Delivering an Air-Tight Envelope from Concept to Completion

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ABSTRACT

With the backing of Oak Ridge National Laboratories, the Zero Energy Building Research Alliance (ZEBRA) embarked on a project exploring the possibility of construction of net zero energy consumption homes using readily-available building methods and materials. In this study, four (4) test homes were built. Building envelope air tightness was considered a crucial component of energy efficiency on all four test homes. To achieve air tightness on one of the homes, the use of a fluid-applied, vapor-permeable membrane was specified. The home showcased in this document is referred to as the "optimal value framing" or "OVF" home in the referenced ORNL report. This was a stick-built home with the structure consisting primarily of lumber framing and OSB sheathing. An air barrier membrane manufacturer was selected to provide the products. This paper explains in detail the planning and installation of the complete fluid-applied air barrier system on the OVF test home. Successful installation of the air barrier required effective use of materials, sound design and details, qualified installers, coordination of adjacent work and willingness to change common building practices. It was found that 87% of the labor to install the air barrier was expended for detailing of joints, terminations and penetrations while the remaining 13% of labor was expended to spray-apply the membrane at full coverage over the walls and onto the ceiling insulation panels. The air barrier was a significant component of the energy-saving package employed on the OVF test home. After construction of OVF test home was completed, it was measured for air tightness, with results indicating the test home was 3 times tighter versus comparable construction without an air barrier. Based on the air tightness measurement and 2-year monitoring of moisture content, the air barrier membrane and accessories made the home airtight while they also protected the underlying wall construction from water intrusion, and allowed dry-through of moisture from the OSB sheathing. Although the OVF test home and the other 3 test homes in the ORNL study did not achieve net zero energy usage, they all exhibited at least 50% lower energy consumption compared to a standard, stick-built home of comparable size complaint with IRC 2006. A full summary of the energy and enclosure performance of the OVF test home, and the other three test homes can be found in the ORNL report ORNL/UT Batelle report "Final Report Envelope Field Performance Deliverable D.3.2" by Miller, Shrestha, Childs & Stannard published August 2012.

1 INTRODUCTION

In September of 2008, with funding provided by the US Dept. of Energy (USDOE), Oak Ridge National Laboratories (ORNL) broke ground on the construction of four (4) test homes for the Zero Energy Building Research Alliance (ZEBRA). The objective of ZEBRA is to determine if construction of net zero energy use homes is possible, using readily-available building methods and materials. The test homes were to be fully-instrumented and monitored over a two-year period to evaluate overall energy use as well as hygro-thermal behavior of the envelope. The test houses were also measured for air tightness. The impact of building envelope air tightness on

HVAC energy savings is most recently quantified in NISTIR 7238. This study indicates that improved building airtightness produces HVAC energy savings, from about 10 to 40%, depending on climate zone and construction. The home showcased in this paper is referred to in the referenced ORNL study as the optimal value framing (OVF) test home. To achieve air tightness on the OVF test home, ORNL specified the use of a fluid-applied, vapor-permeable membrane to be applied over the exterior sheathing and into the ceiling of this conventional stick-built structure. This paper explains the design, materials and methods required for delivery of the complete fluid-applied air barrier system on the OVF test home. A view of the OVF test home under construction is shown in Figure 1.

Figure 1. View of the Front Entrance Side of the OVF Test Home

The air barrier enclosure on the home was approximately 4,200 SQ FT. The membrane air barrier manufacturer chosen for the project, Carlisle Coatings & Waterproofing Incorporated (CCW), provided the materials and also the design and installation of the air barrier.

2 MATERIAL SELECTION

The primary air barrier material used was CCW's Barritech VP, a water-borne, latex-based coating of 66% solids content, which air-dries at ambient conditions. The membrane was selected due to its favorable installation characteristics over OSB and its vapor permeability. The manufacturer specifies installation of this membrane by spray in a single coat at 60 mils (0.060 inch) wet or by two roller-applied coats at 30 mils (0.030 inch) wet per coat. The cured membrane, theoretically 40 mils (0.040 inch) thick, is fully-adhered to the substrate and exhibits elastomeric properties. The air barrier material plus ancillary products used on the project, are listed in Table 1.

Table 1 - Air Barrier Products used on the Project

Item	Application
Barritech™ VP , Liquid-applied membrane, 5-GAL Pail	Fully-adhered 40 mil membrane. Coverage of exterior walls, ceiling and reinforcing fabric details
DCH Reinforcing Fabric, woven polyester fabric, 4" width	Reinforcement and coverage of sheathing joints, imbedded in Barritech VP
DCH Reinforcing Fabric, woven polyester fabric, 12" width	Reinforcement and coverage of inside corners, outside corners and base flashing, imbedded in Barritech VP
CCW-705, 40 mil Self-Adhering Membrane, 18" width	Waterproofing behind ledger board at horizontal projections
CCW-705, 40 mil Self-Adhering Membrane, 9" width	Waterproofing over window and door openings
CCW-705, 40 mil Self-Adhering Membrane, 4" width	Flashing over window and door nail flange at head and jambs
Barritape, 20 mil Self-Adhering Membrane, 4" width	Tape over ceiling insulation board joints
CCW-702 WB, Water-Based Contact Adhesive, 5-GAL Pail	Surface preparation for self adhering membrane
Pre-Kleened EPDM, 45 mil Non-Reinforced Ethylene-Propylene Diene-Monomer (EPDM) Rubber Flashing, 18" width	Transition membrane bridging wall to ceiling air barrier
SURE-SEAL EP-95, EPDM Splicing Cement, 1-GAL Can	Bond EPDM to substrates
SURE-SEAL In-Seam Sealant, 10 fl-oz Tubes	Seal EPDM Laps, and EPDM to top plate
SURE-SEAL SecurTAPE, Splicing Tape, 3" Width	Bond and SEAL EPDM splices and corners
SURE-SEAL Lap Sealant, 10 fl-oz Tubes	Seal EPDM Details and Terminations
DAP® ALEX PLUS® Exterior Grade Latex Caulk, 10 fl-oz Tubes	Seal gaps and holes exceeding ¼" in OSB sheathing. Sealing mechanical/electrical penetrations to air barrier membrane.
Dow Great Stuff™ 1-part, polyurethane expanding foam, portable cans	Fill gaps around windows, doors and mechanical/electrical penetrations

3 AIR BARRIER DESIGN AND INSTALLATION

The membrane and accessories were specified to be installed at full coverage over the exterior side of the wall on OSB sheathing. The position of the Barritech VP membrane and accessories in the wall assembly is shown in Figure 2. The stud cavity was specified to be sprayed with ½" thickness closed cell foam, applied onto the interior side of the OSB sheathing. The remaining stud cavity space was to be filled with R-19 fiberglass batt insulation. Hence, all of the wall's insulation was applied in the stud cavity. As the test homes were built in Oak Ridge, TN (USDOE Heating Zone 4) a dew point occurs within the stud cavity of this wall assembly during winter. Given the dew point location and the position of the non-permeable foam against the interior side of the OSB, the vapor permeable feature of the Barritech VP membrane was critical to allow incidental moisture within the OSB to dry. Furthermore, the Barritech VP was designed to resist rain water intrusion from the exterior, as the fiber cement siding had plenty of gaps and pathways for water passage. And, the Barritech VP was expected to seal around nails used to secure the fiber cement siding, which would be driven into the framing and OSB sheathing through the membrane.

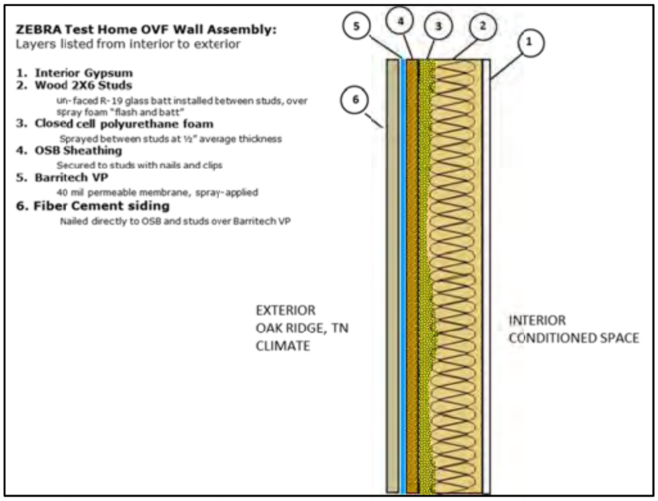

Figure 2. Section Drawing of OVF Wall Assembly

Proper design, detailing and installation techniques are as critical as material selection in the achievement of an airtight building envelope. In cooperation with Barber-McMurray Architects, Schaad Construction and ORNL, CCW created shop drawings and field instructions for installation of the air barrier on the test house. Then from March through May of 2009, personnel from Schaad Construction and CCW installed the air barrier products on the house.

3.1 INSTALLATION OVER SHEATHING BOARDS AND JOINTS

The rough oriented strand board (OSB) substrate and the fit and finish of the OSB boards presented a challenge in achieving complete coverage, see Figure 3.

Figure 3. OSB Wall Construction

Figure 4. DCH Fabric Imbedded in Barritech VP

Figure 5. Spray Installation of Barritech VP

All board joints and inside-outside corners were detailed with a respective 4 inch and 12 inch width woven polyester fabric imbedded in the fluid-applied membrane, as shown in Figures 4, 5, 13 and 18. The fabric effectively covered the joints and metal clips between the boards, as shown in Figures 3 and 4. All open board surfaces and imbedded fabric details were then coated with a minimum of 60 wet mils of fluid air barrier, applied by airless spray as shown in Figure 5.

3.2 CEILING AIR BARRIER AND WALL-TO-CEILING CONNECTION

It was decided that the face of the phenolic foam insulation board used in the ceiling would be the plane of air tightness. As the insulation panels would be secured with screws, and the ceiling would be finished with drywall nailed through the insulation, it was decided to coat the foam boards with Barritech VP to provide sealing around nails and screws. The junction of the wall and ceiling air barrier was particularly challenging to seal, yet it was the most critical for attaining the desired air tightness. The manufacturer's shop drawings addressing these conditions are shown in Figures 6 and 7.

