A Prototype Roof Deck Designed to Self-Regulate Deck Temperature and Reduce Heat Transfer

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Abstract

A prototype roof and attic assembly exploits the use of radiation, convection and insulation controls to reduce its peak day heat transfer by almost 85 percent of the heat transfer crossing a conventional roof and attic assembly. The assembly exhibits attic air temperatures that do not exceed the maximum daily outdoor ambient temperature. The design includes a passive ventilation scheme that pulls air from the soffit and attic into an inclined air space above the roof deck. The design complies with fire protection codes because the air intake is internal and closed to the elements. Field data were benchmarked against an attic computer tool and simulations made for new and retrofit constructions in hot, moderate and cold climates to gauge the cost of energy savings and potential payback.

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Introduction

Single-family homes currently consume 17 quads [quadrillion (10^{15} Btu)] with about 40 percent of the primary energy (6.8 quads) used for space heating and cooling of the residence [1]. Retrofitting inefficient homes already in place and implementing new technology in new construction must be a major focus for developing affordable, durable, and reliable envelope technologies that mitigate part of our national energy consumption. The building sector has green-house-gas (GHG) emissions that exceed both the industrial and transportation sectors. U.S. buildings are responsible for 38

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[1] HERE is an abbreviation for the Higher Education Research Experiences student program.

percent of carbon dioxide emissions, for 71 percent of the electricity consumption and 54 percent of natural gas usage [2]. Therefore, improving building efficiency can have significant, positive effects on emissions reduction.

Florida Solar Energy Center (FSEC) conducted a landmark demonstration on seven Habitat for Humanity homes, adjacent to one another, in Fort Myers, FL. The homes had identical floor plans and orientation, but with different roof and attic systems designed to reduce attic heat gain [3]. Six of the houses had R_{US}-19 h•ft^2•°F/Btu (R_{SI}-3.3 m^2•K/W) ceiling insulation, which is below the current International Energy Conservation Code (IECC) code level of R_{US}-30 (R_{SI}- 5.3). The seventh house had a sealed attic with insulation on the underside of the roof deck rather than the ceiling. All homes had the same 2-ton split system air conditioner with 5 kW of auxiliary backup heat [4]. Results showed that cool roof systems (such as white reflective tile and white metal) reduced cooling energy consumption by 18 to 26 percent and peak demand by 28 to 35 percent [5]. Akbari and Levinson [6] have compiled cool roof studies conducted for non-residential low-slope buildings. They observed summertime daily air-conditioning savings and peak demand reductions ranging from about 10 to 30 percent, though some reported data showed values as low as 2 percent and as high as 40 percent [6]. The findings clearly show that cool roof systems can be a viable strategy for reducing energy consumption. Subsequently, many U.S. states have implemented prescriptive requirements for cool roofs in their energy codes based on the ASHRAE Standard 90.1 “Energy Standard for Buildings Except Low-Rise Residential Buildings” [7], ASHRAE Standard 90.2 “Energy Efficient Design of Low-Rise Residential Buildings” [8], the IECC [9] or the states have developed custom provisions. The U.S. Green Building Council

(USGBC) also reported the need for integrated building strategies to further reduce the energy consumed by buildings [2]:

> "… *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 achieve as low as feasible energy use in buildings and to mitigate GHG emissions. A cool roof is just one of several measures.

Prototype Insulated and Ventilated Roof Deck

A new roof system design is being studied that is usable with almost all roofing products. The heart of the design is a profiled and foil-faced expanded polystyrene (EPS) insulation that fits over and between rafters in new construction (Figure 1) or can be attached on top of an existing shingle roof system. The EPS insulation is profiled to form a 1-inch (0.0254-m) air space between rafters to promote thermally induced convective flows that carry some of the heat penetrating the deck toward a ridge vent and away from the attic. The top and bottom sides of the EPS are foil-faced; the top side acts as a radiation shield in the inclined air space and the bottom-side foil performs as a radiant barrier in the attic (Figure 1). Ventilation is enhanced by cutting a slot near the eave just above the soffit to provide a source of makeup air from the soffit vent and

