representative of a typical production home building environment.

Tables 5 and 6 list construction costs for the wall and mechanical systems, respectively. Table 5 references incremental costs to the frame house, and Table 6 references incremental costs to the SEER 21 air conditioner.

Mechanical system costs for the non-conventional systems were particularly high because of the cost to custom-fabricate the hydronics modules that were used to integrate heating, and in one case cooling, components. Part of the fabrication costs for the modules included installation of sensors for monitoring temperatures and flow rates.

Table 6: Wall Construction Cost Comparison

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House	Description	Cost	Incremental Cost
East Star	Frame	$57,242	-
Wagon	Mass Walls	$99,762	$42,520
DiGiorgio	Mass Walls	$100,301	$43,059
Arrow	SIP	$72,674	$15,432

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Table 7: Mechanical System Construction Cost Comparison

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House	Description	Cost	Incremental Cost
East Star	SEER 21 AC, forced air cooling and radiant floor heating	$15,846	-
Wagon	Evaporative cooling with supplemental SEER 13 condenser and radiant/forced air cooling; radiant heating	$17,923	$2,077

DiGiorgio	Evaporative condenser, forced air cooling with radiant-evaporative floor cooling and night ventilation cooling assist; forced air heating	$20,440	$4,594
Arrow	Evaporative cooling with supplemental SEER 13 condenser and forced air cooling; radiant heating	$21,009	$5,163

CONCLUSIONS

Conclusions from Testing and Monitoring

Although further monitoring and analysis are needed, it is safe to draw the following conclusions from the data collected to date.

- Under similar indoor conditions and occupancy, it appears that seasonal cooling energy use may be very close for the four houses. The standard deviation of normalized use was less than 10%.

- High mass envelopes have clear peak load reduction value. The use of air conditioning, evaporative cooling, and/or nighttime ventilation cooling to discharge heat from (cool) the floor and wall mass can shift a significant amount of the cooling load to off-peak periods. Although not yet verified by this research, the added mass may also serve to reduce winter heating energy use by storing solar heat gain and releasing it during evening hours.

- The distribution efficiency of the radiant floor heating systems is considerably lower than for the forced air system, but more data are needed from occupied houses to determine whether heat build-up in the ground will offset early season ground losses, and to factor in any MRT improvements. Based on the data gathered to date, continuous under slab insulation would be advisable for future radiant floor heating and cooling designs.

- Radiant cooling holds promise as a means of improving system EER as well as for peak load control, however, heat gains from the ground more than offset EER improvements. Under slab insulation could make radiant cooling practical, particularly for houses where ducting is difficult due to architectural constraints.

- Evaporative cooling has the potential to substantially reduce cooling energy use and costs. Occupant behavior will dictate how much the evaporative coolers are used relative to vapor compression systems. More study is needed to determine the practicality of having dual (evaporative + vapor compression) cooling sources in this climate. Cost factors and potential maintenance issues attendant with the evaporative systems may favor high efficiency conventional cooling in extreme hot climates. Additional study of existing and forthcoming data (with houses occupied) will aid in this determination. Water use of the evaporative systems should also be carefully evaluated.

- Based on a comparison of system EER's, results currently favor the high efficiency air conditioner over the evaporative condenser, but corrections to the system to reduce blower power and other improvements could result in more favorable seasonal performance for the evaporative condenser. Evaporative condenser performance is practically unaffected by dry bulb temperature, and moderately affected by wet bulb temperature

Lessons Learned

A key lesson learned was how difficult it is to manage a research project that is remotely located. The construction of the houses could not be regularly monitored by the builder or the design/research team, and many construction defects had to be corrected after the houses were completed. It addition, correction of problems with HVAC systems and monitoring equipment had to wait for several weeks in some cases. Despite these difficulties, the project afforded a very unique opportunity to comparatively evaluate hot climate designs, and is expected to yield additional useful information..

Further Research Needs

It is hoped that conditions will permit a test to evaluate the use of evaporative coolers to pre-cool building mass during the summer of 2007. Since nighttime wet bulb temperatures are much lower than in the daytime, more cooling could be delivered and less water evaporated. This testing will depend on the willingness of the occupants, and/or the availability of local support persons to conduct the tests.

New cooling technologies that integrate direct-indirect evaporative cooling with vapor compression cooling, and evaporative condensers equipped with two-speed compressors and fans would show great promise in this climate. Integration of systems could significantly reduce equipment and installation costs while maintaining the level of performance of the prototype systems.

Because none of the houses and systems are representative of standard construction practice in the area, it is difficult to estimate the percentage of energy savings for the houses. Computer simulations are needed to evaluate long-term performance relative to standard construction practice and operating conditions; there is ample data available for calibration of computer models.

REFERENCES