



“Advanced Systems Performance Evaluation”

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&
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40-50% Total Energy Savings Level
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Performance Evaluations of Prototype House: 50% Total Energy Savings Level - Redding, CA

Abstract

Under Task Orders 8, 9, and 10, the Consortium for Advanced Residential Buildings (CARB) is testing houses at the 30-50% performance level to evaluate production-scale performance benefits from advanced systems. Under Task Order 10, Task D, CARB team member Davis Energy Group (DEG) evaluated one house in the extreme hot climate of Redding, California to determine the cost-effectiveness of quality construction (insulation, draft-stopping, and sealing) on meeting Building America performance goals. Built under the close supervision of building contractor Rick Chitwood, a consultant to the California Energy Commission and a Davis Energy Group colleague, the house also incorporated advanced systems including a condensing water heater and an evaporative condenser.

In accordance with Task Order 10 Task D, this report describes the evaluation of the Redding house, including the Benchmark analysis, monitoring results, and cost-effectiveness from the buyer's perspective. Since a key objective of this task was the comparison of simulated and measured performance, and since completion of construction and the installation of monitoring delayed the initiation of work, this report consolidates Deliverables 10.D.2 (Progress Report) and 10.D.3 (Prototype Performance Evaluation).

Energy use relative to the Benchmark model was computed using DOE-2.1E, and yielded a 34% savings, with most of the savings attributable to reduced cooling energy use. Over the August through December period of monitoring, and excluding lighting and miscellaneous electric loads, Benchmark analysis indicated a 57% savings. Monitored (actual) energy use was on average lower than simulated prototype energy use; from monitoring data a reduction in heating, cooling, and water heating energy use of 60% was estimated relative to the Benchmark. Since the hottest months of the summer were not monitored, actual total energy savings may approach 40% relative to the Benchmark.

Key Words

CARB, Davis Energy Group, Steven Winter Associates, hot-dry climate, Building America Benchmark, construction quality, evaporative condenser, condensing water heater, combined hydronic heating, radiant heating.

1 Background and Project Objectives

Construction quality is an issue that the California Energy Commission, and certainly the Building America teams, has recognized as key to improving energy efficiency. Responding to this issue, in its 2005 Title 24 energy standards rulemaking the Energy Commission reduced the effective U-value of wall insulation unless it is inspected for quality installation. This standards change was supported by research completed by Davis Energy Group (DEG) and Chitwood Energy Management (CEM) under the New Construction Residential Quality Assessment Project. This project evaluated the construction quality of over thirty houses that were built to Title 24 standards and higher.

Drawing from this and other experience, Chitwood has been practicing examples of quality construction for several years, and in early 2005 guided the construction of a house located in Redding, California. The builder of this house, which was entered in Redding Electric's 2005 *Showcase of Homes* program, gave Chitwood free reign to apply quality construction principals. The general objective of the study described in this report was to evaluate the construction process and costs, and to assess what contribution quality construction techniques can provide toward meeting Building America goals.

2 Project Description

2.1 Test House Description & Location

The house selected for this study sits on a ridge above the city of Redding in the Stanford Hills development (Lot 32). Built by Building Adventures, Inc., the house is included in a group of luxury homes built under the City of Redding's *Showcase of Homes* program. The Building Adventures house was one of four houses featured in the city's 2005 program. Pictured in Figure 1, the 3477 ft² ranch style house has an attached 3-car garage, porticos and covered porches, a stucco exterior and terra-cotta roof tiles. A floor plan and additional photos are provided in the Appendix.

