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Creating Energy Independence

Flexible Residential Test Facility Instrumentation Plan

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March 2012

Authors

Robin Vieira
John Sherwin

1679 Clearlake Road
Cocoa, Florida 32922, USA
(321) 638-1000

www.floridaenergycenter.org

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BUILDING TECHNOLOGIES PROGRAM

Flexible Residential Test Facility Instrumentation Plan

R. Vieira and J. Sherwin

March 2012

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U.S. Department of Energy

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Flexible Residential Test Facility Instrumentation Plan

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Prepared by:

Robin Vieira and John Sherwin

Building America Partnership for Improved Residential Construction

Florida Solar Energy Center

1679 Clearlake Rd

Cocoa, Florida, 32922

NREL Technical Monitor: Stacey Rothgeb

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Contents

List of Figures

List of Tables

Definitions

ACH50	Air Changes Per Hour (at 50 Pascals between inside and outside)
AWG	American Wiring Gauge
BA	Building America
BA-PIRC	Building America Partnership for Improved Residential Construction
Btu/hr	British Thermal Units Per Hour
DOE	Department of Energy
EF	Energy Factor
FESC	Florida Energy Systems Consortium
FRTF	Flexible Residential Test Facility
FSEC	Florida Solar Energy Center
HPWH	Heat Pump Water Heating
HVAC	Heating, Ventilation, and Air Conditioning
kW	Kilowatt
kWh	Kilowatt Hour
kWp-dc	Kilowatt Peak–Direct Current
PLC	Power Line Carrier
PV	Photovoltaic
PVC	Polyvinyl Chloride
Qn	Normalized air distribution system leakage
RBS	Radiant Barrier System
R-value	Measure of Thermal Resistance
SEER	Seasonal Energy Efficiency Ratio
SIR	Savings-to-Investment Ratio

Executive Summary

The state of Florida provided funding for the design and construction of two reconfigurable, geometrically-identical, full-scale, side-by-side residential building energy research facilities at FSEC. The Building America Partnership for Improved Residential Construction (BA-PIRC) has instrumented these flexible research homes, and will monitor them to conduct research on advanced building energy-efficiency technologies under controlled conditions.

The purpose of the Flexible Residential Test Facility (FRTF) is to provide a controlled research environment that will serve two main purposes; first it will be used to research and evaluate advanced energy-efficiency technologies and operational strategies. Secondly, it will serve as a venue to validate building simulation programs and algorithms. Built to be continually re-configured, the FRTF will provide a cost effective means to study and optimize residential energy performance related to both individual building efficiency measures as well as the interactions between building energy systems and their environment for many years to come.

This report provides the status of the instrumentation and a test plan for the facility. As this is the first Building America (BA) report on the facility, a description of the design and construction is included as well.

The FRTF is comprised of two identical, side by side residential buildings. The homes are 32’ x 48’ (1,536 ft^2), single story, slab on grade structures with 20’ x 20’ attached garages. The initial envelope configuration involves constructing both homes with infiltration, insulation levels and windows reflecting pre-energy code construction in Florida of the 1960s or early 1970s. The exterior walls are uninsulated concrete block with single-pane windows. The homes are designed with equal window openings on each side and 2’ overhangs around the entire perimeter. The homes allow for three different mechanical system locations popular in Florida – attic, interior and garage. After a null test (monitored period with both homes configured the same), a detailed experimental plan proposes retrofits to one home performed in a sequentially phased manner, much like an incremental cost-effectiveness analysis might select retrofit measures. The second home will remain a control home. The improvements will be determined through a detailed optimization analysis including measures such as:

- Increasing insulation levels
- Improving widows with solar control glazing, tinting, and shading
- Reducing infiltration
- Improving HVAC efficiency
- Improving or replacing ducts
- Retrofitting radiant barrier, white metal roof, or white shingles
- Changing to compact fluorescent lighting
- Improving hot water systems or adding tank/pipe wrap
- Upgrading to ENERGY STAR® appliances

Future testing may investigate complex measures such as sealed attic construction, smart-ventilation schemes, impact of heat pump water heaters on space conditioning loads, and “interiorized” ducting.

Another principal use of the facility will be to investigate specific heat and moisture transport phenomena in hot humid climates. Proposed testing will provide a comprehensive set of empirical residential building energy use data sets (one control and one alternative – simultaneously in the time domain) that can be confidently used to verify the accuracy of engineering models used for retrofit simulation and analysis. The thermal mass and moisture capacity of interior walls will be simulated with temporary building materials and furnishings. In addition, internal gains (sensible and latent) will be simulated with the agreed upon Building America (BA) base case internal load profiles currently under development to be used by all teams. The sensitivity of some results to the internal load schedule will be determined by modifying these profiles and set points (e.g. to mimic an energy conscious or energy intensive lifestyle or different occupancies).

1 Background

The majority of research within the Building America program is based on data taken from a myriad of residential structures with varying construction details, architectural styles and occupancy levels. While this can lead to valuable information about field operations or customer satisfaction levels of a given measure or technology, it is difficult to equate cause and effect with the same high degree of confidence that one might expect in a controlled environment. Also, time constraints often require that project data be taken within a single season. Where pre and post retrofit studies within a single home are concerned, there is increased risk associated with this approach. Changing weather patterns, occupant behavior, and retrofit implementation delays can greatly affect project outcome.

Recommendations given to Building America partner builders to achieve program goals are determined through building simulations. Building simulations, like EnergyPlus, continue to improve but conducting necessary validation of energy models is difficult. Comparative software tests, such as HERS BESTEST (Judkoff and Neymark 1995), involve comparing tested software predictions to "reference software" predictions for a well-defined base-case model and test cases that represent changes relative to the base-case model. While comparative software testing is useful for identifying coding errors and differences relative to other software, additional empirical data are needed to validate software programs (including reference programs in comparative tests).

In fall 2010, FSEC completed construction of the Flexible Residential Test Facility (FRTF). Funded through the Florida Energy Systems Consortium, the facility is comprised of two identical residential homes. Throughout the construction process, on-site personnel closely monitored the job site to enforce the same construction on each building. Installation of some instrumentation ran concurrent with the construction. During construction, sensors and wiring were placed in the ground, slab and walls for detailed monitoring. Other instrumentation (surfaces, attic, mechanical) were added after construction was completed.

1.1 Potential Experiments

The primary goal of the FRTF is to provide a controlled research environment that will be used to evaluate advanced energy-efficiency technologies and operational strategies in a hot, humid climate. It will also serve as a venue to validate building simulation programs and algorithms. Using one building as a control, systems and technologies can be evaluated in a structured environment. The current test plan includes:

- Evaluating strategies to cost effectively retrofit poorly insulated walls and attics.
- Quantifying the effects of flooring options (e.g. carpet vs. tile) on the efficiency of ground coupled (slab) construction. Evaluating effects of slab edge insulation.
- Determining the extent of the energy and interior moisture impacts of air conditioner sizing coupled with varying amounts of duct leakage for a range of SEER technologies.
- Maximizing roofing system performance, specifically concerning vented vs. sealed attics and including their interaction with attic ductwork performance.

- Evaluating high R-value windows. Assessing other window shading options (overhangs, awnings etc), frame types, frame color and glazing types.
- Quantifying effects of duct insulation, leakage and location.
- Examining structures cooled by innovative cooling and distribution systems such as variable frequency drive SEER24+ multi-zone equipment and desiccant based technologies as well as building integrated technologies such as NightCool (a passive cooling concept utilizing night sky radiation).
- Researching innovative water heating technologies: advanced solar water heating systems with smart controls combined with HPWH back-up integrating cooling and dehumidification
- Comparing innovative hot water distribution systems to minimize water and energy use.

2 Design and Construction

The side-by-side residential test structures were designed in late 2009 and early 2010.

2.1 Design

Key factors and timeline progress steps with regard to the design included:

- In order to be most flexible for future research, the homes needed to reflect the existing home market and also be able to represent new homes through minor changes.
- Initially, windows were designed to be equally distributed on four sides with equal overhangs. This allowed window experiments independent of orientation if desired. Windows would also be easily replaceable.
- A Dutch hip roof design was used to provide equal overhangs and still allow an adequate ridge size for attic ventilation.
- The test structures were designed to be full-size to avoid any scaling problems with building loads.
- A decision was made to use concrete block construction, as found in most existing homes in the more heavily populated southern half of Florida. Thus, walls were not made flexible (non structural walls were planned with structural columns early in the design process, but were dropped in favor of structural block walls).
- Walls were designed to be un-insulated, painted concrete block as found in homes in the 1950s through 1970s in Florida. Stucco and minimal wall insulation became more dominant in the 1980s.
- Attic and roof were designed to have conventional shingle with vented attic and R19 ceiling insulation.
- A raised catwalk was designed in the attic space to allow easy maneuvering for changing out instruments without disturbing the thermal performance of ceiling insulation.

- Installation of minimal efficiency HVAC (SEER 13 electric heat pump water heater) and electric resistance water heating equipment (50 gallon, EF 0.91) as well as ductwork with R6 insulation was included in the design.
- Final site selection was made to have the structures sit next to one another with 65' between them. A shading analysis was completed indicating minimal shading at that distance.
- Documents were put out to bid in April 2010. A rendering and floor plan are shown in Figures 1 and 2. The floor plan is for reference; no interior walls and no bathroom build out were in the actual plans, but the plumbing and duct layout follow the floor plan.

Figure 1. Design phase rendering of homes.

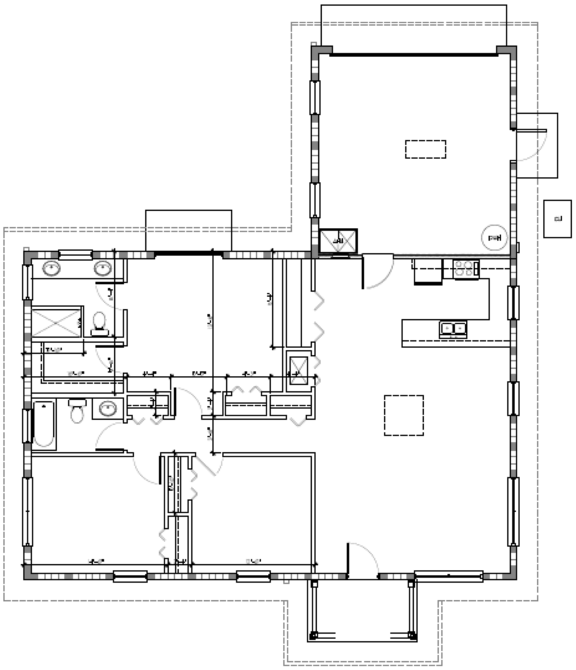

Figure 2. Floor plan for full build out of homes of the dimensions built. In the constructed homes, there are no interior walls or bath fixtures and the kitchen area has a small counter and east facing sink. Note garage, hallway and attic location possibilities for air handler.