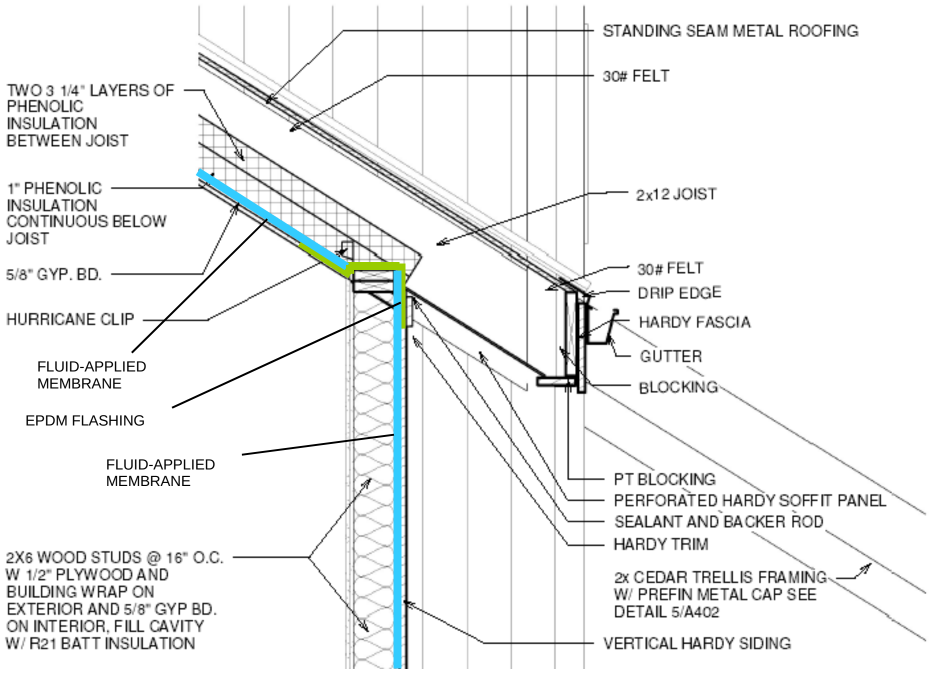

Figure 6. Shop Drawing of Wall to Ceiling Connection

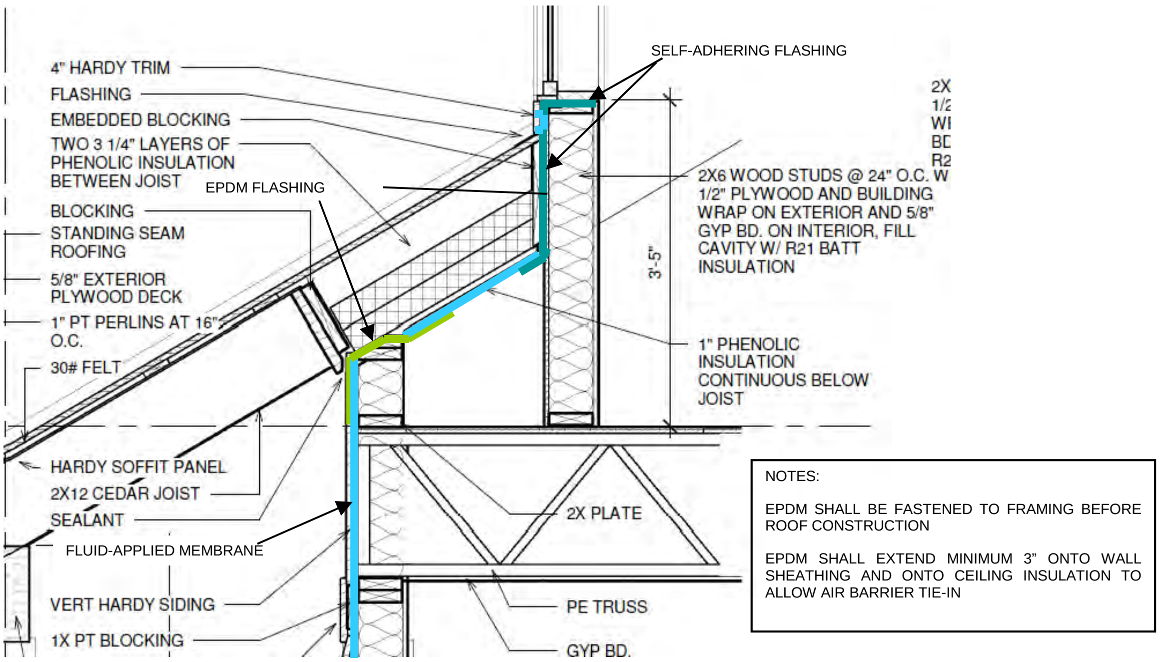

Figure 7. Shop Drawing of Knee Wall Connection

To tie the air barrier membrane on the exterior wall to that in the ceiling assembly, the framer was instructed to attach 24 inch width EPDM flashing at the top plate of all exterior walls and all partition walls projecting to the roofline, see Figure 8.

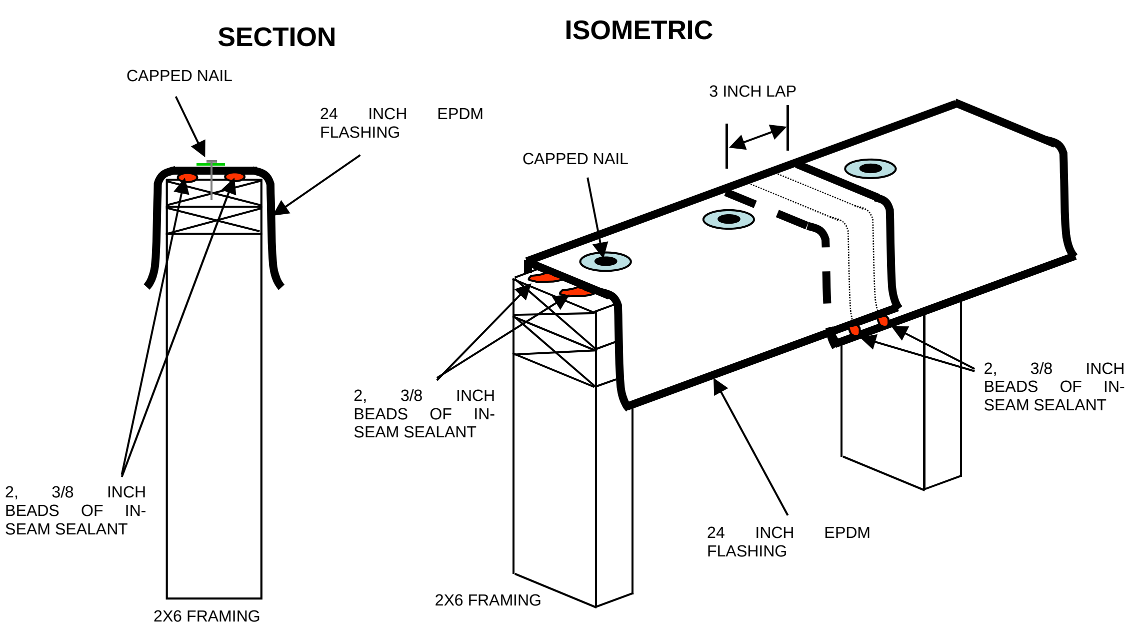

Figure 8. Instructions for the Framer

The EPDM flashing was left hanging during subsequent construction, as shown in Figures 8 and 9. The EPDM flashing was then bonded to the air barrier on the exterior wall surface, and bonded to the air barrier on the underside of the foam insulation in the ceiling assembly. The air barrier was bonded to the cured Barritech VP on the ceiling insulation panels using EP-95 adhesive. The EPDM was bedded directly into un-cured Barritech VP on the walls, and set in place with stapes. All EPDM laps were sealed with EP-95 slicing cement and 3" SecurTAPE. The ceiling air barrier was constructed by spray-applying the fluid membrane to the individual insulation boards, allowing the membrane to dry and then installing the boards across the underside of the roof trusses, see Figure 10. The joints between adjoining boards were taped with 4 inch width self-adhering flashing, and mechanical/electrical penetrations were sealed to the air barrier membrane with latex caulk, see Figure 11.

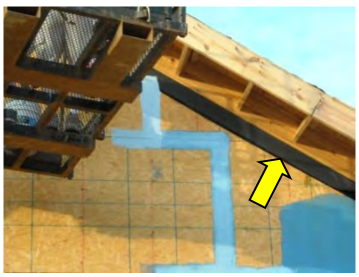

Figure 9. EPDM Flashing Built into Wall

Figure 10. Foil-Faced Boards in Ceiling Coated with Barritech VP

Figure 11. Ceiling Air Barrier, Joints Taped with CCW-705 or Barritape

3.3 DECK AND ROOF PROJECTIONS

The OVF test house had a number of projections attached to the exterior wall. To effectively seal these, an 18" width self-adhering membrane strip was installed over the surface before the deck and wall projections were constructed, see Figure 12.

Figure 12. CCW-705 Self-Adhering Membrane Between Deck and Wall

Figure 13. DCH Fabric Imbedded in Baritech VP as Base Wall Flashing

3.4 BASE OF WALL TERMINATION

Regional building code requires the use of a rigid flashing material around the base of the exterior wall as a termite barrier. A detail of this condition is shown in Figure 14. This detail shows cultured stone cladding, which was used in some areas of the wall for accenting. The air barrier membrane was terminated onto the base flashing with an imbedded 12 inch woven polyester reinforcing fabric, see Figure 13. To keep the blue-colored liquid-membrane from reaching visible space, masking tape was applied over the edge of the termite barrier flashing, and removed after the membrane was installed. The air barrier membrane terminates above the sill-to-slab condition. Therefore, the foam sill gasket installed between wall sill plate and the concrete slab was the primary air seal of this condition.

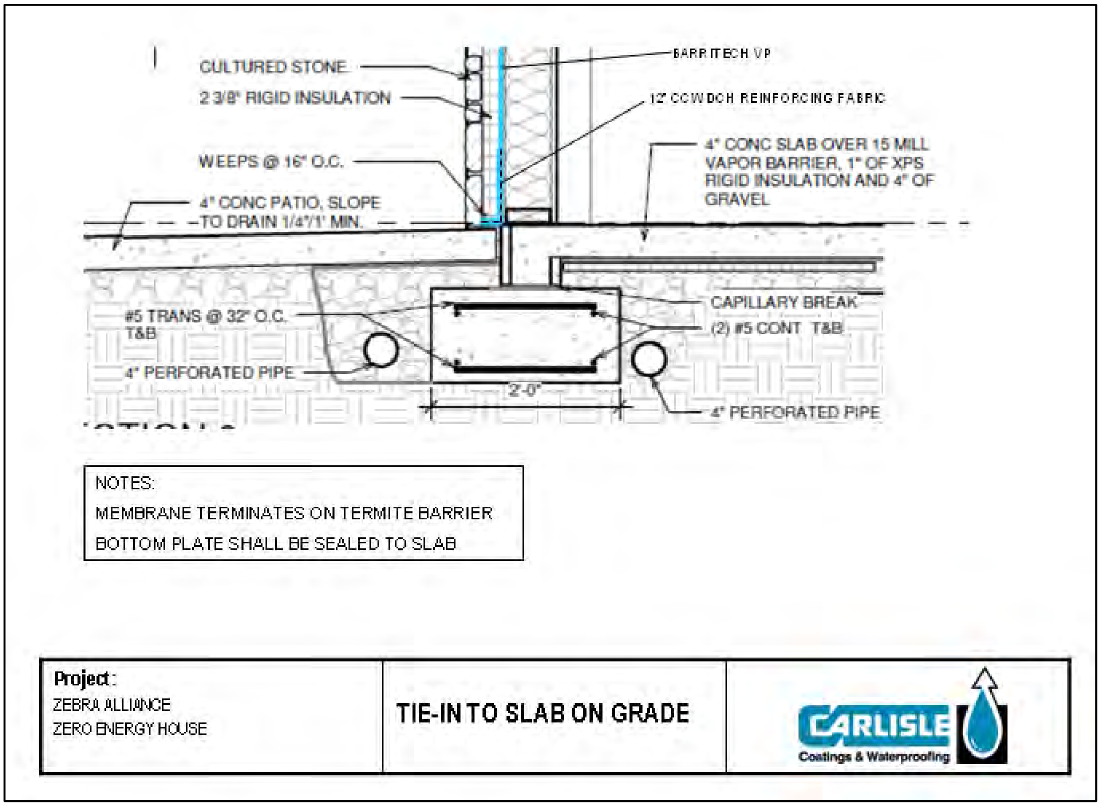

Figure 14. Manufacturer's Shop Drawing of Air Barrier Termination at Slab on Grade

3.5 WINDOW AND DOOR OPENINGS

The windows and doors were of high energy performance, but otherwise quite conventional for residential construction. All openings were wrapped with a 9 inch width self-adhering membrane before installation of the fluid-applied membrane, see Figure 15.

Figure 15. CCW-705 Self-Adhering Flashing in Window Opening

Figure 16. Window Installed in Opening

The combination of liquid-applied membrane and self-adhering flashing provided continuity of the air barrier from the wall surface to the return into the opening. The windows and doors were then installed into the opening, and sealed on all four sides from the interior side with can foam. To provide resistance to rain water intrusion, the nail flange on the exterior was sealed over the head and jambs with 4 inch width self-adhering flashing, see Figures 16 and 17. The nail flange on the sill was deliberately left un-flashed, to allow drainage of any water leaking through the window or door units, shown in Figure 17.