2.2 Energy Measures

The following energy features were included in the design:

- High performance windows (U-value < 0.34, SHGF < 0.32)
- Window placement and exterior architectural shading designed to reduce summer solar heat gain
- Quality installed R21 fiberglass batt insulation in 2x6 walls with 1" R-5 foam sheathing on the exterior and R-38 blown cellulose ceiling insulation
- Radiant barrier roof sheathing
- All chases and ceiling penetrations blocked and sealed with foam board and caulking

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- R-8 ducting with reflective vapor barrier, tightly sealed, and partially buried in attic insulation
- Four-zone distribution system with supplies designed for optimal mixing
- 2-ton Freus evaporative condenser
- Combined hydronic heating using a condensing natural gas water heater (Polaris) and an air handler located in conditioned space

Figure 1: Prototype House Elevations



2.3 HVAC Zoning

Given the low airflow of the two-ton cooling system (0.26 cfm per ft²) it was important to provide zoned distribution. The central portion of the house (Living, Family, and Kitchen/Nook) was used as a “dump” zone; dampers do not control airflow to this central zone, which receives air when any of the other zones are calling, or when the central zone thermostat is calling. Zone thermostats and dampers control three other zones comprised of the Master Bedroom, Bedrooms 1 & 2, and Office/Entry/Dining. Additionally, the hydronic system provides heat to a radiant floor located in the Master Bath. The design airflow for the air handler is 920 cfm.

2.4 The Redding Climate

Redding’s summer design temperature is 103/68°F (0.5% dry bulb/mean coincident wet bulb). The record high is 118°F, and there are 1741 cooling degree-days per year. Redding’s location at the northern extreme of the Sacramento Valley isolates it from the marine flow that cools much of the Central Valley, and the surrounding mountains contribute to compression heating during windy conditions. Winter temperatures are consistent with the rest of the Sacramento Valley, with a 0.2% winter design temperature of 31°F and 2544 heating degree-days. The Building America climate designation is Hot-Dry.

3 Quality Control of the Construction Processes

3.1 Construction Quality Control

Chitwood Energy Management served as the insulation contractor and subcontracted to a mechanical contractor. This relationship to the project gave them complete control over the energy-critical portions of the construction. Examples of the insulating and sealing techniques applied are provided in Figures 2 and 3. Duct runs were kept short and ducts were tightly sealed and tested.

Figure 2: Example of Quality Installation of High Density Fiberglass Batt



Figure 3: Draft-Stopping at Cavity for Gas Fireplace



3.2 Diagnostic Tests

The following tests were performed to verify the quality of duct and house sealing and the forced air distribution system sizing:

- House leakage at 50 Pa
- Duct leakage to outside (measured using a duct blaster while the house was pressurized to 25 Pa with a blower door)
- Airflow at each register

To measure register airflow, each zone was activated one at a time. Airflow readings were then taken from each active register (damper open or no damper controlling airflow).

4 Performance Evaluation Procedures

4.1 Benchmark Analysis

House design characteristics and data from the diagnostic tests (house leakage rate and duct leakage) were applied to the prototype model to estimate energy savings relative to the benchmark. Because DOE-2 lacks modeling capability for an evaporative condenser it was necessary to model the Freus as an evaporatively pre-cooled condenser. Performance curves from RMI's AC-2 system¹ were used in the model and 100% evaporative effectiveness was assumed.

4.2 Long-Term Monitoring

Monitoring Period

Long term monitoring was initiated as soon as the house was occupied and a telephone line could be secured, on August 9, 2005, and is continuing. For purposes of this report, data were included through December 2005.

Measurement Points and Sensors

Due to the narrow time window for installation of monitoring systems (between project initiation and house completion and occupancy), it was not possible to install highly detailed monitoring systems to fully differentiate electric and gas end uses or the various gas end uses. The following items were measured continuously over the monitoring period:

- Indoor temperature
- Outdoor temperature
- Air handler fan energy
- Freus condensing unit energy (including fan & pumps)
- Total house electrical energy
- Water heater gas use

¹ The AC2 was manufactured by RTI, a company managed by the current principals of Freus.

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Sensors were scanned at 15 second intervals and averages or totals were reported on 15 minute intervals. As the delivered capacity of the HVAC system was not measured, the efficiency of the Freus² and Polaris systems could not be determined. However, measured energy use allows for a comparison of simulated vs. measured gas and electric energy use. Additional details on monitoring procedures are provided in Deliverable 10.D.1.