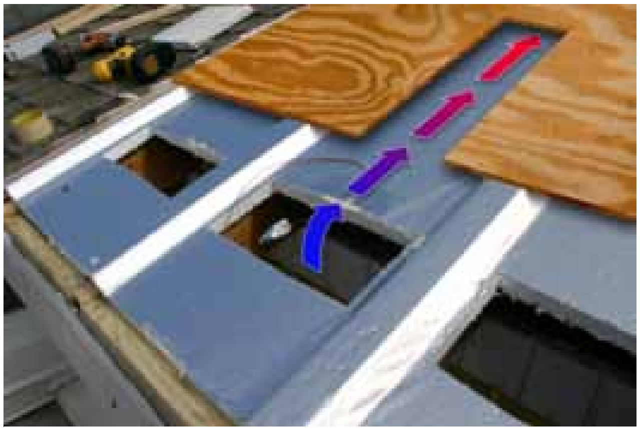

Figure 1. Air in the inclined air space is heated as the shingles absorb solar energy. The hot air rises out the ridge vent while also pulling in cooler makeup air from the soffit and attic.

attic. Buoyant air moves up the inclined air space and creates a negative pressure at the eave. Cool makeup air is pulled from the soffit and attic, which further enhances the temperature driving potential for natural convection heat transfer in the inclined air space. A ridge vent expels the heated air back to the outdoors.

This ventilation scheme keeps the air intake internal to the attic, which eliminates the intrusion of pests and any threat of burning embers entering the inclined space. The 1-inch (0.0254-m) of EPS insulation also serves to reduce the conduction heat transfer trying to penetrate into the attic. The lower deck flux results in a cooler radiant barrier temperature compared to conventional construction having an OSB deck with or without a foil faced radiant barrier. The reduced foil temperature of the EPS therefore further drops the radiation exchange between the roof deck and the attic floor.

As mentioned, the roof assembly can also be installed in retrofit applications provided the existing roof system can bear the added load. Furring strips are attached to the existing shingle roof and the EPS insulation mounted on top of the old shingles with a new OSB deck, weather-resistant sheathing and new layer of shingles.

Field data for the Insulated and Ventilated Roof Deck

Three roofs systems that have the same style of architectural shingle and the same solar reflectance (0.10) and thermal emittance (0.90) were field tested with and without a radiant barrier. Table 1 describes the salient features and Figure 2 displays the roof systems and attics field tested on the Envelope Systems Research Apparatus (ESRA). The radiant barrier used in one assembly (far left in Figure 2) was a perforated, foil-faced, oriented strand board (OSB) with the foil facing into the attic. The insulated and ventilated roof and attic assembly included the profiled and foil faced EPS insulation fit between the roof rafters (Figure 3).

Table 1. Shingle roofs with conventional attic design, with foil-faced OSB deck (RB) and with an insulated and ventilated roof deck field tested on the ESRA.

Roof Type	Identifier	Initial SR[1] and E[2]	Mounting
Asphalt shingle	Control	SR093E89	Direct-to-OSB Deck
Asphalt shingle	Foil-faced OSB RB	SR11E89	Direct-to-OSB Deck, one radiant barrier
Asphalt shingle	Insulated and Ventilated Deck (retrofit construction)	SR11E89	1-inch EPS with 1-inch air gap, one active low-e surface[3]
Asphalt shingle	Insulated and ventilated Deck (new construction)	SR083E93	1-inch EPS with 1-inch air gap, one radiant barrier, one active low-e surface[3]

[1] SR is used as an abbreviation for the solar reflectance of the asphalt shingle being field tested on the ESRA.
[2] E is used as an abbreviation for the thermal emittance of the shingles.
[3] Foil-faced OSB faced down into inclined air space of roof system.

Figure 2. Envelope Systems Research Apparatus (ESRA) with the rightmost roof lane identified as the control system (conventional asphalt shingle roof system), the ventilated and insulated roof deck (center lane) and conventional roof system with foil-faced OSB deck (far left lane).

A foil-faced OSB was also used as the top deck for the insulated and ventilated roof system and the foil faced down into the air space (Figure 3).

Figure 3. Setup of a prototype roof for new construction shows the EPS with vent slots and a perforated foil-faced OSB deck lying on top of the EPS to create an air space. The slots in EPS provide a passageway for air from the soffit vents and also from the attic space.

