Field Study and Energy-Plus Benchmarks for Energy Saver Homes having Different Envelope Designs

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ABSTRACT

An alliance to maximize energy efficiency and cost-effective residential construction (ZEBRAlliance) built and field tested four homes that are 50 percent more energy efficient than a code compliant home. The homes are located in Oak Ridge, TN, and are unoccupied for the duration of a two-year field study, thereby eliminating the confounding issue of occupancy habits. All homes have the same setpoint temperature and consistent and scheduled internal load. Each home showcases a unique envelope strategy: 1) structural insulated panel (SIP), 2) optimal value wall framing (OVF), 3) advanced framing featuring the benefits of insulations mixed with phase change materials (PCM), and 4) an exterior insulation and finish system (EIFS). All homes have different weather resistive barriers (WRBs) and/or air barriers to limit air and moisture infiltration. Three homes provide space conditioning and water heating via a ground loop heat exchanger, while the fourth home uses a high efficiency air-to-air heat pump and heat pump water heater. Field performance and results of EnergyPlus V7.0 benchmarks were made for roof and attics as compared to cathedral design and for wall heat flows to validate models. The moisture content of the wall sheathing is shown to prove the protecting effectiveness of WRBs. Temperature distributions through insulations in the wall and ceiling with and without PCMs are described to characterize the performance of the PCM building envelopes.

Introduction

This paper describes the performance of four homes built to maximize energy efficiency and cost-effective residential construction. An alliance (ZEBRA[1]) composed of Schaad Companies LLC, the Tennessee Valley Authority (TVA), the Oak Ridge National Laboratory (ORNL), Barber McMurry Architects (BMA) and the Department of Energy (DOE) are showcasing and demonstrating several active and passive energy saving technologies, Liu (2010) and Biswas et al (2011). The paper compares field measured data with EnergyPlus simulation results. All homes are serving as breadboards to help develop a portfolio of the best available materials and construction methods that are resistance to water damage, reduce carbon emissions, cost less to operate, and showcase several energy-efficient building benefits. Field data show that each home uses only half the energy consumed by a conventional IECC (2006) code compliant house. Salient features of the homes were described by Miller et al. (2010) while the homes were still under construction.

[1] ZEBRA Zero-Energy-Building–Research-Alliance

Demonstration Homes — Envelopes

Each of the four demonstration homes use different envelope approaches, Figure 1, and the key envelope feature names each home (Table 1).

Table 1. Footprint and Key Feature That Identifies the Envelopes

Key Envelope Feature	Footprint in square feet[1]			
	Basement	**1st Floor**	**2nd Floor**	**Total**
Structural Insulated Panels (SIP home)	1518	1518	677	3713
Optimal Value Framing (OVF home)	1518	1518	677	3713
Dynamic Envelope (PCM home)	NA	1802	919	2721
Exterior Insulation & Finish System (EIFS home)	NA	1802	919	2721

[1] Conversion: $m^2 = 9.290304E-02 * ft^2$

Figure 1. ZEBRAlliance Energy Efficient Homes

SIP House

OVF House

PCM House

EIFS House

The SIP and OVF homes are a pair of homes having cathedral ceiling and walk-out basement. The PCM and EIFS pair have conventional attics and crawlspace foundations. Each pair of homes has a similar design; however, each design differs slightly in the construction method and materials, HVAC, lighting, etc. The roof ridge for all homes has the same solar orientation to enable direct comparison of the diurnal heat flows crossing all roof decks and exterior walls and windows. All ducts in the SIP and OVF homes are located in the conditioned space while a small section of the ducts are located at unconditioned attic in the PCM and EIFS homes. No air distribution system was located in the crawl space.

Home Energy Rating System (HERS) Rating

A HERS rater reviewed the homes and used the Residential Energy Analysis and Rating Software (Rutherford, 2010) to appraise the four homes with the scores listed in Table 2. The SIP and OVF pair of homes had scores of 46 and 47, respectively and the PCM and EIFS pair of homes had HERS ratings respectively of 47 and 50. The slightly higher score for the EIFS home is attributed to the use of a high-efficiency air source heat pump and heat pump water heater as compared to the geothermal equipment used for comfort conditioning and hot water in the PCM home. A conventional stick built house built fairly close to the IECC building code (2006) scored at 93.

Table 2. HERS Rating and Infiltration Rates as Compared to IECC (2006)

Description	SIP Strategy	Optimal Value Framing Strategy	PCM Envelope	EIFS Envelope	Builders House[1]
HERS	46	47	47	50	93
Annual (kWh per ft^2 per year)	4.66	4.50	5.43	5.70	11.14
ACH[2] at 50 Pa	1.23	1.74	3.18	2.18	5.7
Tracer Gas[3] ACH	0.05/0.09	0.05/0.13	0.11/0.14	0.08/0.07	NA

[1] International Energy Conservation Code (2006).
[2] Air exchanges per hour (ACH) measured by blower door testing conducted at 50 Pa.
[3] Tracer gas test using concentration decay method and R-134a refrigerant. Measured values in summer/winter 2011.