Since the condensing water heater provides heat for both water heating and space heating, these uses were combined in the water heater gas measurements. To separate them, any gas use that occurred while the air handler fan was operating was assumed to be for space heating, and the rest of the gas use was assigned to water heating. A threshold of 20 Watts of fan energy averaged over the 15 minute periods was used as the threshold for distinguishing space heating from water heating. Since the air handler fan does not operate while the bathroom radiant floor heating is operating, the estimate of water heating energy use is expected to be artificially high.

5 Evaluation Results

5.1 Benchmark Analysis

Table 1 compares simulated annual site energy use for the Building America benchmark to the Chitwood house if built to Title 24 standards (Region Standard), and to as-built conditions (BA prototype). Consistent with Benchmark analysis procedures, there was assumed to be no difference in appliance and plug load usage. Since the house includes no mechanical ventilation, this was not accounted for in the analysis. Electric and gas energy savings of 36% and 27% respectively were estimated vs. the Benchmark.

Table 1: Simulated Annual Site Energy Use Comparison

End Use	Annual Site Energy					
	BA Benchmark		Region Standard		BA Prototype	
	(kWh)	(therms)	(kWh)	(therms)	(kWh)	(therms)
Space Heating	362	290.1	496	365.1	337	239.6
Space Cooling	9148	0	5824	0	2368	0
DHW	0	267.9	0	267.9	0	141.2
Lighting	3200		3200		3200	
Appliances + Plug	6280	106.7	6280	106.7	6280	106.7
OA Ventilation	0		0		0	
Total Usage	18990	664.7	15800	739.7	12185	487.5
<i>Site Generation</i>	0	0	0	0	0	0
<i>Net Energy Use</i>	18990	664.7	15800	739.7	12185	487.5

² Freus performance was reported in Deliverable 8.C.2.

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Table 2 lists annual source energy use using the Benchmark source energy conversion factors of 10.78 source kBtu's per kWh for electricity and 102,000 source Btu's per Therm for gas. The house as built ("prototype") used about 34% less source energy than the Benchmark, whereas the Title 24 design is about a 10% improvement over the Benchmark. The greatest end use savings were achieved by reducing cooling energy use (74%), followed by water heating (47%) and space heating (16%). Plug loads and miscellaneous electrical usage constituted the greatest source energy usage at 43%, followed by lighting (19%), space heating (16%), space cooling (14%), and water heating (8%).

Table 2: Simulated Annual Source Energy Use Comparison

End Use	Estimated Annual Source Energy			Source Energy Savings			
	MMBtu per Year			Percent of End-Use		Percent of Total	
	Benchmark	Regional Standard	Prototype	Bld. Am. Base	Regional Base	Bld. Am. Base	Regional Base
Space Heating	33.5	42.6	28.1	16%	34%	2%	6%
Space Cooling	98.6	62.8	25.5	74%	59%	27%	15%
DHW	27.3	27.3	14.4	47%	47%	5%	5%
Lighting	34.5	34.5	34.5	0%	0%	0%	0%
Appliances + Plug	78.6	78.6	78.6	0%	0%	0%	0%
OA Ventilation	0.0	0.0	0.0	-	-	0%	0%
Total Usage	272.5	245.8	181.1	34%	26%	34%	26%
<i>Site Generation</i>	0.0	0.0				0%	0%
<i>Net Energy Use</i>	272.5	245.8	181.1	34%	26%	34%	26%

5.2 Diagnostic Test Results

House pressurization tests (conducted at 50 Pa) yielded a total leakage under pressurization of 1976 cfm equating to 0.17 natural air changes. Duct pressurization tests resulted in leakage to outdoors of 31 cfm at 25 Pa, or 3.3% of system airflow, well below the 6% Title 24 requirement for "tight" ducts.

Airflow test results are presented in Table 3. The design airflows for each space represent the expected airflow when the zones where the rooms are located are active (the values in the Design column are not additive). The totals at the bottom of the table are total airflows measured when each of the individual zones is active. The measured total airflow was close to the design airflow of 920 cfm in most cases, and except in one case, always greater than 400 cfm per ton. In most cases, the dump zone tended to steal airflow from the zones that were calling, and design airflow rates in those rooms with controlled airflow were not achieved. Despite this finding, there have been no comfort complaints from the owners.