The conventionally pigmented asphalt shingle (SR11E89)[2] with a foil-faced OSB radiant barrier dropped the peak day heat transfer by 20 percent of that measured for the control shingle (SR10E89) (Figure 4b). The only difference between the two shingle roof systems and their attic assemblies was the addition of the foil-faced, OSB radiant barrier. The surface temperatures of shingles were similar; the control shingle roof system reached a high of 160°F (71°C) at solar noon, and the other shingle roof system with radiant barrier was slightly higher but within two or three degrees. Most local code officials and manufacturers now recognize that the radiant barrier does not excessively heat fiberglass asphalt shingles whether the roof and attic is ventilated or not [10]. However, the underside temperature of the foil-faced OSB was a measured 15°F (8.3°C) hotter than the underside deck temperature for the control (Fig. 4a). The foil

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[2] SR11E89 is a shorthand notation for identifying the solar reflectance [SR], it being 0.11 and the thermal emittance [E] it being 0.89 for the conventionally pigmented shingle roof.

prevented the transfer of thermal radiation into the attic space and retained the heat making the underside of the foil-faced OSB hotter than the control. By comparison, the attic assembly with the profiled and foil-faced EPS radiant barrier was 32 degrees Fahrenheit (17.8°C) cooler than the control shingle roof system around solar noon; it was 50 degrees Fahrenheit, or 27.8°C cooler than the foil-faced OSB (Fig. 4a). The reduced temperature (which is measured at the underside of the foil-faced EPS insulation) is the result of the above-sheathing ventilation (ASV) [11] that carries heat away from the deck by natural convection to the ridge vent, the low-e surfaces in the air space and the thermal resistance of the EPS insulation. Therefore, because heat transfers to the attic floor primarily by convection and radiation, the cooler temperatures for the foil-faced EPS (i.e., radiant barrier) further reduces the heat transfer crossing the attic floor. As a result, the attic air temperature did not exceed the outdoor air temperature during the summer.

Winter Field Tests of the Prototype Roof and Attics

During winter nights, field data revealed that night sky temperatures were much lower than the surface temperatures of the test roof systems, a situation that drives radiation heat loss to the sky. Good roof design should ideally limit heat gains during the summer while also limiting heat losses in the winter, which is why insulation works better than cool roof systems in cold climates. As shown in Figure 5, the ventilated and insulated roof assembly limits daytime heat gains from 8 a.m. to 6 p.m., which does not benefit a home during winter months. However, it also limits the nighttime losses as

