



“Advanced Systems Research: Final Report”

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Results of Advanced Systems Research

Abstract

Davis Energy Group, working through the Consortium for Advanced Residential Buildings (CARB) and in collaboration with the Building Industry Research Alliance (BIRA) evaluated the performance of four unique mechanical system designs in four identical homes built in the extreme hot climate of Borrego Springs, California. Construction of the homes was mostly completed in May of 2006 and monitoring was continued until November 2007. Two of the houses employ high mass walls, the third SIP walls, and the fourth standard framing. Mechanical systems evaluated include advanced evaporative cooling, evaporative condensing, ventilation cooling, and both forced air and radiant distribution. This report describes the comparative performance of mechanical systems. The four houses and subsystems were monitored for over one year. Only one of the houses was occupied continuously during the monitoring period.

Outstanding issues with envelope leakage and the photovoltaic system installation were addressed over the course of the project. This report focuses on results of testing and monitoring of cooling system operation from May through October 2007, during which time conditions were reasonably well controlled.

Except for the high SEER system tested, air conditioners performed below manufacturers' specifications. Measured EER's for the two evaporative coolers tested ranged from 26.5 to 34.9, but they could not maintain comfort at outdoor wet bulb temperatures above 65°F. A hybrid forced-air radiant chilled water cooling system had about twice the EER of a typical forced-air system using the same condenser, but heat gains from the ground were excessive. Summer energy use for the four houses and systems varied by a standard deviation of 10%, and there were no clear winners.

Key Words

CARB, Davis Energy Group, Steven Winter Associates, BIRA, Clarum Homes, SIPs, high mass walls, hot-dry climate, evaporative cooler, evaporative condenser, radiant floor cooling, radiant floor heating, Borrego Springs.

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1 Background, Objectives, and Scope

The southern desert areas of California, Nevada, and Arizona experience extreme conditions characterized by mostly very hot, dry summers. Clarum Homes, a leading California builder and participant in the US Department of Energy's Building America Program (BAP), took the initiative to build four experimental houses in the extreme hot-dry climate of Borrego Springs in an effort to identify house construction techniques and system designs that they could employ in other similar climates and that would yield substantial energy savings relative to conventionally built homes. Preliminary meetings were held with project team members to select the design features to be evaluated. Construction began in 2004 and was substantially completed by May 2006. The BIRA Building America team worked with Clarum to select wall constructions, and the CARB team led by Davis Energy Group (DEG) consulted on the selection of and designed mechanical systems intended to yield substantially improved performance in this unique climate. The project was selected by NREL as a monitoring site, and DEG, NREL, and BIRA collaborated to install the instrumentation.

This is the last of several reports previously issued by CARB and others on the Borrego Springs project (prior reports are listed in Section 10). This report reviews house and system designs, summarizes monitoring methods, and reports on results from more than a year of performance monitoring of HVAC systems. Relative performance of the building envelopes was not directly evaluated due to the differences in occupancy and operation of the houses¹. Interactions between systems and components, comfort and health issues, durability, reliability, maintainability, and other issues are addressed, and house and system characteristics are reviewed with respect to BAP stage gate criteria.

2 Project Description

2.1 Location and Climate

Borrego Springs is located in a low valley surrounded by Anza-Borrego State Park, between the Salton Sea and Escondido and about 60 miles northeast of San Diego. During July of 2006 the high temperature ranged from 105° to 120°F and the low ranged from 75° to 90°F. Conditions can vary from extremely hot and dry with dry bulb temperatures exceeding 115°F to hot and humid with temperatures over 100°F and corresponding relative humidity of 50% or higher. 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. During mid-to-late summer "monsoon" conditions can cause outdoor wet bulb temperatures to exceed 80°F, and even high performance evaporative coolers are unable to provide comfort under these conditions.

Normals and ranges for the months of July and December, measured at the local airport, are listed in Table 1. Summer nighttime temperatures generally remain above indoor temperatures, making cooling energy use as well as peak demand much higher than in many other hot climate regions where houses can benefit from some nighttime cooling. Figure 1 graphs temperatures and relative humidity for a week in July 2007 when monsoon conditions prevailed.

¹ In their Building America report, Consol reported on the behavior of the envelopes in response to over-cooling tests. NREL is in the process of simulating some of the house-system combinations.

Table 1: Borrego Springs Winter and Summer Temperatures

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

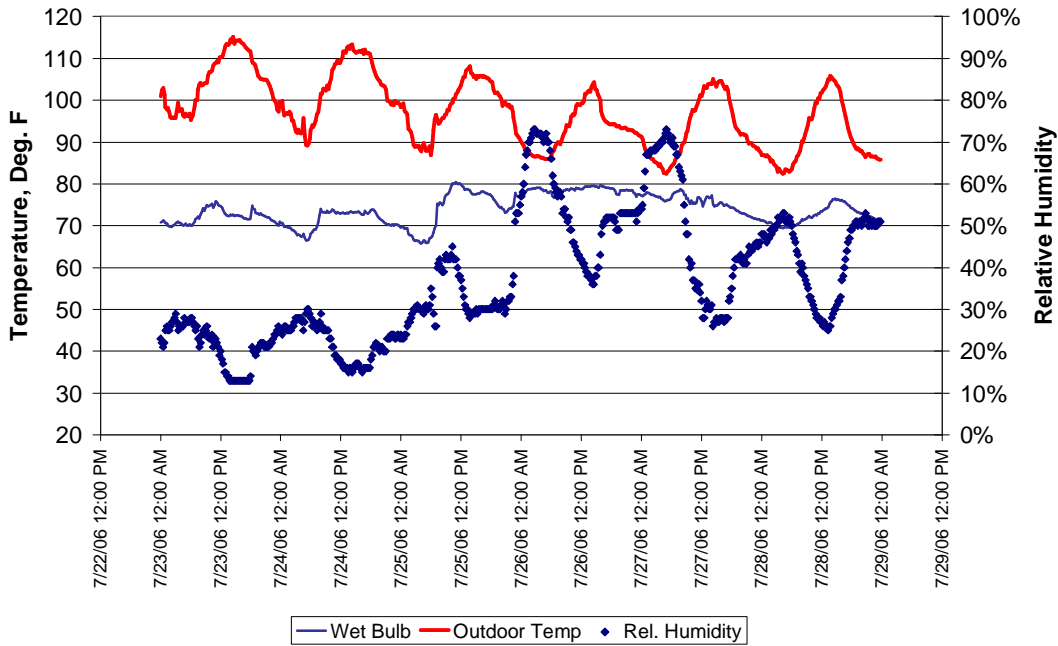


Figure 1: July Weather Sequence Illustrating Monsoon Conditions

2.2 House Descriptions and Expected Performance

House Designs

All four homes were built using the same floor plan, and except for the different wall types, all houses are architecturally identical. Figure 2 shows an elevation of one of the 2000 ft² one-story houses. The floor plan is shown in Figure 3. Wall types used include standard frame², Dow T-Mass, and structural insulated panels (SIP). Foundations are slab-on-grade, and the edges of the slabs are insulated. Table 2 lists the wall types (and mechanical systems) that were applied to each house.

² Optimal Value Engineered (OVE) framing originally intended for the East Star house was not fully implemented.



Figure 2: One of Four Borrego Springs Prototype Houses



Figure 3: Floor Plan

Table 2: Building Envelope and System Type Combinations

Site Name	Envelope Type	Cooling Source	Distribution	Other
“East Star”	Advanced frame 2x6	21 SEER 2-speed condenser with var. speed fan coil	Radiant heating; forced air cooling	Ventilation via bath fans
“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.

The pre-cast T-Mass wall system was selected for two of the houses under the expectation that high mass construction might provide energy and comfort benefits in this climate. A cross-section of this wall assembly is 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.



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

Envelope and Duct Leakage

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. Duct leakage (CFM₂₅) ranged from 24 (East Star) to 72 (Wagon), or from 2% to 6% of fan flow.

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

2.3 General Description of Mechanical Systems

Integration of Systems with Houses

Different mechanical systems were selected for each house to test their comparative performance in this climate. The original architectural program assumed that all heating and cooling could be supplied from the floor with no ducting used. 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 evaporatively cooled air. All ducting was installed in soffits within the conditioned space.

Cooling System Types

Since outdoor wet bulb temperatures are low during much of the summer, advanced, 2 stage, evaporative coolers were selected for two of the houses. The two-stage coolers used in the Wagon and Arrow houses are prototype³ two-stage (direct-indirect) units that utilize a single down-flow variable speed blower that moves air 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 problems and reduce cost the blower housing, air passages, and water reservoir were fabricated of a single rotationally molded plastic part.

The two evaporatively cooled houses also are equipped with 3-ton 13 SEER air conditioners, which provide supplemental cooling during the monsoon season and backup cooling in the event the prototype coolers fail. Evaporatively cooled air is ducted in both houses, which are also provided with “up-ducts” to automatically vent relief air to outside.

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. The fourth house (East Star) is equipped with a comparatively conventional, 3-ton two-speed high performance Lennox air conditioner and typical ducting system.

³ Developed by Davis Energy Group (DEG) under a grant from the California Energy Commission’s Public Interest Energy Research (PIER) program. Similar systems are currently marketed by the Speakman Company under the name OASys.

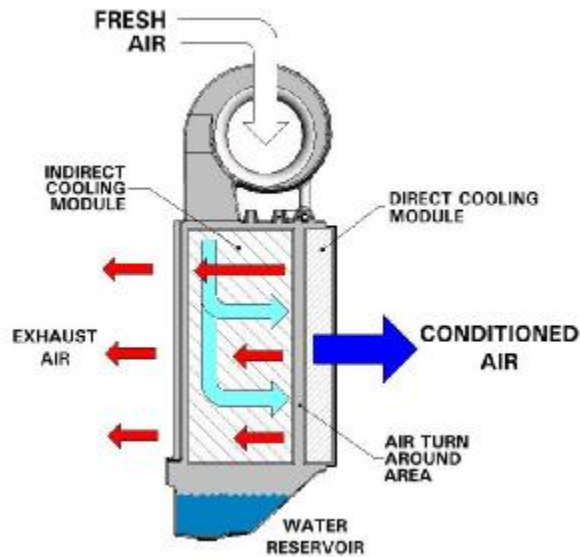


Figure 5: Schematic of 2-Stage Evaporative Cooler

2.4 Space and Water Heating Systems

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. The same water heaters provide hot water for domestic use. Plate heat exchangers isolate domestic water from the water used for radiant heating. DiGiorgio is heated by a variable speed fan coil that is also used for cooling. The fan coil incorporates a heating coil that is connected to the tankless water heater, and a cooling coil (evaporator) is also attached.

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

2.5 Ventilation Systems

All of the houses except DiGiorgio rely on bathroom fans for fresh air ventilation. DiGiorgio utilizes a 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. The same system also provides ventilation cooling when conditions permit.

2.6 Detailed Cooling System Descriptions

East Star House

East Star is equipped with a Lennox XC21-036 two-speed condensing unit (nominal SEER 19.25). The condensing unit is coupled to a Lennox CBX32MV-036 variable speed fan coil. A typical ducting system located in the attic distributes the air to living areas and bedrooms.

Broken Arrow House⁴

The “Arrow” house uses the prototype two-stage evaporative cooler, and for cooling during humid conditions, a 13 SEER Carrier 38TXA036 condensing unit and Carrier FC4C-036 air handler with cooling coil. The two systems share the same ductwork. Motorized dampers were installed in the supply ducts of the air handler and evaporative cooler to prevent backdrafting, and a control interlock prevents operation of the air conditioner while the evaporative cooler is running. The damper in the evaporative cooler supply also prevents leakage to outdoors while the cooler is not operating. Indoor air is relieved through “up-ducts” (barometric dampers) installed in the ceilings of the bedrooms while the evaporative cooler is operating.

The changeover between evaporative and vapor compression cooling is dictated by the homeowner. Evaporative cooler controls continuously vary the speed of the ECM-powered blower fan based on the difference between indoor temperature and the thermostat set point. Cooler controls also maintain the water quality of recirculated water by discharging the contents of the sump based on the amount of water evaporated to maintain no more than two cycles of concentration.

Wagon House

The Wagon house uses the same evaporative cooler and condensing unit as Arrow. The distinction between this house and Arrow is that the Wagon condensing unit is coupled to a plate heat exchanger that chills water instead of a refrigerant-to-air evaporator coil. As shown in Figure 6, chilled water from the evaporator is first routed to a fan coil and then through tubing in the floor. This design allows higher temperature water to be returned to the evaporator. A low limit temperature control cycles the condensing unit to limit the chilled water temperature to 45°F. The fan coil was sized to meet about one third of the cooling load and is ducted to the kitchen, dining, and living areas only. Its primary function is latent cooling, since the cooled floors are only able to provide sensible cooling.

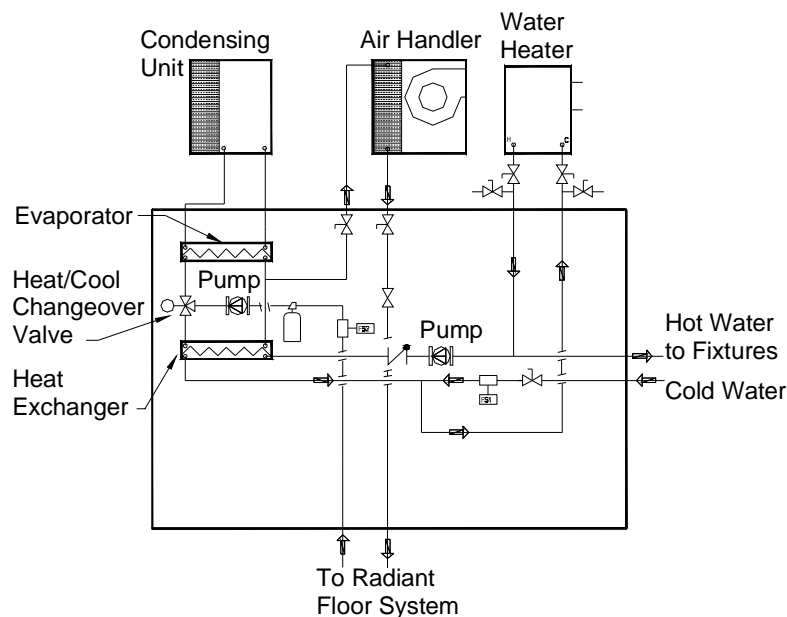


Figure 6: Schematic of “Wagon” Heating & Cooling System

⁴ Also referred to as “Country Club” in other reports.



