Advanced Residential Envelopes for Two Pair of Energy-Saver Homes

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

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[1] Urbana, IL has ASHRAE 99% winter design temperature of -3°F (-19°C).

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 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.

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[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.

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°C) when covered with an IRR painted metal roof. Temperatures of about 170°F (76.7°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°C) down to 136°F (57.8°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 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.

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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).

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** 5½-in (0.14-m) of EPS	**R-21** 2x6 wood frame, 24-in (0.61-m) O.C. with ½" (0.13-m) thick OSB	**R-30** 2- 2x4 stud walls; 24-in (0.61-m) O.C. ½" (0.13-m) OSB sheathing with polyethylene dimple sheet for wall ventilation	**R-30** 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

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

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 4th 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). 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.

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 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.

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[8] National Fenestration Rating Council

[9] Ethylene propylene diene monomer elastomer

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 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 45 using the Residential Energy Analysis and Rating Software (Rutherford, 2010). Construction delays occurred on the 2nd pair of homes and both blower door testing and HERS ratings are not available.

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

Descriptive	SIP Strategy	Optimal Value Framing Strategy	Builders House[1]
ACH[2] at 50 Pa	1.2	1.74	5.7
HERS	45	46	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 the SIP and OVF homes predicts the homes should save about 50% of the energy used by a conventional home built to IECC (2006) specifications.

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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

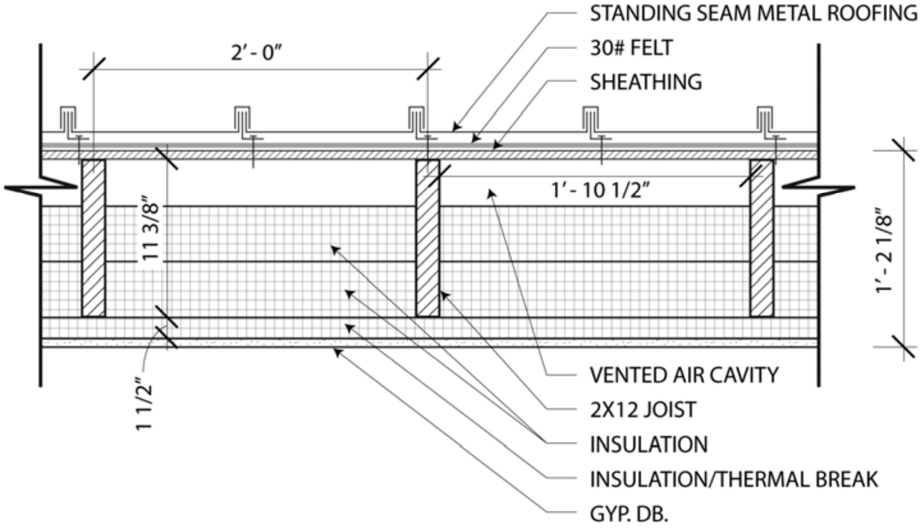

Figure 3. IRR Asphalt Shingle Roof Assembly Having the Deck Made of a Profiled and Foil-Faced EPS Insulation. The Profile Provides an Inclined Air Space for Above Sheathing Ventilation. Slots are Cut Above the Soffit for Introducing Ventilation Air into the Air Space which Exhausts out a Ridge Vent