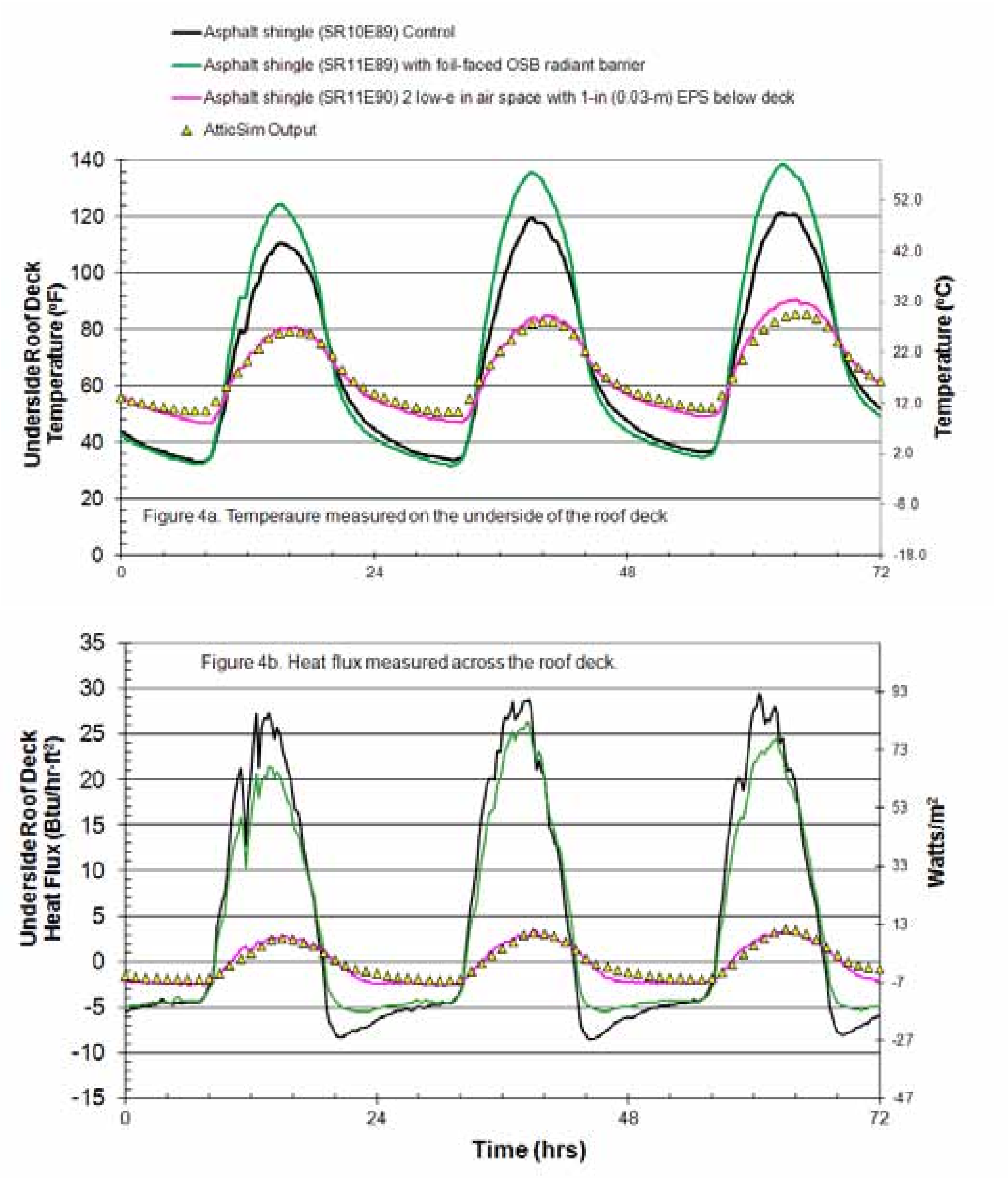

Figure 4 *Temperature measured on the underside of the roof deck (4a) and the measured heat flux crossing the roof deck (4b*. Field data for August 2010 is benchmarked against AtticSim (triangle symbols are AtticSim prediction)

compared to the base assembly (Figure 5). The foil-faced OSB assembly limits losses occurring from 8 p.m. until 8 a.m. So the amount of heat retained at night by a ventilated and insulated roof deck must exceed the daytime penalty (Figure 5) for it to be adopted in cold climate design. Seasonal simulations are needed for verification.