2.2 Construction

Key events with regard to construction were:

- Bids were submitted by four companies. Contractor bids for the construction (funded by FESC), were opened on June 11, 2010. The lowest bid for State of Florida / University of Central Florida **Flexible Residential Test Structure** FI 10FSEC01 was from Jordan Development and Construction LLC for just under $300,000. The contract was signed in July 2010.
- Construction on the side-by-side lab homes began in August 2010. Utilities were run to the site. Each site was filled to the same height, mixing and leveling the dirt for both pads to provide similar ground characteristics for both homes. Sensors to measure ground temperature were specified and installed in September 2010 prior to pouring of the slabs.
- By the end of September 2010, the slab, walls and roofing system were largely completed for the two homes. (See Figures 3 - 5).
- Wall sensors to measure temperatures were installed prior to the drywall phase of construction.
- Exterior walls were painted.

Figure 3. Construction phase shows trusses on the East house and the West house shown without trusses in background.

Figure 4. Truss design provides a walkway above insulation level for easier experiment maneuverability.

Figure 5. September 30, 2010 photo shows plywood sheathing near completion. Dutch hip roof design allows for overhang on all four sides while providing an attic ridge area as well.

2.3 Short Term Test Results

Initial testing consisted of measuring solar absorptance of exterior finishes, conducting air leakage measurements, and an initial pre-instrumentation data collection phase where a single temperature/relative humidity probe was located in the center of each lab and monitored while all HVAC equipment was off.

2.3.1 Air Leakage

The envelope leakage of each lab was measured with a blower door using a five-point test on January 11, 2011, which followed extra contractor sealing of windowsills on the outside which were discovered to be leaky. The ducts were tested for leakage. Results are presented in Table 1. The envelope leakage was better than existing Florida homes we have tested, and the ductwork was tighter than most (see Figure 6). Additional envelope duct tightening or leakage may be added to the homes prior to beginning experimental testing.

Table 1. Home and Duct Leakage Test Results.

East Lab	West Lab
ACH50 = 3.82	ACH50 = 3.62
Qn = 0.050	Qn = 0.049

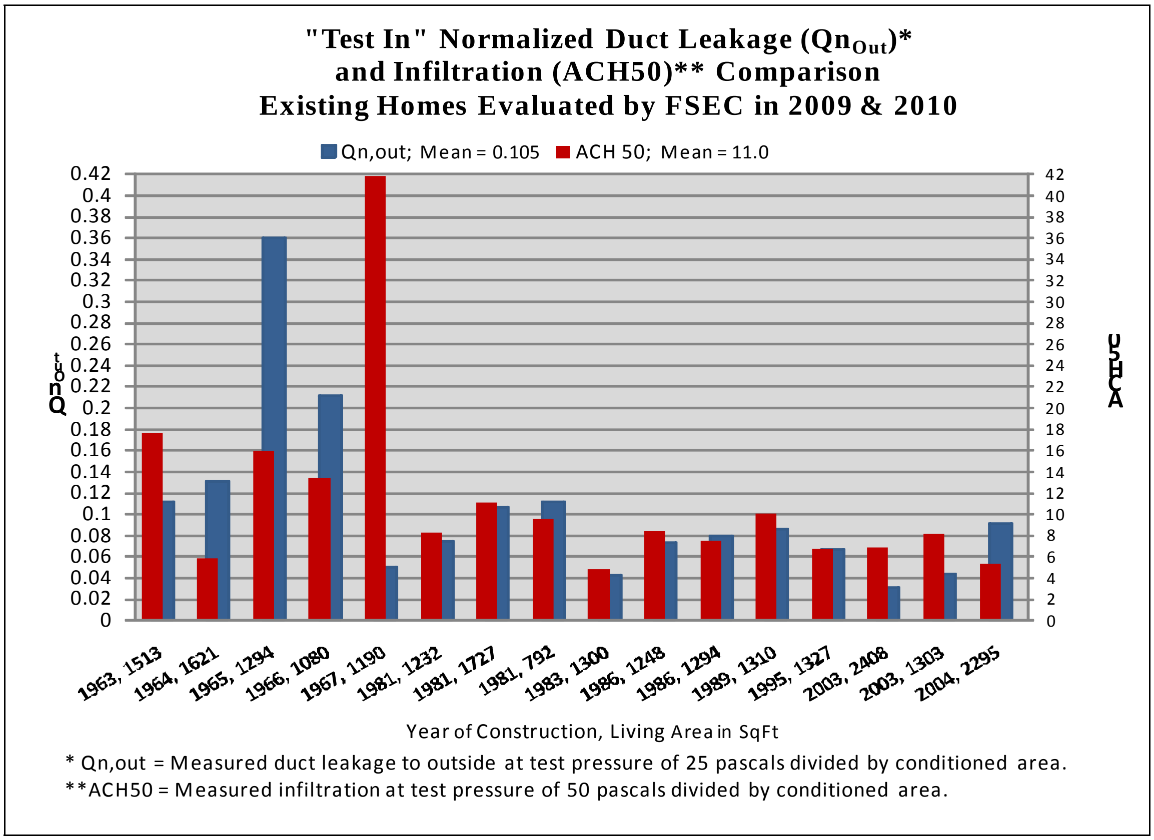

Figure 6. Existing home duct and home leakage measurements. (McIlvaine, 2010).

2.3.2 Solar Reflectance

Specimens of the painted concrete block and the roof shingle were sent to Atlas Material Testing Solutions lab. The solar reflectance results are shown in Table 2. The goal of achieving a wall solar reflectance in the 0.4 to 0.6 range was met. Although many modeled reference homes (HERS, IECC) use lower solar reflectance values, in our experience, existing and new home wall colors are typically much more reflective than the specified reference homes. The roof shingle is typical, with about 10% solar reflectance.

Table 2. Solar Reflectance of Wall and Shingle.

Specimen Code	% Solar Reflectance
Painted cement block	56.5

Asphalt shingle	10.5

2.3.3 Passive-Mode Temperature and Relative Humidity

The homes operated in a closed, passive mode during parts of the first quarter of 2011. At other times staff were in the units installing instruments. No heating, cooling or natural ventilation occurred, and no internal loads were generated. The buildings tracked each other well, as shown in Figure 7. Blinds were installed on March 22 in the East lab (except for the North-facing sliding glass door blinds which were installed on March 24) and on March 24 on the west lab. Thus, March 23 was a short experiment where one home had blinds turned so that the majority of light was blocked (see Figure 8). As expected, the East building stayed cooler in the afternoon, as shown in the March data comparing no blinds on March 20 to the March 23 plot. Two April plots showed excellent agreement on a cloudy April 15, but some slight differences on the hottest day measured, April 28 (see Figures 9 – 12).

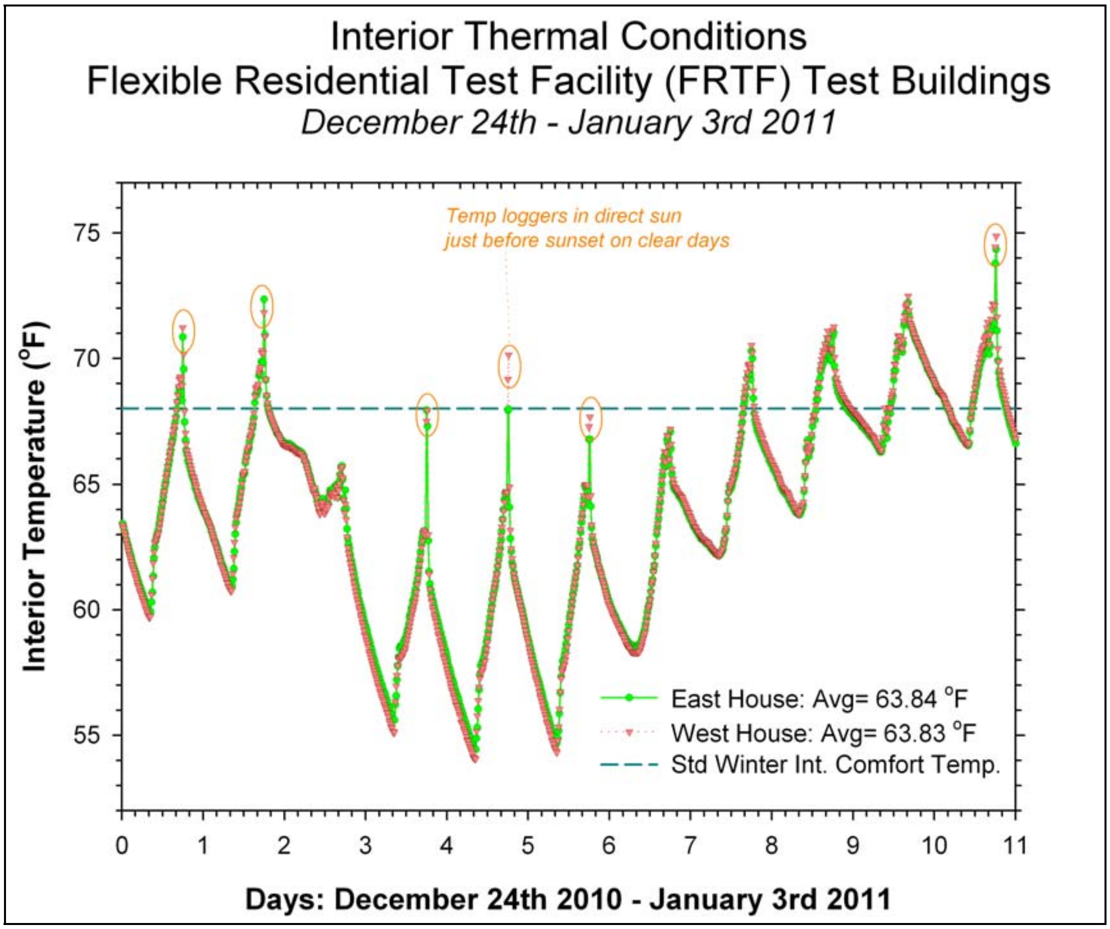

Figure 7. Multi-day test indicating close agreement in temperature between two labs operated without any HVAC system.