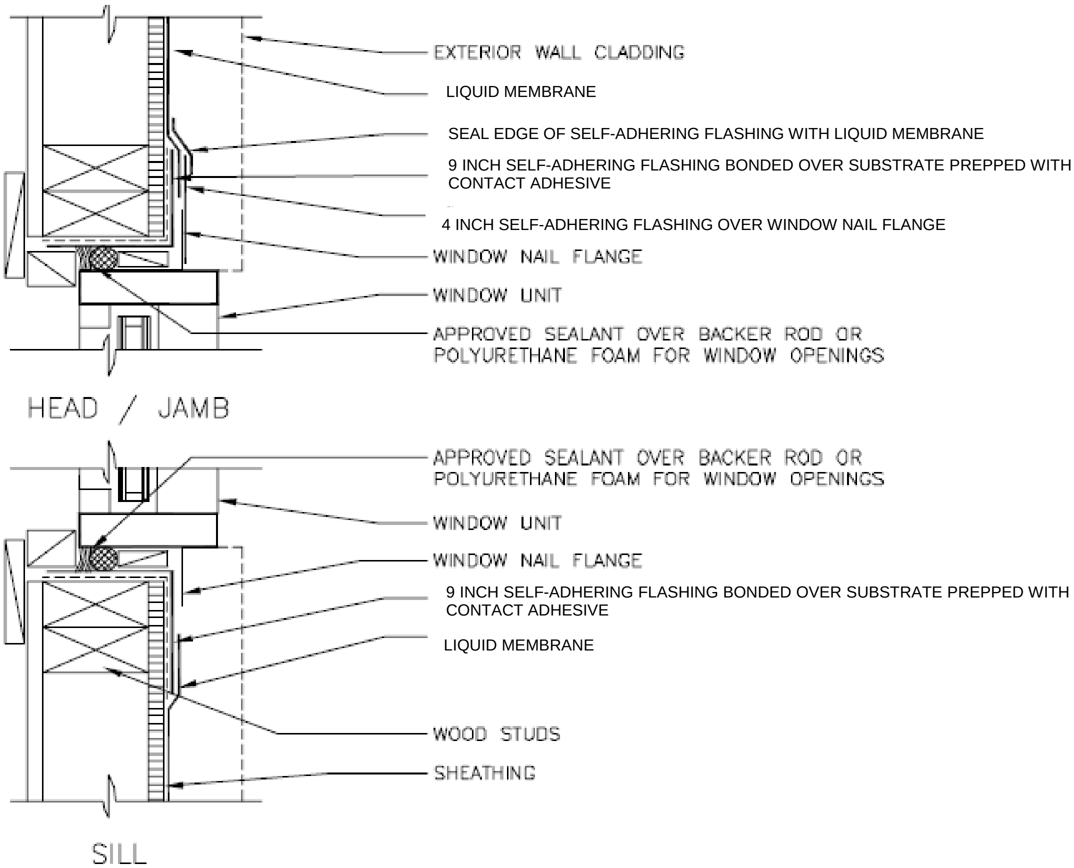

Figure 17. Manufacturer's Detail Drawing of Window Section

3.6 FINISHED INSTALLATION

The OVF test home was effectively enclosed with the air barrier, including full coverage of walls and necessary tie-ins made at terminations and penetrations as shown in Figures 18 and 19. After complete installation of the air barrier, any mechanical/electrical penetrations made through the wall after air barrier installation were inspected and sealed, as shown in Figure 20. Finally, fiber cement siding was installed over the walls by nailing it to the OSB sheathing and wood framing, through the air barrier membrane, see Figure 21. Man-hours for installation of the air barrier were tracked from start to completion. It was found that 87% of the labor was expended for "detailing" - that is to install the products over joints, terminations and penetrations, as shown in Figures 18 and 11. The remaining 13% of labor was expended to spray-apply the membrane at full coverage over the walls and onto ceiling insulation panels as shown in Figures 5, 10 and 19. During construction, wall and roof assemblies were instrumented in various locations by ORNL to monitor hygro-thermal behavior over the two -year study.

Figure 18. Overview - Detailing of Joints and Penetrations

Figure 19. Full-Coverage of Exterior of the OVF test Home with Barritech VP Fluid-Applied Membrane

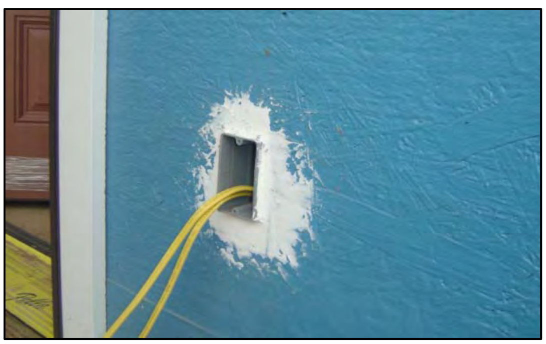

Figure 20. Sealing Penetrations made Through the Barritech VP Air Barrier

Figure 21. Fiber Cement Cladding Installation over Walls of OVF Test Home

4 RESULTS

After construction was completed, ORNL performed a whole-building air tightness test on the OVF test home according to ASTM E 779. The measured value of the OVF test home was 1.74 air changes per hour (ACH) @ 50 Pa. By comparison, air leakage of a standard stick-built house was measured at 5.7 ACH @ 50 Pa. It was also observed during construction that the fully-adhered membrane system made the enclosed space very quiet, like being inside a vault. The value of this feature was not quantified. After 2 years of continuous monitoring, the OVF home, on which the Barritech VP was installed, exhibited 50% lower energy consumption than a standard home (comparable size, complaint with IRC 2006) and the wall components remained within an acceptable range of moisture content.

5 CONCLUSIONS

The Barritech VP air barrier was a significant component of the energy-saving package employed on the OVF test home. Installation of the air barrier resulted in the OVF home measuring more than 3 times tighter versus comparable construction without an air barrier. Based on the air tightness measurement and 2-year monitoring of moisture content, the Barritech VP and accessories made the home airtight while they also protected the underlying wall construction from water intrusion, and allowed dry-through of moisture from the OSB sheathing. Achievement of air barrier continuity on this project required effective use of materials, sound design and details, qualified installers, coordination of adjacent work and willingness to change common building practices. A full summary of the performance of the 4 test homes can be found in the ORNL/UT Batelle report "Final Report Envelope Field Performance Deliverable D.3.2" by Miller, Shrestha, Childs & Stannard published August 2012.

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REFERENCES

William Miller PHD ORNL "Letter Report Describing the As-Built Envelope Sub Systems Deliverable 3.1" Oak Ridge National Laboratory, Managed by UT Batelle for the Department of Energy, August 2012

William Miller PHD ORNL, Som Shrestha ORNL, Kenneth Childs ORNL & Eric Stannard UT "Final Report Envelope Field Performance Deliverable D.3.2" Oak Ridge National Laboratory, Managed by UT Batelle for the Department of Energy, August 2012

Steven J. Emmerich, Tim McDowell and Wagdy Anis (2005) NISTIR 7238 "Investigation of the Impact of Commercial Building Envelope Airtightness on HVAC Energy Use" National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce

ASTM International (2003) ASTM E 779-03 "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization" 100 Barr harbor drive, PO Box C700, West Conshohocken, PA 19428-2959 USA

2006 International Residential Code® (IRC) for One- and Two-Family Dwellings. International Code Council 500 New Jersey Avenue, NW 6th Floor, Washington, DC 20001

2006 International Energy Conservation Code® (IECC). International Code Council 500 New Jersey Avenue, NW 6th Floor, Washington, DC 20001

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MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Letter report describing the as-built envelope subsystems

Deliverable 3.1

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Prepared by

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Letter Report Describing the as-built Envelope Subsystems

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Letter report describing the as-built envelope subsystems

Advanced Residential Envelopes for Two Pair of Energy-Saver Homes

ABSTRACT

Four homes are under construction in the Tennessee Valley to showcase homes that are expected to be 50% more energy efficient than homes built to local code. Schaad Companies LLC, the Tennessee Valley Authority (TVA), the Oak Ridge National Laboratory (ORNL), Barber McMurry Architects (BMA) and the Department of Energy (DOE) intend to transform new and existing buildings into affordable, durable and efficient housing. All formed a private- and federal-sector consortium herein called the Zero Energy Building Research Alliance (ZEBRAlliance). The consortium is about to evaluate the market viability for making two pairs of homes 50 percent more energy efficient than homes of similar size and style. Achieving the goal requires the most advanced building technology, products and techniques available. The homes are located on adjacent cul-de-sacs and are unoccupied for the duration of a two-year field study, thereby eliminating the confounding issue of occupancy habits.

Introduction

The U.S. stock of residential and commercial buildings consumes almost 40% of the primary energy (U.S. DOE, 2008). Retrofitting inefficient buildings already in place and implementing new technology in new construction should be a major thrust for developing affordable, durable, and reliable envelope technologies that mitigates part of our national energy consumption and reduces carbon emissions. The building sector also has green-house-gas (GHG) emissions that exceed both the industrial and transportation sectors of the U.S., and therefore buildings have the best potential for reducing emission (Climate Change 2007). The U.S. Green Building Council (USGBC) also reported the need for integrated building strategies to reach Net Zero Energy buildings (USGBC 2007):

> "*… To achieve Net Zero Energy buildings, prescriptive, independent measures will no longer suffice. Leaps forward in building performance require designs that fully integrate building systems…*"

Therefore, continued research and the demonstration of energy efficient buildings are of paramount importance to the clarion call to conserve energy and mitigate GHG emissions. Florida Solar Energy Center (FSEC) conducted a landmark demonstration on seven Habitat for Humanity homes, adjacent one another, in Fort Myers, Florida. The homes had identical floor plans and orientation, but with different roofing systems designed to reduce attic heat gain, Parker and Sherwin (1998). Six of the houses had R_{US}-19 h•ft^2•°F/Btu (R_{SI}-3.3 m^2•K/W) ceiling insulation, and the seventh house had an unvented attic with insulation on the underside of the roof deck rather than the ceiling. All homes had the same two-ton split system air conditioner with 5 kW of auxiliary backup heat, Parker et al. (2001). Results showed that the white reflective tile and metal roofs reduced cooling energy consumption by 18-26% and peak demand by 28-35%, Parker et al. (2002). Their findings clearly show that cool roofs are a viable strategy for reducing energy consumption; however, a cool roof is just one of several measures needed to achieve near-zero energy use.

Zero-energy home demonstrations across the country have two outstanding and common envelope features; the envelope is airtight and the envelope is well insulated. Klingenberb (EDU 2004) built a 1,450 square foot (134.7 m^2) home in Urbana, IL that had R_{US}-56 h•ft^2•°F/Btu [R_{SI}-9.9 m^2•K/W] on all walls, the roof and the floor of the home. The design emphasized the use of insulation and opted to not include thermal solar and/or advanced comfort conditioning systems. The heating bill of the Klingenberb home for January in Urbana, IL[1] totaled only $35 (EDU 2004). Norton and Christensen (2006) reported on the performance of a 1,280 square foot (118.9 m^2) Habitat for Humanity home in Denver, CO that produced 24% more source energy than it consumed over a year of study. The home used a 4-kw grid-tied photovoltaic (PV) system to generate renewable energy and the envelope was super-insulated with R_{US}-40 (R_{SI}-7) fiberglass batt in the walls, R_{US}-60 (R_{SI}-10.6) insulation in the attic and R_{US}-30 (R_{SI}-5.3) insulation in the floor. Space heating was accomplished using a direct vent natural gas furnace and baseboard electric resistance heaters in each of the three bedrooms. In the hotter climate of Las Vegas, NV, Building America worked with Pardee Homes (BA 2003) to showcase a 5,300 square foot (492 m^2) home that features an 8.6-kW grid-tied PV, solar hot water system, tank less hot water heaters, 0.95 efficient gas furnace and a 16 SEER air-conditioning unit. The building envelope has R_{US}-38 (R_{SI}-6.7) insulation in an attic shielded by a radiant barrier, R_{US}-21 (R_{SI}-3.7) insulation in the walls and R_{US}-30 (R_{SI}-5.3) insulation in the floor above the garage. The home is expected to use 90% less energy than a home built to local building code.