A year of revenue meter readings show all ZEBRA homes consumed 50% less energy per unit footprint than did the Builder's home, Table 2. (Christian, 2010) conducted blower door tests to document the air tightness of the homes, Table 2. Results show all four homes are tighter than the conventional Builders House. ASHRAE 62.2 (2009) recommends a minimum of 70 cubic feet per min (0.033-m^3/s) for the 3 bedroom homes (i.e., 0.11 ACH).

Tracer gas tests were conducted using a gas analyzer based on photoacoustic spectroscopy to determine the air change with the outdoors as induced by weather conditions and by mechanical ventilation. Tests were conducted during summer and winter of 2011 to evaluate seasonal variation in air change rate, which showed significant increase in air change in winter compared to that in the summer for the SIP, OVF and PCM homes; whereas little change was detected in the EIFS house, Table 2.

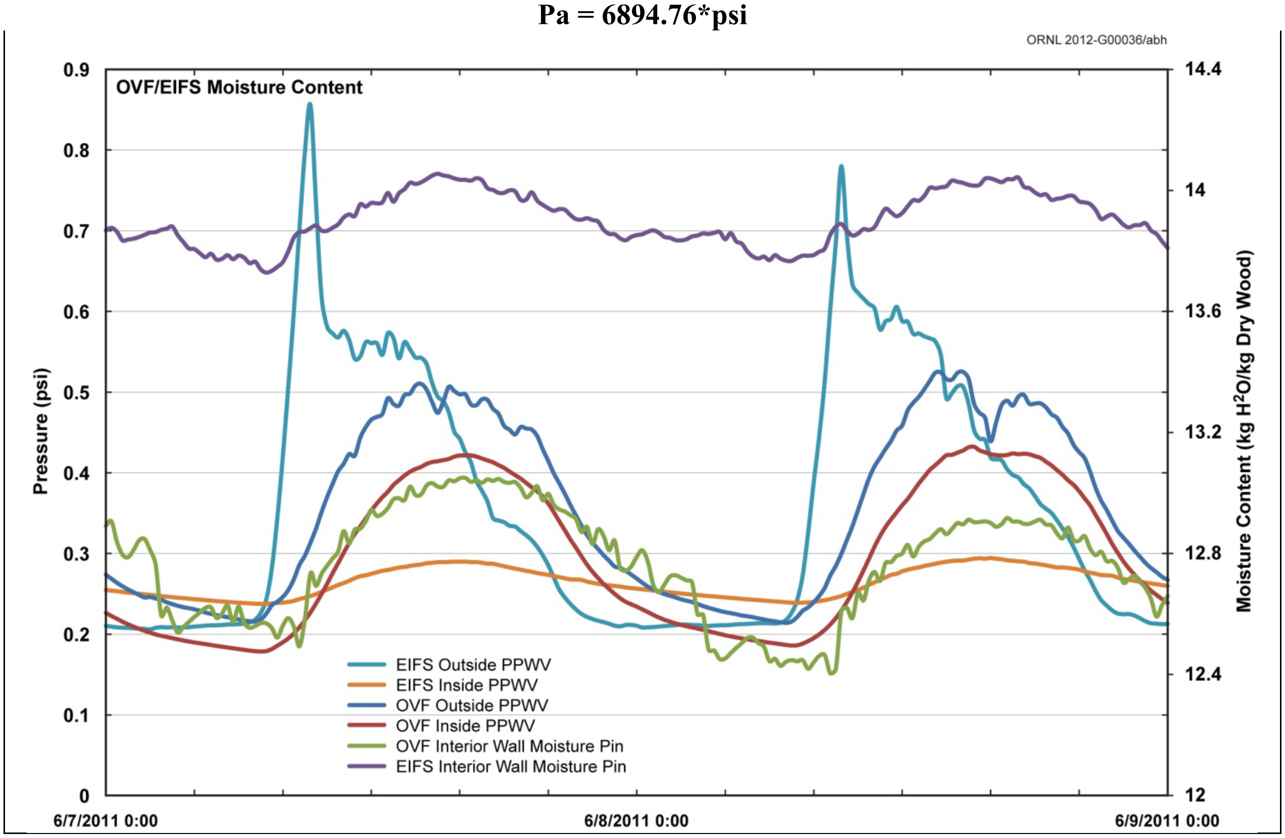
Weather Resistive Membranes

These barriers are of paramount importance for protecting a building from water intrusion and from preventing water from making contact with a building's sheathing. All four envelopes use weather resistive barriers and/or air barriers to limit air leakage. Features of the barriers are described by Miller et al. (2010). The OVF house has a fully adhered liquid applied WRB on all exterior walls. The WRB was applied using a water based spray adhesive. The wall cavity for the OVF home contains about a ½-in (0.013-m) of sprayed-in closed-cell polyurethane foam and R_{US}-19 (R_{SI}-3.3) fiberglass batt insulation (i.e., termed flash and batt).