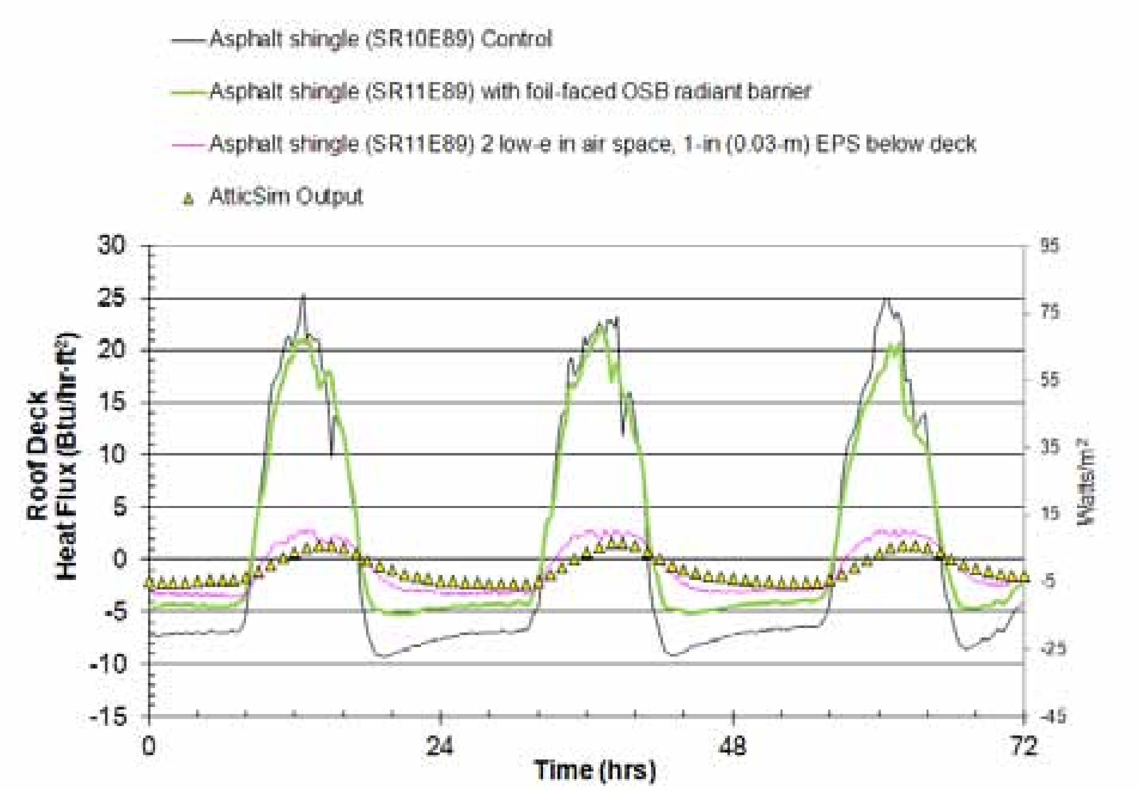

Figure 5 *Heat flux crossing the roof deck of the asphalt shingle roofs for three consecutive winter days in the climate of East TN. Average daytime and nighttime temperatures (48/38)^{o}F.* Field data for February 2010 is benchmarked against AtticSim (triangle symbols are AtticSim prediction)

Computer Simulations

ASTM C1340-04, “Standard Practice for Estimation of Heat Gain or Loss through Ceilings under Attics Containing Radiant Barriers by Use of a Computer Program,” [12] was benchmarked against field data for the insulated and ventilated shingle roof system (Figure 4 and 5). Simulations were made for the hot climates of Miami; Austin, TX; Atlanta and the cold climate of Baltimore with and without air-conditioning ducts in the attic. An attic of 1539 square feet (143 m^2) with a roof slope of 18 degrees was modeled with and without a cool color shingle roof; the cool color shingle’s solar reflectance was 0.25. The supply duct surface area was set at 304 square feet (28.7 m^2). The return duct assumed 176 square feet (16.4 m^2) of surface area exposed in the unconditioned attic. Energy Plus [13] estimated the hourly run times for an air-conditioner certified with a Seasonal Energy Efficiency Ratio (SEER) of 13 and for an 85 percent efficient gas furnace that heated the home. The hourly indoor air temperature for the house and the run time for the HVAC were estimated by Energy Plus and read by AtticSim to better estimate the roof and attic load as coupled to the building envelope.

Building Practices to Mull Over for New Homes

All too often HVAC ducts are in an attic, and the ducts are poorly insulated and are not well sealed so they leak conditioned air into the attic. Simulation results indicate that homeowners typically pay an added \$100 to \$300 more per year because of leaky and poorly insulated air conditioning ducts operating in an unconditioned attic. Energy costs are also increased if the attic floor leaks air to or from the home. Duct location and sealing the attic floor are of paramount importance and should take precedence over all other energy efficient roof system and attic strategies. The simulation results of Figure 6 illustrates why these practices should be a priority component of a building program. The dark blue bars represent a dark heat absorbing roof and attic that contains poorly insulated and leaky ducts and a leaky attic floor. The orange bars show energy use where the practitioner repaired the leaks in the attic and sealed and rewrapped the ducts in R_{US}-8 (R_{SI}- 1.4) insulation. The light green bars show the benefit of moving the ducts into the conditioned space. The light blue bars are for the new-design ventilated and insulated roof deck with the attic floor repaired for leakage and the ducts moved to the conditioned space.