Table 3: Results of Airflow Tests

Room	Design	THERMOSTAT CALLING			
		Bed. 1&2	Kitchen	Office	M. Bedrm
Entry/Dining	160	0	0	147	0
Office	240	0	0	137	0
Kitchen and Family*	300	219	271	200	226
Nook and Kitchen*	400	230	319	206	235
South bed	240	153	0	0	0
East bed	160	157	0	0	0
Living*	160	121	160	116	128
M.Closet*	60	38	44	38	41
M. Bed	240	0	0	0	128
M. Bath	160	0	0	0	192
	Totals	918	794	844	950

*"Dump" zones, or zones with no damper control

5.3 Monitoring Results

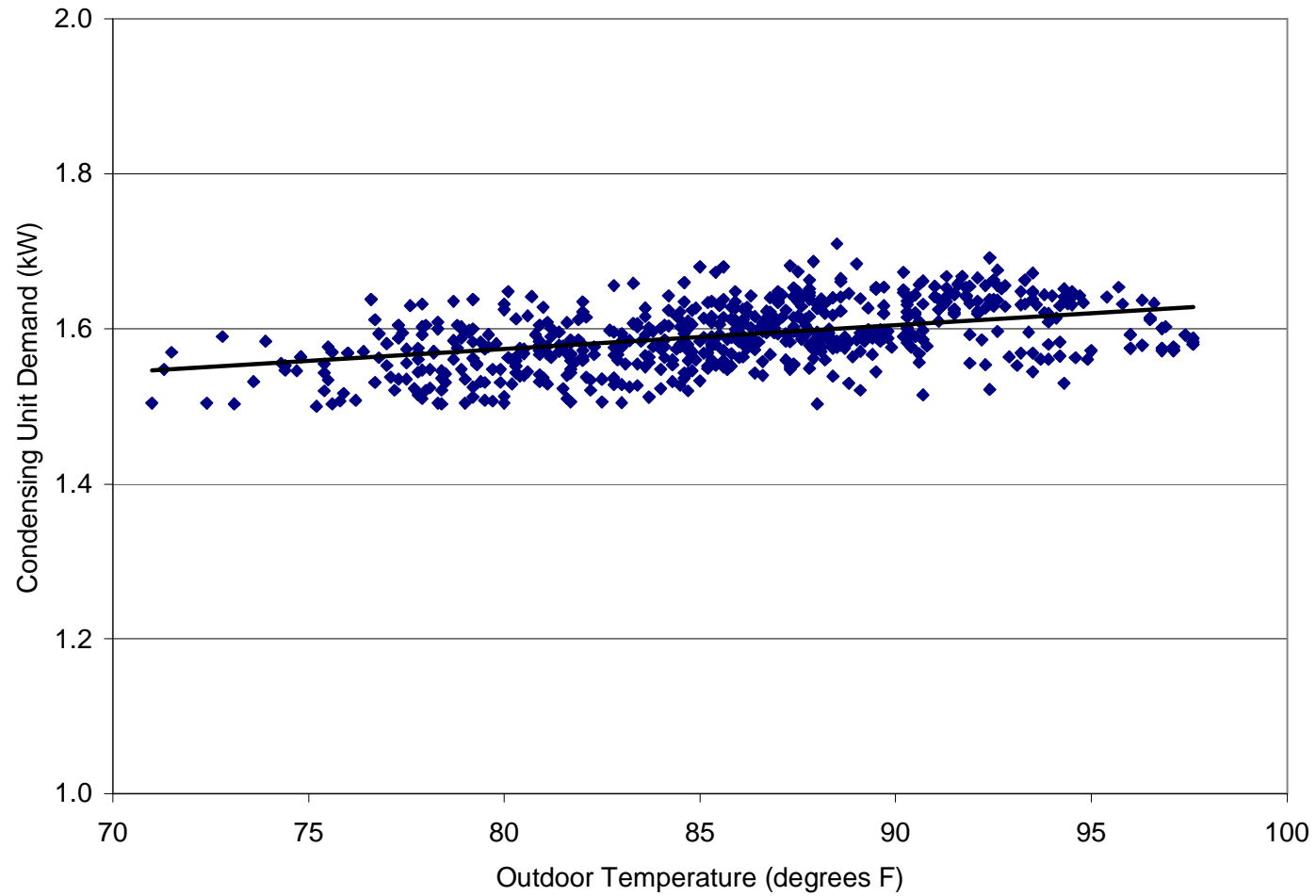
A primary goal of monitoring was to determine how closely actual energy use was predicted by simulated use. Table 4 compares the simulated (modeled) energy use for the prototype to monitored use for each month. Compressor, fan, gas space heating, and gas water heating end uses are broken out by month. Monthly monitored vs. modeled compressor energy use varied substantially, but the period total only differed by 43%. The lower measured compressor use suggests the DOE-2 model of the Freus may have under-estimated performance. Similar large variations are seen with fan energy, though the period totals only differed by 2%. The least variation occurred with combined space and water heating gas use, which over the period were equivalent for the modeled vs. monitored results.