The WRB for the EIFS home is an integral part of the exterior wall assembly. The plywood sheathing of the EIFS home is coated in a flexible polymer-based membrane which was manually trowel applied as a liquid over all plywood sheathing. A cementitious adhesive was applied onto the WRB to adhere the EPS insulation. The trowel application formed rows of the adhesive about 0.25-in (6-mm) high which provided a small drainage cavity between the WRB and the EPS insulation board to allow incidental water to weep towards the outdoor ambient.

After a full year of exposure to the elements both WRB systems are adequately protecting the sheathing on the south-facing wall as viewed by the low water content of the sheathing, Fig. 2 (view right ordinate for moisture content computed from moisture pins).

Figure 2. The Partial Pressure of Water Vapor (PPWV) Measured Across the Wall Sheathing of the EIFS and PCM Envelopes (left ordinate) is Displayed Along with the Water Content of the Sheathing (right ordinate) on the OVF and PCM Homes
Pa = 6894.76*psi



Temperature and relative humidity sensors were fixed to the interior and exterior of the sheathings on the OVF and EIFS houses. The sensors were attached about 7 feet (2.1 m) above ground level. The field measures were converted to the partial pressure of water vapor and plotted in Fig. 2 (left ordinate) for two contiguous days during June 2011 when it is expected that the ambient water vapor pressure is the highest over the year. The exterior surfaces of both sheathings had the largest vapor pressures across the sheathing for each wall assembly. The interior vapor pressure is much reduced revealing a driving potential for water intrusion. However, moisture pins on the interior side of the sheathing and about 7 feet (2.1 m) above ground level indicate an OSB moisture content of about 13 to 12.6 kg H_2O per kg of dry wood in the OVF home and about 14 to 13.8 kg H_2O per kg of dry wood in the EIFS home. Theses moisture contents for the OSB sheathing in the OVF home and the plywood sheathing in the EIFS home are below levels (Xiaoshu 2002) subject to wood rot and mold or mildew growth[2].

Roof and Attics

All four homes feature cool color roof materials, Table 3. The SIP and OVF homes highlight infrared reflective standing seam metal roofs having a Zinc Gray color. Solar reflectance of the painted metal is 0.30 and its thermal emittance is 0.85. The PCM house contains an aluminum shake roof with solar reflectance of 0.34 and thermal emittance of 0.85. The EIFS house demonstrates a cool color shingle roof, which is by far the least expensive roofing option. The cool color shingle is about 0.25-solar reflectance; thermal emittance of the shingle is 0.88. The roof decks of the EIFS home also contain a profiled and foil faced 1-in (0.0254-m) EPS insulation that is attached over the roof rafters and covered by foil faced OSB sheathing. The assembly provides a radiant barrier facing the attic plenum, 2 low-e surfaces facing into the inclined 1-in (0.0254-m) high air space, and passive ventilation from soffit to ridge. Miller et al. (2011) provides details of the unique prototype roof assembly.

The cathedral ceilings of the SIP and OVF homes have respectively a thermal resistance to heat flow of about R_{US}-35 (R_{SI}-6.2) and R_{US}-50 (R_{SI}-8.8). The cathedral roof of the OVF home is fitted with two continuous layers of phenolic foam insulation. The two pieces of 3.15-in (80 mm) thick phenolic foam are fitted between the joists. The foam is foil faced and limits radiation heat transfer across the inclined air space. Perforated fiber cement siding and a metal ridge cap ventilate the inclined air space in the cathedral roof of the OVF home. Additionally, a 1.18-in (30 mm) thick cover board made of phenolic foam insulation is attached to the underside of the 2 by 12 joists to help reduce thermal bridging. The roof of the SIP home is ventilated using a unique sheathing with dimpled spacers that provided a ¼-in (6-mm) air space between the metal and OSB SIP roof panel.

[2] At an ambient temperature of 80°F (26.7°C) and 80% relative humidity the moisture storage function for wood should be less than 16 to 18% moisture content (kg H_20 per kg wood) to protect against mold and mildew.

Table 3. Salient features of the roofs and attics for the four envelope systems

Description	SIP	Optimal Value Framing	PCM	EIFS
Roof	Standing-seam metal	Standing-seam metal	Aluminum Shake	Asphalt shingle
Solar reflectance Thermal emittance of the Roofs	SR = 0.30 ε = 0.85	SR = 0.30 ε = 0.85	SR = 0.34 ε = 0.85	SR = 0.25 ε = 0.88
Roof deck	**R_{US}-35 (R_{SI}-6.2)** Cathedral (SIPs 10-in)	**R_{US}-50 (R_{SI}-8.8)** Cathedral (aged phenolic)	Perforated foil-faced OSB radiant barrier	**R_{US}-3.5 (R_{SI}-0.6)** Foil-faced & Profiled EPS radiant barrier
Attic	NA	NA	**R_{US}-50 (R_{SI}-8.8)** Floor filled with blown-fiber insulation	**R_{US}-50 (R_{SI}-8.8)** Floor filled with blown-fiber insulation
Ventilation	NA	Open cavity at soffit and ridge	Soffit and gable vents with solar fans	Soffit and gable vents with solar fans

Attic Systems

The PCM and EIFS homes are built with conventional attics. The PCM home has an OSB deck and the OSB is overlaid with a micro-perforated aluminum foil that faces into the attic. Solar powered gable ventilators are installed on the interior of the attic gables to enhance attic ventilation. At solar noon with clear sky the fans will induce about 10 air changes per hour from the perforated fiber cement soffit panels and the gable vents. Total soffit and gable-end vent area exceeds the 1:150-code. The attic floor is insulated with 12-in (0.3-m) of regular cellulose insulation. PCM was intended to be added to the floor insulation; however, samples pulled after the field study showed no evidence of the PCM.