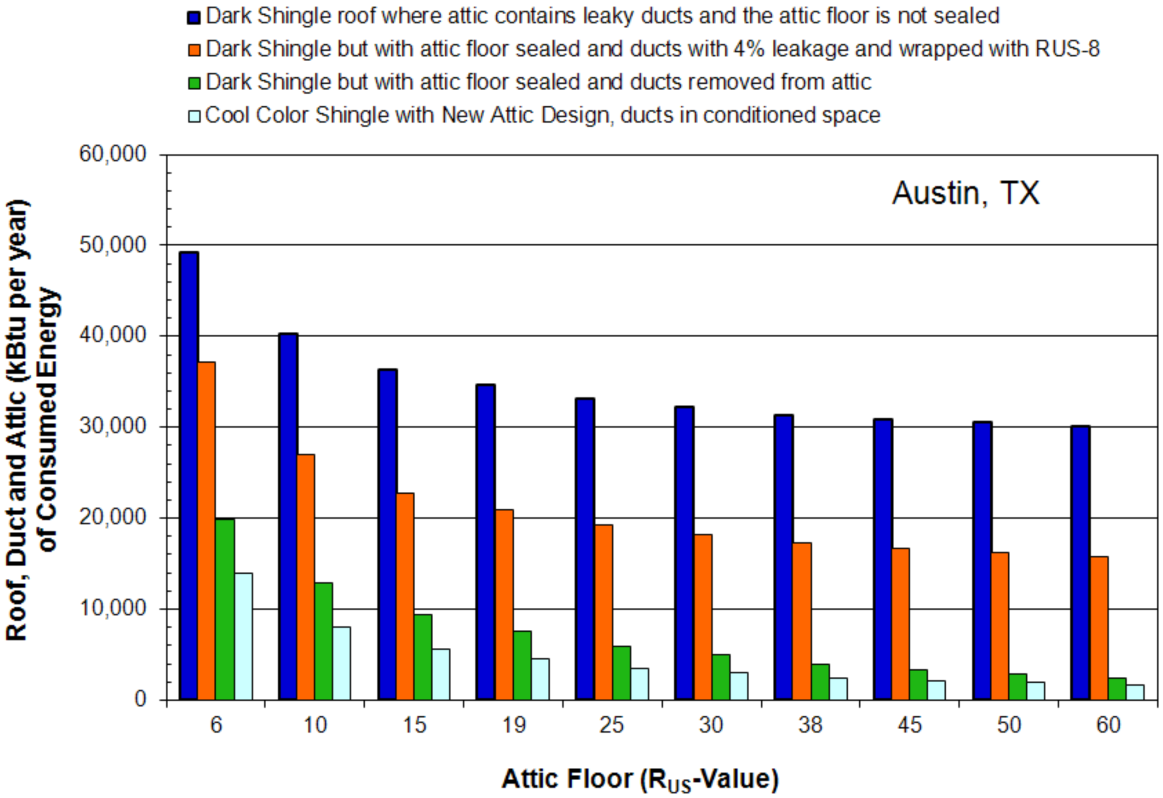

Figure 6. Comparison of energy effects of leaky ducts in attic space, sealing attic floors, insulating attic floors, and eliminating energy losses from HVAC ducts in unconditioned attics.

The heat gains and losses from leaky ducts and a leaky attic floor are double if not triple the heat gains and losses crossing the attic floor. Adding insulation to the attic helps but the heat transfer tends to level off for floor insulations exceeding R_{US}-30 (R_{SI}-5.3) because losses from the ducts predominate. Adding insulation does reduce the energy bill for all assemblies represented in Figure 6, but if all one does is add insulation then the energy consumed due to the roof system and attic is not minimized as clearly seen in Figure 6. Sealing all duct joints with mastic and wrapping the ducts with R_{US}-8 (R_{SI}-1.4) insulation drops the energy losses for ducts in the attic by roughly

40 percent (Fig. 6 dark blue bars compared to orange bars). However, more savings can be achieved if the ductwork is simply kept out of the attic. An attic with R_{US}-60 (R_{SI}-10.6) floor insulation but with leaky ducts and a leaky floor (Fig. 6 dark blue bar) has 30 percent greater heat energy losses than an attic with just R_{US}-5 (R_{SI}-0.9) floor insulation but with no ducts and no air leakage across the attic floor (Fig. 6 green bars). In many homes, the ductwork increases air-conditioner energy use by roughly 18 percent for moderately leaky ducts in a well-insulated attic [14] and [15].

Pre 1990 homes were hopefully built to the presiding ASHRAE Standard 90-80 "Energy Efficient Design of Low-Rise Residential Buildings" [18]. Therefore the payback for adding insulation above the 1980 code level set at R_{US}-20 (R_{SI}-3.52) was computed for an attic assembly with sealed attic floor and inspected ductwork[3], Figure 7. Adding R_{US}-19 (R_{SI}-3.3) of insulation pays for itself in about 35 years when added to an existing R_{US}-20 (R_{SI}-3.52) batt. Increasing the ceiling insulation to R_{US}-60 (RSI-10.6) yields a 34-year payback if the basis of savings starts at R_{US}-20 (R_{SI}-3.52) batt.