Figure 8. Typical blind configuration during late March and April 2011.

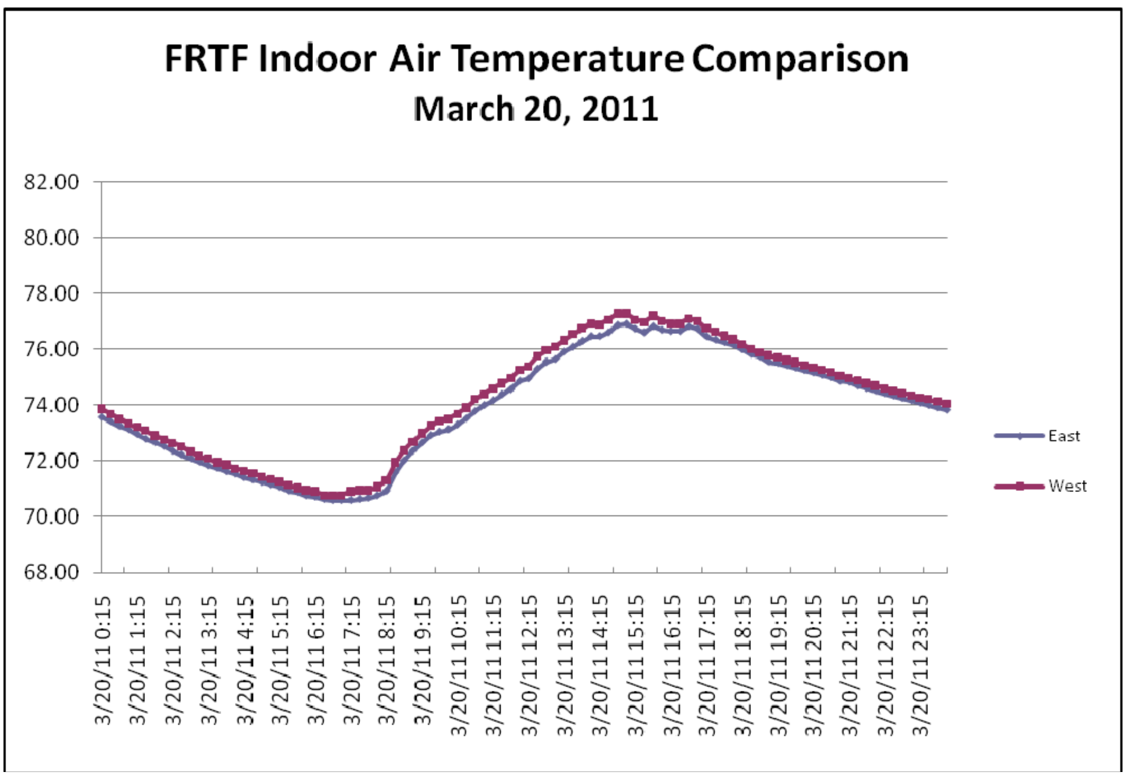

Figure 9. FRTF temperature without HVAC track well prior to installing blinds.

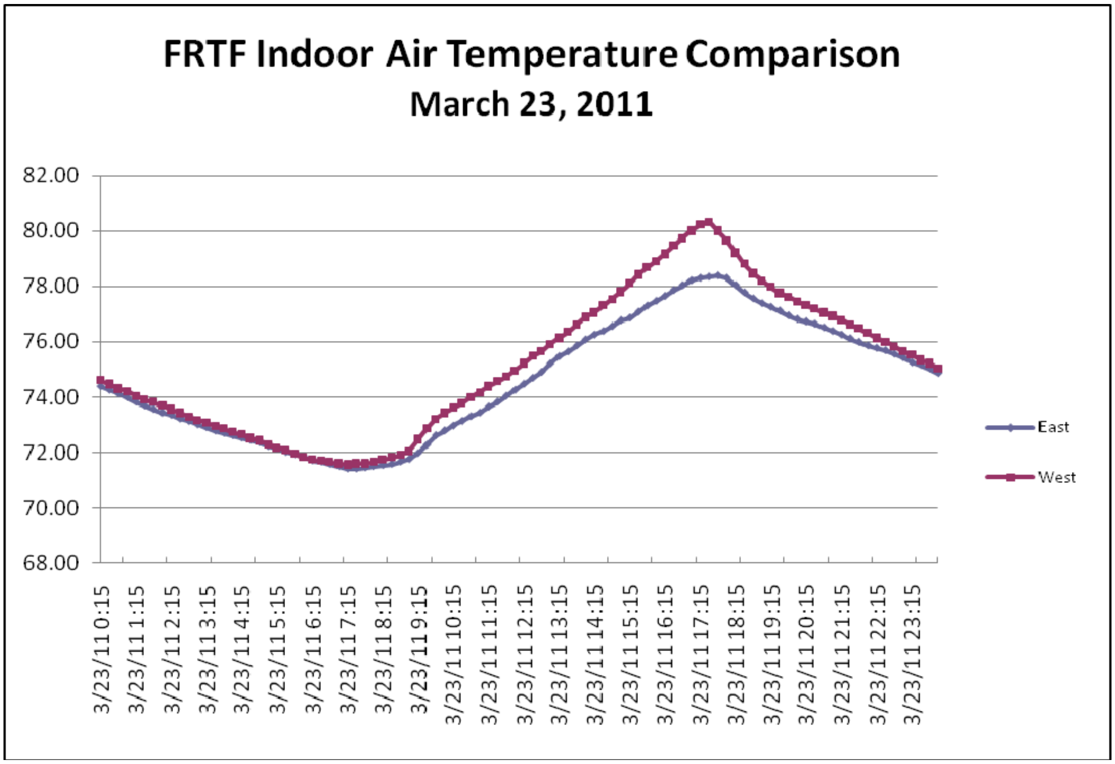

Figure 10. March 23rd demonstrates temperature differences with blinds installed on East home windows and no blinds on West home.

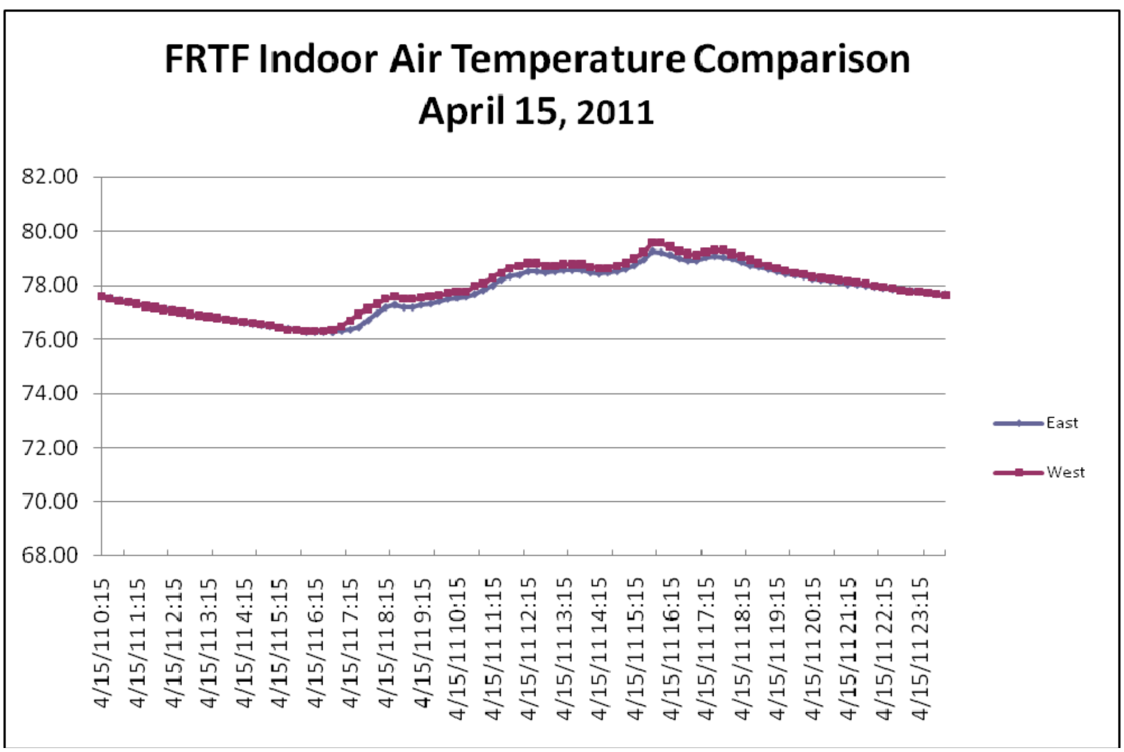

Figure 11. Data tracking well on cloudy day.