A similar arrangement is setup for the attic floor of the EIFS house. Here the radiant barrier is the foil faced EPS insulation (Table 3). Our strategy being to mitigate almost all of the heat transfer penetrating past the roof deck using IRR paint pigments in the roofs, the natural ventilation and/or EPS insulation and then the radiant barrier. The heat, which passes these barriers, will be contained by blown-fiber insulation. The blown fiber ceiling insulation yielded about an R_{US}-50 (R_{SI}-8.8) layer.

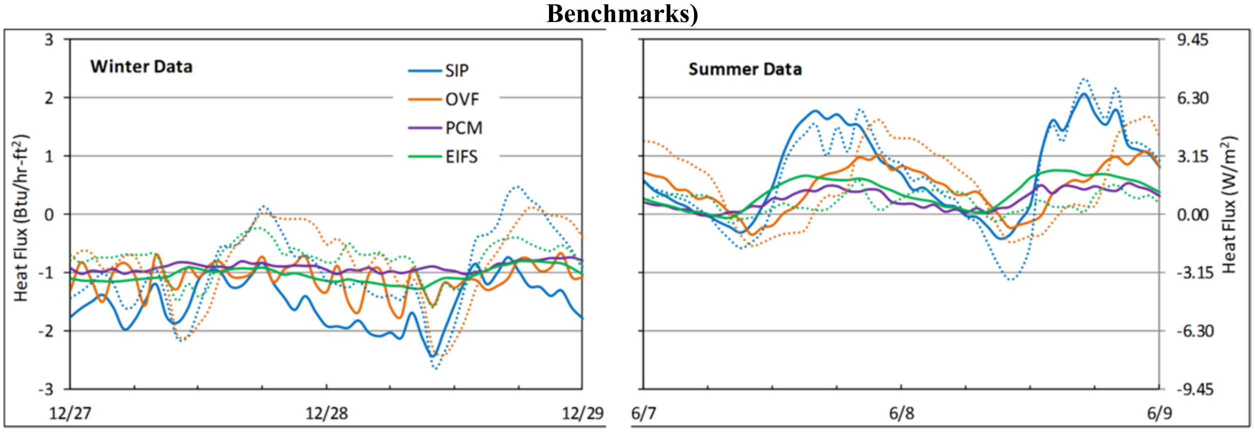
Heat Fluxes and Benchmarks

We evaluated the performance of the different roof configurations by comparing the measured heat flow crossing into the conditioned space. The SIP and OVF homes have cathedral roofs with 7:12 slope. We therefore corrected[3] the measured flux to account for the projected

[3] An area-weighted heat flow was computed for the conditioned space using the horizontal surface area for each house.

area of the roof in order to make fair comparison to the pair of homes with attics. Figure 3 contains the measured ceiling heat flux for each home and also illustrates benchmarks of Energy Plus against the measured heat flow.

Figure 3. Winter and Summer Heat Flux Measured Across the Ceiling Plane of the Cathedral Ceilings for the SIP and OVF Homes and Across the Attic Floor of the PCM and EIFS Homes. The Dashed Color Lines Represent Energy Plus Benchmarks Against the Field Data (Solid Lines Highlighted in the Same Colors as Benchmarks)



Cathedral Roof Versus Conventional Roof and Attic

There is a larger variation in the measured heat flows of the cathedral roofs as compared to the pair of homes with attics as depicted by two contiguous winter days in Fig. 3. The attic enclosure, which contains R_{US}-50 (R_{SI}-8.8) of cellulose insulation on the floor, appears to dampen the variation in heat flux crossing the floor as compared to the cathedral roofs. The heat lost into the attics of the PCM and EIFS homes is about -1.0 Btu/(hr·ft^2) [3.15 W/m^2]. We also observed an almost hourly cyclic variation (see PCM home) in heat flows which coincided with the operation of the HVAC unit. Supply air from floor vents near the heat flux transducers caused the repetitive cycling. In comparison, the heat losses vary from about -2.0 to -0.9 Btu/(hr·ft^2) [-6.3 to -2.8 W/m^2] for the SIP and OVF pair of homes. In summer, the cathedral roof of the SIP home yields the highest peak heat flow; it reaching about 2 Btu/(hr·ft^2) [6.3 W/m^2] at peak day irradiance. It is also very interesting to note that the heat flows measured for the EIFS home had the steadiest measures over the day for all homes.