Figure 7: Hydronics Module for the Wagon House

DiGiorgio House

The DiGiorgio house uses a Freus 10M03-36 evaporative condenser instead of an air-cooled condenser. The condensing unit is connected to an Amana CHF-60T evaporator coil, which is mounted to a NightBreeze NB10-2-120A variable speed air handler. The NightBreeze air handler, outside air damper, and controls provide nighttime ventilation cooling when conditions permit (5°F cooler outdoors than indoors).

Tubing was installed in the slab when the house was built but it is only used for cooling. A second pump was installed in the sump of the Freus to circulate evaporatively cooled water through the floor, effectively using the Freus as a cooling tower when it is not being used as a condensing unit. The system operates predominantly during the nighttime and the slab stores cooling to mitigate house cooling loads during the day. To avoid the need for complicated wet bulb sensing controls, outdoor temperature was used as a proxy for wet bulb temperature by applying the assumption that the wet bulb depression would be at least 10°F. (An analysis was completed to test this assumption using measured dry bulb and relative humidity data.) Controls initiate slab cooling when the outdoor temperature falls below 80°F. Floor cooling operation is enabled when the outdoor temperature exceeds 90°F and disabled when it falls below 60°F.

2.7 Expected Performance

Analysis completed by BIRA estimates that annual source energy savings for the four houses will range from 61 to 67% relative to the Building America Benchmark, neglecting contributions from the PV systems. This analysis also did not include cooling efficiency improvements resulting from operation of the evaporative coolers, evaporative condenser, or floor cooling; these systems cannot be accurately modeled using benchmarking tools.

As of the date of this report, NREL is working on models to compare the SEER 13, SEER 21 and Freus cooling systems using the SIP-built plan (Arrow). It is probable that NREL will use performance maps developed from this monitoring to develop DOE-2 performance curves.⁵

3 Project Approach

3.1 General Approach

Benchmark models are not yet up to the challenge of evaluating the unique systems designed for the Borrego Springs houses, requiring that performance information be obtained by monitoring the houses in detail. The objective of monitoring was to collect sufficient data to characterize the performance of each of the systems and sub-systems, with an emphasis on determining cooling performance of systems and whole houses, and how the advanced systems can contribute to Building America goals.

3.2 Monitoring Methods

DEG and NREL installed power monitors to determine electrical energy consumption of systems and whole houses, as well as PV electricity production. DEG and NREL also installed temperature, relative humidity, and air and water flow sensors to obtain data on cooling and heating capacities and other performance parameters. NREL installed a weather station at the East Star site to measure local outdoor temperature, relative humidity, outdoor wet bulb temperature, wind direction and velocity, and horizontal solar radiation.

Data loggers were installed to collect data from the 42 to 54 sensing points in each house. Sensors were scanned and calculations of energy flows were completed on 15 second intervals. Raw and calculated data averages and totals were recorded on 15 minute intervals. Data loggers were connected to telephone modems and polled each day, and data were transferred to a server. Macros were used to automatically review data and to report any out-of-range data. A more detailed description of the monitoring systems is included in CARB Deliverable 12.B.1a.

The same data loggers were used to collect data from sensors installed by BIRA to assess building envelope performance and ground coupling effects. 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 locations⁶. 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). Results of testing that incorporates data from these sensors are included in BIRA reports.

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. 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.

⁵ This work is being completed by Paul Reeves.

⁶ Few of the thermocouples installed in the soil and slabs survived, being damaged during construction or affected by corrosion.

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 7). Sensors were placed so as to allow energy applied to domestic uses to be separated from energy applied to space heating.

3.3 Monitoring Schedule and System Operation

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, some of the initial data collected was invalid or inaccurate. Improvements to systems through the summer and fall of 2006 improved data reliability.

Monitoring was continued until the systems were decommissioned at the end of October, 2007. The East Star house sold in August and was decommissioned at that time. As the weather station was located at East Star, it had to be relocated to the DiGiorgio house. Missing data after the relocation cut off some of the analysis in mid-August 2007.

Because of the remote location it was difficult to regulate the operation of the heating and cooling systems. Efforts to establish set temperatures and changeover between evaporative and vapor compression cooling were not successful during most of 2006, but a concerted effort was made to overcome this problem during the summer of 2007, resulting in improved data reliability. Evaporative coolers at the Wagon and Arrow houses were operated in the spring of 2007 until the second week of July, at which time the houses were switched to the vapor compression systems. There was little and sporadic use of the evaporative coolers in the fall of 2007.

3.4 Building Occupancy

For accurate house and system comparisons it is 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, occupant behavioral influences and internal gains resulting from operation of lighting and appliances are missed when monitoring unoccupied houses. Because there was virtually no hot water use in the unoccupied homes, water heater performance could only be assessed for space heating uses, not for domestic hot water heating use.

Only one of the houses, DiGiorgio, was sold and occupied during the monitoring period. A second house, Wagon, sold in September 2006 but has been occupied only sporadically and mostly during winter months. The East Star home was sold in late August 2007, and the new homeowner was unwilling to participate in the monitoring program and all sensors were removed from this site as of 8/31/2007. The sale of the Arrow and East Star houses did not occur until monitoring was concluded.

Monitoring and Operational Issues

Problems with HVAC systems and monitoring equipment that affected monitoring results should be noted. All of the houses were to have been equipped with photovoltaic arrays, but the arrays were not fully operational until December 2006 due to issues with county approval of the mounting method. All of the houses experienced inverter and other problems that interrupted the operation of the PV systems.

Control issues were encountered with the evaporative condenser and the Wagon house's cooling control interlock. A leak in the domestic water system disabled the evaporative cooler for a period of time at the Arrow site. Water pressure regulators were added to two of the houses after they were completed, but were placed such that they only lowered cold water pressure to the fixtures (not the cold water supply to the water heater). The hot-cold water crossover created by the Metlund hot water recirculation system allowed the higher pressure hot water to flow to the cold water fixtures. Debris in the piping clogged a flow switch at the Wagon site, preventing the heating system from operating.

The evaporative cooler at the Wagon house was originally installed without a damper to prevent leakage to the outside when the cooler is off. A motorized damper was retrofitted in the fall of 2006. Both evaporative coolers were also retrofitted with hoods on their outside air discharges to prevent entry of sand during wind storms and to better regulate the balance between supply and secondary air.

3.5 Analytical Methods

The lack of occupancy and inconsistent maintenance of indoor temperatures amongst the four buildings precluded an accurate comparison of building envelope performance. The primary analytical approach employed by CARB in this study was first to compare the performance of the high efficiency air conditioners (SEER 21 system and evaporative condenser) to manufacturers' performance ratings, and second to compare energy consumption for the high performance cooling systems (including evaporative coolers) to that of a standard SEER 13 air conditioner operating under the same load and temperature conditions. NREL completed most of the work to evaluate performance relative to manufacturers' ratings.

DEG used NREL's performance map for the SEER 13 system (see Figure 20), to estimate energy savings for the high performance systems. A linear fit of the SEER 13 data yielded Equation 1.

$$EER_{13} = 16.94 - 0.114 \times T_o \text{ where } T_o = \text{outdoor temperature} \quad \text{Equation 1}$$

This equation was applied to 15-minute load and temperature data from the other houses to calculate what the and the estimated energy consumption for the 13 SEER unit would have been if installed under similar conditions, using Equation 2.

$$kWh_{13} = Q / EER_{13} \text{ where } Q \text{ is the monitored 15 minute cooling load} \quad \text{Equation 2}$$

The sum of the calculated energy 15-minute energy use values the 13 SEER unit was compared to the measured energy use of the high efficiency systems to estimate energy savings. Due to lack of confidence in relative humidity measurements, all calculations were done using sensible cooling loads only.

Other specialized analysis was used to evaluate floor-cooling systems and to assess the level of comfort provided by the evaporative cooling systems, as described in the results. Evaluation of heating and water heating systems was restricted by the amount of data available, which was limited by the lack of occupants in three of the houses.

4 RESULTS

4.1 System Performance - East Star House

Cooling System

The two-stage Lennox XC-21 air conditioner used at the East Star site was selected to represent one of the highest efficiency air conditioners currently available to the residential market. This cooling system features 2-stage operation such that the air handler, compressor and condenser fan will operate with a nominal 2-ton 1st stage cooling capacity and a nominal 3-ton 2nd stage cooling capacity. Figures 8 and 9⁷ compare the manufacturer's power draw and sensible cooling capacity data to field monitored data for the SEER21 air conditioner in 2 and 3-ton modes.

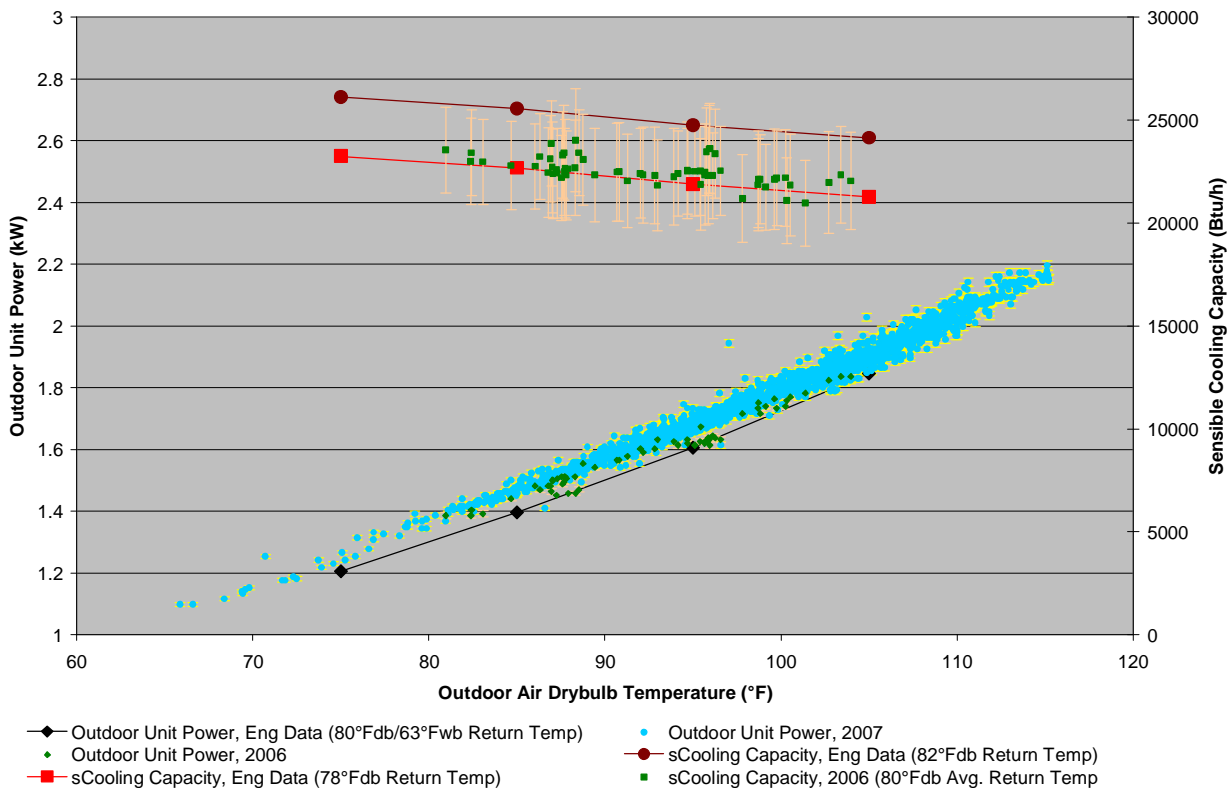


Figure 8: Lennox XC-21 Cooling Performance Relative to Manufacturer's Data, 1st Stage

In first stage operation measured power closely approximates manufacturer's performance specifications. Measured cooling capacity also agrees reasonably well with manufacturer's data, falling between the 78° and 82°F lines. The actual return temperature averaged 80°F (the vertical lines are error bands for the measured data).

Both measured power and capacity also agrees well with manufacturer's data in second stage cooling operation. The measured capacity at a 75°F return temperature falls between the manufacturer's rating lines of 70° and 80°F return temperature.

⁷ Figure credit, Mark Eastment, NREL.