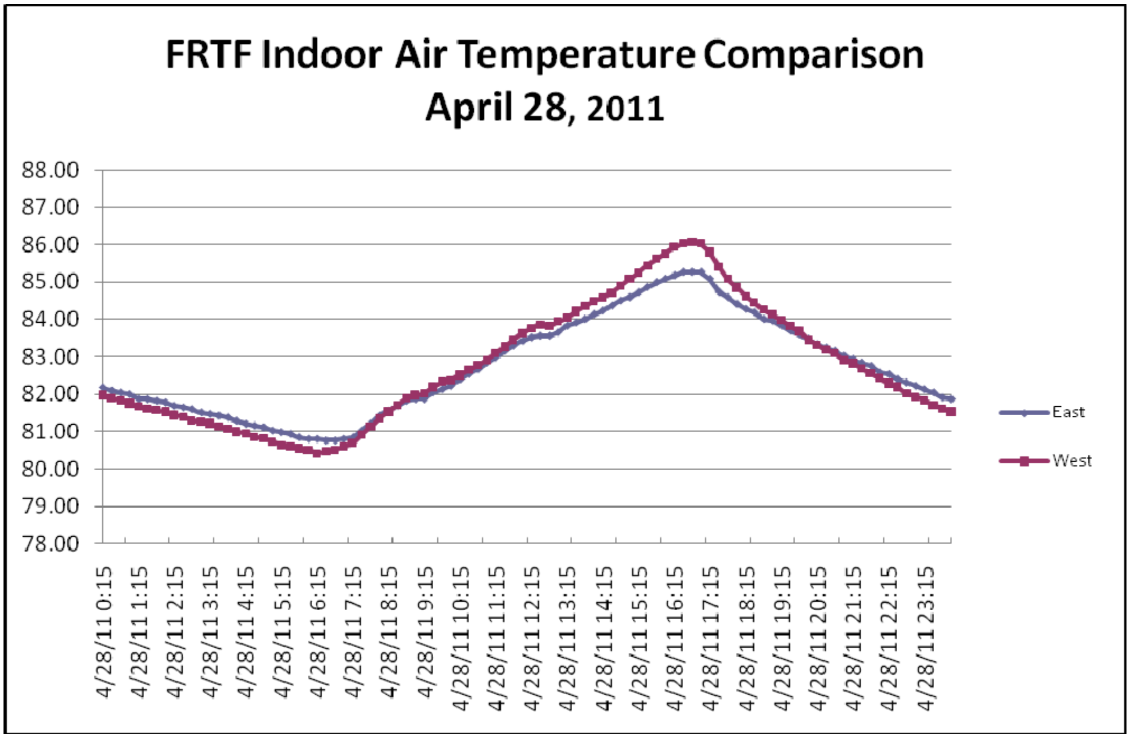

Figure 12. Peak day in April shows some slight difference in temperatures.

2.4 Completed Construction

Construction of the flexible residential test structures was completed in December 2010 (see Figure 13). A number of DOE staff toured the facility when they visited the Florida Solar Energy Center in January 2011 during the International Builders Show. A press release on the facility was distributed (See Appendix).

Figure 13. Completed flexible residential test structures on FSEC campus.

3 Instrumentation

Data will be taken on meteorological parameters, ground temperatures, the envelope, the HVAC system, and interior space conditions. The instrumentation package will consist of multiple dataloggers and associated peripherals. The proposed configuration will allow over 200 data channels to be monitored and collected in each building. Sensors will be polled every 10 seconds and averaged over a 15 minute interval. The averaging routine can change if needed for a particular experiment.

Temperature measurements shown in the following sections are taken with thermocouples made form Type T special limits of errors wire which conform to ANSI mc 96.1 (+/- 0.5 deg C or 0.4%). Previous work performed at the center using wire with these specifications has often shown accuracy to be better than 0.1 deg C.

3.1 Ground Instrumentation

Ground instrumentation was installed in September 2010. Sensors were installed to characterize and ground temperatures below the structures. Consisting primarily of thermocouples, over 75 sensors were installed under each slab at depths ranging from one to twenty feet. A well-digging company was brought in to help facilitate the ten-foot and twenty-foot holes. Water was reached at the eight-foot level the day of installing the ground sensors. All thermocouples were 22AWG type T, butt-welded and coated with thermal epoxy. They were attached to 3/8” PVC dowels for the ten and twenty foot length holes. Table 3 and Figure 14 indicate the sensor locations, and Figures 15 - 17 show some of the thermocouple installations. Soil moisture content will be monitored at the center of each structure and at a reference point between the two buildings. These measurements will take place at one and five foot depths.

Table 3. Under Slab Temperature Measurements.

Configuration	Quantity	0′	1′	2′	5′	10′	20′	Moisture at 1′ & 5′	Location
A	3	✓	✓	✓	✓	✓	✓	✓	Center of homes and midway between homes
B	6	✓	✓	✓	✓	✓	✓		Footer midway on east and west sides and two-feet out from home
C	12	✓	✓	✓	✓	✓			Corners of home and midway on North and South side footers
D	12	✓	✓	✓					Eight feet in from each corner in both directions and eight feet in from midway edge points on North and South sides

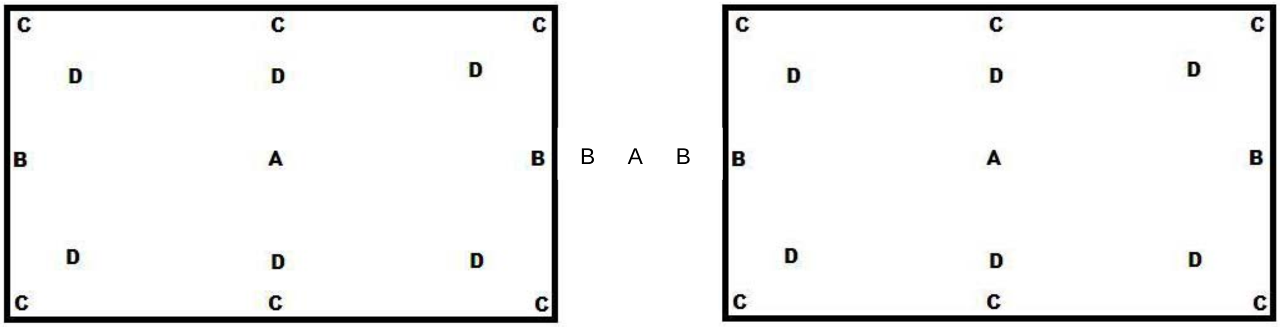

Figure 14. Under slab measurement location as described in Table 3.

Figure 15. Well is dug using water.

Figure 16. FSEC's John Sherwin measures for exact depth placement. Yellow strings mark top of slab.

Figure 17. PVC rod with thermocouples tied to it is lowered into hole.

3.2 Envelope Measurements

Table 4 summarizes locations of wall and roof temperature sensors. During construction, wall sensors were placed behind the drywall, as shown in Figures 18 and 19, and at locations depicted in Figure 20. The roof and attic sensor locations are shown in Figure 21.

Table 4. Wall and Roof Temperature Measurements.

Wall Surface Temperatures	Orientation	Height	Type	TC Channels	MV Channels	Pulse
Exterior block surface	n,s,e,w	mid wall	tc	4	-	-
Interior block surface	n,s,e,w	mid wall	tc	4	-	-
Drywall backside	n,s,e,w	mid wall	tc	4	-	-
Drywall interior surface	n,s,e,w	mid wall	tc	4	-	-
Furring strip	n,s,e,w	mid wall	tc	4	-	-
			total	20	-	-

Roof System Temperatures	Orientation	Height	Type	TC Channels	MV Channels	Pulse
Shingle above living space n/s	n,s	low,mid,high	tc	6	-	-
Living space decking n/s	n,s	low,mid,high	tc	6	-	-
Shingle above living space e/w	e,w	low,mid,high	tc	2	-	-
Shingle above garage space e/w	e,w	low,mid,high	tc	2	-	-
Garage space decking e/w	e,w	low,mid,high	tc	2	-	-
			total	18	-	-

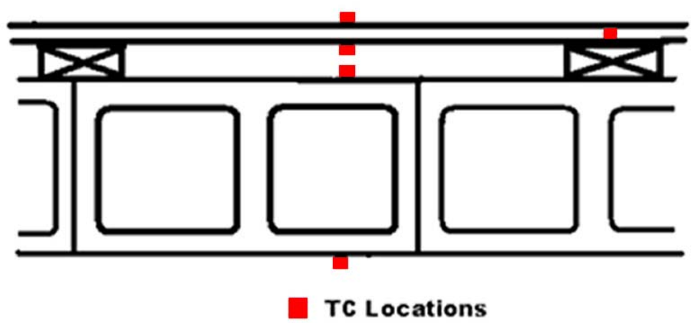

Figure 18. Wall temperature measurement locations.

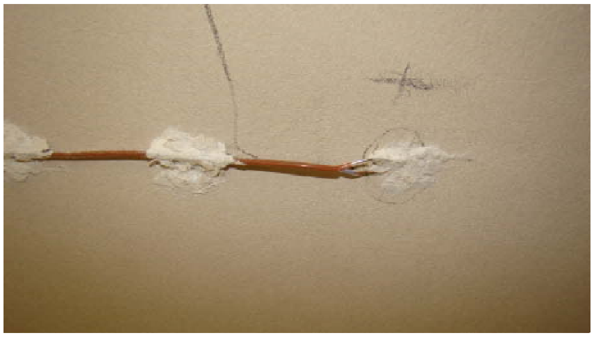

Figure 19. Thermocouple attached to concrete block and dry wall.