EnergyPlus Benchmark of Attic Heat Flux

The EnergyPlus simulations were performed using detailed building models and actual weather data collected at the building location. Thermal and physical properties such as thermal conductivity, specific heat, thickness, density, solar reflectance, and thermal emittance of building materials were determined by conducting laboratory tests, gathered from the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) Handbook, or obtained from manufacturers' data sheets. Each type of envelope system was then assigned one or more layers of materials based on the actual construction. Building geometry was set up using architectural drawings while important parameters such as the exact location of heat flux transducers, windows, and shading surfaces were verified with field measurements.

Modeling PCM house and benchmarking EnergyPlus against controlled field data has been presented in detail in Shrestha et. al (2011). EnergyPlus simulation results for the SIP, OVF and EIFS homes are presented in Figure 3. In general, EnergyPlus predicted heat flux match better with field measured data in summer as compared to that in winter. Difference between measured and simulation results for the average heat loss in winter were 0.55 [1.73], 0.28 [0.88], and 0.27 [0.85] Btu/(h·ft^2) [W/m^2] and that for summer was 0.07 [0.22], 0.08 0.25], and 0.17 [0.54] Btu/(h·ft^2) [W/m^2], respectively for SIP, OVF, and EIFS homes. It is suspected that the higher differences are mainly due to thermal stratification and proximity of heat flux transducers location to the air diffusers.

Cladding and Exterior Walls

The exterior décor of the SIP, OVF and PCM homes features lap siding, Fig. 1. The siding is in part composed of a fiber cement material and has excellent resistance to blistering sun, hurricane-force winds and driving rain. The cladding is fireproof, water resistant and therefore will not crack or rot. Stack stone covers the exposed wall sections that are below grade and the stone extends up to the bottom of the 1st floor windows. The EIFS home showcases an EIFS system covered with a textured acrylic stucco finish that complements the stack stone placed around the masonry block of the home's crawlspace.

The cladding of the SIP and OVF homes is painted with cool color materials made of water-based acrylic copolymer paint. Solar reflectance and thermal emittance of the various color paints are listed in Table 4. Cladding on the exterior wall of the PCM house used conventionally pigmented paints because of the expected high R-value resultant from the PCMs in the wall insulation. However, the cladding had a baked-on paint finish from the factory and the fiber cement siding is guaranteed for 15 years against cracking, chipping or peeling.

Table 4. Cladding and Wall Sections for Each of the Four Research Homes

Description	House 1 SIP	House 2 Optimal Framing	House 3 *PCM*	House 4 Exterior Insulation
Cladding	Fiber cement lap siding and stack stone	Fiber cement lap siding and stack stone	Fiber cement lap siding and stack stone	Acrylic stucco and stack stone
Exterior paints				
Gray	SR= 0.48 ε = 0.90	SR= 0.48 ε = 0.90	SR= 0.30 ε = 0.90	SR=0.23 ε = 0.90
Light Green			SR= 0.37 ε = 0.90	
Dark Green	SR= 0.33 ε = 0.90	SR= 0.33 ε = 0.90		
Cream	SR= 0.75 ε = 0.90	SR= 0.75 ε = 0.90		
Yellow			SR= 0.59 ε = 0.90	
Wall	**R-21 (R_{SI}-3.7)** 5½-in (0.14-m) of EPS	**R-21 (R_{SI}-3.7)** 2x6 wood frame, 24-in (0.61-m) O.C. with ½" (0.13-m) thick OSB	**R-30 (R_{SI}-5.3)** 2- 2x4 stud walls; 24-in (0.61-m) O.C. ½" (0.13-m) OSB sheathing with polyethylene dimple sheet for wall ventilation	**R-20 (R_{SI}-3.7)** 2x4 wood 16-in (0.41-m) O.C. 5-in (0.13-m) EPS exterior insulation with ½" (0.13-m) plywood
Wall cavity	SIP (EPS)	Flash & batt [½-in (0.13-m)] foam with R_{US}-19 (R_{SI}-3.3) batt)	Fiber insulation with PCM (exterior wall) and without PCM (interior wall)	Empty cavity with low-e foil faced gypsum board

Exterior Walls

The walls of the SIP house contain 6-in thick expanded polystyrene insulation (EPS) yielding a thermal resistance of R_{US}-21 (R_{SI}-3.7 W/m^2). The walls of the OVF house are built with 2 by 6 wood studs installed 24-in. on center. The wall studs and roof rafters are aligned in an effort to reduce the wood needed to frame the house and to reduce thermal bridging caused by the studs. Typical wall construction is done 16-in on center (0.41-m) and 10% of the exterior surface area is framed in wall studs. The wall cavity for the OVF house contains about a ½-in (0.013-m) of sprayed-in closed cell polyurethane foam and R_{US}-19 (R_{SI}-3.3) fiberglass batt insulation. The PCM house showcases an exterior wall assembly made of two 2 by 4 walls. Wall studs are made of laminated strand lumber and are installed 24-in (0.61-m) on center. The studs from one wall are offset 12-in (0.3-m) from the other wall's studs, Miller et al. (2010). A fabric is stapled between the two sets of 2 by 4 studs to separate and hold two different types of blown fiber insulation. Conventional blown fiber is contained in the interior cavity while 20% by weight microencapsulated PCMs were added to blown fiber in the exterior framed cavity. The EIFS system is an insulated cladding made of 5-in (0.13-m) of EPS insulation on the outside of the exterior wall. The 5-in (0.13-m) of EPS insulation [(R_{US}-20, (R_{SI}-3.7)] reduces the heat losses caused by thermal bridging. The system is lightweight, highly energy efficient and vapor permeable. The EPS insulation extends from about 1-ft (0.31-m) above the ground up to the soffit of the roof.