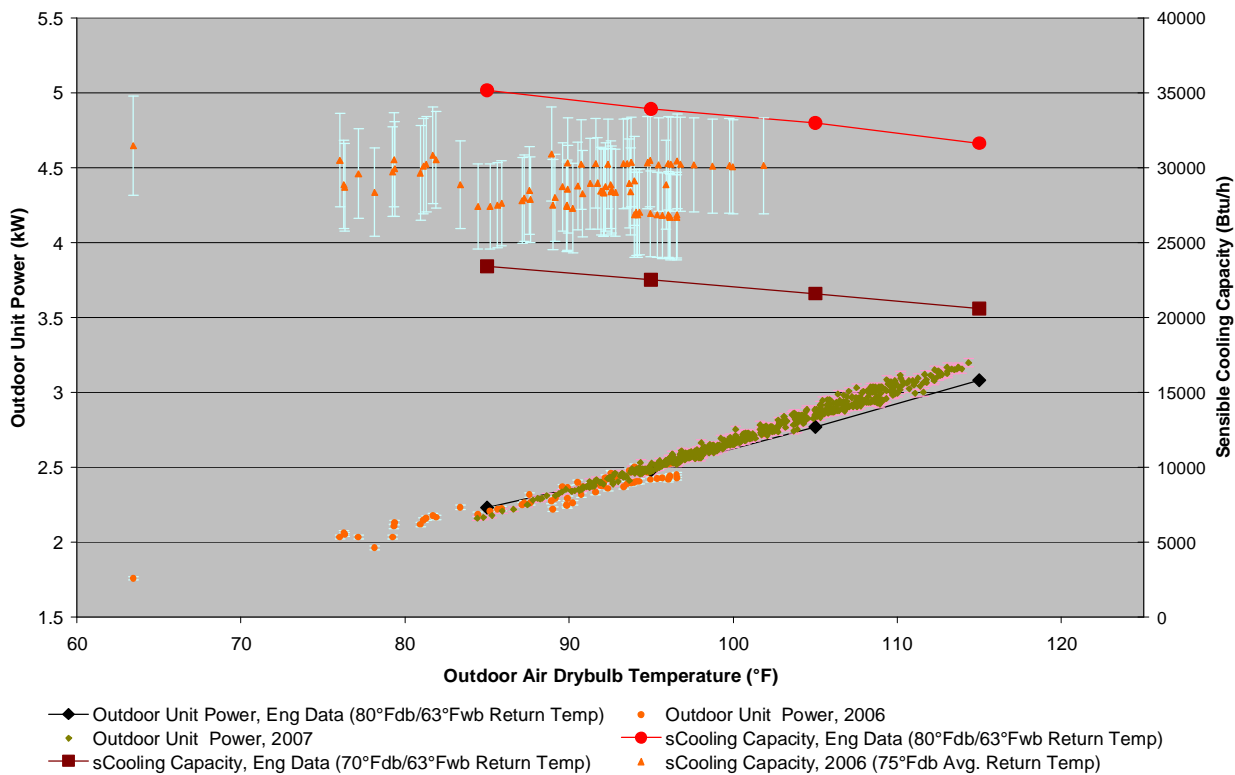


Figure 9: Lennox XC-21 Cooling Performance Relative to Manufacturer's Data, 1st Stage

Initial tap settings at the indoor unit were resulting in airflows of approximately 600 cfm per ton. After making adjustments to tap settings to achieve 400 cfm per ton, the airflows and static pressures listed in Table 5 were measured. Manufacturer's static pressure and fan power values are nominal (not at measured conditions).

Table 5: Comparison of Manufacturer's and Measured Fan Coil Performance Data

	Manufacturer's Specs		Measured	
	1 st Stage	2 nd Stage	1 st Stage	2 nd Stage
Airflow (cfm)	825	1375	822	1217
Static Pressure (in)	0.10	0.20	0.13	0.18
Fan Power	230	260	125	359

Additional testing would be necessary to resolve the inconsistencies between the measured external static pressure, 2nd stage airflow rate and measured indoor fan power data and the manufacturer's published performance data.

Heating and Water Heating Systems

Heating system performance data were compiled for the months of November 2006 through March 2008 for all four houses. The heating season did not begin until late November, when outdoor temperatures were still into the 80's. Very little useful data were obtained for the unoccupied houses, particularly since thermostats were not consistently set to maintain temperatures.

The East Star house was not occupied during the heating season, but 1798 kBtu of hot water were used in early January, perhaps by cleaning crews. The water heater consumed 2113 kBtu

of propane gas over the winter season, resulting in an average heating efficiency of 0.86. Because this value is greater than the rated water heater efficiency of 0.82, an error in the assumed heat value of the gas is suspected. A calibration error with the flow and/or temperature sensors is another possibility, although these sensors are typically very reliable. A gas flow meter was used to measure gas consumption. The assumed heat content of the gas of 2516 Btu/ft³ is based on a heat value of 91,600 Btu/gal and a gas volume of 36.38 ft³ per gallon of liquid⁸. The locally supplied LP gas may include a mixture of butane, which would impart a higher heat value and would explain the abnormally high water heater efficiencies monitored.

4.2 System Performance - Broken Arrow House

Vapor Compression Cooling System

Data from the Arrow house 13 SEER air conditioner were evaluated to determine if the system performed in accordance with the manufacturer’s published performance data. Figure 10 compares manufacturer’s power and sensible cooling capacity data to measured data plotted against outdoor dry bulb temperature⁹. Again, the vertical lines represent error bands for the measured data.

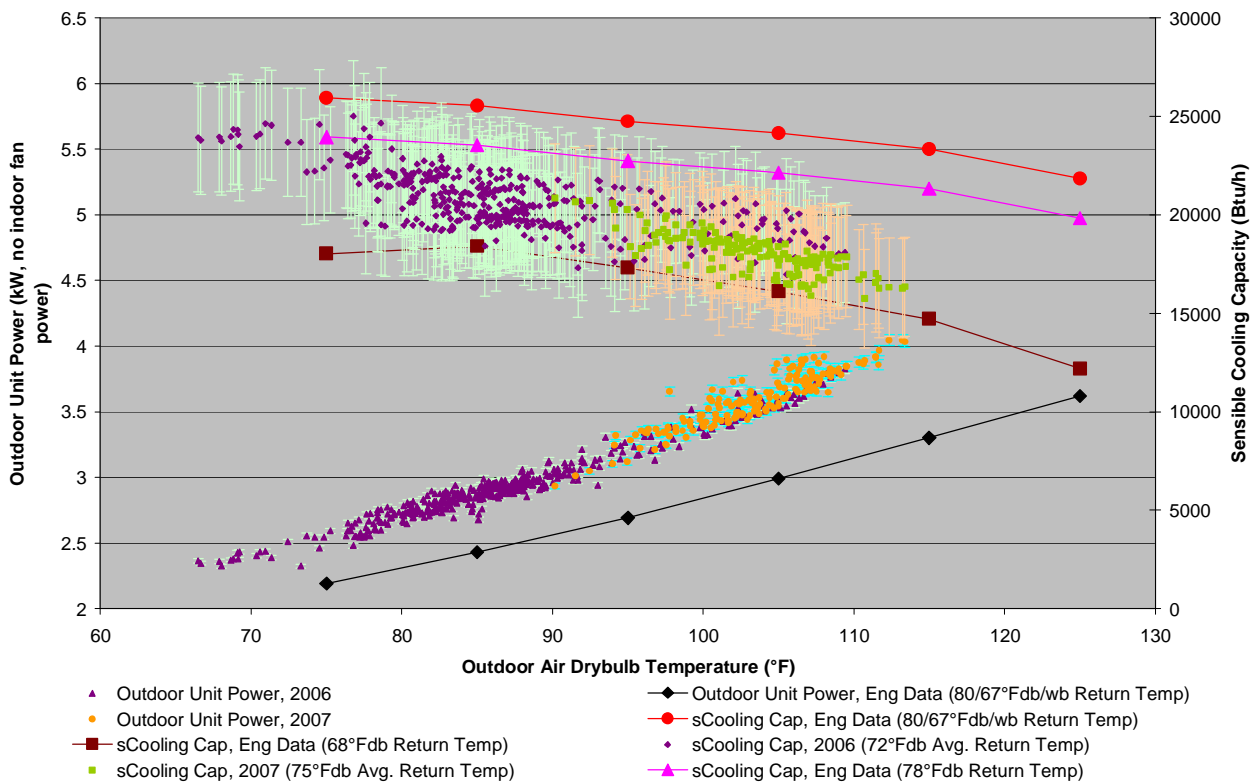


Figure 10: Carrier 38TXA Cooling Performance Relative to Manufacturer’s Data

Measured sensible cooling capacity for the 13 SEER Carrier condensing unit appears lower than specified by the manufacturer and measured power was higher as shown in Figure 10, except that the rated capacity falls within the measurement uncertainty of the measured data. The measurement of sensible cooling capacity was calculated by monitoring temperatures in the supply and return duct along with repeated “one time” measurements of air handler fan airflow.

⁸ Ref. <http://www.propanegas.ca/FileArea/PGAC/Propane%20properties.pdf>

⁹ Figure credit, Mark Eastment, NREL

Because measured indoor fan power for this site was higher than the assumed indoor fan power used to generate the manufacturer's performance data, manufacturer's sensible cooling capacity data was corrected for the difference between the assumed indoor fan power and the actual indoor fan power. A range of return air conditions were generated from the manufacturer's data using a correction procedure per the manufacturer's documentation in order to give sensible cooling capacities that reflect measured return air temperatures. Discussions with the manufacturer have not yielded a clear explanation as to why this unit shows such a large discrepancy between measured and expected values.

Evaporative Cooling System

The prototype evaporative coolers at both the Arrow and Wagon sites were monitored from the spring of 2006 through the fall of 2007. Due to erratic operation of the houses and airflow measurement problems, only data from May 13, 2007 when the cooling season started, through July 7, 2007 are presented¹⁰. The efficiency of the cooler at the Arrow site averaged 26.5 Btu per Watt-hour during this period. The cooler used a total of 4421 gallons of water, or 0.62 gallons per kBtu of cooling delivered.

Evaporative cooler performance can also be characterized by "effectiveness" or "saturation efficiency" as defined by Equation 3¹¹. During the spring-summer of 2007 the evaporative effectiveness averaged 0.99 for the Arrow system, and ranged from a low of 0.91 to a high of 1.03. The supply air temperatures were very close to the wet bulb temperature, the daily average of which ranged from 57 to 64°F during this period.

$$\text{Effectiveness} = (T_{\text{out}} - T_{\text{supply}}) / (T_{\text{out}} - T_{\text{wb}}) \quad \text{Equation 3}$$

Where: T_{out} is the outdoor dry bulb temperature
 T_{supply} is the evaporative cooler supply air temperature
 T_{wb} is the outdoor wet bulb temperature

A key question regarding the applicability of evaporative coolers is, under what outdoor conditions can they provide comfort? Figure 11 shows comfort conditions for the Arrow house plotted relative to the ASHRAE Standard 55 comfort zone for the relatively hot week of July 1, 2007. Indoor and outdoor temperature and relative humidity conditions during the same period are provided in Figure 12. Despite outdoor temperatures that exceeded 115°F, indoor conditions were entirely within the comfort zone during this period. During times that outdoor wet bulb temperatures were lower than 65°F, indoor temperatures were maintained below 80°F.

¹⁰ After July 7 the systems at the Arrow and Wagon houses were switched to air conditioning.

¹¹ ASHRAE Standards 133-2001 and 143-2000 provide test methods for direct and indirect evaporative coolers, respectively.