Table 4 also provides a comparison of savings relative to the Benchmark for the modeled vs. monitored data. Because the savings vs. the Benchmark are relatively large, there is not a large difference between the percentage savings determined using actual vs. simulated prototype data.

Table 5 summarizes the energy use data provided in Table 4, and converts total usage to source energy units. Since this table includes only cooling, heating, and water heating data and excludes lighting and miscellaneous use, the 57-60% energy savings listed is greater than the 34% energy savings shown in Table 2.

The performance of the Freus was also of interest. The lack of energy delivery data prevents calculation of an EER, but Figure 2 shows how the energy use varied with outdoor temperature. A typical condensing unit will draw about 1 kW per ton of nominal capacity at ARI conditions of 95°/67°, whereas the two-ton Freus condenser drew less than 1.7 kW under these conditions.

Figure 2: Freus Power vs. Outdoor Drybulb Temperature



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Table 4: Comparison of Modeled vs. Monitored HVAC and Water Heating Energy Use by End Use and Month

ELECTRICAL USE (SITE kWh)						
Compressor Energy						
	Benchmark	Modeled	Monitored	% Error Modeled vs. Monitored	Modeled Savings vs. BM	Monitored Savings vs. BM
August	1840	500	530.7	-6%	73%	71%
Sept	1370	330	128.7	156%	76%	91%
Oct	800	130	5.2	2400%	84%	99%
Nov	0	0	2.4	-100%	-	-
Dec	0	0	4.2	-100%	-	-
Totals	4010	960	671.2	43%	76%	83%

GAS USE (SITE Therms)						
Space Heating						
	Benchmark	Modeled	Monitored	% Error Modeled vs. Monitored	Modeled Savings vs. BM	Monitored Savings vs. BM
August	0	0	0	-	-	-
Sept	0	0	0	-	-	-
Oct	2.6	1.7	2.6	-35%	35%	0%
Nov	33.3	28.5	16.7	71%	14%	50%
Dec	85.2	59.7	42.2	41%	30%	50%
Totals	121.1	89.9	61.5	46%	26%	49%

Cooling Fan Energy						
	Benchmark	Modeled	Monitored	% Error Modeled vs. Monitored	Modeled Savings vs. BM	Monitored Savings vs. BM
August	290	110	154.9	-29%	62%	47%
Sept	220	70	42.5	65%	68%	81%
Oct	128	18	1.6	1025%	86%	99%
Nov	0	0	2.9	-100%	-	-
Dec	0	0	0	-	-	-
Totals	638	198	201.9	-2%	69%	68%

Domestic Hot Water						
	Benchmark	Modeled	Monitored	% Error Modeled vs. Monitored	Modeled Savings vs. BM	Monitored Savings vs. BM
August	20.6	10.2	11.0	-7%	50%	47%
Sept	19.9	9.8	14.2	-31%	51%	29%
Oct	21.1	10.6	10.6	0%	50%	50%
Nov	21.4	11.1	20.2	-45%	48%	6%
Dec	23.2	12.4	26.0	-52%	47%	-12%
Totals	106.2	54.1	82.0	-34%	49%	23%