Heat Flux Field Data for the East- and South-facing Walls

Two contiguous days of field data are plotted for winter and for summer measurements of the heat flow crossing the east-facing walls (Fig. 4) and also the south-facing walls (Fig. 5) of the homes. Winter data for the east-facing wall all show a continual heat loss to the cold outdoor ambient, Fig. 4. It is interesting that from about 8 AM till 10 AM the heat loss increases sharply until about 10 AM when the rising sun begins to warm the exterior surface. The early morning trend with the sun low in the sky is consistent for all homes because the homes have the same solar orientation. By about 4 PM the walls are losing the least amount of heat to the outdoors; heat loss at 4 PM is about -1.0 Btu/(hr·ft^2) [-3.2 W/m^2]. In comparison, the summertime heat gain is about 2.0 Btu/(hr·ft^2) [6.3 W/m^2] at roughly 4 PM for data collected June 6 and 7, 2010, Fig. 4.

Figure 4. Winter and Summer Heat Flux Measured Across the East Walls of the Homes. The Dashed Lines Represent Energy Plus Benchmarks Against the Field Data

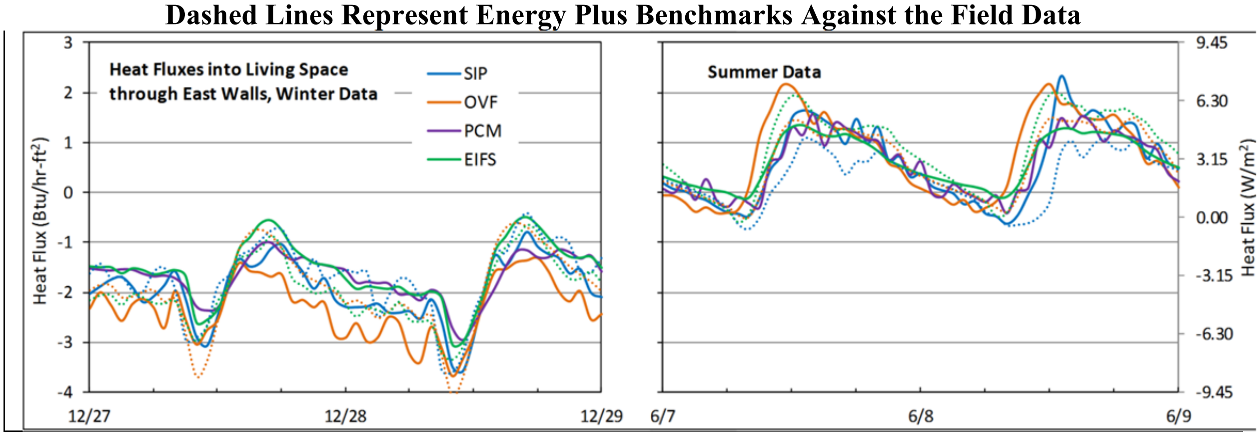
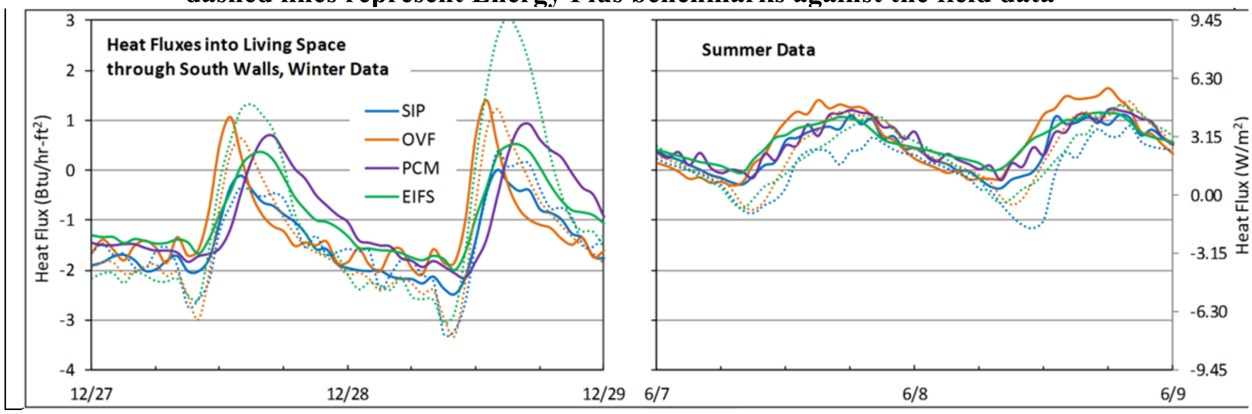