Building America (BA) has a residential benchmark [16] that calls for no ducts in the attic, sealing the attic floor and R_{US}-50 (R_{SI}-8.8) insulation placed on the attic floor. The seasonal roof heat transfer was computed for the BA benchmark and for the new roof and attic design (Figure 7). Increasing the level of insulation on the attic floor from IECC [9] code level of R_{US}-30 (R_{SI}-5.3) in Austin, TX to the BA benchmark of R_{US}-50 (R_{SI}-8.8) lowers the ceiling heat transfer by 41.5 percent of that computed for the code level of insulation (view red squares in Figure 7). At R_{US}-50 (R_{SI}-8.8) there is only 2,900 kBtu per year crossing the attic floor; however, the new attic design with R_{US}-30 (R_{SI}-5.3) shows heat flow of about 3,000 kBtu per year. Therefore, the ventilated and insulated

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[3] Simulated data is also represented by the green bars in Figure 6.

roof system performs as well as the BA benchmark while using only IECC code level of insulation (i.e., R_{US}-30 for insulated and ventilated roof deck; R_{US}-50 for BA benchmark)

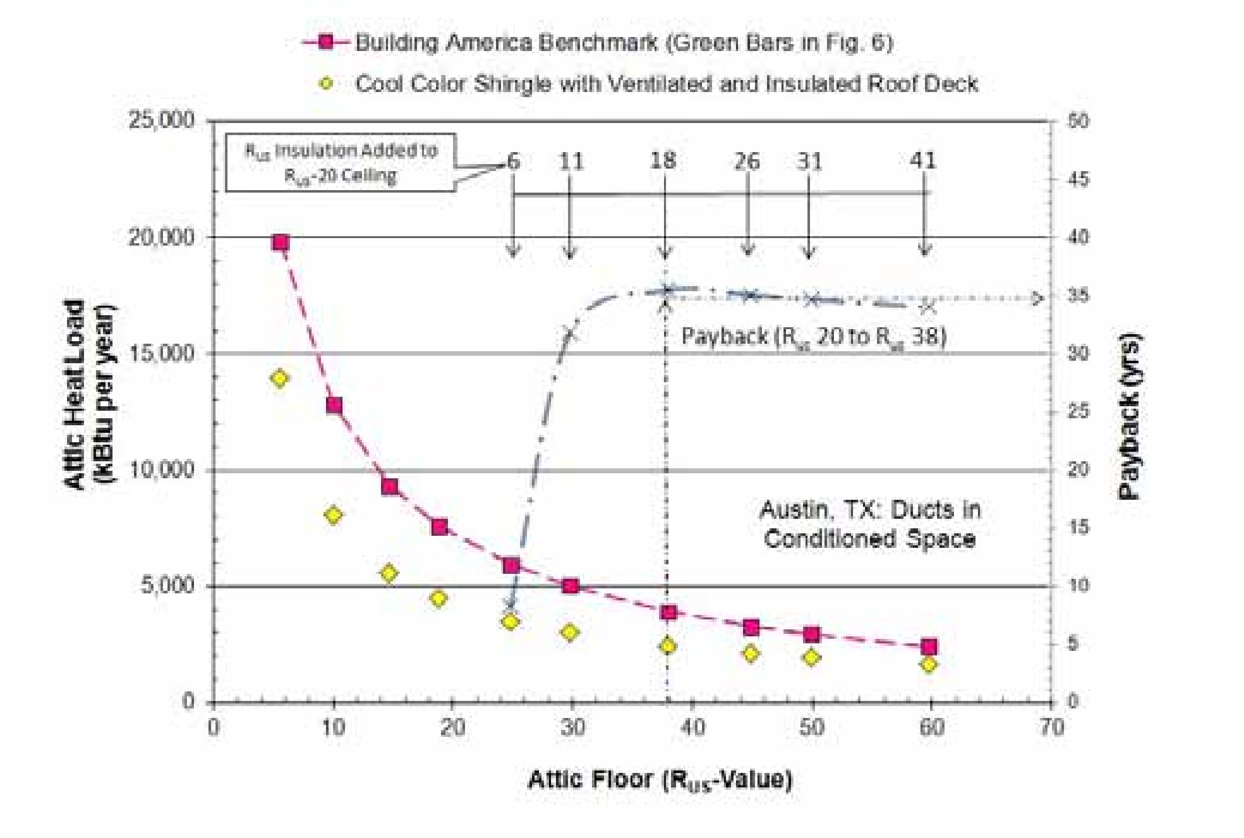

Figure 7. Building America Benchmark at R_{US}-50 (R_{SI}-8.8) is compared to the new roof system design having an insulated and ventilated roof deck.

Building Practices to Consider for Improving a Home

Simulations were also conducted to judge the best economic options for retrofit practice, (see Table 2). Shingle roofs are by far the least expensive roofing option as evidenced by the predominance of these roofs throughout the USA. F.W. Dodge [17] reported that about 85 percent of all U.S. homes have replaced existing worn-out roofs with asphalt shingles, and homeowners typically replace their roof simply to protect the underlying structure (i.e., when the roof leaks). Asphalt shingle roof systems were therefore simulated with and without a cool color roof, with and without a radiant barrier, and with and without an air space fitted above the deck. Simulations were also made for a sealed attic having conventional shingles. The sealed attic is becoming popular for hot, humid climates for sealing the attic interior from the outdoor elements.