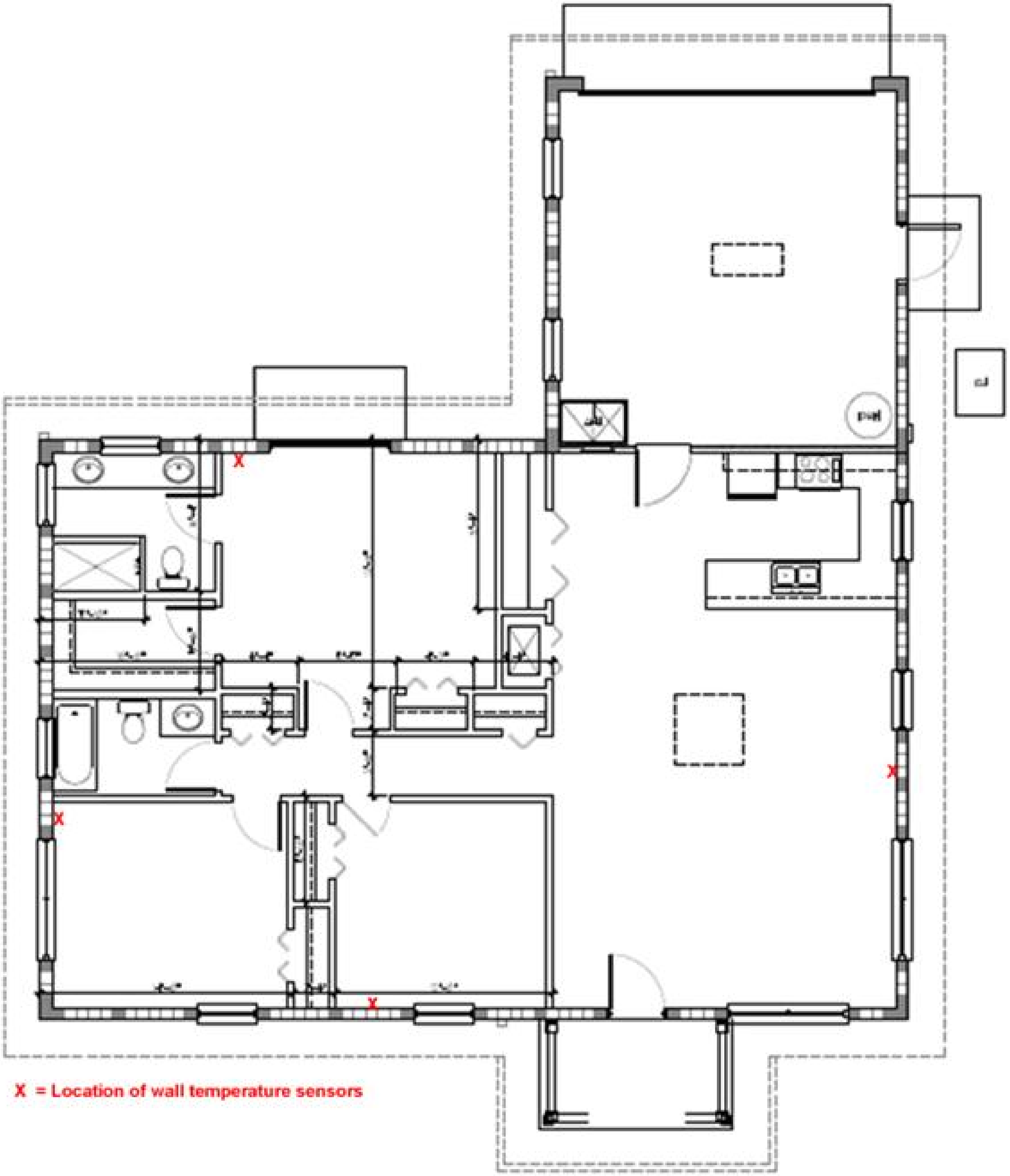

Figure 20. Floor plan showing wall temperature sensor locations.

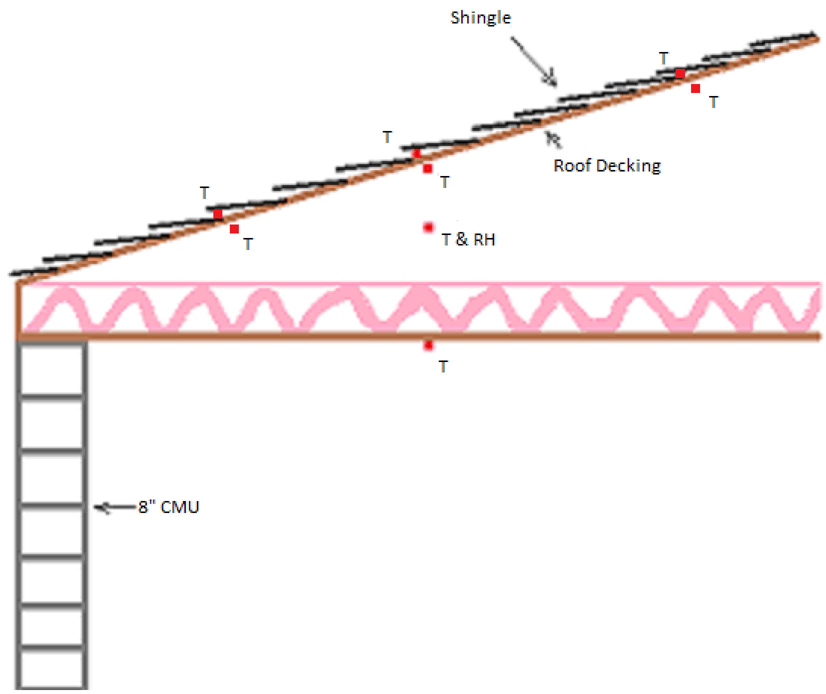

Figure 21. Attic and roof sensor locations.

3.3 HVAC and Interior Condition Measurements

Thermocouples were placed at important locations, and key power measurements are being taken, as indicated in Table 5.

3.4 Weather Tower Instrumentation

Meteorological parameters, shown in Table 6, will be taken on a 10-meter tower. A second wind speed measurement will be taken at roof height. Temperature sensors will be aspirated and shielded. Longwave radiation data will be taken from a pyrgeometer on the FSEC site within 25 yards of the lab buildings.

3.5 Automation

A PLC (power line carrier) automation system will provide control over sensible and latent loads in the FRTF. The automation system consists of a stand-alone master controller and point of use control modules. Commands from the master controller are sent to the modules over the test homes' power lines, providing flexible load placement and control.

Sensible load sources consist of an automation controlled standard 240V range oven (which also serves as an evaporative mechanism for latent loads) and automated dimmable heat lamps. The heat lamp output levels are varied throughout the day in accordance with a simulated occupancy schedule. WattNode® power meters provide power consumption data and help validate correct load control functionality. The automation instrumentation equipment is shown in Table 7.

Table 5. HVAC and Power Measurement Sensor Plan.

HVAC Performance	Location	Type	TC Channels	MV Channels	Pulse
Supply t/rh	Duct	t/rh volts	-	2	-
Return t/rh	Duct	t/rh volts	-	2	-
End of supply t/rh	Duct	t/rh volts	-	2	-
Airflow	Duct	volts	-	2	-
		total		8	

Interior Room Conditions	Location	Type	TC Channels	MV Channels	Pulse
Center t/rh	Center	t/rh volts	-	2	-
Center mrt	Center	tc	1	-	-
Ceiling surface	Center	tc	1	-	-
T stat t/rh	Tstat	t/rh volts	-	2	-
		total	2	4	-

Power/Use Measurements	Location	Type	TC Channels	MV Channels	Pulse
Air handler	-	pulse watt hrs	-	-	1
Condenser	-	pulse watt hrs	-	-	1
Interior fans	-	pulse watt hrs	-	-	1
Interior lights	-	pulse watt hrs	-	-	1
Outdoor lights	-	pulse watt hrs	-	-	1
Water heater	-	pulse watt hrs	-	-	1
Total use	-	pulse watt hrs	-	-	1
		total			7

Table 6. Meteorological Measurement Plan.

Weather	Type	TC Channels	MV Channels	Pulse
Ambient t/rh	t/rh volts	-	2	-
Solar irradiation (horiz)	volts	-	2	-
Solar irradiation (south roof plane)	volts	-	2	-
Wind speed-ambient	pulse	-		1
Wind direction-ambient	volts	-	1	
Wind speed-building	pulse	-	-	1
	total	-	7	2

Latent loads will come from water evaporated inside the range oven. Although FSEC has used showers in their manufactured housing lab, the difficulty with showers is not knowing how much moisture is delivered into the space. Since one of the goals of the buildings is to validate models, all moisture delivered to the space needs to be measured. A metered pump will supply the scheduled amount of water to the range oven over a 24 hour period. The quantity of water supplied to the range oven is validated by a Texas Electronics, Inc TR-4 tipping bucket, placed in the metered pump's water supply path.

Table 7. Automation Instrumentation Equipment.

Item	Quantity Per Home	Purpose
INSTEON® automation controller	1	Provide synchronized delivery of sensible and latent internal loads
INSTEON® lamplinc dimmer	4	Schedules and dims lamp operations
INSTEON® appliancelinc	4	Control on/off operation of shower, latent pump, oven, and other heat source used to evaporate water
Heat Lamps/reflectors/socket neck extensions	4	Directing sensible heat
12 V power supplies	4	Activate relays on oven, shower
24 V water solenoid & float switch	1	Supply incremental water flow
30 gallon water reservoir	1	Storage of latent load to be delivered
Range – Whirlpool® 30-in. electric	1	Used for evaporating moisture and supplies sensible load
Water Pump	1	Delivery water from reservoir to oven
Tipping Buck	1	To measure latent delivery to oven

Internal gains (sensible and latent) will be simulated within the buildings. Historically, the sources of these loads are labeled either people or non-people (equipment/appliance/plug). Table 8 is a daily load summary based on current, collaborative research between FSEC and NREL (Parker, et. al., 2010). The daily non-people loads are a function of the conditioned area and the number of bedrooms.

Table 8. Sensible and Latent Internal Daily Loads (Btu/day).

Non-People Formula*	a	b	c	CFA	Nbr	Total = a+b(CFA) + c*Nbr
Sensible (non-people)	20096	14.75	830	1536	3	45242
Sensible (people)**						10364
Sensible Total						55606
Latent (non-people)	2100	0.38	592	1536	3	4460
Latent (people)**						7677
Latent Total						12137

*From Parker, Fairey and Hendron, 2010, p. 49
**From Table 10 in this document.

Table 9. People Loads in Watt hours.

	Values per Person in Wh*							Total in Wh	
Hour	Fraction in living area	Fraction in bedrooms	Sensible living = frac*68W	Sensible bedrooms = frac*62W	Latent living = frac*56W	Latent bedrooms = frac*41W	People = bedroom	Sensible	Latent
1	0	1	0	62	0	41	3	186	123
2	0	1	0	62	0	41	3	186	123
3	0	1	0	62	0	41	3	186	123
4	0	1	0	62	0	41	3	186	123
5	0	1	0	62	0	41	3	186	123
6	0	1	0	62	0	41	3	186	123
7	0.5	0.5	34	31	28	20.5	3	195	145.5
8	0.5	0.33	34	20.46	28	13.53	3	163.38	124.59
9	0.29	0	19.72	0	16.24	0	3	59.16	48.72
10	0.125	0	8.5	0	7	0	3	25.5	21
11	0.125	0	8.5	0	7	0	3	25.5	21
12	0.125	0	8.5	0	7	0	3	25.5	21
13	0.125	0	8.5	0	7	0	3	25.5	21
14	0.125	0	8.5	0	7	0	3	25.5	21
15	0.125	0	8.5	0	7	0	3	25.5	21
16	0.125	0	8.5	0	7	0	3	25.5	21
17	0.125	0	8.5	0	7	0	3	25.5	21
18	0.5	0	34	0	28	0	3	102	84
19	1	0	68	0	56	0	3	204	168
20	1	0	68	0	56	0	3	204	168
21	1	0	68	0	56	0	3	204	168
22	1	0	68	0	56	0	3	204	168
23	0.5	0.5	34	31	28	20.5	3	195	145.5
24	0	1	0	62	0	41	3	186	123
Total	7.29	8.33	495.72	516.46	408.24	341.53		3036.54	2249.31

*From Fang, 2010 page 28

Hourly human occupancy schedules and disbursements were developed by NREL and are shown in Tables 9 in Watt hrs and in Table 10 in Btu/hr (Fang, 2010). Tables 11 and 12 use the hourly fractions provided by Fang to divide the daily total provided by Parker et.al, into hourly non-people sensible loads in Btu/hr and Watt hrs, respectively. Tables 13 and 14 apply the same methodology to obtain the latent loads in Btu/hr and pounds of moisture. The automation equipment used in delivering the sensible loads is supplied in Watts and the water displacement is measured in fractions of pounds.