Figure 5. Winter and summer heat flux measured across the south walls of the homes. The dashed lines represent Energy Plus benchmarks against the field data



The architect designed the south-facing walls of the envelopes to be shaded during summer solstice when the sun is its highest in the sky. Therefore, the heat fluxes through the east-facing walls slightly exceed the measured flux on the south-facing walls. Flux on the south-facing walls of the SIP, PCM and EIFS homes peaks at around 4 PM and is only about 1.0 Btu/(hr·ft^2) [3.2 W/m^2] because of the wall's thermal design and in part the shading design. The OVF house shows slightly higher fluxes on its south facing wall, but does not exceed 1.5 Btu/(hr·ft^2) [4.7 W/m^2]. During December the flux on the south-facing wall peaks at noon for the OVF and SIP pair of homes. Again the PCM and EIFS homes show peaks later in the day at about 3 to 4 PM.

EnergyPlus Benchmark of Wall Heat Flux

Heat flux transducers (HFT) were installed on interior surfaces of the walls and covered by an extra layer of 5/8 in. (16 mm) thick gypsum board and placed halfway between outer and inner studs in order to measure the flux through the wall insulation with minimal effect from the studs. EnergyPlus assumes one-dimensional heat transfer. Therefore, a thermally equivalent wall description (ASHRAE 1145-TRP) in the EnergyPlus model would account for the thermal bridging effect caused by framing. However, the thermally equivalent wall cannot be used for this analysis because the equivalent wall predicts average heat flux for the whole wall, whereas the heat flux transducers installed in the test facility measures the heat flux through a small section of the wall aligned between the studs.

EnergyPlus predictions of the heat flux through East and South walls into the living spaces of the SIP, OVF and EIFS homes are presented in Figures 4 and 5. In general, EnergyPlus predicted heat flux matched better with field measured data for the SIP and OVF homes as compared to that for the EIFS house. A low-e perforated foil (facing into the wall's air cavity) was laminated on the gypsum board of the EIFS home. The EnergyPlus V7.0 accounted for shading effects; however, it does not accurately account for the radiation effect between the plywood sheathing and the gypsum board and therefore requires modification of the code.

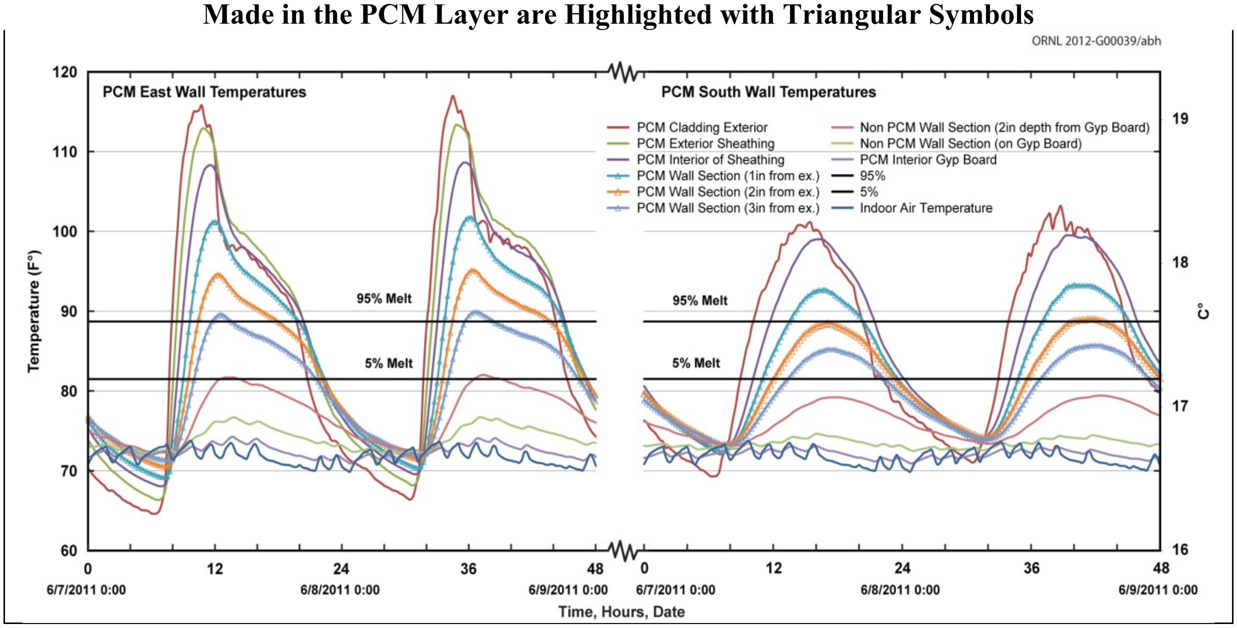
Differences between measured and simulation result for average heat loss for East walls in winter were 0.24 [0.76] and 0.36 [1.13] Btu/(h·ft^2 [W/m^2] and that for the summer were 0.30

[0.95] and 0.11[0.35] Btu/(h·ft^2 [W/m^2], respectively for SIP and OVF homes. Similarly, the values for South walls in winter were 0.03 [0.09] and 0.25 [0.79] Btu/(h·ft^2 [W/m^2] and that for the summer were 0.41 [1.29] and 0.23[0.72] Btu/(h·ft^2 [W/m^2], respectively for SIP and OVF homes.