Heating Fan Energy						
	Benchmark	Modeled	Monitored	% Error Monitored vs. Modeled	Modeled Savings vs. BM	Monitored Savings vs. BM
August	0	0	0	-	-	-
Sept	0	0	0	-	-	-
Oct	2	2	6.8	-71%	0%	-240%
Nov	40	20	15	33%	50%	63%
Dec	110	50	32	56%	55%	71%
Totals	152	72	53.8	34%	53%	65%

Total Gas Use						
	Benchmark	Modeled	Monitored	% Error Modeled vs. Monitored	Modeled Savings vs. BM	Monitored Savings vs. BM
August	20.6	10.2	11.0	-7%	50%	47%
Sept	19.9	9.8	14.2	-31%	51%	29%
Oct	23.7	12.3	13.2	-7%	48%	44%
Nov	54.7	39.6	36.9	7%	28%	33%
Dec	108.4	72.1	68.2	6%	33%	37%
Totals	227.3	144.0	143.5	0%	37%	37%

Table 5: Summary of Modeled vs. Monitored Energy Use for HVAC and Water Heating

		Benchmark	Modeled	Monitored	% Error Monitored vs. Modeled	Modeled Savings vs. BM	Monitored Savings vs. BM
Total Electric Energy	Site	4800	1230	926.9	33%	74%	81%
	Source	51.7	13.3	10.0	"	"	"
Total Gas Energy	Site	454.6	288.0	287.0	0%	37%	37%
	Source	46.4	29.4	29.3	"	"	"
Total Source Energy		98.1	42.6	39.3	9%	57%	60%

Notes: Site Electric is in kWh and Site Gas is in Therms. Source energy is in MMBtu. All values are for the August through December period monitored.

6 Upgrade Costs and Economics

6.1 Cost of Improvements

The cost of the improvements to the house that were in excess of what they would have been for a house that meets the regional energy standard (Title 24), are listed in Table 6. The \$5139 incremental cost was passed on to the buyer with essentially no builder markups.

Table 6: Net Cost of Improvements

COST ADDITONS		
Additional labor cost for zero defect insulation		\$1,809
Additional cost for condensing water heater		\$2,200
Additional labor and material cost for water pipes for hydronic coil		\$200
Incremental cost of condensing unit		\$500
Incremental cost for high performance windows		\$380
Incremental cost for radiant barrier		\$0
Additional labor and materials for draftstopping attic		\$400
Incremental cost of R8 ducts		\$50
Additional cost of ceiling insulation		\$0
	Total Cost Additions	\$5,539
COST REDUCTIONS		
Eliminate gas lines to furnace		-\$200
Smaller and shorter duct runs due to optimized system and lower need for heating and cooling (due to higher insulation level)		-\$500
	Total Cost Reductions	-\$700
NET COST		\$5139
HOUSE SALE PRICE		\$1,205,200
% COST OF IMPROVEMENTS		0.4%

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The builder considered the incremental costs of some items too small to report, hence the zero entries for radiant barrier and added ceiling insulation. Some of the measures were sold as comfort amenities (hydronic floor in bathroom, four zone AC system) for a premium, negating the need for the builder to reduce his profit margin or raise the price to recover costs.

One of the best ways to evaluate the economic value of improvements from the buyer's perspective is to determine the annual cost of ownership based on the added incremental mortgage payments for the improvements and utility cost savings. Table 7 compares amortized costs (at 6% over 30 years) and energy savings of the base case (Title 24 compliant) house and the improved prototype. Utility rates were assumed to be flat and maintenance costs equivalent in this analysis, which shows a positive cash flow of \$268.