In each of these demonstrations the consumed operational energy was reduced and the durability of the envelope improved over conventional practice by focusing on envelope design as much if not more so than the active energy subsystems. Therefore, the ZEBRAlliance used a systems approach to integrate all parts of the home into a working envelope to reduce the home's operational energy and environmental impact while increasing its durability.

Demonstration Homes — Envelopes

Four homes are nearing completion and will soon demonstrate four different envelope approaches, Figure 1. The key envelope feature names each home:

	Footprint in square feet[1]			
Key Envelope Feature	**Basement**	**1st Floor**	**2nd Floor**	**Total (ft^2)**
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] Urbana, IL has ASHRAE 99% winter design temperature of -3°F (-19°C).

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

The SIP and OVF homes are a pair of homes having cathedral ceiling and walk-out basement. The PCM and EIFS pair has 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 daily heat flows crossing all envelopes. All four homes have weather resistive barriers (WRB) to limit infiltration.

Christian and Bonar (2008), Christian et al. (2006) and Christian (2004) showcased SIP systems in five side-by-side Near-Zero Energy Homes (ZEH). The SIP envelope provides an excellent ratio of cost to R-value and was therefore selected for one ZEBRAlliance home to exploit the evolution of design gained from the ZEH field studies conducted by Christian (2008). The OVF envelope was selected to directly compare it to the SIP enclosure. OVF is a modified framing method known in construction practices as either advanced framing or optimum value engineering. It increases the center-to-center distance of standard framing to save lumber and allow for more insulation. The direct comparison of the two enclosures will enable a fair assessment of cost and thermal performance of the two framing techniques. The third home uses advanced wall framing but focuses on the benefits of insulations mixed with phase change materials (PCM house). A double wall assembly made of two 2 by 4 walls uses the interior insulated wall as a thermal buffer against heat absorbed by PCM in the exterior insulated wall. During the summer evenings the thermal capacitance in the exterior wall is released to the night-sky rather than penetrating into the conditioned space. The fourth home's cladding is composed of an Exterior Insulation Finish System (EIFS house) and was selected because of its potentials for energy efficiency, cost-effectiveness, and smaller carbon footprint. Placing insulation on the exterior of a building makes EIFS suitable for either new construction or refurbishment projects, and EIFS eliminate thermal bridges while also reducing air, wind and moisture penetration through the cladding. Kośny (2002) conducted hotbox testing of EIFS with 2-in EPS and compared it to claddings made of brick, insulated glass, stucco, precast concrete, wood and masonry. The EIFS achieved an 84% higher "whole wall R-value[2]" as compared to the next best-performing cladding. The National Institute of Standards and Technology (NIST) performed a life cycle analysis of EIFS using its BEES[3] software (Scheuer and Keoleian 2008) and found it resulted in less carbon contaminants over the life cycle of the product as compared to brick, stucco, aluminum, cedar and vinyl.

All homes are serving as breadboards to help develop a portfolio of the best available materials and construction methods that reduce carbon emissions, cost less to operate, and provide an impressive example of energy-efficient building benefits. The builder Schaad is keeping tab of all construction costs and will share the data with ORNL for assessing the economics of higher up-front material and installation costs as compared to the operational

[2] The whole wall R-value accounts for the entire wall construction, including material discontinuities and thermal bridging effects.

[3] Building for Environmental and Economic Sustainability (BEES) software estimates the environmental performance of building products by using the life-cycle assessment approach specified in the ISO 14040 series of standards.

costs of the homes. We are reporting and documenting herein principally details about the envelope systems as all demonstration homes are still under construction as of this writing.

Roof Systems

The roof cover on the SIP and OVF pair of homes is standing seam metal that exploit infrared reflective (IRR) paint pigments to boost solar reflectance. The painted metal is an IRR zinc-gray color with solar reflectance[4] of 0.30 and thermal emittance of 0.85. The metal roof is 26 gage galvanized steel and its polyvinylidene fluoride paint finish is warranted to not fade for 30 years. A unique sheathing material having a dimpled spacer mat elevates the metal roof about ¼-in (6-mm) off the deck to protect the SIP roof from moisture and excessive heat. Kriner, Miller and Desjarlais (2001) observed that the underside temperature of the oriented strand board (OSB) deck peaks at almost 160°F (71.1^{o}C) when covered with an IRR painted metal roof. Temperatures of about 170°F (76.7^{o}C) can cause potential damage to expanded polystyrene insulation (EPS). Therefore, we opted to include the ¼-in (6-mm) air space to help reduce deck temperatures. Field measures by Miller and Kośny (2008) for standing seam painted metal shows that a ¾-in (0.019-m) air space drops the OSB underside temperature from about 160°F (71.1^{o}C) down to 136°F (57.8^{o}C). The sheathing with dimpled spacers provides a ¼-in (6-mm) air space that should reduce the OSB peak summer temperature an estimated 10°F (5.6°C).

The IRR zinc-gray metal is also installed on the OVF house. The cathedral roof is fitted with three layers of phenolic foam insulation (Figure 2). A cover board being 1.18-in (30 mm) thick is attached to the underside of the 2 by 12 joists to help reduce thermal bridging. 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. Aged phenolic foam has a thermal resistance of about R_{US}-6.2 per in. Therefore the roof assembly is estimated to have an overall resistance of about Rus-50 (R_{SI}-8.8). Perforated fiber cement siding[5] and a metal ridge cap ventilate the inclined air space in the cathedral roof of the OVF home.

An IRR painted metal shake is installed on the PCM home. Solar reflectance of the metal shake is 0.34 and its thermal emittance was measured at 0.85. A tapered EPS insulation is inserted under the metal shakes to provide walking support and some resistance to heat transfer across the deck.

The EIFS house demonstrates an IRR asphalt shingle roof, which is by far the least expensive roofing option but has a slightly lower solar reflectance because of the effect of the aggregate granules. Solar reflectance is 0.26 and the thermal emittance of the shingle is 0.88. To mitigate the heat transfer effects of the darker more heat absorbing shingles, a profiled and foil[6] faced 1-in (0.0254-m) EPS insulation was placed over the roof rafters and covered by a foil[6] faced OSB with the foil facing into the inclined air space (Figure 3). The assembly provides a radiant barrier facing into 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. A slot is cut into the roof deck near the eave just above the soffit vent to provide make up air from the

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[4] Solar reflectance was measured using ASTM C1549-09 (ASTM 2009).

[5] The concrete textured siding has 5 square inches of open vent per linear foot of the panel.

[6] Thermal emittance of the foils is 0.04 as measured using ASTM C-1371 (ASTM 1997).

soffit vent and attic. As thermally induced airflows move up the inclined air space, cool make up air is pulled from the soffit and attic plenums to enhance thermal performance of the deck. The design (Fig. 3) puts the air intake of the inclined air space within the enclosure, just above the soffit. A perforated metal soffit vent acts as a fire block to prevent any burning embers from entering the air space.

The assembly was field tested at ORNL on the Envelope Systems Research Apparatus (ESRA) and results showed it one of the best performing prototype roof assemblies (Figure 4). We observed in August shingle temperatures of almost 170°F (76.7°C), air space temperature of 130°F (54.4°C) and an EPS insulation temperature of only 110°F (43.3°C). Therefore, the air space helped protect the insulation from excessive temperature which would degrade it and compromise the roof. Heat transfer crossing the roof deck of the prototype shingle roof was about the same as that observed for a prototype IRR painted metal and IRR clay tile roof. The IRR standing seam metal prototype was designed with two 2-in (0.051-m) inclined air spaces separated by a fiber cement board to add conventional thermal mass to the roof. The other prototype has clay tile attached to 1¼-in (0.032 m) of EPS foam [R_{US}-6.25 (R_{SI}-1.1)] with the foam adhered to the deck. The shingle roof assembly as well as the painted metal and clay tile assemblies dropped the peak day deck heat flow at least 80% of the control shingle assembly (Figure 4). Their attic air temperatures did not exceed the outdoor air temperatures for this hot July period in East Tennessee.

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 phase change materials (PCMs) added to the blown fiber insulation on the attic floor of the PCM house will absorb the remaining heat that escapes the reflective metal shake roof, the radiant barrier and the solar powered attic ventilation. The attic floor is insulated with 10-in (0.25-m) of regular cellulose insulation and an additional 4-in (0.10-m) of 20% by weight PCM-enhanced cellulose insulation.

A similar arrangement is setup for the attic floor of the EIFS house. Here the radiant barrier is foil faced EPS insulation (Figure 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. Ceiling insulation will yield about an R_{US}-50 (R_{SI}-8.8) layer.

Cladding and Exterior Paint

The architect selected plain lap siding and vertical siding as the cladding for the SIP, OVF and PCM homes. A 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 siding has excellent resistance to blistering sun, hurricane-force winds and driving rain. It is composed of a fiber cement material that is fireproof, water resistant and therefore will not crack or rot. 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.

Infrared reflective water-based acrylic copolymer paint coats the cladding of the SIP and OVF homes. Solar reflectance and thermal emittance of the various color paints are listed in Table 1. The paint has low VOC[7] and is a green building product that reflects the sun's energy by diffraction and refraction. It helps keep the exterior wall cooler than conventional paint pigments. The lower temperature therefore reduces the driver for heat transfer penetrating into the house. 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 1. Cladding Selected for Each of the Four Research Homes

Descriptive	House 1 SIP Strategy	House 2 Optimal Value Framing Strategy	House 3 *PCM* Strategy	House 4 Exterior Insulation Strategy
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	

Exterior Walls

The walls of the SIP house are 5½-in (0.14-m) thick and have a thermal resistance of R_{US}-21 (R_{SI}-3.7), Table 2. The walls for the OVF home are made of 2 by 6 Douglas-fir wood installed at 24-in (0.61-m) on center. The wall studs and roof rafters are aligned in an effort to reduce the wood needed to frame the home and to reduce thermal bridging caused by the wood studs. Typical wall construction done 16-in on center (0.41-m) has 10% of the exterior surface area as framing from wall studs. The wall cavity for the OVF home contains about a ½-in (0.013-m) of sprayed-in polyurethane foam and R_{US}-19 (R_{SI}-3.3) fiberglass batt insulation (i.e., termed flash and batt).

Table 2. Wall and Cavity Design for Each of the Four Research Homes

Descriptive	House 1 SIP Strategy	House 2 Optimal Value Framing Strategy	House 3 Dynamic Envelope Strategy	House 4 Exterior Insulation Strategy
Wall	**R-21**	**R-21**	**R-30**	**R-30**

[7] Volatile organic compounds (VOC) < 150g/l

	5½-in (0.14-m) of EPS	2x6 wood frame, 24-in (0.61-m) O.C. with ½" (0.13-m) thick OSB	2- 2x4 stud walls; 24-in (0.61-m) O.C. ½" (0.13-m) OSB sheathing with polyethylene dimple sheet for wall ventilation	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

The PCM home 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 by 12-in (0.3-m) from the other wall's studs, Figure 5. The interior framing is supported on top of the floor truss while the exterior framing is supported on the sill plate and is fastened to the floor truss. A top plate was used to tie the two walls together for lateral strength. A fabric is stabled 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 exterior wall OSB sheathing has a built-in protective weather resistive barrier (WRB) overlaid at the factory to eliminate the need for house wrap. All joints were taped to also make the sheathing air tight. A high-density polyethylene sheet having about a ¼-in (6-mm) high dimpled profile was also installed on the exterior of the sheathing to ventilate the exterior walls. It provides drainage of transient moisture migrating through the wall and creates two independent air flow streams to dry out both the cladding and the concealed wall cavities. The product eliminates the impact of solar driven moisture problems, and reduces the impact of interior loading at the same time. It is expected that the combination of phase change insulation, the polyethylene dimpled sheet and the OSB sheathing will provide additional benefit as the air flow at the interface of the WRB and dimpled sheet will allow enhanced charging and discharging potential while also limiting air infiltration across the sheathing.