Table 10. People Loads in Btus/hr.

	Values per Person in Btu/hr *							Total in Btu/hr	
Hour	Fraction in living area	Fraction in bedrooms	Sensible living = frac*232.1 Btu/hr	Sensible bedrooms = frac*211.6 Btu/hr	Latent living = frac*191.1 28 Btu/hr	Latent bedrooms = frac*133.9 Btu/hr	People = bedrooms	Sensible	Latent
1	0	1	0	212	0	140	3	635	420
2	0	1	0	212	0	140	3	635	420
3	0	1	0	212	0	140	3	635	420
4	0	1	0	212	0	140	3	635	420
5	0	1	0	212	0	140	3	635	420
6	0	1	0	212	0	140	3	635	420
7	0.5	0.5	116	106	96	70	3	666	497
8	0.5	0.33	116	70	96	46	3	558	425
9	0.29	0	67	0	55	0	3	202	166
10	0.125	0	29	0	24	0	3	87	72
11	0.125	0	29	0	24	0	3	87	72
12	0.125	0	29	0	24	0	3	87	72
13	0.125	0	29	0	24	0	3	87	72
14	0.125	0	29	0	24	0	3	87	72
15	0.125	0	29	0	24	0	3	87	72
16	0.125	0	29	0	24	0	3	87	72
17	0.125	0	29	0	24	0	3	87	72
18	0.5	0	116	0	96	0	3	348	287
19	1	0	232	0	191	0	3	696	573
20	1	0	232	0	191	0	3	696	573
21	1	0	232	0	191	0	3	696	573
22	1	0	232	0	191	0	3	696	573
23	0.5	0.5	116	106	96	70	3	666	497
24	0	1	0	212	0	140	3	635	420
Total	7.29	8.33	1692	1763	1393	1166		10364	7677

*Converted from Table 9 which is from Fang, 2010 page 28

Table 11. Non-People Sensible Loads in Btu/hr.

	Living Area	Each Bedroom (3 Total)	Master Bedroom	Living Area	3 Bedroom Total	Master Bedroom	Total House
Hour	Fraction of daily total*	Fraction of daily total*	Fraction of daily total*	Btu/hr	Btu/hr	Btu/hr	Btu/hr
1	0.0200	0.0715	0.0283	556	971	109	1635
2	0.0187	0.0704	0.0258	519	956	99	1575
3	0.0177	0.0704	0.0252	493	956	97	1546
4	0.0175	0.0704	0.0252	485	956	97	1538
5	0.0185	0.0715	0.0264	514	971	101	1587
6	0.0227	0.0763	0.0346	633	1036	133	1802
7	0.0443	0.0517	0.0447	1232	703	171	2106
8	0.0485	0.0432	0.0478	1350	587	184	2121
9	0.0419	0.0181	0.0403	1167	246	155	1567
10	0.0362	0.0155	0.0346	1007	210	133	1350
11	0.0361	0.0155	0.0334	1005	210	128	1343
12	0.0366	0.0155	0.0321	1017	210	123	1350
13	0.0366	0.0155	0.0308	1017	210	118	1345
14	0.0354	0.0155	0.0308	985	210	118	1314
15	0.0353	0.0165	0.0315	983	225	121	1328
16	0.0380	0.0187	0.0346	1058	254	133	1444
17	0.0484	0.0251	0.0453	1348	341	174	1862
18	0.0675	0.0320	0.0573	1879	435	220	2534
19	0.0800	0.0373	0.0680	2227	507	261	2995
20	0.0770	0.0405	0.0736	2142	551	283	2976
21	0.0748	0.0416	0.0743	2082	565	285	2932
22	0.0735	0.0357	0.0648	2046	485	249	2780
23	0.0490	0.0555	0.0516	1362	754	198	2314
24	0.0256	0.0763	0.0390	712	1036	150	1898
Total	1	1	1	27819	13586	3838	45242

*Fraction of daily total load derived from Fang, 1020, page 29.

Table 12. Non-People Sensible Loads in Watts.

	Living Area	Each Bedroom (3 Total)	Master Bedroom	Living Area	3 Bedroom Total	Master Bedroom	Total House
Hour	Fraction of daily total*	Fraction of daily total*	Fraction of daily total*	Watts	Watts	Watts	Watts
1	0.0200	0.0715	0.0283	162.8	284.5	31.8	479.1
2	0.0187	0.0704	0.0258	152.1	280.2	29.0	461.4
3	0.0177	0.0704	0.0252	144.4	280.2	28.3	452.9
4	0.0175	0.0704	0.0252	142.2	280.2	28.3	450.8
5	0.0185	0.0715	0.0264	150.7	284.5	29.7	464.9
6	0.0227	0.0763	0.0346	185.4	303.6	38.9	527.9
7	0.0443	0.0517	0.0447	360.9	205.9	50.2	617.1
8	0.0485	0.0432	0.0478	395.6	172.0	53.8	621.3
9	0.0419	0.0181	0.0403	341.8	72.2	45.3	459.3
10	0.0362	0.0155	0.0346	295.1	61.6	38.9	395.6
11	0.0361	0.0155	0.0334	294.4	61.6	37.5	393.5
12	0.0366	0.0155	0.0321	297.9	61.6	36.1	395.6
13	0.0366	0.0155	0.0308	297.9	61.6	34.7	394.2
14	0.0354	0.0155	0.0308	288.7	61.6	34.7	385.0
15	0.0353	0.0165	0.0315	288.0	65.8	35.4	389.2
16	0.0380	0.0187	0.0346	310.0	74.3	38.9	423.2
17	0.0484	0.0251	0.0453	394.9	99.8	51.0	545.6
18	0.0675	0.0320	0.0573	550.6	127.4	64.4	742.3
19	0.0800	0.0373	0.0680	652.5	148.6	76.4	877.5
20	0.0770	0.0405	0.0736	627.7	161.3	82.8	871.8
21	0.0748	0.0416	0.0743	610.0	165.6	83.5	859.1
22	0.0735	0.0357	0.0648	599.4	142.2	72.9	814.5
23	0.0490	0.0555	0.0516	399.1	220.8	58.0	677.9
24	0.0256	0.0763	0.0390	208.8	303.6	43.9	556.2
Total	1	1	1	8150.8	3980.6	1124.5	13255.8

*Fraction of daily total load derived from Fang, 1020, page 29.

Table 13. Non-People Latent Loads in Btu/hr.

	Kitchen	Each Bedroom (3 Total)	Master Bedroom	Kitchen	3 Bedroom Total	Master Bedroom	Total House
Hour	Fraction of daily total	Fraction of daily total	Fraction of daily total	Btu/hr	Btu/hr	Btu/hr	Btu/hr
1	0.0080	0.1197	0.0340	23	144	13	181
2	0.0072	0.1197	0.0302	21	144	12	177
3	0.0062	0.1197	0.0302	18	144	12	174
4	0.0059	0.1197	0.0302	17	144	12	173
5	0.0065	0.1197	0.0283	19	144	11	174
6	0.0083	0.1197	0.0340	24	144	13	181
7	0.0478	0.0608	0.0415	137	73	16	226
8	0.0540	0.0405	0.0472	155	49	19	222
9	0.0471	0.0000	0.0415	135	0	16	151
10	0.0375	0.0000	0.0358	107	0	14	121
11	0.0367	0.0000	0.0358	105	0	14	119
12	0.0383	0.0000	0.0358	110	0	14	124
13	0.0390	0.0000	0.0340	112	0	13	125
14	0.0367	0.0000	0.0340	105	0	13	118
15	0.0359	0.0000	0.0358	103	0	14	117
16	0.0385	0.0000	0.0377	110	0	15	125
17	0.0504	0.0000	0.0453	144	0	18	162
18	0.0799	0.0000	0.0547	229	0	21	250
19	0.0982	0.0000	0.0604	281	0	24	305
20	0.0871	0.0000	0.0604	249	0	24	273
21	0.0820	0.0000	0.0604	235	0	24	258
22	0.0882	0.0000	0.0585	252	0	23	275
23	0.0494	0.0608	0.0509	141	73	20	235
24	0.0111	0.1197	0.0434	32	144	17	193
Total	1	1	1	2862	1205	392	4460

Table 14. Non-People Latent Loads in Pounds Water.