Table 7: Cash Flow Comparison, Title 24 Compliant House vs. Prototype

	Title 24 House	Prototype	Difference
Sale price	\$1,200,000	\$1,205,200	
Annual mortgage payment	\$72,000	\$72,312	\$312
Annual Electric Cost	\$1,389	\$1,072	-\$317
Annual Gas Cost	\$666	\$439	-\$227
Net Annual Cost	\$71,436	\$70,859	-\$268

7 Non-Energy Benefits and Costs

7.1 Occupant Comfort and Health

Comfort benefits are expected from the well-sealed building envelope and ductwork, high performance windows, and from supply air temperatures that are lower than what is typically delivered by furnaces. Monitored indoor air temperatures show that the two-ton Freus air conditioning system had adequate cooling capacity. The highest outdoor temperature recorded during the August-to-December monitoring period (on August 13) was 97.6°F. The maximum indoor temperature on that day was 72.8°F. During the cooling season temperatures were maintained in the 68-75° range.

During the heating season indoor temperatures generally ranged from 68-74°. The peak heating event occurred on a day that reached a low of 29.3°F while the indoor temperature was maintained at 67.4°F. The radiantly heated floor in the master bathroom is undoubtedly contributing to comfort by raising the temperature of the tiled floors.

The tight construction of the house and the lack of a mechanical ventilation system suggests that indoor air quality could be an issue. Occasional drops in indoor temperature during the winter and increases during the summer suggest that windows were used for ventilation to some extent.

7.2 Durability, Maintainability, and Reliability

Most of the energy measures incorporated will yield energy savings over the life of the house with no need for maintenance or replacement. These include high performance windows and shading, insulation and draft stopping, and the radiant barrier.

Some of the measures included in the home contribute to durability and reduced maintenance costs. For example, mastic-sealed duct joints will probably not require re-sealing over the lifetime of the house. The reduced heating and cooling loads will result in longer equipment life because of the fewer operating hours required.

The mechanical energy measures may require more maintenance than standard equipment. Igniter failure is common with some condensing water heaters, and there is not sufficient experience with Freus evaporative condensers to predict what maintenance costs will be.

8 Conclusions & Recommendations

8.1 Construction Quality Assurance

This project verified that attention to detail and higher standards of quality, combined with efficient HVAC and water heating equipment, can produce savings that exceed 30% relative to the Building America Benchmark. In this case, the contractor himself insured the quality installation of insulation and HVAC systems. Widespread implementation of quality control will require inspections by trained personnel. Since building officials are not likely to fill this role due to their multiple responsibilities, energy raters are the best candidates. Eventually, ongoing inspections and remediation should lead to improved quality from installing subcontractors, thereby decreasing the time and cost of inspections.

Careful equipment sizing is an important component of quality assurance that allows equipment savings resulting from reduced size to offset the cost for more efficient equipment. In this case, Manual J calculations that took into account the improved quality and higher R-value of insulation, window shading, and other factors were used to justify much smaller heating and cooling systems than contractors would normally have been inclined to install.

8.2 Accuracy of Models and the Need for Additional Field Data

Despite that monitored summer indoor temperatures (and presumably thermostat settings) were much lower than the 76°F Benchmark assumption, monitored condensing unit usage was 43% lower than modeled. This difference could stem from two factors: (1) better envelope performance than predicted, and (2) inexact modeling of the evaporative condenser. Building America affords an opportunity to improve modeling techniques by calibrating DOE-2 and other models using monitored performance. The collection of data to facilitate calibration (either by the teams or NREL) is an effort that should be considered in future task orders. Also, computer predictions of evaporative condenser performance would benefit greatly from either the development of an evaporative condenser model, or development of inputs for the existing evaporative pre-cooler model that could better emulate evaporative condenser performance. Both lab and field test data

are now available that can be used to facilitate this effort, and more detailed performance data will be obtained from the Borrego Springs project.

8.3 Persistence of Savings

Persistence of savings is a subject that Building America should be addressing. An effort to track long-term performance of emerging technologies and systems would yield valuable information on their maintenance costs, lifetimes, and the persistence of energy savings that could be used to guide future design and equipment selection decisions. For example, the significant savings resulting from the evaporative condenser in this climate suggest that its use should be widespread provided that its performance does not degrade significantly, and that maintenance costs do not compromise energy savings.

APPENDIX

Floor Plan



Entry – North Elevation



West Elevation and Freus Evaporative Condenser



South Elevation and Architectural Shading



South Elevation



East Elevation



Polaris Condensing Water Heater



Air Handler and Evaporator Coil