The 4^{th} home has an EIFS system, which 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}-3.5)] will reduce thermal bridging losses that are a major contributor to energy losses. 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. A flexible polymer-based membrane was manually applied as a liquid over all of the plywood sheathing. The membrane resists water penetration and eliminates air infiltration to make the home air tight. Afterwards, a fiber-reinforced cementitious adhesive was trowel applied to the weather resistive membrane to adhere the EPS insulation. The trowel application forms rows of the adhesive with each row about 0.25-in (6-mm) high. The rows provide a small drainage cavity between the WRB and the EPS insulation board through which incidental water can weep to the outdoor ambient. The exterior is finished in an acrylic-based coating finish over stucco. The interior has gypsum board fitted with a perforated low-e foil facing to reduce radiation exchange across the wall cavity, which was left void of insulation.

Windows

The U-factor, solar heat gain coefficient (SHGC) and visible transmittance of windows for the two pair of homes are tabulated by Miller et al. (2010) and are in Appendix A. The triple pane windows installed in the first pair of homes has a removable third pane and serves as a storm window. In situ measurements of the argon filled air space of the insulated glass unit (IGU) showed it to be 7/16 - in (11-mm) thick. The amount of argon gas was also measured in situ; its concentration was about 97%, which is very good. Most manufacturers try to maintain at least a 90% concentration within the air space. The window assembly's low-e surface is on the inside surface of the exterior pane. The low-e surface reduces the radiant heat transfer across the air space within the IGU. The low-e coating also blocks selective wavelengths of sunlight which helps reduce the SHGC. The NFRC[8] U-factor for these windows is typically 0.29 and the SHGC is 0.25.

The second pair of homes also has triple pane windows; however, both air spaces of the IGU are filled with argon gas. Argon gas is denser and less conductive than air. Therefore, in sealed glass units the argon reduces the convection within the air space, creating a better IGU. Windows in the PCM house are glazed, argon gas filled triple pane vinyl units that have a U-factor of 0.22 and a SHGC of 0.17. Numbering the surfaces of the panes from 1 to 6 with 1 being the outside surface and 6 being the inside surface, we found that the 2nd and the 4th surfaces were low-e surfaces. The two spacing's between the three panes of the IGU are the same; it being 5/16 -in (8-mm). For the EIFS home we selected U-values and SHGC based on the window's orientation on the home. South facing windows had U-values of 0.24 and a SHGC of 0.50. North facing windows had a U-value of 0.18 and SHGC of 0.22, see Appendix A.

Flooring

The floors of the SIP home have 20-in (0.51-m) high trusses between the basement and the 1st floor and an 18-in (0.45-m) high truss between the 1st and 2nd floor. The floor for the OVF home has 20-in (0.51-m) high trusses for both floors. The second pair of homes has 24-in high trusses (0.61-m) that accommodate most of the ductwork. The perimeter area of the floor joist is sealed with 6-in (0.15-m) of sprayed foam for insulation, with exception of the SIP home. A tongue and grove subflooring is used in all homes. It provides an air tight seal for the 2nd pair of homes having crawlspace foundations. The OSB subflooring is a pre engineered panel designed and treated for low water absorption and warp characteristics and is guaranteed to not delaminate.

Weather Resistive Barrier (WRB)

A weather resistive barrier made of polyolefin sheet having a surface texture to create drainage channels is installed under all fiber cement lap siding on the SIP home. The WRB has vertical creased grooves in the material's surface to channel water to the outside and to

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[8] National Fenestration Rating Council

help manage rain driven water that penetrates through the cladding. Microscopic pores enable moisture vapors to escape through the WRB and wall cavity, but these pores are so small that bulk water and air do not penetrate the building envelope.

The OVF house has a fully adhered liquid applied WRB on all exterior walls. The WRB was applied using a water based spray adhesive. Afterwards, the windows were installed and flashed. A 24-in (0.61-m) wide EPDM[9] sheet was draped over the 2 by 6 exterior walls prior to constructing the cathedral roof assembly. The EPDM was glued to the WRB to make an airtight seal from the exterior wall and up the underside of the cathedral roof.

The WRB for the PCM and EIFS pair of homes is an integral part of the exterior wall assembly and is discussed above in the section on Exterior Walls.

Foundation

The basement walls for the SIP and OVF pair of homes are 12-in (0.31-m) poured concrete. A fiberglass waterproofing protects the basement from the intrusion of ground water both above and below grade. The system is composed of a polymer-enhanced asphalt membrane that is spray-applied to the concrete wall. About 2⅜-in (0.06-m) of fiberglass insulation is placed against the asphalt membrane to adhere it to the membrane. The fiberglass serves dual purposes. It insulates the foundation wall and acts as a drainage plane for water runoff.

The PCM and EIFS pair of homes is built on crawlspace foundations. The PCM home's crawlspace uses conventional ventilation practices; however, the crawlspace for the EIFS home is sealed and insulated on the interior side of the block wall. Inside the crawlspace, a 20 mil liner covers the floor and overlaps a 10 mil wall liner. The wall liner is adhered to the masonry block using a polyurethane caulk. The vented crawlspace of the PCM home has the wall liner stop just below the vent ports. In the sealed crawlspace the wall liner stops about 3-in below the sill plate to allow for termite inspections. Rigid foil-faced polyisocyanurate foam insulation is fastened to the wall liner using a polyurethane caulk adhesive. The insulation board has an R_{US}-10 (R_{SI}-1.8), which is code requirement for the Tennessee Valley region.

The exterior of the masonry block on both homes is waterproofed using an emulsion based asphalt coating. A stack stone is installed on the exterior wall up to the termite barrier.

Demonstration Homes — Lighting, Appliances, HVAC and Hot Water

High-efficiency compact fluorescent (CFL) or LED lighting (Willmorth et. al 2010) and Energy Star appliances are showcased in all homes, Table 3. The SIP and OVF pair of homes feature high efficiency water-to-air heat pumps (WAHPs) and water-to-water heat pumps (WWHPs) using geothermal loops for source and sink heat flows. A unique ground-source heat exchanger is buried in the over-cut made for building the basement and is placed around the home's foundation and in existing utility trenches. In the other pair of homes, a

[9] Ethylene propylene diene monomer elastomer

WAHP with vertical geothermal well was selected for the PCM house; while a high-efficiency air-source heat pump with continuously variable speed blower heats and cools the EIFS home. Hot water is again supplied by a WWHP in the PCM home while a commercially standard electric water heater is used in the EIFS home.

The ductwork for all homes is placed in the conditioned space. Eliminating duct losses from heat transfer in unconditioned attics and eliminating the duct air leakage by placing the ducts in the conditioned space yields savings comparable to the best simulated roof and attic system studied by Miller and Kośny (2008).

Methodology for Monitoring Envelopes and Energy Subsystems

The field study will collect data for the envelopes, the WAHP, the WWHP and water heater (WH) water heating subsystems, the ERVs, the Energy Star appliances, and the geothermal heat exchangers. Each home will have two micro-loggers, and a dedicated desktop PC having 2.4 GHz speed with 4 MB of RAM. Subsystems will be segregated between the two micro-loggers based on the systems energy load interactions with the WAHP and the WWHP/WH subsystems. Data from both loggers will be stored on desktop PCs, which will have internet connections for downloading the data to a server. Miller et al. (2010) provides a complete listing of instrumentation used in the homes.

Table 3. Active Energy Subsystems Used in the ZEBRAlliance Homes. Water-Source Heat Pump Ratings Based on ANSI/ARI/ASHRAE ISO Standard 13256-1:1998 for WAHP and 13256-2:1998 for WWHP

Subsystem	SIP	OVF House	PCM House	EIFS House
Lighting	CFL	CFL	CFL	LED
Hot water	WWHP ▪ 1½-ton capacity ▪ COP[a] 3.1	WWHP ▪ 1½-ton capacity ▪ COP[a] 3.1	WWHP ▪ 1½-ton capacity ▪ COP[a] 3.1	Electric Water Heater ▪ 0.9 Energy factor
HVAC	WAHP ▪ 2-ton capacity ▪ Variable speed blower ▪ Cooling COP[b] 5.4 ▪ Heating COP[c] 4.0 ▪ Horizontal loop 1815 ft (553-m)	WAHP ▪ 2-ton capacity ▪ Variable speed blower ▪ Cooling COP[b] 5.4 ▪ Heating COP[c] 4.0 ▪ Horizontal loop 2610 ft (796-m)	WAHP ▪ 2-ton capacity ▪ Variable speed blower ▪ Cooling COP[b] 5.4 ▪ Heating COP[c] 4.0 ▪ Vertical well depth 310-ft (94.5-m)	Air-source heat pump ▪ 2-ton dual capacity ▪ Variable speed blower ▪ SEER[d] 18.4 ▪ HSPF[d] 9.1
ERV[e]	TRE[f] 52% ASE[g] 75% Single-speed blower	TRE 52% ASE 75% Variable speed blower	NA	NA

[a] WWHP COP based on source entering water temperature (EWT) of 32°F (0°C) and load EWT of 100°F (37.8°C)
[b] WAHP Full Load Cooling based upon 80.6°F (27°C) DB, 66.2°F (19°C) WB entering air and EWT of 77°F (25°C)
[c] WAHP Full Load Heating based upon 68°F (20°C) DB, 59° (15°C) WB entering air temperature and EWT of 30°F (-1.1°C)
[d] Air-source Heat Pump SEER rated at 95°F (35°C); HSPF rated at 47°F (8.3°C)
[e] Energy Recovery Ventilator
[f] Total Recovery Efficiency (TRE) at 95°F (35°C)
[g] Apparent Sensible Effectiveness (ASE) at 32°F (0°C)

The SIP and OVF homes have four comfort conditioned zones; the PCM and EIFS homes have 2 zones. Variations in the temperature of the interior thermostats can have large effects on the comfort cooling and heating. Therefore, calibrated thermistor probes are placed near each thermostat and will be used to adjust each thermostat to maintain the same interior temperature across all homes. All homes will be operated with the same prescribed thermostat settings. Some brief testing at different thermostat settings will be conducted to characterize the cooling load and later the heating load for each house. The brief tests will help evaluate the impact of the thermostat set points.

The data acquisition and control systems will simulate occupancy in the homes with methods developed for simulated occupancy by Christian (2010) with exception of the refrigerator. Heat and moisture will be generated in the home based on the Building America Research Benchmark Definition (2008) for domestic hot water usage and for plug loads. Two infrared space heaters, one 500 Watt unit upstairs and one 1500 Watt unit on the main level, will be controlled to simulate loads for sensible heat from occupancy. Loading of the washer and dryer is based on the Code of Federal Regulations (2010a) and refrigerator loading is based on the Code of Federal Regulations (2010b). The master shower in the homes is used to simulate the domestic hot water (DHW) usage for the showers, baths, and sinks. Since the clothes washer and dishwasher are being automatically turned on during the day these hot water draws are not simulated by the master shower, Gehl et al. (2010).

HERS Ratings

A HERS rating was estimated for the SIP and OVF pair of homes and is compared to a conventional stick built house built fairly close to the IECC building code (2006). Christian (2010) conducted blower door tests to document the air tightness of the homes, Table 4. Blower door testing consists of a variable-speed propeller fan and its support mounting, which is inserted and sealed in a doorway. Pressure gauges connected to the fan measure and control the rate of airflow required to maintain the building at a certain pressure; typically 50 Pa (0.2-in of water column). This controlled airflow is used to find specific leaks and indicates the relative tightness of the envelope, Table 4. Results show both the SIP and OVF homes are tight as compared to a 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). The HERS rating for both homes is estimated at about 46 and 47, respectively using the Residential Energy Analysis and Rating Software (Rutherford, 2010). Construction delays occurred on the 2^{nd} pair of homes. The PCM home (Dynamic Envelope) was scored at a HERS of 47. The EIFS scored highest of all homes because of the air-source heat pump used for comfort conditioning as compared to the geothermal units used in the other homes. The EIFS home scored 50 on the HERS scale.