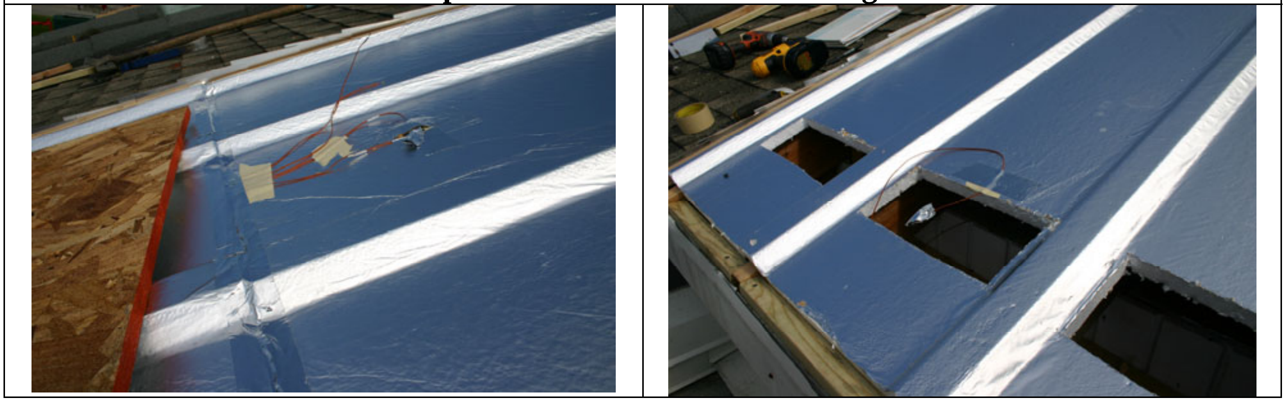

Figure 4. Peak Day Heat Flux Crossing the Roof Deck of Asphalt Shingle, IRR Painted Metal and IRR Clay Tile Roofs Field Tested on the Envelope Systems Research Apparatus. Flux in W/m^2 = 3.152*Btu/(hr•ft^2); Temperature in ^{o}C = (^{o}F – 32)/1.8

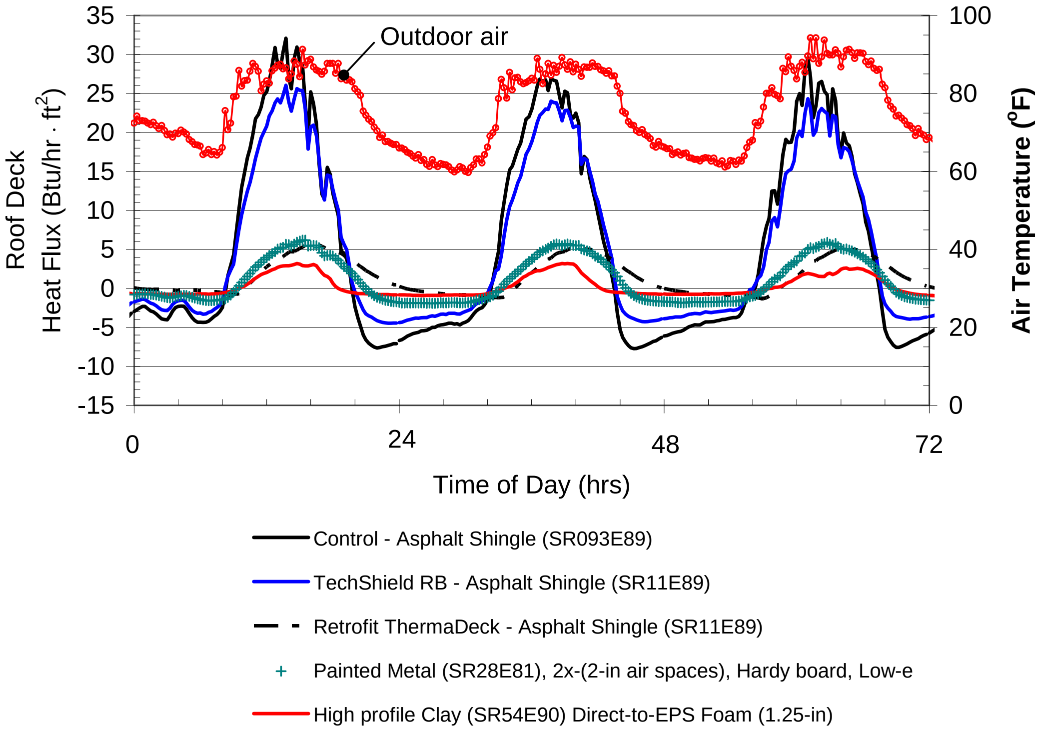

Figure 5. Top View of the Double Wall Assembly Used in the PCM House