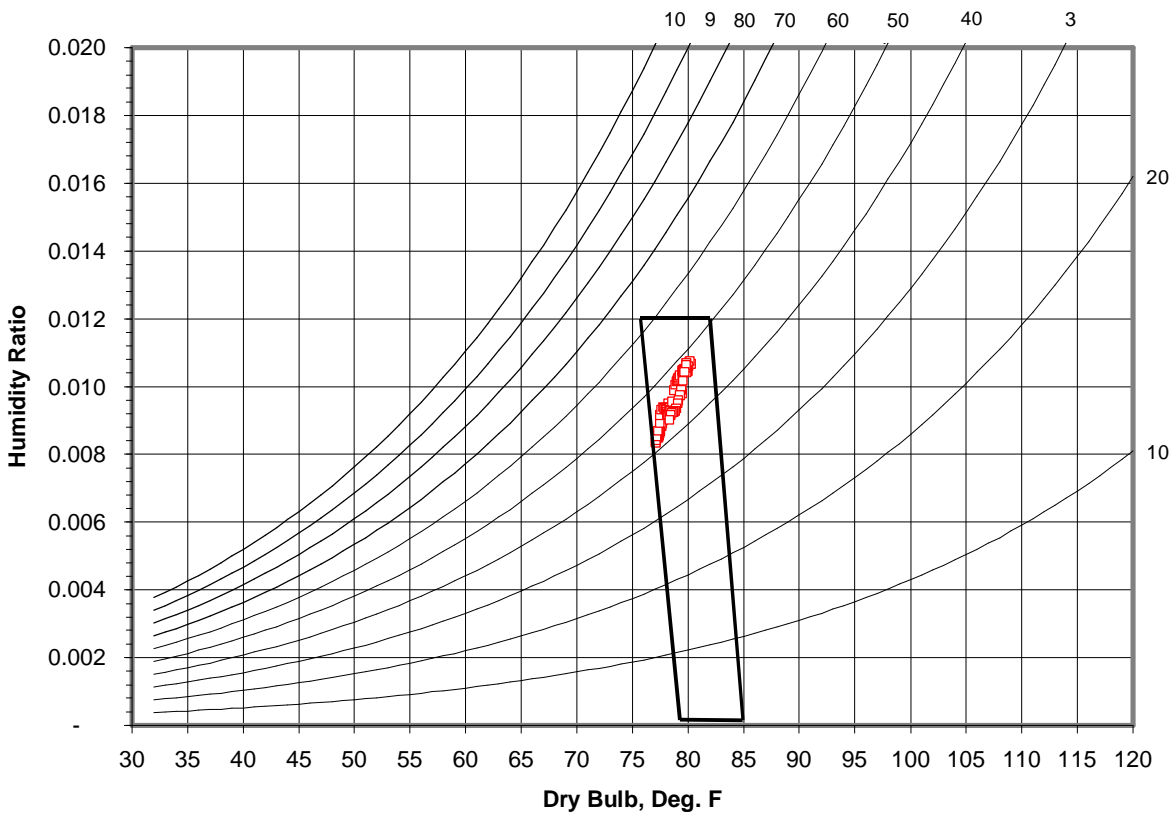


Figure 11: Comfort Conditions, Arrow House, Week of July 1, 2007

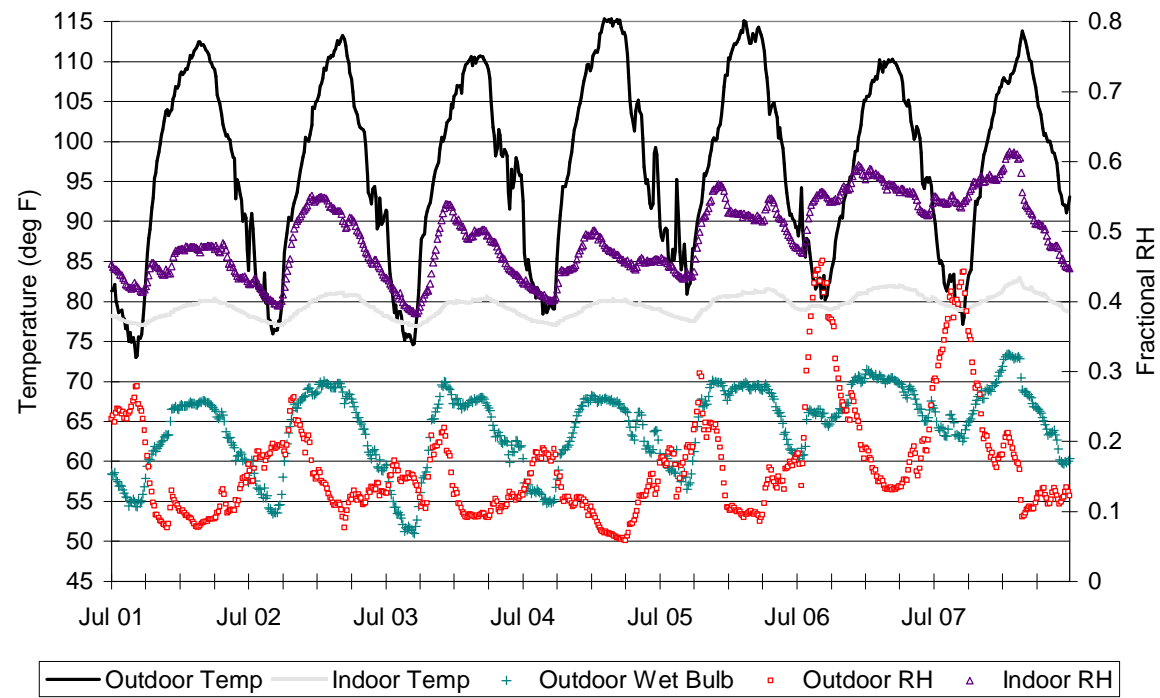


Figure 12: Temperature and Relative Humidity, Arrow House, Week of July 1, 2007

Heating and Water Heating Systems

The thermostat at the Arrow house appears to have been set very high (over 80°F) between January 8th and 11th, 2007, but the heating system was inoperative the remainder of the season, during which indoor temperature averages ranged from about 66° to 70°F. There was very little use of domestic hot water during this time. The combined water heating and space heating efficiency during Jan. 8 - 11, measured using water flows and temperature differences, was 90%. As for the East Star house, the assumed heat content of the gas is suspect.

4.3 System Performance – Wagon House

Hybrid Vapor Compression Cooling System

A detailed evaluation of the air conditioner performance relative to manufacturer's performance curves was not completed for the Wagon cooling system because the system was modified to chill water, and no manufacturer's ratings exist for this application. Since both the Wagon and Arrow houses utilize the same condensing units it was possible to compare the performance of the forced air and chilled water delivery systems. "Air side" cooling energy delivery was measured at both houses, and "water side" cooling delivery was also measured at the Wagon house by monitoring the flow rate through the coil and the temperatures into and out of the coil, and out of the radiant floor system.

Table 6 compares average daily cooling loads and energy use for the Wagon and Arrow houses for the period from July 18th through October 2nd 2007 (evaporative cooling was used prior to July 18). Thermostats were set to 78°F and indoor temperature averages during this period were nearly identical. The total cooling load ("water side" includes radiant and forced air distribution) for the Wagon house was 91% higher than the cooling load for the Arrow house, indicating that nearly half the cooling produced by the hybrid radiant cooling-forced air system used at Wagon was lost to the ground. However, most likely as a result of higher evaporator temperatures, the EER of the Wagon system was twice that of the Arrow system. The end result was that the total cooling energy use for the two houses was very comparable. Even though the houses were subject to the same environmental conditions (neither was occupied) this comparison must be qualified by the fact that the two houses use different wall systems.

Table 6: Comparison of Daily Average Cooling System Loads and Energy Use

	Arrow	Wagon
Sensible Load, kBtu/day	147.4	118.4
Total Load, Air Side kBtu/day	165.8	122.0
Sensible Heat Ratio	0.89	0.97
Total Load, Water Side, kBtu/day	-	317.1
EER, Btu/Wh	5.1	10.3
AC Energy, kWh/day	27.1	27.8
Fan & Pump Energy, kWh/day	5.6	3.3
Total Cooling Energy, kWh/day	32.6	31.1

The hypothesis that much of the cooling energy was going to the ground is supported by Figure 13, which graphs weekly cooling energy use over the same time period. At the beginning of the cooling season cooling energy use is higher for the Wagon house as the ground is being "charged". By mid August the cooling energy use for the two houses equalizes, and from that

point onward Wagon’s cooling energy use declines relative to Arrow’s as the stored cooling is recaptured.

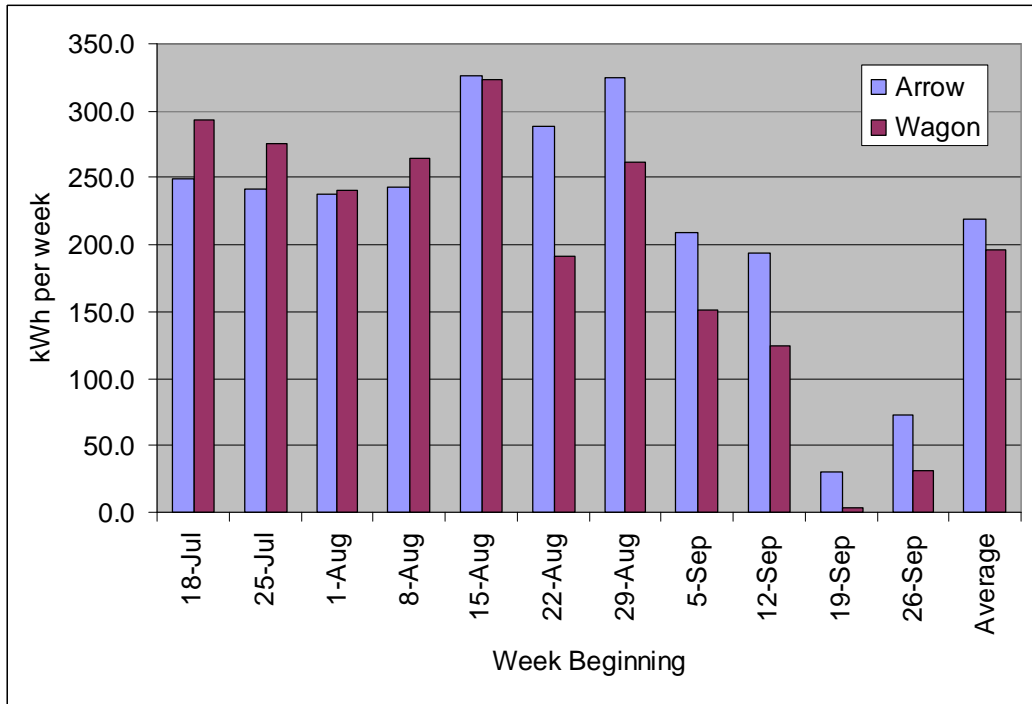


Figure 13: Comparison of Weekly Total Cooling Energy Use

If insulation had been applied below the Wagon slab, the hybrid chilled water system might have produced a significant performance improvement. The greatly improved EER, seasonal storage of cooling in the ground, peak load reduction benefits, and the impact of insulation all deserve further research.

The cooler floor of the Wagon house has the potential to provide superior comfort due to the lower operative temperature, but this cannot be quantified because none of the sensors installed in the slab of the Arrow house survived, and few of those in the Wagon house survived. During the testing there was no condensation observed on the floor surfaces of the Wagon house, so the combined effects of the 50°F chilled water temperature setting, heat gained by the water through the cooling coil, heat transfer resistance in the slab, and moisture removal by the cooling coil appear to have prevented the surface of the slab from approaching the dewpoint temperature.

Evaporative Cooling System

The efficiency of the cooler at the Wagon site averaged 34.9 Btu per Watt-hour during May 13 through July 7, 2007, which was several points higher than the Arrow site. The Wagon cooler used a total of 5033 gallons of water, or 0.52 gallons per kBtu of cooling delivered (compared to 0.62 gal/kBtu for Arrow).

Evaporative effectiveness during the spring-summer of 2007 averaged 0.98 and ranged from a weekly low of 0.91 to a high of 1.02. The supply air temperatures were very close to the wet bulb temperature, the daily average of which ranged from 57 to 64°F during this period.

Figure 14 shows comfort conditions for the Wagon house plotted relative to the ASHRAE Standard 55 comfort zone for the week of July 1, 2007. There was a brief excursion into uncomfortable conditions, but most of the time the comfort standard was met. Indoor and

outdoor temperature and relative humidity conditions during the same period are provided in Figure 15. Based on corresponding indoor dry bulb and outdoor wet bulb temperatures, the Wagon house appeared to require slightly cooler supply air temperatures to maintain indoor temperatures below 80°F than the Arrow house.

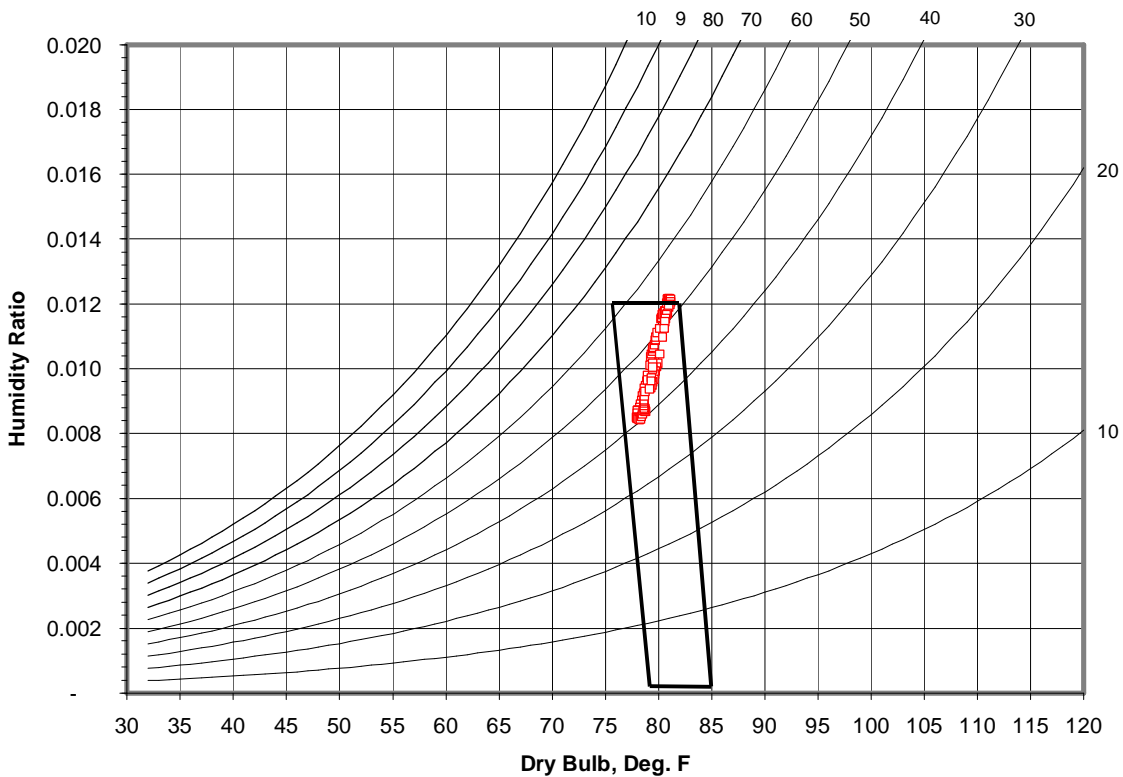


Figure 14: Comfort Conditions, Wagon House, Week of July 1, 2007

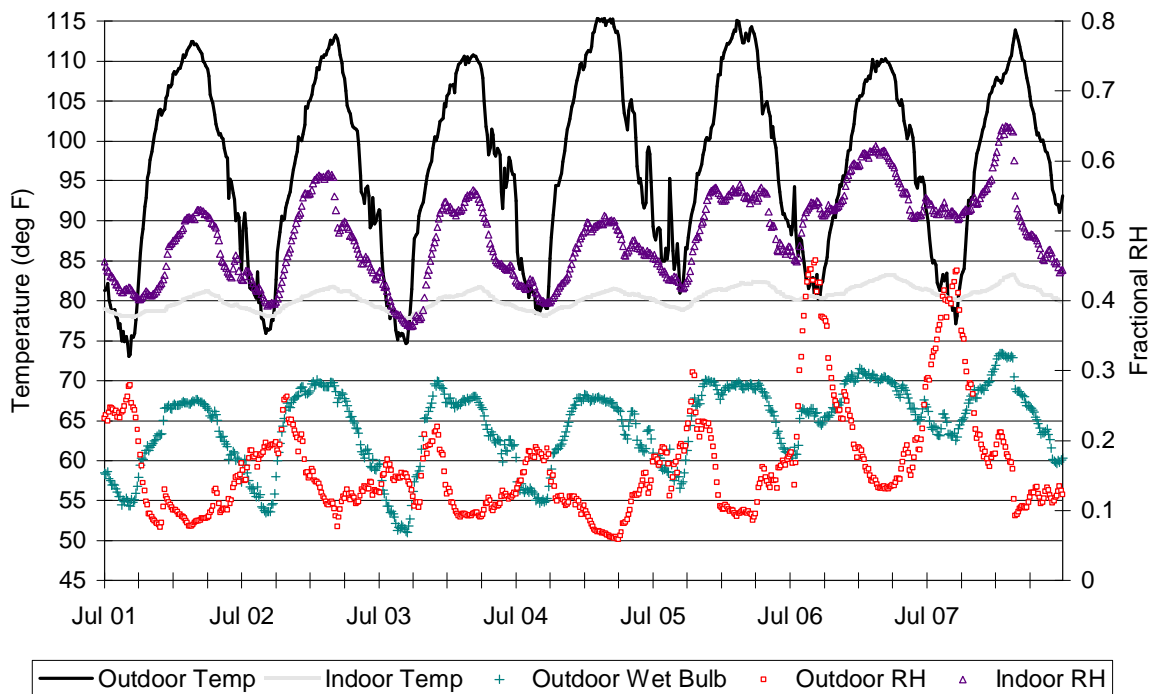


Figure 15: Temperature and Relative Humidity, Wagon House, Week of July 1, 2007

4.4 System Performance – DiGiorgio House

Evaporative Condenser

Manufacturer's performance data for the Freus evaporatively cooled condensing unit at the Borrego site is limited to ARI rating conditions; expanded engineering data for this unit is not available and therefore conclusions from these comparisons are limited. Figure 16 shows the comparison of manufacturer's power and sensible cooling capacity data to field monitored data plotted against outdoor unit inlet wetbulb temperature for the evaporative condenser at the DiGiorgio site.