Table 4. HERS rating and infiltration rates as compared to IECC (2006)

Descriptive	SIP Strategy	Optimal Value Framing Strategy	Dynamic Envelope	EIFS Strategy	Builders House[1]
ACH[2] at 50 Pa	1.23	1.74	3.18	2.18	5.7
HERS	46	47	47	50	101

[1] International Energy Conservation Code (2006).
[2] Air exchanges per hour (ACH) measured by blower door testing conducted at 50 Pa.

Conclusions

Four unique envelopes were designed and nearing completion for field tests. They exploit a multiplicity of building subsystems to enhance thermal performance. The HERS ratings for all four envelopes predicts the homes should save about 50% of the energy used by a conventional home built to IECC (2006) specifications (Builders House).

References

ASHRAE 62.2 2009. **Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.**

ANSI/ARI/ASHRAE ISO Standard 13256-1. 1998. **Water-Source Heat Pumps — Testing and Rating for Performance- Part 1: Water-to-Air and Brine-to-Air Heat Pumps**. 1998.

ANSI/ARI/ASHRAE ISO Standard 13256-2. 1998. **Water-Source Heat Pumps — Testing and Rating for Performance- Part 2: Water-to-Water and Brine-to-Water Heat Pumps**. 1998.

ASTM. 2009. Designation C 1549-09: **Standard Test Method for Determination of Solar Reflectance near Ambient Temperature Using a Portable Solar Reflectometer**. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2004. Designation C 1371-04a: **Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers**. American Society for Testing and Materials, West Conshohocken, PA.

Building America Research Benchmark Document, NREL/TP-550-44816. 2008. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/44816.pdf

Building America. 2003. **The Ultimate Family Home**. U.S. DOE, DOE/GO-102003-1827, Dec. 2003.

Christian, J. 2010. "The Robo Retrofit House: 2400 ft^2 that Has 42% Energy Savings Compared to Next Door Builder House" ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2010.

Christian, J. and Bonar, J. 2008. "**Building a 40% Energy Saving House in the Mixed-Humid Climate**", ORNL/TM-10081/08, Oak Ridge National Laboratory, February 2008

Christian J.E., Childs, P., Pate, P, Atchley, J , "**Small House with Construction Cost of $100K, Total Energy Cost of $0.88 a Day**", ASHRAE Transactions, Volume 112, Part 1, 2006.

Christian J. E., "**Simple Affordable Near Zero Energy Habitats**", ASHRAE/DOE Thermal Performance of the Exterior envelope of Buildings Conference IX, Clearwater Beach, Fl, December 5–10, 2004.

Code of Federal Regulations. 2010a. **Uniform Test Method for Measuring the Energy Consumption of Automatic and Semi-Automatic Clothes Washers**. Title 10 part 430, Subpt B, Appendix J1, http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=6de07a43f47ca869f23b5d2e416ff012&rgn=div9&view=text&node=10:3.0.1.4.16.2.9.6.11&idno=10

Code of Federal Regulations. 2010b. **Uniform Test Method for Measuring the Energy Consumption of Electric Refrigerators and Electric Refrigerator-Freezers**, Title 10 part 430, Subpt B, Appendix A1, http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=6de07a43f47ca869f23b5d2e416ff012&rgn=div9&view=text&node=10:3.0.1.4.16.2.9.6.1&idno=10

Energy Design Update**. An Illinois Passivhaus**. May 2004, Vol. 24, Number 5.

Gehl, T., Boudreaux, P., Christian, J. and Miller, W. 2010. Deliverable to the Tennessee Valley Authority: **Appliances and Control Methodology for the ZEBRA Homes.**

Intergovernmental Panel on Climate Change. 2007. **Summary for policymakers. In Climate change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change** (B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer [eds]). Cambridge University Press, Cambridge, United Kingdom and New York

International Energy Conservation Code (IECC), 2006.

Kośny, J., Childs, P., Desjarlais, A. and Christian, J. "**Whole Wall Rating/Label for EIFS Wall Systems: Steady State Thermal Analysis**." Report submitted to Dryvit Corporation. June 21, 2002.

Kriner, S., Miller, W. A., and Desjarlais, A. 2001. "**The Thermal Performance of Painted and Unpainted Structural Standing Seam Metal Roofing Systems Exposed to Two Years of Weathering**," in Thermal Performance of the Exterior Envelopes of Buildings, VIII, proceedings of ASHRAE THERM VIII, Clearwater, FL., Dec. 2001.

Norton, P. and Christensen, C. 2006. "**A Cold-Climate Case Study for Affordable Zero Energy Homes.**" Proceedings of Solar 2006, American Solar Energy Society, Denver, Colorado.

Miller, W.A. and J., Kośny. 2008. "**Next Generation Roofs and Attics for Homes**," in ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2008.

Miller, W.A., Ally, M., Baxter, V., Childs, P., Christian, J., Karagiozis, A., Kośny, J., Im. P., and Vinedyard, E. 2010. **Demonstration Homes Showcasing DOE BT Energy Research**: Collaborative Study with the Schaad Company, ORNL, TVA and Barber McMurry Architects. To be published 2 months after completion of construction of all homes.

Parker, D. S., Sherwin, J. R. 1998. "**Comparative Summer Attic Thermal Performance of Six Roof Constructions.**" ASHRAE Trans., Vol. 104, pt. 2, 1084–1092.

Parker, D.S., Sonne, J. K., Sherwin, J. R. 2002. "**Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida**," in ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2002.

Parker, D.S., Sonne, J.K., Sherwin, J.R. and Moyer N. 2001. "**Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida**," Final Report FSEC-CR-1220-00, prepared for the Florida Power and Light Company, May 2001.

Rutherford, C. 2010. Schaad Company private communication of HERS rating.

Scheuer, C. and Keoleian, G. 2002. **Evaluation of LEED™ Using Life Cycle Assessment Methods**," NIST GCR 02-836.

U.S. Department of Energy, 2008. **Buildings Energy Data Book.** http://buildingsdatabook.eren. doe.gov/

U.S. Green Building Council Research Committee. 2007 (revised 2008). **A National Green Building Research Agenda,** http://www.usgbc.org/ShowFile.aspx?DocumentID=3402

Willmorth, K., Zaderej, V., Miller, W. A. 2010. "**Solid State Lighting in Residential Buildings**," in ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2010.

Figure 1. ZEBRAlliance Energy Saver Homes	
SIP House at 100 Cove Pointe Lane 	OVF House at 102 Cove Pointe Lane 
PCM House at 100 Cross Creek Place 	EIFS House at 102 Cross Creek Place 

Figure 2. Cross Section of Cathedral Roof with Phenolic Foam Insulation Used in OVF Home

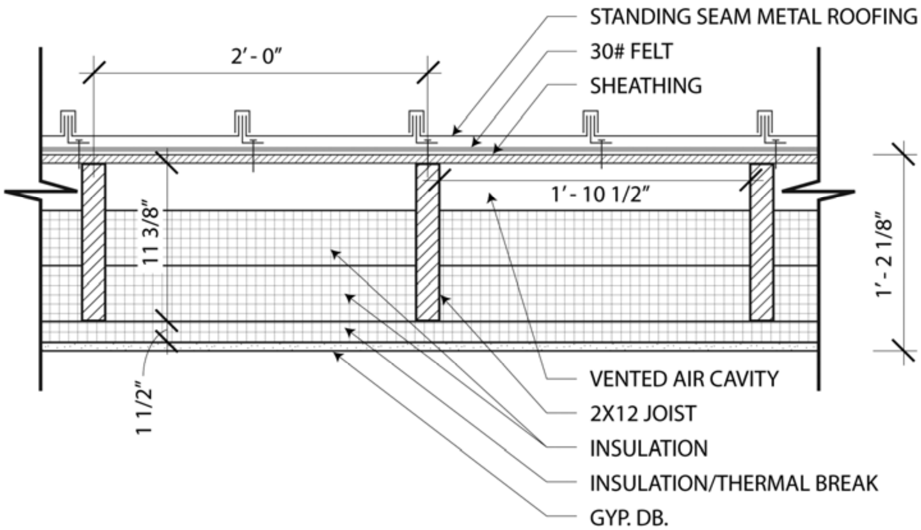


Figure 3. IRR Asphalt Shingle Roof Assembly Having the Deck Made of a Profiled and Foil-Faced EPS Insulation. The Profile Provides an Inclined Air Space for Above Sheathing Ventilation. Slots are Cut Above the Soffit for Introducing Ventilation Air into the Air Space which Exhausts out a Ridge Vent

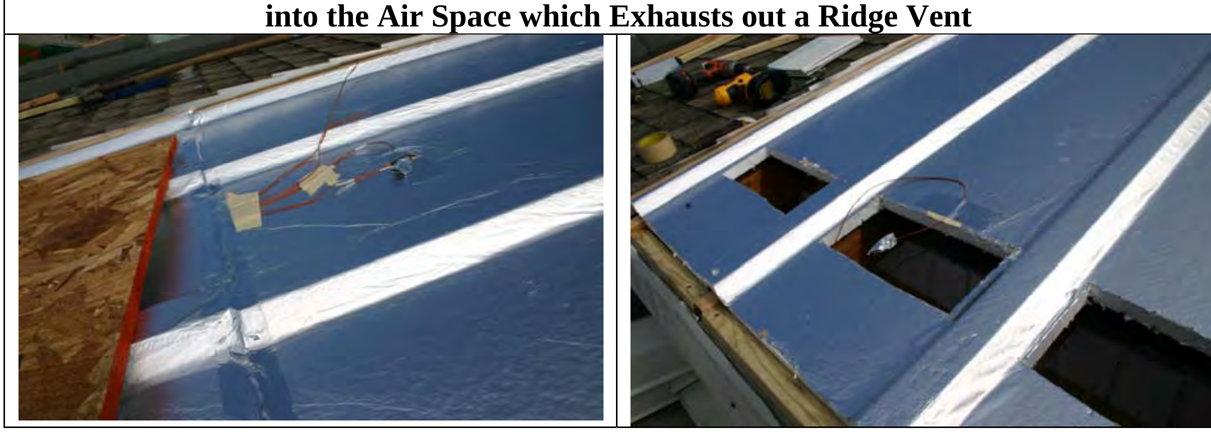


Figure 4. Peak Day Heat Flux Crossing the Roof Deck of Asphalt Shingle, IRR Painted Metal and IRR Clay Tile Roofs Field Tested on the Envelope Systems Research Apparatus.
Flux in W/m^2 = 3.152*Btu/(hr•ft^2); Temperature in ^{o}C = (^{o}F – 32)/1.8