	Kitchen	Each Bedroom (3 Total)	Master Bedroom	Kitchen	3 Bedroom Total	Master Bedroom	Total House
Hour	Fraction of daily total	Fraction of daily total	Fraction of daily total	Pounds Water	Pounds Water	Pounds Water	Pounds Water
1	0.0080	0.1197	0.0340	0.022	0.136	0.013	0.170
2	0.0072	0.1197	0.0302	0.020	0.136	0.011	0.167
3	0.0062	0.1197	0.0302	0.017	0.136	0.011	0.164
4	0.0059	0.1197	0.0302	0.016	0.136	0.011	0.163
5	0.0065	0.1197	0.0283	0.017	0.136	0.010	0.164
6	0.0083	0.1197	0.0340	0.022	0.136	0.013	0.171
7	0.0478	0.0608	0.0415	0.129	0.069	0.015	0.214
8	0.0540	0.0405	0.0472	0.146	0.046	0.017	0.209
9	0.0471	0.0000	0.0415	0.127	0.000	0.015	0.142
10	0.0375	0.0000	0.0358	0.101	0.000	0.013	0.114
11	0.0367	0.0000	0.0358	0.099	0.000	0.013	0.112
12	0.0383	0.0000	0.0358	0.103	0.000	0.013	0.117
13	0.0390	0.0000	0.0340	0.105	0.000	0.013	0.118
14	0.0367	0.0000	0.0340	0.099	0.000	0.013	0.112
15	0.0359	0.0000	0.0358	0.097	0.000	0.013	0.110
16	0.0385	0.0000	0.0377	0.104	0.000	0.014	0.118
17	0.0504	0.0000	0.0453	0.136	0.000	0.017	0.153
18	0.0799	0.0000	0.0547	0.216	0.000	0.020	0.236
19	0.0982	0.0000	0.0604	0.265	0.000	0.022	0.288
20	0.0871	0.0000	0.0604	0.235	0.000	0.022	0.258
21	0.0820	0.0000	0.0604	0.221	0.000	0.022	0.244
22	0.0882	0.0000	0.0585	0.238	0.000	0.022	0.260
23	0.0494	0.0608	0.0509	0.133	0.069	0.019	0.221
24	0.0111	0.1197	0.0434	0.030	0.136	0.016	0.182
Total	1	1	1	2.700	1.137	0.370	4.208

4 Determination of Experimental Plan

An analysis of the homes was conducted using FSEC's in-house version of the EnergyGauge® USA software package, which includes a cost optimization module. Results of these and other simulations will be used to identify the order of experiments in the FRTF. Initial results fell into two categories: cost-optimized and technology-optimized. The cost optimized results were cast in terms of estimated costs and lifetimes of potential retrofit measures. They were analyzed in an iterative fashion to arrive at the cost-optimized order in which retrofit measures might be expected to occur. Figure 22 presents results from the initial analysis.

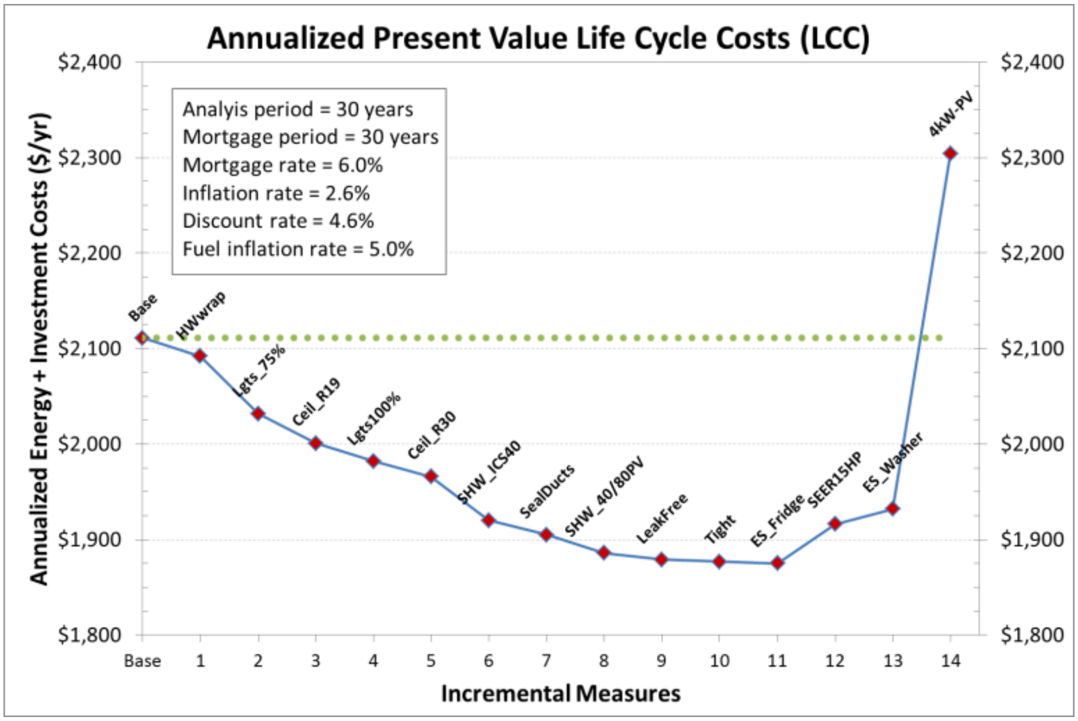

Figure 22. Present value annualized cost of optimized retrofit measures for FRTF.

This figure comprises 57 retrofit options that were rank ordered by their savings-to-investment ratio (SIR). The options were evaluated on the basis of life cycle cost over the analysis period using the mortgage and rate characteristics shown. The solution was iterative, with the SIR for each option being calculated based on the previously selected option included in the building. The analysis was constrained at the upper end by the cost effectiveness of adding a 4 kWp-dc photovoltaic system. All options with an SIR greater than the 4 kW PV system were added first, and all options with an SIR less than PV system were excluded from results.

Building enclosure characteristics were of primary importance to this task because they are the most difficult to implement within the context of a reconfigurable research facility. Once they are made they may be extremely difficult to undo. It is virtually almost always possible to switch out equipment at any point within an experimental plan but it may not be possible to completely undo an enclosure change.

Given that a number of the options selected were not related to this and that the cost measure was a primary driver of the order selected, a second form of the optimization analysis was conducted. Setting all of the measure costs to $10 and lifetimes to 30 years, a rank ordering based solely on technical potential was possible. Additionally, all equipment options were removed from consideration in order to concentrate the analysis on what could be accomplished through envelope and related options.

The reason why less cost-effective measures should be part of this research goes to the fact that many of these measures can have a substantial impact on energy use, even though they do not show to be cost effective at estimated current prices (which could easily change with the right market forces or signals). For example, high-performance windows do not show up in the cost effective options (Figure 22), however they are the first selected measure in the technology analysis (Figure 23). A large part of this project's objective is to verify the performance of such measures under field conditions. Therefore, it is appropriate for measures that potentially save large quantities of energy to be evaluated in the field, even when the cost-effectiveness analysis, which is highly dependent on estimated costs, does not show them as being the most cost-effective measures.

Figure 23 illustrates results from this analysis, albeit in a slightly different format. These results show 1st year costs and savings of the option packages along with the electricity use for the packages as the analysis proceeds. Since each option had the same cost and lifetime, the most energy conserving of each of the technologies was selected from the available options. Thus, R-49 ceiling insulation was selected when we knew from cost optimization analysis that R-38 would likely be the top end of cost effectiveness in this climate (Orlando, FL TMY3 data).

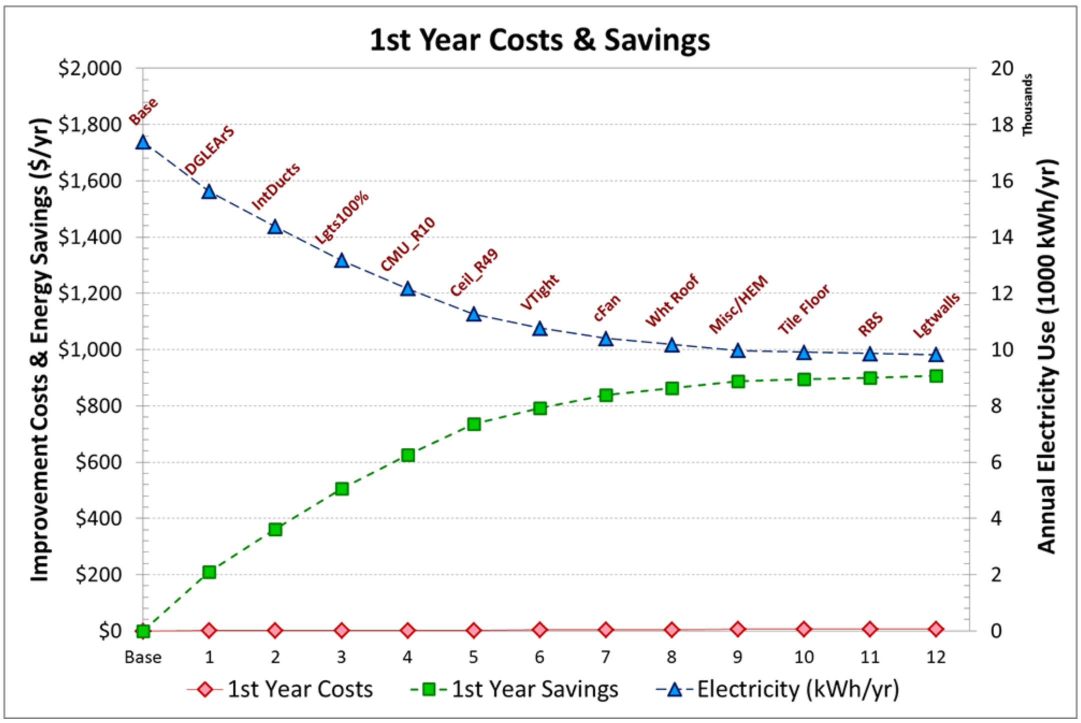

Figure 13. Technology-optimized envelope and envelop related retrofit options.

In addition, Figure 23 shows that certain measures selected toward the end of the optimization analysis produce only small quantities of kWh energy savings. This led to the concern that savings from these measures may be completely masked by savings achieved by previous measures. This also makes it very difficult to detect a "signal" from their inclusion in an experimental measurement if the retrofit options are selected for step-wise experimentation in the order shown.

To determine the degree to which the energy saving "signal" for a particular measure may be masked by a preceding complementary measure, the results of the technology optimization are compared against the results of the first iteration of the optimization. Table 15 shows the cost and benefits for this iteration. In Figure 24, the first iteration of each measure was compared against the base configuration in what amounted to a single measure analysis. This yielded the energy savings for each measure unencumbered by competing options. Note that in Figure 24, the energy "signal" of some measures was significantly impacted by the optimization selection order.