The comparison to manufacturers power data shows measured data for two outdoor units. The summer 2006 data represents the original condensing unit installed at the site. The 2007 data shows performance for a new condensing unit that replaced the original unit. When the 2006 data showed a higher than expected outdoor unit power draw, the manufacturer was to determine possible causes. The manufacturer visited the site in May 2007 and, based on his inspection and a review of performance data, he offered to replace the original unit at no cost. The homeowner at DiGiorgio agreed to pay for the HVAC contractor's labor to replace the unit and the new unit was installed on July 10, 2007.

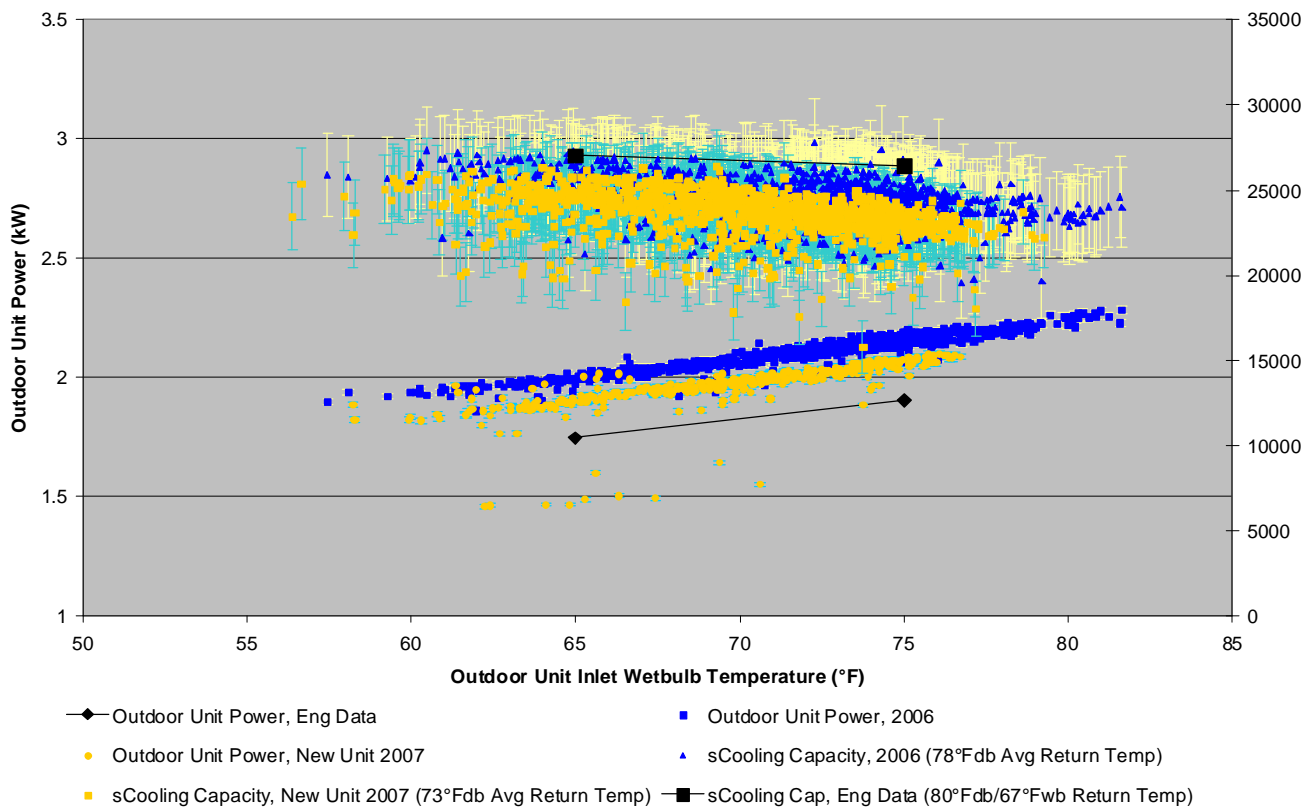


Figure 16: Freus Evaporative Condenser Cooling Performance Relative to Manufacturer's Data

While the 2007 data in Figure 16 shows reduced outdoor unit power compared to the original unit, the 2007 measured power data is still higher than the manufacturer's performance data would suggest. The reason for the higher than expected outdoor unit power is not understood.

Refrigerant charge was measured in August 2007 by the HVAC contractor and NREL staff, and at 8.9°F was slightly higher than the 6°F recommended by the manufacturer (subcooling data for the original unit is not available). It is possible that the higher measured subcooling value would affect the outdoor unit power, however, due to time constraints during the August 2007 site visit no attempt to vary subcooling and record outdoor unit power draw were.

Power data from the long term monitoring equipment was verified against a handheld power meter during various site visits and showed good agreement with the data from the long term monitoring system. The measured sensible cooling capacity appears to agree within measurement uncertainty for the 2006 data when compared to the manufacturer's sensible cooling capacity data. The 2007 data has an average return air temperature that is significantly lower than the return air condition assumed by the manufacturer's published data, however, some of the 2007 data does agree within measurement uncertainty with the manufacturer's data.

The initial expectation for the variable speed air handler at this installation was that the indoor fan power would be similar to that for SEER 21 indoor fan. The indoor fan power for the DiGiorgio house is considerably higher than for the East Star SEER21 installation. It was concluded that the higher indoor fan energy appears to be the result of unexpectedly high external static pressure, which was measured to be 0.87" at 1200 cfm and 1.45" at 1600 cfm. The high static pressure is apparently a result of small plenums and tight duct turns required to accommodate the soffit-mounted equipment, as shown in Figure 17.



Figure 17: NightBreeze Air Handler and Damper Installation, DiGiorgio Site

Floor Cooling System

The floor cooling system uses the Freus unit as a cooling tower, operating both the “spray” pump to evaporatively cool sump water and another pump that circulates the water through tubing in the floor when the controls determine that conditions are right (floor cooling enabled, outdoor temperature less than 80°F.) Although the cooling energy supplied to the floor was monitored, it is not possible to determine how much this cooling contributes to lowering indoor air

temperature (or air conditioning load), because a portion of this cooling is absorbed into the ground¹².

Figure 18 shows the effect that floor cooling has on the temperature of the underside of the slab and earth below (the sensor at the top surface of the slab had failed). These data from 2006 show that after two days of operation the underside of the slab was lowered from a starting temperature of 80°F to an average temperature of 73°F. Applying ASHRAE equations for radiant and convective heat transfer¹³ and assuming an indoor temperature of 78°F, lowering the temperature of the slab from 80°F to 73°F provides a cooling capacity of approximately 9 Btu/ft². Assuming that about three-quarters of the slab is covered by tubing, the system supplies about 13,500 Btu/hr of cooling while it is operating. During the one-week period shown in Figure 18, the system delivered 881 kWh of cooling and the condensing unit fan and two pumps used 37 kWh resulting in an EER of 23.8.

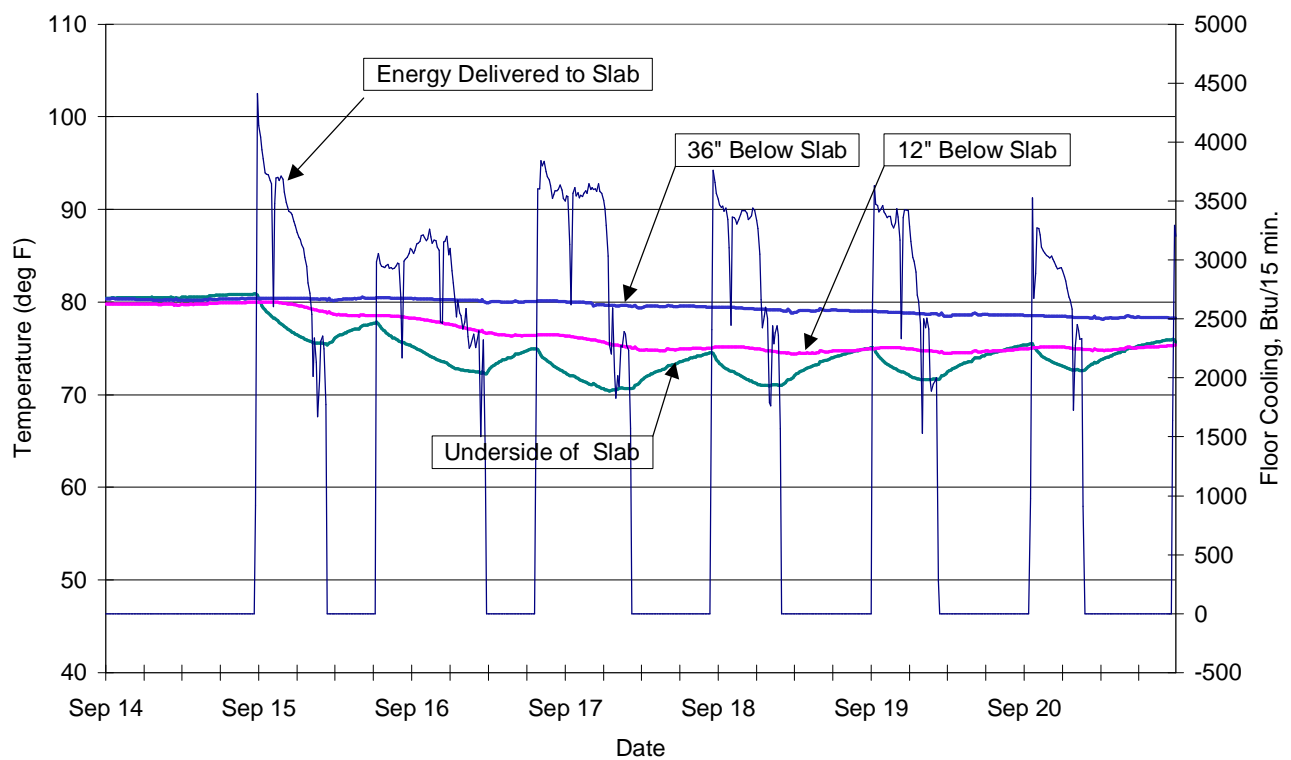


Figure 18: Slab and Ground Temperatures as Affected by Floor Cooling System, DiGiorgio Site

Unfortunately, this cooling system contributes no cooling during peak load periods, during which outdoor temperatures do not drop low enough for the system to operate in the Borrego Springs climate. A wet bulb temperature control might expand its cooling contribution. Repeated failure of the sensor measuring flow through the floor due to the high mineral content of the water made it impossible to quantify seasonal cooling energy. The monthly run hours for the summer of 2006 obtained from energy use data, listed in Table 7, indicate that most of the cooling

¹² A comparison would have been possible if the Wagon house had been equipped with a standard forced air cooling system.

¹³ ASHRAE Systems and Equipment Handbook, 1996, pp. 6.2-6.3.

contribution occurred during the fall months, but this result may have been influenced by how the system was operated by the owner.

Table 7: DiGiorgio Floor Cooling System Operation, 2006

Month	Operating Hours
June	54.4
July	18.5
August	17.2
Sept	163.8
Oct	248.2
Nov	256.8

Heating and Water Heating Systems

Hot water use data indicate that the DiGiorgio house was probably occupied most of the winter, though data were lost between December 8, 2006 and January 12, 2007. Excluding these days, hot water energy use totaled 992 kBtu, space heating energy use totaled 11,037 kBtu, and 15,594 kBtu of gas were consumed. The water heater efficiency calculated from these totals is 0.77. A review of hourly data during times when there was a continuous 15 minute load shows that monitored efficiency appears to be about 12% higher than the rated performance, so the seasonal efficiency of the water heater was more likely closer to 0.69.

Ventilation Cooling System

The NightBreeze ventilation cooling system was programmed to cool the house to a minimum temperature of 68°F when outdoor temperatures are 5°F cooler than indoor temperatures. The system varies the fan speed in proportion to predicted indoor temperatures for the following day. For example, on a hot day the system will operate the fan at its maximum speed (programmed at 1200 cfm), and on cooler days when the indoor temperature is not predicted to approach the air conditioner setpoint, the fan operates at a lower speed to reduce fan energy use and prevent over-cooling.