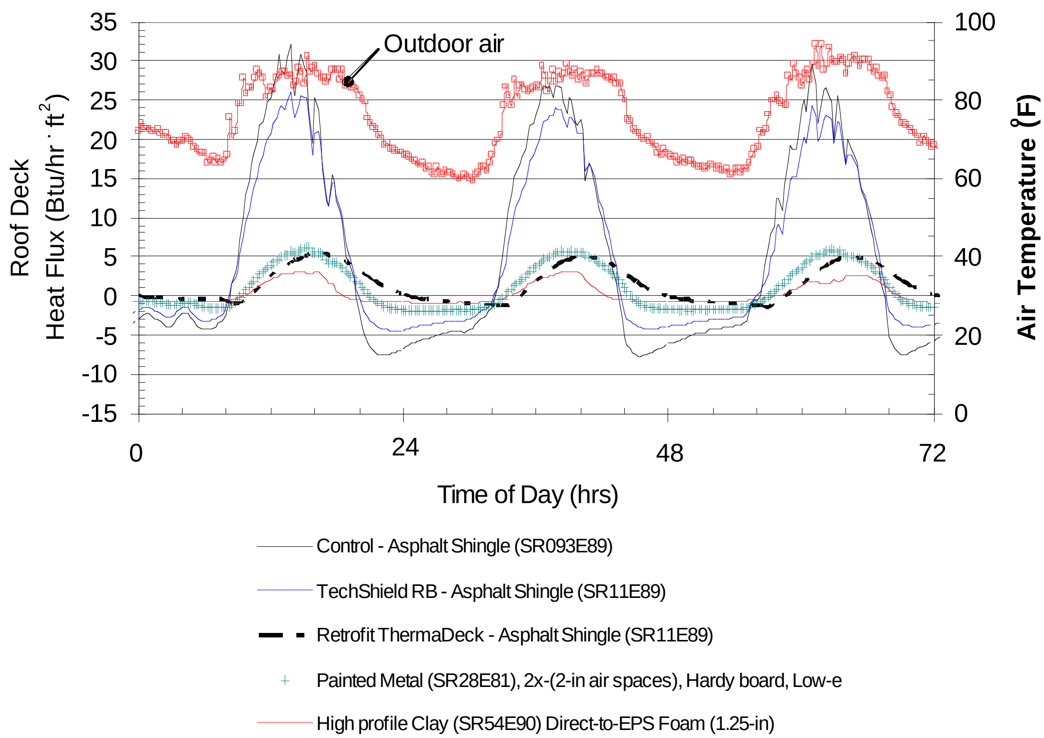
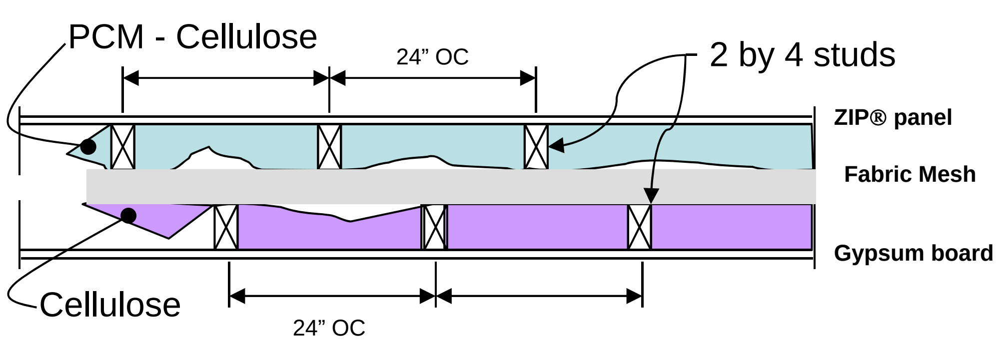


Figure 5. Top View of the Double Wall Assembly Used in the PCM House



APPENDIX A

SIP Home - Lot 55, 100 Cove Pointe Lane, Oak Ridge, TN 37830									
OVF Home - Lot 56, 102 Cove Pointe Lane, Oak Ridge, TN 37830							**Triple-Pane**	**Triple-Pane**	**Triple-Pane**
	Qty	**Type**	**Width**	**Height**	**Operation**	**Comments**	**U-Value**	**SHGC**	**Transmittance**
Northeast Elevation									
Stairwell	2	2' 6" by 3' 5"	2'-5"	3'-5"	Casement		0.26	0.30	0.50
	2	2' 6" by 1' 2"	2'-5"	1' 2"	Fixed		0.26	0.30	0.50
Northwest Elevation									
Liv Rm	6	2' 6" by 5'	2'-5"	4'-11"	Casement	Transom	0.30	0.25	0.41
	6	2' 6" by 1' 2"	2'-5"	1'- 2"	Fixed		0.26	0.30	0.50
Upstairs Sky Lights	7	2' 6" by 2' 1"	2'-5"	2'-1"	Fixed		0.26	0.29	0.50
Front door	2	1' 5" by 1' 2"	1'-5"	1' 2"	Fixed		0.32	0.36	0.62
	1	3' by 1' 2"	3'-0"	1'-2"	Fixed	Transom	0.32	0.36	0.62
	2	12" by 80"	1' - 0"	6' - 8"	Fixed	Side Light	0.27	0.16	0.23
Hallway	1	2' 6" by 5'	2'-5"	4'-11"	Casement	Transom	0.30	0.25	0.41
	1	2' 6" by 1' 2"	2'-5"	1' 2"	Fixed		0.26	0.30	0.50
Southeast Elevation									
Basement	4	2' 6" by 5'	2'-5"	4'-11"	Casement		0.30	0.25	0.41
	1	2' 6" by 3' 5"	2'-5"	3'-5"	Casement		0.26	0.30	0.50
Mas Bed	2	2'-6" by 4'	2'-5"	3'-11"	Casement		0.30	0.25	0.41
		2' 6" by 1' 2"	2'-5"	1'- 2"	Fixed		0.26	0.30	0.50
Mas Bath	2	2' 6" by 2' 11"	2'-6"	2' - 11"	Casement	TEMPERED	0.26	0.29	0.50
Kitchen	1	2' 6" by 2' 11"	2' - 6"	2' - 11"	Casement		0.30	0.25	0.41
	3	2' 6" by 5'	2'-5"	4'-11"	Casement		0.26	0.29	0.50
	3	2' 6" by 1' 2"	2'-5"	1'- 2"	Fixed		0.26	0.30	0.50
Mud room	1	2' 6" by 5'	2'-5"	4'-11"	Casement		0.32	0.31	0.53
Up Bed #1	3	2' 6" by 3' 5"	2'-5"	3'-5"	Casement	Provide Egress Hardware	0.29	0.25	0.42
Up Bed #2	3	2' 6" by 3' 5"	2'-5"	3'-5"	Casement	Provide Egress Hardware	0.29	0.25	0.42
Southwest Elevation									
Liv Rm	1	2' 6" by 5'	2'-5"	4'-11"	Casement		0.30	0.25	0.41
	1	2' 6" by 1' 2"	2'-5"	1'- 2"	Fixed		0.26	0.30	0.50
Garage	1	2' 6" by 5'	2'-5"	4'-11"	Casement		0.30	0.25	0.41
	2	2' 6" by 1' 2"	2'-5"	1'- 2"	Fixed		0.26	0.30	0.50
	3	2' 6" by 4'	2'-5"	3' - 11"	Fixed		0.32	0.31	0.53

PCM House, Lot #47, 100 Cross Creek Place, Oak Ridge, TN 37830							Triple-Pane	Triple-Pane	Triple-Pane
	Qty	**Type**	**Width**	**Height**	**Operation**	**Comments**	**U-Value**	**SHGC**	**Transmittance**
Northeast Elevation									
Stairwell	2	30 1/4 x 48	2'-5 1/2"	3'-11 1/4"	Casement	TEMPERED	0.22	0.17	0.32
Northwest Elevation									
Liv Rm	4	2'-6 1/4" x 6'-2 13/16"	2'-5 1/2"	6'-2 1/16"	Casement		0.22	0.17	0.32
Study	3	2'-6 1/4" x 6'-2 13/16"	2'-5 1/2"	6'-2 1/16"	Casement		0.22	0.17	0.32
Multi-Purpose Rm (2nd Floor)	5	32 1/4" x 40 1/8"	2'-7 1/2"	3'-3 3/8"	Casement		0.22	0.17	0.32
Southeast Elevation									
Mas Bed	2	2'-6 1/4" x 6'-2 13/16"	2'-5 1/2"	6'-2 1/16"	Casement		0.22	0.17	0.32
Up Bed #1	3	32 1/4" x 55 7/8"	2'-7 1/2"	4'-7 1/8"	Casement	Provide Egress Hardware	0.22	0.17	0.32
Up Bed #2	3	33 1/4" x 55 7/8"	2'-7 1/2"	4'-7 1/8"	Casement	Provide Egress Hardware	0.22	0.17	0.32
Kitchen	3	30 1/4 x 48	2'-5 1/2"	3'-11 1/4"	Casement		0.22	0.17	0.32
Mas Tub	1	30 1/4 x 48	2'-5 1/2"	3'-11 1/4"	Casement	TEMPERED	0.22	0.17	0.32
Southwest Elevation									
Din Rm	2	2'-6 1/4" x 6'-2 13/16"	2'-5 1/2"	6'-2 1/16"	Casement		0.22	0.17	0.32
Liv Rm	2	2'-8 1/4" x 6'-2 13/16"	2'-7 1/2"	6'-2 1/16"	Casement		0.22	0.17	0.32

EIFS Home, Lot #48, 102 Cross Creek Place, Oak Ridge, TN 37830						Triple-Pane	Triple-Pane	Triple-Pane
	Qty	**Width**	**Height**	**Operation from inside looking out**	**Comments**	**U-Value**	**SHGC**	**Transmittance**
Northeast Elevation								
Stairwell	2	2'-5 1/2"	3'-11 1/4"	Hinge on left	TEMPERED	0.18	0.22	0.42
Northwest Elevation								
Liv Rm	4	2'-5 1/2"	6'-2 13/16"	Hinge on Right		0.18	0.22	0.42
Study	3	2'-5 1/2"	6'-2 13/16"	Hinge on Right		0.18	0.22	0.42
Multi-Purpose Rm (2nd Floor)	5	2'-7 1/2"	3'-3 3/8"	Hinge on Right		0.18	0.22	0.42
Southeast Elevation								
Mas Bed	2	2'-5 1/2"	6'-2 13/16"	Hinge on Left		0.24	0.5	0.49
Up Bed #1	3	2'-7 1/2"	4'-7 1/8"	Hinge on Left	Provide Egress Hardware	0.24	0.5	0.49
Up Bed #2	3	2'-7 1/2"	4'-7 1/8"	Hinge on Left	Provide Egress Hardware	0.24	0.5	0.49
Kitchen	3	2'-5 1/2"	3'-11 1/4"	Hinge on Left		0.24	0.5	0.49
Mas Tub	1	2'-5 1/2"	3'-11 1/4"	Hinge on Left	TEMPERED	0.24	0.5	0.49
Southwest Elevation								
Din Rm	2	2'-5 1/2"	6'-2 13/16"	Hinge on Left		0.24	0.5	0.49
Liv Rm	2	2'-7 1/2"	6'-2 13/16"	1 LEFT, 1 RIGHT		0.24	0.5	0.49

OAK RIDGE NATIONAL LABORATORY

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Final Report Envelope Field Performance

Deliverable D.3.2

2012

Prepared by

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Eric Stannard, UT

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Energy and Transportation Science Division

Final Report Envelope Field Performance

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

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Eric Stannard, University of Tennessee-Knoxville

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: $m^2 = 9.290304E\text{-}02 * ft^2$

Figure 1. ZEBRAlliance Energy Efficient Homes

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 101.

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	101
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 from summer to winter was detected in the EIFS house, Table 2.