Effective Usage of PCM

The inclusion of PCM dispersed in the insulation adds heat capacity (or thermal mass) to the wall which can damp diurnal variations in the wall's temperatures and in the heat flux at the interior surface. This damping may reduce the net energy transport through the wall or reduce the electricity needed to meet the net load through the wall by shifting the time of the peak load to a time when the cooling system operates more efficiently. However to gain any benefit the diurnal temperature swings within the wall must span the melt range for the PCM. To get some indication of how effectively the PCM may have been utilized during this period the recorded temperature history at locations within the PCM layer were examined. An example of the temperature data collected is shown in Figure 6 for east-facing and south-facing walls for two summer days. The curves for locations in the PCM layer are highlighted with triangular symbols. For each day the minimum and maximum temperatures at all measured locations were examined. If all of the minimum temperatures were below the melt range and all of the maximum temperatures were above the melt range, then a complete phase change occurred for all of the PCM; and the PCM is said to be "Fully Active." If the PCM undergoes at least some melting but not complete melting everywhere during a day it is said to be "Partially Active." Using these criteria on the data in Figure 6, the PCM is fully active in the east wall for both days and partially active in the south wall. The PCM usage for the entire year in East Tennessee's climate is presented in Table 5.

Figure 6. Summer Temperatures Measured in the East and South Wall of the PCM Home. The Solid Black Lines Represent Melt Temperatures for the PCM. The Temperature Measures Made in the PCM Layer are Highlighted with Triangular Symbols



To better understand the performance of PCM detailed, transient, finite-difference models of the wall and ceiling were developed. These models were run using measured field data from the house for the time periods of June and July 2011 to define boundary conditions. Thermal properties of the materials making up the walls had previously been measured in the lab (Shrestha et. al, 2011) and these measured properties were used in the modeling. Data from the east and south walls were examined to see how closely the model matched the measured inside surface heat flow and the measured temperatures at locations through the insulation thickness. The match between the calculations and measurements was disappointing. The calculated heat flux showed a longer time lag and greater amplitude reduction than was observed in the measurements. The calculated and measured temperatures showed similar discrepancies in phase and amplitude. Since the primary impact of PCM is to produce time lag and amplitude reduction, the amount of PCM in the wall was adjusted in an effort to match the observed behavior. The best match between modeled and observed results was obtained when the detailed finite-difference model assumed there was no PCM dispersed in the insulation. It appears that either the PCM migrated after installation or the installer did not actually have 20% by weight of PCM added to the blown fiber. Fiber insulation with PCM was in self-contained bags that had been premixed by the manufacturer. Samples will be pulled from the walls to check the concentration of PCM and therefore the data and results need further investigation.

Table 5. ZEBRA House PCM Usage for a Full Year

	South Wall		East Wall	
	Fully Active[1]	Partially Active[2]	Fully Active[1]	Partially Active[2]
Days out of Year	0	130	31	140
Percent of Days out of Year	0%	36%	8%	38%

CONCLUSIONS

HERS scores and revenue meter data for the four demonstration homes prove that each house consumes only about half the energy consumed by a conventional IECC (2006) code compliant house. All envelopes were made energy efficient and air tight with air exchange rates less than 0.1 ACH when induced by weather conditions.

The field data for the sheathing of the OVF home is of keen interest because the closed cell insulation, serving as an excellent air barrier on the interior of the OVF home, is a vapor retarder (permeance of about 0.8 perm) and could be construed to possibly trap moisture. On the exterior side, the fluid applied air barrier is vapor permeable with a water vapor permeance of 12 perms for a 40 mil thick membrane. Hence driving rains incident on the south-facing wall do not penetrate the vapor permeable air barrier and the sheathing is protected from the elements.

EnergyPlus V7.0 predicted heat flux through the roofs and attics matched better with field measured data in summer compared to that in winter, yet did an acceptable job in matching the trends in summer and winter. Average difference between measured and simulation result in winter were within 0.55 [1.73] Btu/(h·ft^2) [W/m^2] and that for summer were within 0.17 [0.54] Btu/(h·ft^2) [W/m^2]. Differences between measured and simulation result for average heat loss for the East walls in winter were within0.36 [1.13] Btu/(h·ft^2) [W/m^2] and that for the summer were within 0.30 [0.95] Btu/(h·ft^2) [W/m^2]. Similarly, the values for the South walls in winter were within 0.25 [0.79] Btu/(h·ft^2) [W/m^2] and that for the summer were within 0.41 [1.29] Btu/(h·ft^2) [W/m^2].

The use of PCM in East Tennessee's climate showed the PCM fully active in an east oriented wall but only partially active in the south-facing wall due in part to the home's shading design. PCM is not active in the attic because of an application error. Samples pulled from the attic showed no evidence of PCM in the blown fiber insulation. Therefore attempts to predict the effect of the PCM in transient finite difference models failed simply because there was no PCM.

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