Data from the fall of 2006 and spring of 2007 were reviewed to determine the amount of cooling provided and the cooling efficiency. Cool temperatures during winter conditions and hot nights during the summer sandwiched the available times that ventilation cooling could be used between early September and mid-November in the fall, and early March to mid-June in the spring. During the fall of 2006 the system provided 1451 kBtu of cooling at an average EER of 10.5, and during the spring of 2007 the system provided 1724 kBtu of cooling at an average EER of 10.4. The low EER's were primarily a result of non-optimal operation and small indoor-outdoor temperature differences.

Figure 19, plots actual cooling delivery (Q_{actual}) for the week of April 25 as well as expected cooling delivery ($Q_{expected}$), and shows the system was not operating at its full potential. Expected cooling delivery is based on measured indoor-outdoor temperature differences and an airflow rate of 1500 cfm. No air conditioning was used during this weekly period, which had the highest contribution from ventilation cooling of any week during the fall of 2006 and spring of 2007. The high outdoor temperatures leading up to April 29th should have resulted in a high ventilation rate. It appears that the owner may have raised the low limit temperature, thereby limiting fan operation on the 29th and 30th, which would have provided efficient cooling because of the high indoor-outdoor temperature differences. The control algorithm lowers the fan speed as the indoor temperature approaches the low limit temperature, accounting for the low airflows

and minimal cooling on the two days when it would have been most effective at cooling the building's massive walls.¹⁴

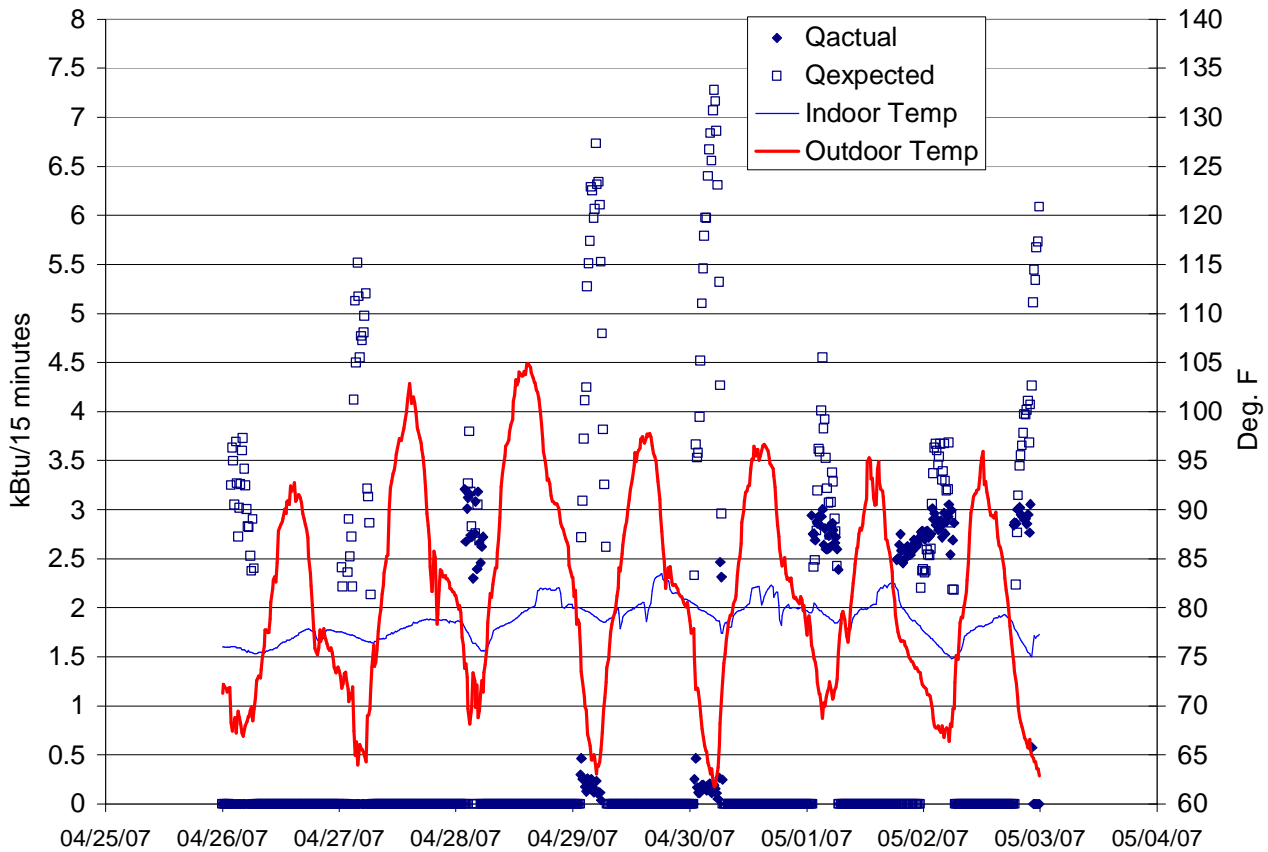


Figure 19: Actual and Expected Ventilation Cooling Rates, Week of April 25, 2007

4.5 Cooling System Performance Comparison

Vapor Compression Cooling System EER Comparison

A comparison of the performance of the vapor compression cooling systems at the Borrego Springs site was complicated by occupant behavior in one home, changes in thermostat settings in both occupied and unoccupied homes, data acquisition system and sensor failures and incorrect equipment setup. Figure 20 compares the performance of the air conditioning system for data that was determined to be reasonably representative of correct operation for the air conditioners and their respective data acquisition systems.

Average return air temperatures for each dataset do vary and would tend to give the SEER21 system the advantage of higher sensible capacity compared to the SEER13 and Evaporative Condenser systems, which had lower average return air temperatures for the datasets considered here. The SEER13 and Evaporative Condenser systems also have higher indoor fan power, which does reduce the net sensible cooling capacity when compared to the SEER21 system. Discrepancies between the outdoor unit power and manufacturer’s published performance data also will contribute to lower measured sensible EER for the SEER13 and Evaporative Condenser

¹⁴ The fan control algorithm has since been modified to provide a steeper ramp-down as the indoor temperature approaches the low limit temperature.

system (assuming the manufacturer’s documentation is correct), however, the two high performance systems clearly have an advantage compared to the SEER13 system. The Evaporative Condenser sensible EER is also noticeably flat with outdoor drybulb temperature compared to the air source systems. The cooling capacity of the Evaporative Condenser is a stronger function of outdoor wetbulb temperature than drybulb temperature.

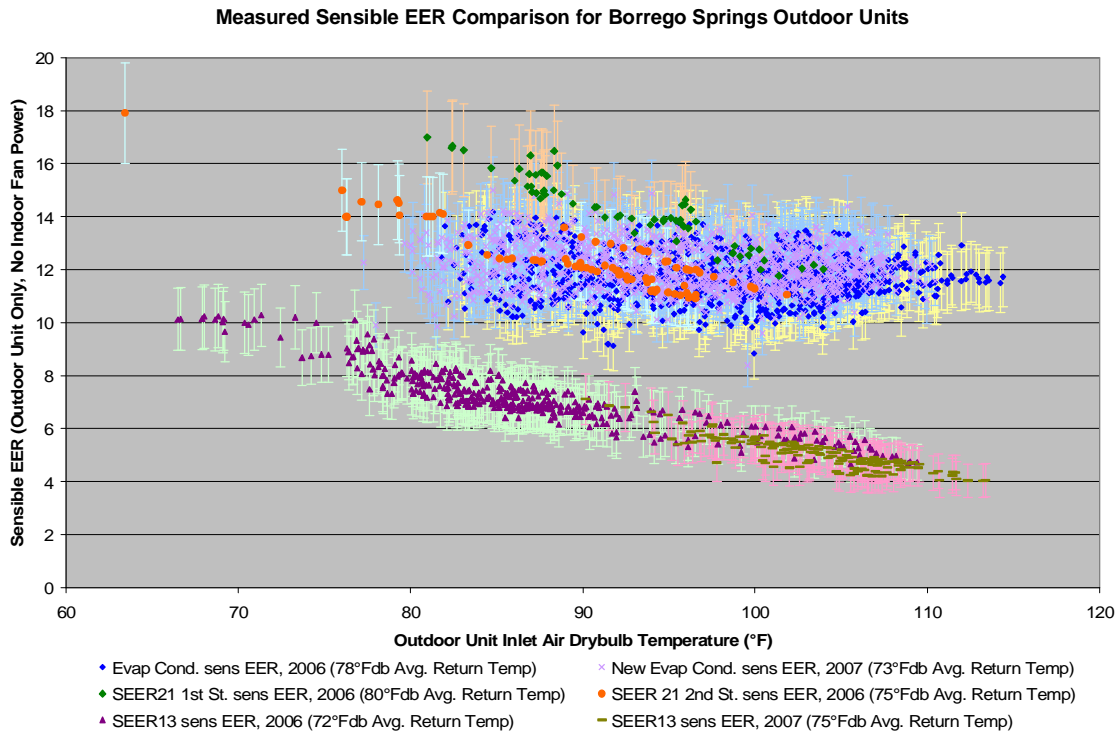


Figure 20: Measured Sensible EER Comparison of Borrego Springs Condensing Units

Evaporative Condenser Water Use

In order to compare the water consumption of the Evaporative Condenser to the air source outdoor units, a source water-to-site energy use multiplier of 4.64gal/kWh was applied to the outdoor unit daily average energy use for each system. The water use was then normalized to the total cooling delivered. Table 8 shows the average water use for this comparison.

Table 8: Normalized Water Consumption for Borrego Springs Air Conditioners¹⁵

Air Conditioner	Normalized Average Water Consumption (gal/Ton-hr)
SEER13	10.4
Evaporative Condenser	9.4
SEER21	6.9

Data in Table 8 represents a variety of indoor and outdoor conditions, which may not be directly comparable. Issues with air conditioner operation and data acquisition system reliability

¹⁵ Cooling energy represents total cooling delivered

prevented a more direct comparison, however, data for the evaporative condenser represents higher outdoor temperatures as the evaporative condenser data was filtered to ignore data for days when the floor cooling system was operated. Floor cooling operation occurred during times of the year when temperatures were milder.

Cooling System Energy Savings Relative to the 13 SEER System

Cooling system energy savings were estimated by applying the performance map for the 13 SEER system at Arrow to the 15-minute monitored cooling loads and outdoor temperatures for the SEER 21 (East Star) system and the evaporative condenser (DiGiorgio). Since the cooling loads are measured at the plenums, they do not include distribution loss. This analysis was completed for the period from July 1 to August 26¹⁶. Over this period the 21 SEER Lennox system should have saved 725 kWh, or 29.5% relative to the 13 SEER system, and the EER averaged 8.1 relative to the average EER for the 13 SEER system of 5.7. Over the same period the Freus evaporative condenser should have saved 892 kWh, or 36.7% relative to the 13 SEER system with an average EER of 9.2. The Freus EER was more greatly affected by fan energy use than the Lennox system.

The average EER's given above were calculated by dividing the total energy delivered by the electrical energy consumed for the period. These are much lower than those indicated in Figure 20, most likely because of cycling losses, which appear to have been greater for the SEER 21 system than the evaporative condenser.

A similar approach was used to identify evaporative cooler energy savings relative to the 13 SEER air conditioners using data from the Arrow and Wagon sites for May 19th to June 16th, 2007. Table 9 shows the results of this analysis, including measured evaporative cooler energy, estimated air conditioner energy use calculated using Equation 1, and estimated evaporative cooler savings. Energy use values for the Arrow site are lower because several weeks of evaporative cooler data were lost due to a faulty sensor. The lower percentage energy savings seen for the Arrow system are attributable to higher evaporative cooler fan energy resulting from resistance in the ductwork. The higher estimated air conditioner energy use seen for the Wagon site is attributable to higher evaporative cooling delivery monitored for that site. Similar indoor temperatures (averaging about 76.5°F) were maintained at both sites.

Table 9: Approximate Evaporative Cooler Savings Relative to the 13 SEER Air Conditioner

Site	Evap Cooler KWh	Estim. Air Cond. kWh	Savings kWh	Percent Savings
Arrow	120.8	312.2	191.4	61%
Wagon	271.5	1552.5	1281.0	83%

4.6 Overall House Cooling Energy Use Comparison

Because three of the four houses were unoccupied and the only substantive electric load was for cooling, it is not reasonable to compare whole house energy use. Even though differences in the envelope designs would be expected to yield slightly different building loads, it is still of interest to compare the cooling energy use for the four houses.

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

¹⁶ This cut-off date is due to the removal of the East Star monitoring system.

in Figures 21 and 22. 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.

Because of the improvements made to systems and monitoring prior to the summer of 2007, the 2007 data are more credible. Despite the large differences in system and envelope types, the percent standard deviation of the total cooling energy use for the four houses was less than 10% in 2007.

Everything else being equal, the DiGiorgio house would be expected to have higher cooling energy use because it is the only one of the four houses with any appreciable internal gain. Its higher energy use in June could be attributed to poorer part load performance relative to the other systems and early season floor cooling operation.

Despite the lower EER of the Arrow condensing unit and the slab loss of the Wagon system, the summer energy use for these two houses was held low by the operation of the evaporative coolers in early June. Evaporative cooler temperature setpoints and operation was more consistent during 2007, accounting for the lower energy use compared to 2006.