Table 15. Cost and Benefits for First Iteration

Run_Name	SIR	Cost_net	PVal_Invest	PVal_Save	NPV
Base Case	n/a	n/a	n/a	n/a	n/a
HWwrap	5.734	$50	$122	$698	$576
Ceil_R19	3.167	$479	$469	$1,486	$1,017
Lgts_75%	2.662	$230	$1,128	$3,003	$1,875
Ceil_R30	2.578	$1,069	$1,047	$2,699	$1,652
Lgts100%	2.351	$384	$1,883	$4,428	$2,545
Ceil_R38	2.189	$1,499	$1,469	$3,215	$1,746
Std_GHW	1.994	$700	$1,703	$3,397	$1,694
ES_GHW	1.861	$750	$1,825	$3,397	$1,572
Ceil_R49	1.778	$2,089	$2,046	$3,640	$1,593
SealDucts	1.677	$480	$814	$1,365	$551
LeakFree	1.573	$864	$1,465	$2,305	$840
SHW_ICS40	1.405	$3,150	$3,432	$4,822	$1,390
HPWH	1.341	$1,610	$3,370	$4,519	$1,149
SHW_40/80PV	1.330	$4,200	$5,222	$6,945	$1,723
Tight	1.299	$358	$607	$789	$181
SEER15HP	1.273	$4,724	$8,955	$11,404	$2,449
SEER18HP	1.169	$6,161	$11,679	$13,648	$1,969
LowFloSh	1.108	$130	$246	$273	$27
TGWH	1.062	$900	$3,199	$3,397	$198
ES_Fridge	1.058	$1,000	$2,093	$2,214	$121
SEER15GF90	1.028	$4,745	$8,995	$9,250	$256
ES_Washer	0.978	$1,200	$2,512	$2,457	-$55
SEER15AC	0.969	$4,045	$7,668	$7,431	-$237
RBS	0.937	$2,304	$2,656	$2,487	-$169
HRUnit	0.907	$1,500	$3,008	$2,730	-$279
IntDucts	0.907	$6,144	$6,019	$5,459	-$560
Std_EHW	0.886	$408	$993	$880	-$113
SEER13HP	0.841	$5,097	$9,662	$8,128	-$1,534
DGLEArS	0.677	$9,605	$9,410	$6,369	-$3,040
cFan	0.667	$1,080	$2,045	$1,365	-$680
4kW-PV	0.658	$24,500	$32,618	$21,473	-$11,145
DGLES	0.639	$8,475	$8,303	$5,308	-$2,995
Tighter	0.624	$1,433	$2,430	$1,516	-$914
SEER13GF78	0.605	$4,918	$9,323	$5,641	-$3,681
IntAHU	0.583	$384	$728	$425	-$303
SGreflect	0.536	$7,910	$7,749	$4,155	-$3,594
SEER13AC	0.532	$4,418	$8,375	$4,458	-$3,916
VTight	0.474	$2,866	$4,860	$2,305	-$2,555
CMU_R10	0.427	$9,498	$9,305	$3,973	-$5,332
Misc/HEM	0.427	$600	$1,706	$728	-$978
ES_dWash	0.398	$400	$837	$334	-$504
WinTint	0.370	$1,766	$4,673	$1,729	-$2,944
CMU_R5	0.358	$9,334	$9,144	$3,276	-$5,868
Tile Floor	0.333	$3,072	$3,009	$1,001	-$2,009
Lgtwalls	0.322	$746	$1,414	$455	-$959
Wht Roof	0.218	$10,752	$12,393	$2,699	-$9,694
WhShngl	0.130	$3,072	$5,823	$758	-$5,065
Wood Floor	-0.024	$5,107	$5,003	-$121	-$5,124
SOG_R5-4h	-0.663	$1,120	$1,097	-$728	-$1,825
SOG_R5-2h	-0.774	$800	$784	-$607	-$1,390

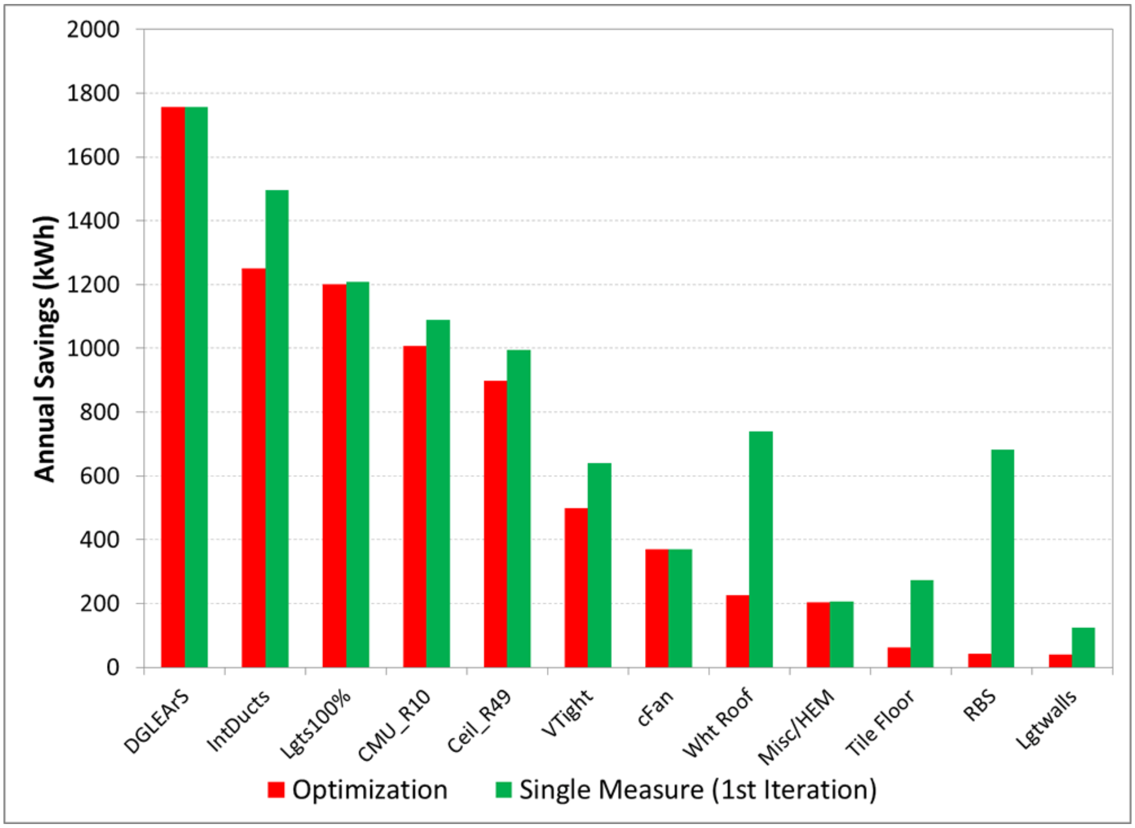

Figure 24. Annual energy savings "signal" for technology optimized retrofit measures.

By way of example, if one is attempting to investigate the impact of light walls, the energy "signal" would be enhanced by about three times if this option is included first, rather than last, in a step wise experimental plan. The same is true for other options, such as RBS (attic radiant barrier system), tile flooring, a white roof (metal) and a very tight envelope (ach50 = 3). This same phenomenon is seen in many of the other options. However, for the options that save larger quantities of energy, the energy "signal" from the improvement is likely to be easily detectible.

Based on the preliminary analysis, we are recommending that envelope tests be conducted first in the following order (reverse of technology optimization results):

- Attic Radiant Barrier System (RBS)
- Very tight enclosure (ach50 = 3.0)
- R-38 ceiling insulation
- R-10 exterior block wall insulation
- Interior ducts and air handler
- High performance windows

Each of these measures will be conducted individually to one home while the other home remains as a control. The cooling and heating savings, effect on interior humidity, and peak demand can all be examined for each measure. Following these tests, additional tests looking at HVAC equipment performance will be conducted. Simultaneously, hot water system options are being measured in other tasks within BA-PIRC. Many of the heating and cooling energy contributions caused by higher efficiency appliances may be measured by altering the automated internal gains schedule of the laboratory homes in subsequent experiments.

The tests will provide a set of empirical residential building energy use data sets (one control and one alternative – simultaneously in the time domain) that can be confidently used to verify the accuracy of engineering models used for retrofit simulation and analysis—currently an area of controversy and speculation.

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Appendix Press Release on New Lab

New Research Facility to Test Home Energy Improvements

COCOA, Jan. 14, 2011 – Recognizing the need for statewide energy efficiency, UCF's Florida Solar Energy Center celebrates the completion of its newest research facility for testing energy improvements in new and existing homes. A ribbon-cutting ceremony for this endeavor was held today on UCF's Cocoa campus.

Initial research at the Flexible Residential Test Facility will focus on energy improvement potentials in vintage Florida homes. Those constructed prior to 1975 make up 63 percent of Florida's more than eight million existing homes, which represents a substantial energy and cost savings potential for cost-effective, "deep" home energy improvements, or retrofits. Prospective savings could result in 30 to 50 percent of current residential energy use.

Funded by the state's Florida Energy Systems Consortium, the research facility was instrumental in attracting a major multi-million dollar, four-year research grant from the U.S. Department of Energy (DOE).

Figure A-1. Cutting the ribbon at the opening of the Flexible Residential Test Facility are (left to right) Robin Vieira, Director, Buildings Research at Florida Solar Energy Center; David Lee, U.S. Department of Energy's Supervisor for the Residential Deployment Program; James Fenton, Director, Florida Solar Energy Center.

"As we address greenhouse gas emissions, we have to look at retrofitting existing homes. This facility will be instrumental in researching the impacts of home energy efficiency improvements in hot climates," said Mr. David Lee, Supervisor[1], Residential Deployment Program, Office of Buildings Technologies, U.S. Department of Energy.

The facility consists of two side-by-side homes that will assist researchers in evaluating a large variety of both envelope and systems improvements. The homes will be heavily instrumented, and occupancy effects will be

[1] Mr. Lee's title in the published press release was listed as U.S. Department of Energy's Director of Residential Building Programs, it has been changed to his current official title for this report.

simulated by scheduled computer-controlled heat and moisture generation and appliance use. Monitored results from these experiments will test and verify computer simulation models now in widespread use for existing and new home energy efficiency evaluation.

For more information about this new research facility, contact Robin Vieira, Buildings Research Director at robin@fsec.ucf.edu or 321-638-1404.

FSEC – Creating Energy Independence: The Florida Solar Energy Center (FSEC), a research institute of the University of Central Florida, is the largest and most active state-supported energy research institute in the nation. Current divisions and their research activities include Advanced Energy Research: alternative transportation systems, hydrogen fuel and fuel cells; Buildings Research: energy-efficient buildings; and Solar Energy: solar water and pool heating and solar electric and distributed generation systems. For more information about the center, visit http://www.floridaenergycenter.org or call the FSEC Public Affairs Office at 321-638-1015.

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