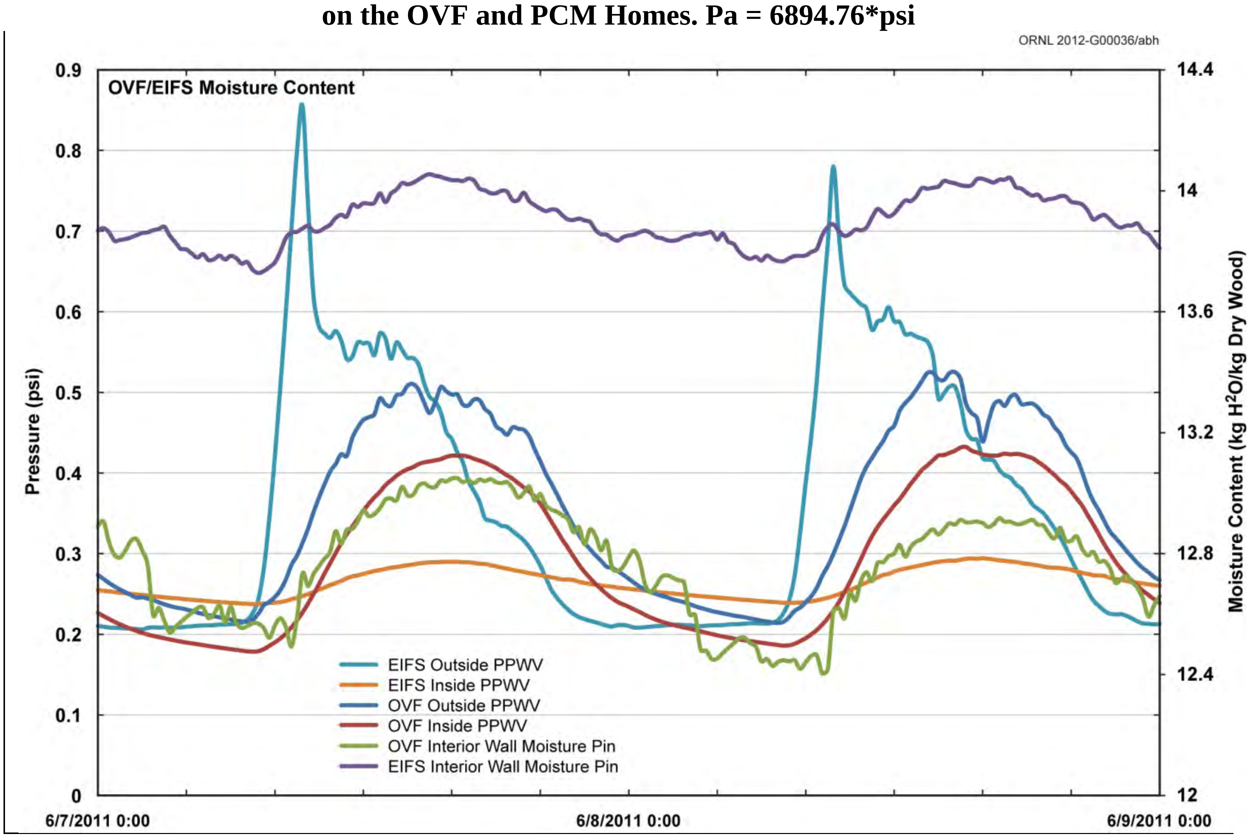
Weather Resistive Membranes

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 is Displayed Along with the Water Content of the Sheathing 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

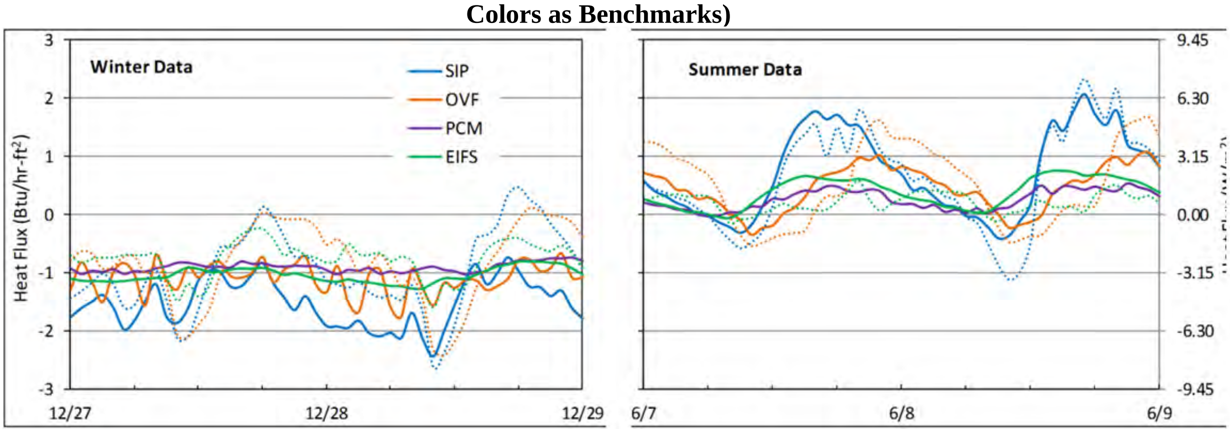
The PCM and EIFS homes are built with conventional attics. The PCM home has an OSB deck and the OSB is overlaid with a micro-perforated aluminum foil that faces into the attic. Solar powered gable ventilators are installed on the interior of the attic gables to enhance attic ventilation. At solar noon 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 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

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

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	**R-20 (R_{SI}-3.7)** 2x4 wood 16-in (0.41-m) O.C. 5-in (0.13-m) EPS exterior insulation

			polyethylene dimple sheet for wall ventilation	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

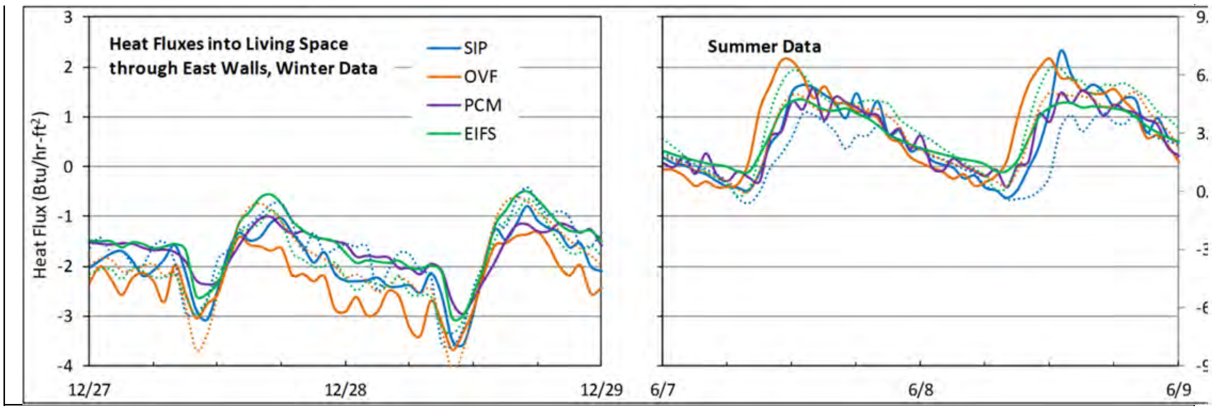
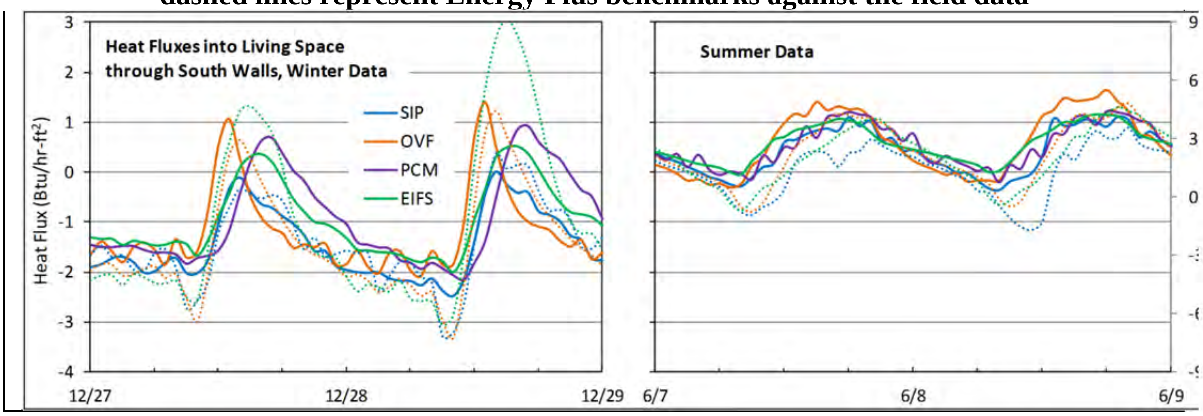


Figure 5. Winter and summer heat flux measured across the south walls of the homes. The dashed lines represent Energy Plus benchmarks against the field data



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.

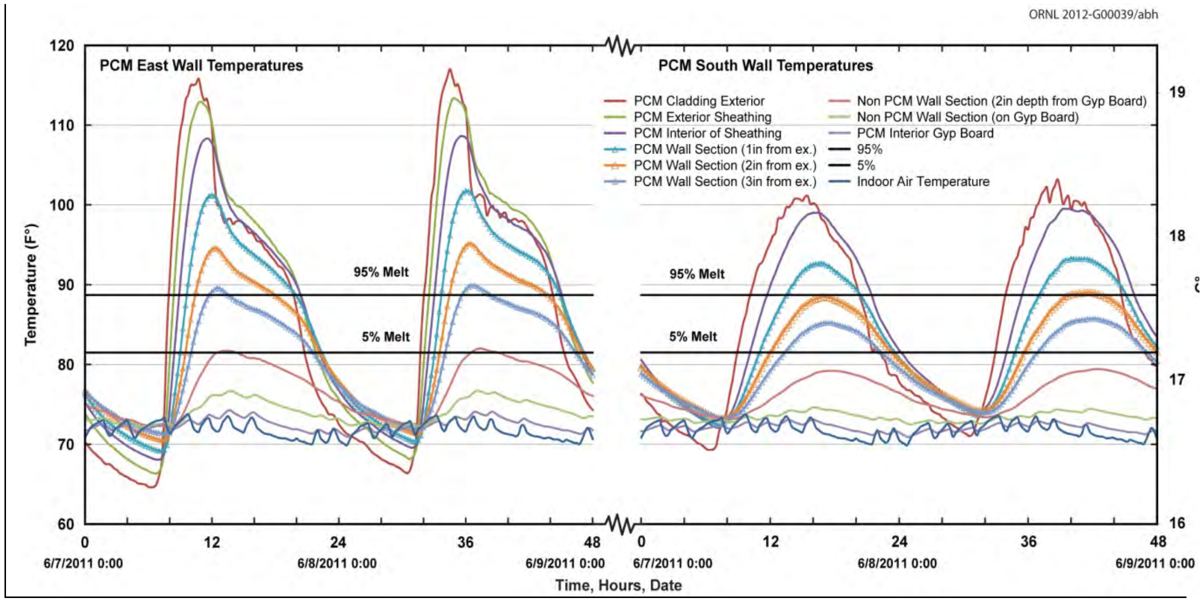
EnergyPlus predictions of the heat flux through East and South walls into the living spaces of the SIP, OVF and EIFS homes are presented in Figures 4 and 5. In general, EnergyPlus predicted heat flux matched better with field measured data for the SIP and OVF homes as compared to that for the EIFS house. 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.

References

ASHRAE 62.2 2009. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

ASHRAE 1145-TRP. 2001. Modeling Two- and Three-Dimensional Heat Transfer through Composite Wall and Roof Assemblies in Transient Energy Simulation Programs.

Biswas, Kaushik, Christian, Jeff and Gehl, Anthony. 2011. " Comparative Study of Vented vs. Unvented Crawlspaces in Identical Side-by-ide Homes in the Mixed Humid Climate," ORNL/TM-2011/438.

Christian, J. 2010. "The Robo Retrofit House: 2400 ft^2 that Has 42% Energy Savings Compared to Next Door Builder House" ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2010.

[IECC] International Energy Conservation Code, 2006.

Liu, Xiaobing. 2010. "Assessment of National Benefits from retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems," ORNL/TM-2010/122.

Miller, W., A. Karagiozis, J. Kosny, S. Shrestha, J. Christian and C. Kohler. "Demonstration of Four Different Residential Envelopes," ACEEE Summer Study on Energy Efficiency in Buildings, proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA., Aug. 2010.

Miller, W.A., Graves, R. and Atherton, S. 2011. "A Prototype Roof Deck Designed to Self-Regulate Deck Temperature and Reduce Heat Transfer," NRCA International Roofing Symposium, Washington D.C, Sep 2011.

Rutherford, C. 2010. Schaad Company private communication of HERS rating.

Shrestha S., W. Miller, T. Stovall, A. Desjarlais, K. Childs, W. Porter, M. Bhandari, and S. Coley. 2011. "Modeling PCM-Enhanced Insulation System and Benchmarking EnergyPlus against Controlled Field Data," Building Simulation 2011, proceedings of International Building Performance Simulation Association, Sydney, Australia, November 2011.

Xiaoshu, Lu. 2002. Modeling of heat and moisture transfer in buildings: I. Model Program. Energy and Buildings, V. 34, Issue 10, Nov. 2002, p. 1033-1043.