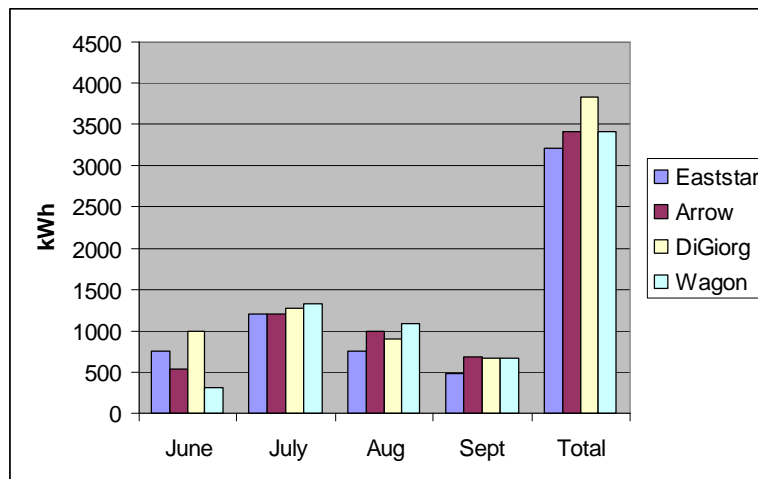


Figure 21: Normalized Cooling Energy Use, Summer 2006

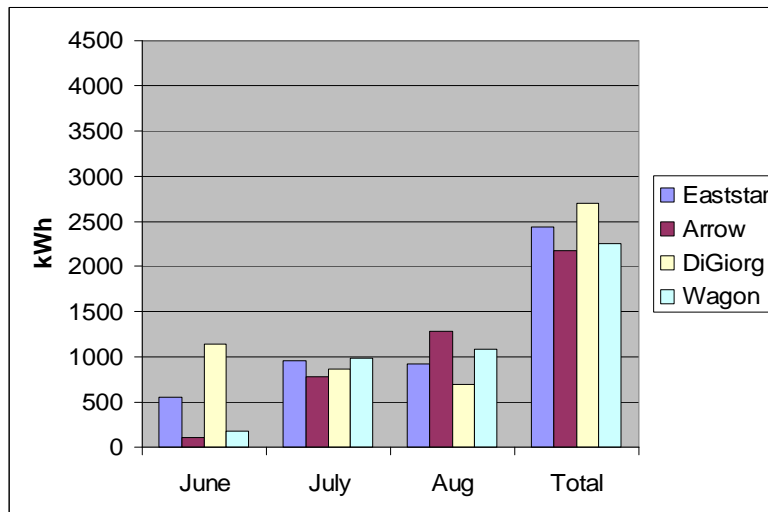


Figure 22: Normalized Cooling Energy Use, Summer 2007

It is interesting to note that the energy savings of the 21 SEER and Freus systems estimated from calculated performance of the 13 SEER system do not appear significant in the monitored cooling energy use data in Figures 21 and 22. This might suggest that the Arrow SIP constructed building envelope had lower loads than, and outperformed the other houses. But when monitored cooling loads (including evaporative systems) are compared for the same period covered by Figure 22 (June 1 – August 17), the Arrow house turns out to have the highest cooling load. With the differences in the building envelopes it is risky to draw firm conclusions from any of the data beyond the focused analysis of the performance of the individual cooling systems based on the energy use and how much energy was delivered to the duct systems.

5 Summary of Interactions Between Components and Systems

5.1 Building Envelope – Mechanical Systems Interactions

It was an early objective of the study to identify the preferred building envelope-mechanical system combination. It was also anticipated that evaporative cooling and high mass walls might provide an ideal solution for extreme hot-dry climates because the cooler could be operated at night to lower the temperature of the mass. It is apparent from the Wagon house data that the evaporative cooler could maintain comfort without the need to store cooling, but that as soon as the outdoor wet bulb temperature rose much above 65°F the cooler no longer had sufficient capacity to meet cooling loads, with or without storage.

Neither of the high mass houses (Wagon or DiGiorgio) appeared to have an advantage over the SIP and frame wall houses because the outdoor temperature was consistently above the indoor temperature throughout most of the cooling season. Notwithstanding peak load shifting benefits, the critical characteristic of the walls was their conductance, not their mass.

5.2 Evaporative Cooler and Vapor Compression Systems (Wagon and Arrow)

The Wagon and Arrow house systems integrate advanced evaporative cooling and vapor compression cooling as previously described. The evaporative coolers are stand-alone packaged systems except that they share ducting (in the case of the Arrow house) and are interlocked with the vapor compression systems to avoid concurrent operation. Unfortunately there was no opportunity to test homeowner response to the two systems, which would have shed light on comfort tolerances and might have revealed operational issues that were not apparent from the test protocol.

The air handler and cooling coil paired with the Arrow 13 SEER system met manufacturers specifications. There is of course no ARI rating for the Wagon system that applied a plate heat exchanger, liquid cooling coil, and floor tubing in lieu of a refrigerant cooling coil, but performance of these components exceeded expectations, except for the floor losses previously noted. The balance of air and floor cooling appeared to work well together to maintain indoor temperatures and comfort.

Components of the radiant floor heating systems include the floor distribution system (in-slab tubing), hydronic modules (including pumps, heat exchangers, expansion tanks, and other components), tankless water heaters, and controls. All components functioned as designed. No system integration issues were noted during the tests.

5.3 Evaporative Condenser, Floor Cooling System, and Ventilation Cooling Systems (DiGiorgio)

There were no operational issues with the unique usage of the evaporative condenser as a cooling tower to cool water for floor cooling, though it was necessary to add a pump to the evaporative condenser and to modify its controls. The two modes (air conditioning and floor cooling) are mutually exclusive and priority is given to air conditioning.

The NightBreeze air handler used on the DiGiorgio house is a component of the ventilation cooling system, but also delivers air for heating and vapor compression cooling. The air handler integrated well with the Freus condensing unit and the tankless water heater, which was used as a heating source.

The ventilation cooling system is designed to use outside air as a cooling source when the outside air is cooler than indoor air, and admits outside air if this condition is met whether the air conditioner is operating or not. There were no observed instances of the air conditioner operating when the outdoor temperature was lower than the indoor temperature. Ventilation cooling should perform better with the added benefit afforded by the mass walls used in the DiGiorgio house. Since none of the other three houses included ventilation cooling, the impact could not be comparatively assessed.

Both “natural cooling” approaches contributed to lowering the cooling load, although neither had any impact during the hottest parts of the summer. Further study is needed to determine quantitatively the energy use impact of each of these sub-systems in extreme hot-dry climates.

5.4 High SEER System (East Star)

The East Star system utilized a Lennox air handler matched to the condensing unit. Since all heating was provided by the radiant floor system, the air handler was dedicated to cooling only. The same thermostat was used for both heating and cooling, and there were no integration issues.

5.5 Hydronic Heating and Water Heating Systems

Tankless water heaters were used in all houses to provide heat for space heating. The three houses with radiant heating utilized a heat exchanger to isolate the heating system water from the domestic hot water. A flow switch was installed in the cold water line feeding the water heaters to disable space heating when there was a hot water draw. Failure of these flow switches led to them being bypassed, but there have been no complaints of hot water shortage from the 190,000 Btuh water heaters. No other system integration issues have been noted with the heating systems, though only one of the houses was fully occupied during the evaluation period.

6 Cost and Performance Trade-offs

6.1 Costs

Construction costs were abnormally high because of the remote location and difficult working 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. Table 10 lists construction costs provided by the builder for the wall systems, and references incremental costs to the cost of the frame house.

Table 10: Wall Construction Cost Comparison

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

Table 11 lists costs, provided by the builder, for mechanical systems. Presumably, builder costs for mechanical systems include the \$13,800 total cost to build the four hydronic modules, and mechanical, plumbing, and electrical subcontractor costs. The four tankless water heaters that provide heat water heating and space heating were donated to the project by Rinnai, and the evaporative condenser for the DiGiorgio house was donated by Freus. The prototype OASys evaporative coolers used on the Wagon and Arrow houses were provided by Speakman Company at a cost of \$1950 per unit.

Table 11: Builder Costs for Mechanical Systems

House	Description	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
DiGiorgio	Evaporative condenser, forced air cooling with radiant-evaporative floor cooling and night ventilation cooling assist; forced air heating	\$20,440
Arrow	Evaporative cooling with supplemental SEER 13 condenser and forced air cooling; radiant heating	\$21,009

Table 12 was prepared in an effort to estimate what “mature market” costs might have been had the houses been located in a more favorable environment, all equipment was in production, and all equipment was purchased. Only the East Star house costs are similar in Tables 11 and 12, because the mechanical system components are relatively standard.

Table 12: Estimate of Mature Market Costs for Mechanical Systems

House	Description	Total Cost	Cond & A/H	Evap Cooler	Evap Condenser*	Hydronic Modules	Radiant Floor
East Star	SEER 21 AC, forced air cooling and radiant floor heating	\$15,800	\$10,800	\$0	\$0	\$3,000	\$2,000
Wagon	Evaporative cooling with supplemental SEER 13 condenser and radiant/forced air cooling; radiant heating	\$17,200	\$6,400	\$4,000	\$0	\$4,800	\$2,000
DiGiorgio	Evaporative condenser, forced air cooling with radiant-evaporative floor cooling and night ventilation cooling assist; forced air heating	\$13,400	\$7,400	\$0	\$1,000	\$3,000	\$2,000
Arrow	Evaporative cooling with supplemental SEER 13 condenser and forced air cooling; radiant heating	\$15,400	\$6,400	\$4,000	\$0	\$3,000	\$2,000

*Estimated Incremental cost, including floor cooling controls

The estimated base cost for a complete 13 SEER system, installed, is about \$5000. Thus the estimated “mature” incremental costs for the systems ranged from about \$8,000 for DiGiorgio to \$12,000 for Wagon.

6.2 Energy Savings and Cost Neutrality

A key question for this study is, to what extent is the cost of the high efficiency cooling equipment justified by energy savings? Limitations of Benchmark models for simulating energy use of evaporative condensers, mixed evaporative and vapor compression cooling systems, radiant heating and cooling, as well as comfort parameters such as mean radiant temperature and relative humidity rule out the use of these models for estimating energy savings relative to a Benchmark system. Although the lack of occupants makes side-by-side comparisons of the monitored houses less complicated, the monitoring data do not reflect occupant comfort preferences, particularly for the evaporatively cooled and radiant cooled houses. These conditions make attempts to estimate whole house energy savings from “unoccupied” monitoring data presumptuous.

Standard vs. High Performance Cooling Systems

Energy savings estimated for the Lennox SEER 21 and Freus evaporative condensers were estimated to be 725 and 892 kWh, respectively (see Section 4.5). At an electric rate of \$0.14 per kWh, annual cost savings would be \$102 and \$125 respectively. Amortized at 7% over 30 years, these costs would justify incremental costs of \$1271 for the SEER 21 unit and \$1563 for the Freus. Referring to Table 12, the estimated mature market cost for the SEER 21 system is \$4400 and for the Freus is \$2000. Neither system proves to be cost-neutral using this analysis, but since the energy savings were not compiled over the full cooling season, the Freus could be close to cost-neutral, neglecting its increased maintenance costs.

Standard Vapor Compression vs. High Performance Evaporative Cooling System

Using the Wagon system as an example, if energy savings during the fall months are roughly equivalent to the spring months, the annual energy savings would be approximately double that shown in Table 9, or about 2562 kWh per year. At an electricity cost of \$0.14 per kWh, the annual cost savings would be \$358.68. If the cost of the cooler were amortized over 30 years at 7%, these energy savings would justify an installed cost of \$2246. The installed cost of an OASys evaporative cooler is estimated at \$4000, so despite its substantial energy savings, the system is difficult to justify as a supplemental cooling system at the \$0.14 per kWh electricity rate. As a stand-alone replacement for air conditioners in mild climates, the economics would be much more favorable.

Floor Cooling Systems and Chilled Water Distribution

As previously noted, Wagon’s refrigerant to water evaporator doubled the EER of the 13 SEER unit compared to Arrow’s refrigerant to air system. More research is needed to identify what the energy savings could have been had the slab been insulated. Chilled water delivery could improve the performance of forced air systems as well if chilled water temperatures are set in the 50-60°F range, thereby reducing compressor energy by increasing the condensing temperature in addition to increasing the sensible heat ratio, which is desirable in hot-dry climates. A study to find the optimal tradeoff between chilled water temperature, condenser energy use, and fan energy use is recommended.

Although it clearly provides a cooling benefit, it is similarly difficult to estimate the annual energy savings for the DiGiorgio floor cooling system. Since this system relies on a source of

evaporatively cooled water, it must be paired with an evaporative condenser, evaporative cooler, or a cooling tower. If any of this equipment is justified on its own grounds, there is a possibility that floor cooling (with under floor insulation) could withstand a cost neutrality test.

7 Comfort and Health Issues

Air change rates, indoor relative humidity, air temperature and velocity, and surface temperatures contribute to define both indoor comfort and health. Evaporative coolers provide 100% outside air and discharge contaminated indoor air, but also increase indoor relative humidity, which can lead to increased dust mite growth. Heated floors increase the mean radiant temperature, and in theory allow equivalent comfort at lower indoor air temperature settings, thereby reducing building envelope heat loss. Another advantage of heated floors is that they are more likely to be acceptable when left uncarpeted than unheated floors, and carpet provides a substrate for dust mites and other allergens. Conversely, cooled floors reduce the mean radiant temperature and can provide greater comfort at higher indoor air temperatures. If the floor is cooled too much the air adjacent to the floor can approach saturation, facilitating mold growth. This study showed that floor surface temperatures of the Wagon house remained well above the dewpoint temperature while the floor provided a large percentage of the cooling.

Since only the DiGiorgio house was occupied, subjective information on comfort could not be obtained for all four houses. The owner of the DiGiorgio house commented that the floors are cool in winter (this is the only house without heated floors), and expressed a strong liking for the fresh air and comfort provided by the ventilation cooling system.

8 Durability, Reliability, and Maintainability

8.1 Air Conditioning Systems

By virtue of their volume manufacture, warranty support, and proven performance the three conventional condensing units and air corresponding handlers meet all Building America criteria for durability, reliability, and maintainability, though the air handlers are somewhat difficult to access for service.

The Freus evaporative condenser failed on two occasions. In both cases the problem was with a faulty sequencing relay. After the first season of operation the pump basket became clogged with mineral deposits, but the pump continued to operate. A recommendation was made to supply the unit with treated makeup water from the water softener instead of water directly from the well, which has a very high alkalinity. A photo of the pump is provided in Figure X. The Freus was replaced at the beginning of the summer of 2007 to provide a unit that had lower fan energy use and improved placement of the added floor cooling loop pump.

8.2 Evaporative Cooling Systems

The two evaporative coolers operated reliably throughout the two summers. After the first cooling season hoods were added to keep out sand and improve the ratio of primary to secondary airflow. As the coolers were prototypes, long term reliability is an unknown. At the end of the test period it became apparent that the coolers will require annual maintenance to remove salt deposits as indicated by Figure 23. As with the Freus, a recommendation was made to supply the coolers with conditioned water.



Figure 23: Evaporative Cooler Indirect Media After Two Cooling Seasons

Replacement of evaporative media is somewhat tedious in the prototype units. The commercial version of the OASys cooler has been improved to make media removal and replacement easier and to improve access to the pump and other components. Given the quality of Borrego Springs water, replacement of the direct evaporative media could become a necessity in three to five years.

8.3 Hydronic Modules and Controls

The one-off built-up hydronic modules were assembled of proven components and are durable, reliable, and easily maintained. Minor problems were encountered with two of the modules. Flow switches were installed to disable the heating systems while a domestic hot water draw was occurring, and in one instance a flow switch was held open by debris in the piping, preventing the heating system from operating. Another module developed a leak in a plumbing fitting near the end of the test period.

8.4 Tankless Water Heaters

Although only one of the tankless water heaters was exposed to an appreciable domestic hot water load, all performed well during the very limited amount of time that they were used for space heating. Maintenance in the form of periodic flushing (as recommended by the manufacturer) will have to be performed to remove mineral deposits, although water softeners will probably reduce the frequency of flushing. Given their track record over more than a decade of use in the U.S., the high capacity electronic ignition units are expected to be otherwise reliable. Due to their complexity they require more training to repair, and parts availability could be an issue, particularly for remote locations such as this.

9 Conclusions and Recommendations

Until the performance and particularly the reliability of evaporative condensers is improved and proven, the high SEER air conditioner is clearly the best cooling system choice at present for extreme hot dry climates such as Borrego Springs. Coupling the high SEER condensing unit with the ventilation cooling system would also provide ventilation cooling and distributed fresh air ventilation, though results suggest that ventilation cooling in the Borrego Springs climate is probably not cost-effective based on its energy saving merits alone.

Forced-air hydronic heating as used in the DiGiorgio house can be competitive with furnaces since the cost of an air handler is comparable to and, in a mature market, likely lower than the

cost of a furnace provided that it is installed in a combined heating application where the added cost for an efficient heat source is shared by the domestic hot water system. The effort made to package pumps, heat exchangers, and controls, clearly defined roles for the HVAC, plumbing, and electrical contractors, and thorough commissioning no doubt contributed to the trouble-free installation of the combined systems. Newer condensing tankless water heaters and mini-boilers can be used to boost heating efficiency of combined systems to higher levels.

There is a cost penalty for installing the dual distribution systems required to provide radiant floor heating and forced-air cooling. This cost is mitigated somewhat by the small amount of ducting needed by the supplemental forced-air cooling system of the radiantly cooled Wagon house, which probably provides the greatest summer and winter comfort. Radiant floor cooling and chilled water systems in general, deserve further research, both to identify the distribution efficiency of a fully insulated slab, and to quantify the benefits of high evaporator temperature and increased sensible heat ratio. To the limited extent they were used, the tankless water heaters proved to be effective devices for combined heating system applications, potentially making radiant floor heating a viable design alternative if the majority of the cooling ducting can be eliminated. This approach also meets the architectural demands of flat-roof buildings with no attics.

The advanced two-stage evaporative coolers provided good comfort with outdoor temperatures exceeding 105°F while wet bulb temperatures were below 65°F, but they could not meet comfort requirements (per ASHRAE Standard 55) throughout the summer months. The cost savings resulting from their relatively high EER's during their use in spring and fall months does not justify their incremental cost as a supplemental system, particularly if expected maintenance costs are accounted for. In climates with less extreme cooling loads and design wet bulb temperatures of around 70°F they have great potential as a vapor-compression cooling substitute.

The 9 Btu/ft² cooling load offset and over 20 EER of the DiGiorgio evaporative floor cooling system suggests that this technology should be considered for future Building America applications where an evaporative condenser, evaporative cooler, or other evaporatively cooled water source is available. As with the Wagon floor cooling system, much of the cooling energy was probably lost to the ground, lowering the distribution efficiency. The best application of this system may be in non-ducted systems in milder cooling climates where the cooling load is met by evaporative cooling and radiant floor cooling, and the radiant distribution system is also used for heating.

The most compelling result from this research is the doubling in EER stemming from the use of a refrigerant-to-water instead of a refrigerant-to-air evaporator. Additional research is needed to (1) determine the extent to which the system efficiency of radiant floor cooling can be improved by adding insulation below the slab, and (2) determine whether similar savings can be achieved with fan coil distribution. The combination of fan coil cooling, which removes excess moisture and allows some degree of control of the sensible heat ratio by adjusting chilled water temperatures, and floor cooling, which increases evaporator temperatures and improves comfort, may be the most efficient way to apply vapor compression cooling in hot-dry climates.

10 Other Reports and References

10.1 Other Building America Reports on Borrego Springs

As a collaborative effort with NREL and BIRA, numerous other reports have been completed on this multi-year effort, which began in 2004 with meetings to discuss system and envelope alternatives with Clarum Homes. Other CARB reports include:

- Deliverable 7.C.2 – Field Test Plans
- Deliverable 10.A.1 – Advanced Systems Research Plan & Evaluation
- Deliverable 10.A.2 – Advanced Systems Research: Progress Report
- Deliverable 12.A.2 – Evaluation of Advanced Systems Concepts
- Deliverable 12.B.1b – Advanced Systems Research: Final Report

The CARB 10.A.1 deliverable report contains the most information on system design and monitoring details. The 12.B.1b deliverable reports on monitoring completed in 2006, some of which is repeated and/or updated in this report.

BIRA reports include:

- Deliverable 12.B.2 – Completion of Evaluations of Research Houses
- Deliverable 12.C.2 – Performance Evaluations of Research Houses
- Deliverable 15.B.2 – Research House Case Studies

At least two documents have been completed by NREL related to Borrego Springs work and technologies, including:

- Borrego Springs Field Test Summary (Mark Eastment, 2006)
- Projected Benefits of New Residential Evaporative Cooling Systems: Progress Report #2 (Mark Eastment, Chuck Kutscher, Ed Hancock, Paul Reeves, 2006)

NREL and DEG have also collaborated on an ASHRAE paper that is scheduled for presentation at the summer 2008 meeting in Salt Lake City.

10.2 References

Research completed by DEG staff and described in the following papers led in part to the designs implemented in the Borrego Springs houses.

Hoeschele, M. “Residential Indirect/Direct Evaporative Cooler Performance in Sacramento”. Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings.

Hoeschele, M., et al. “Evaporative Condensers: The Next Generation in Residential Air Conditioning?”. Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings.

Bourne, R., M. Hoeschele. “Applying Natural Cooling to Slab Floors”. Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings.

Springer, D., L. Rainer, B. Dakin. “Development and Testing of an Integrated Residential Night Ventilation Cooling System. ASHRAE Transactions Vol. 111, Pt. 2. 2005.

Springer, D. “Implementation and Operation of an Integrated Design Desert House”. Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings.

11 Stage Gate Criteria

The inception of the research described in this report preceded the implementation of the Stage Gate process, and the research plan was not developed with Stage Gate criteria in mind. However, Gate 1B: Systems Evaluations can be applied to this research. Because there were several systems evaluated, each should be assigned a separate gate analysis. These systems include, in order of Stage Gate acceptability:

- High SEER air conditioner
- Evaporative Condenser
- Advanced Evaporative Cooler
- Ventilation Cooling
- Hybrid Chilled Water Cooling
- Integrated Slab Cooling with Evaporatively Cooled Water

Each system type is addressed separately in the context of the Borrego Springs testing.

11.1 High SEER Air Conditioner

Must Meet: The Lennox XC-21 air conditioner tested provides significant source energy savings and can be expected to provide the same comfort, durability, and reliability of lower performing conventional air conditioners.

Should Meet: All performance-based code approvals are met. The cost-benefit did not appear to be favorable in this project, although costs may decrease as the market for high efficiency systems increases and standards drive up minimum SEER levels. Two-speed operation has the potential to improve comfort when used in combination with zoned systems, if designed properly. The system is favored by high reliability, durability, installer familiarity with the system, and a high level of logistical support.

11.2 Evaporative Condenser

Must Meet: The Freus evaporative condenser has been evaluated in other Building America projects and by other investigators. Davis Energy Group has been testing a predecessor system, the AC2000, and the Freus on its office building for eight years. Freus has an ARI performance rating as well as approval as a Compliance Option under California Title 24 standards. Despite reliability problems with the Borrego Springs system, the technology has been proven in other demonstrations, and competes with other air-based high performance systems. Evaporative condensers by other manufacturers are beginning to enter the market. No additional testing should be required before being deployed to community scale projects.

Should Meet: Evaporative condensers meet performance-based codes. Cost-performance advantages vary by climate region and installed cost. This evaluation found the Freus to be less than cost-neutral, but higher volume production should bring the cost down to a level where it can contribute to a positive cash flow. The Freus case and evaporative section is designed to handle up to a 10 ton cooling load. Reduction of the size to meet the 2-3 ton size required for high efficiency houses will also reduce costs. Improvements in manufacturer support and improved infrastructure are needed, but should come as the market grows. Publication of realistic performance ratings would improve manufacturer credibility in the industry.

11.3 Evaporative Cooler

Must Meet: The OASys advanced prototype evaporative coolers tested demonstrated significant source energy savings relative to vapor compression cooling, but when indoor comfort is accounted for, energy savings are less than the 83% predicted by DOE-2.1 simulations completed by NREL. Tests showed they could not meet comfort requirements when outdoor wet bulb temperatures were above 65°F. Because the systems were prototypes, further testing of production units is needed to verify energy savings. The production version of the OASys has been laboratory tested in accordance with ASHRAE standards and is currently undergoing field tests by PG&E.

Should Meet: Evaporative coolers generally meet performance-based codes. When installed as a supplement to vapor compression air conditioning, the OASys systems are not cost-neutral. Long-term reliability and durability could be an issue in areas with high mineral content in the water, but can be mitigated by water treatment. Because of their practically non-existent market penetration in production homes, logistical support is somewhat wanting. Technical barriers include the need for and integration with supplemental cooling in hot semi-humid climates. Significant resistance to evaporative coolers persists in the new home market.

11.4 Ventilation Cooling

Must Meet: The NightBreeze ventilation cooling system used with the evaporative condenser is adaptable to all combined hydronic systems and a limited number of furnaces. Hydronic versions have been in use in production homes since 2002, and have since been used in several community scale projects. Their cost is additive, but is offset by the potential elimination of other fresh air ventilation systems and zone controls, if needed (NightBreeze controls include zoning capability).

Should Meet: There are no health, safety, or other building code issues with ventilation cooling systems, and they provide improved indoor air quality. Energy savings have been demonstrated in other projects and by simulation, but were not demonstrated in the Borrego Springs test because of the high nighttime temperatures, minimal use during swing seasons, and high cooling efficiency of the evaporative condenser. They have proven reliability, but the range of supply is currently limited to California and Western Nevada and the level of logistical support varies by region.

11.5 Hybrid Chilled Water Cooling

Must Meet: Residential chilled water systems have not been used in production homes, and have been engineered into a very small percentage of custom homes. Much more refinement of systems and testing is needed to reduce costs and improve performance, particularly of the associated cooling distribution system. Uncarpeted floors are a prerequisite for radiant cooling distribution, and are an impediment to widespread use by production builders. (The radiant cooling distribution system can also be used for heating, as it was in this project.) The doubling of EER seen in this project supports the need for further evaluation of chilled water systems that combine radiant and forced air distribution.

Should Meet: Performance ratings for small chillers in residential applications are non-existent, and systems must be individually engineered. Costs will remain high until packaged systems become available. The use of low cost plastic (PEX) pipe for chilled water distribution and the opportunity to eliminate ducting by the use of small, dedicated fan coils holds promise for lower costs, higher performance, improved comfort (through increased zoning), and more architectural

freedom. Although no reliability or durability problems were observed, field-testing is needed to develop stronger evidence. There are currently no manufacturers of complete systems, although some radiant heating specialists are capable of assembling them.

11.6 Integrated Slab Cooling with Evaporatively Cooled Water

Must Meet: These systems are even more scarce than residential chilled water systems, though in the commercial sector they are referred to as “water side economizers”. Most commercial systems employ fan coils, although there are a number of prototype systems installed in Northern California that are designed for slab cooling. DEG has designed systems for San Francisco condominiums that utilize cooling towers to provide 100% of the cooling, instead of just offsetting the cooling load as was done on the DiGiorgio house. To be cost-effective systems should utilize an existing source of cooled water and share an in-slab coil with a radiant heating system. As with chilled water systems, they must be engineered. Substantially more work is needed to demonstrate compliance with must-meet criteria.

Should Meet: There are substantial gaps in all areas of the should-meet criteria, including the lack of manufactured components, cost information, design details, and logistical support.