Because cool color shingles are relatively new, the conventional replacement shingles are dark heat absorbers with about 0.10-solar reflectance and 0.90-thermal emittance. The attics of these homes (built around 1980 to 1990) have R_{US}-20 (R_{SI}-5.67) or less insulation on the attic floor and at best R_{US}-5.5 (R_{SI}-0.97) insulation wrapped around leaky ducts operating in the attic [18]. Air leakage of the ductwork is unknown; however, for demonstration purposes, simulations assumed air losses of 10 percent of supply airflow based on field studies conducted by Cummings et al. [14].

A pre-1980 home built to the existing ASHRAE code [18] but operating with a SEER 13 air-conditioner shows for Miami that the heat gains from the roof and attic cost the homeowner about $234 per year, Table 2. The Energy Information Administration (EIA) [19] publishes typical residential electric and gas heating bills for various U.S. regions (see Table 2), and for Miami the roof and attic of the simulated home contributes to about 15 percent of the electrical bill. For Austin and Atlanta, the heating load increases (see Table 2 and view HDD_{65}). In Austin and Atlanta the roof and attic are about 17 percent and 28 percent, respectively of the house's total use of gas and electricity. In Baltimore's colder climate, the pre-1980 home's roof and attic is roughly 27 percent of the total energy consumed by the home. Therefore cold climate design of roof systems and attics is just as important as hot climate design because on a national basis, residential homes use more energy for heating than for cooling (EIA [19]).

Table 2. Simulated cost of energy from roof and attic retrofits.

- **Home has SEER 13 Heat Pump; attic footprint 1539 square feet (143 m^2)**
- **Attic ventilation 1:300 with exception of sealed attic**

	Miami	**Austin**	**Atlanta**	**Baltimore**	Material and Labor Costs	Potential Payback (yrs)
ASHRAE Climate Zone	1	2	3	4		
HDD$_{65}$ (°F)	222	1481	2614	4731		
CDD$_{65}$ (°F)	9368	7435	4814	3598		
ASHRAE 90.2 [Note 1] Attic Insulation (R_{US})	30	30	30	38		
EIA[Note 2] Annual Electric Bill	$1,570	$1,770	$1,368	$1,724		
EIA[Note 2] Annual Heating Bill	NA	$590	$780	$1,070		
	$[Note 3] per square [100 square feet (9.3 m^2)]					
Pre-1990 Home[Note 4] Shingle Roof (SR 0.10) Attic Floor R_{US}-20 Duct with R_{US}-5.5	$15.23	$27.12	$39.18	$49.35		
Sealed Attic Floor Attic Floor R_{US}-20 Inspected Duct R_{US}-8 Duct; Leakage 4%	$9.57	$16.39	$23.40	$27.98	$50	9 to 3
Pre-1990 Home[Note 5] Shingle Roof (SR 0.10) Attic Floor R_{US}-20; No Duct in Attic	$3.47	$6.23	$9.26	$9.98		
Pre-1990 Home Retrofit Option(1): Code Insulation Shingle Roof (SR 0.10); No Ducts in Attic	$2.23	$4.17	$6.41	$5.60	$65 $103	50 to 20
Pre-1990 Home Retrofit Option(2): Radiant Barrier in Attic Attic Floor R_{US}-20; No Ducts in Attic	$2.41	$5.03	$8.27	$8.94	$40	≈ 40
Pre-1990 Home Retrofit Option(3): Above Sheathing Vent Shingle Roof (SR 0.10) Attic Floor R_{US}-20; No Ducts in Attic	$4.95	$5.49	$8.56	$9.37	$55	> 75
Pre-1990 Home Retrofit Option(4): Cool Shingle (SR 0.25) Attic Floor R_{US}-20; No Ducts in Attic	$3.05	$5.95	$9.32	$10.04	$50	> 100
Insulated and Ventilated Roof ASHRAE 90.2 Code Insulation Duct in Attic; R_{US}-8, 4% Leak	$5.68	$12.04	$20.05	$20.54	$215 $253	30 to 11
Sealed Attic with Spray Foam Roof Solar reflectance 10% Attic Floor R_{US}-5 Duct R_{US}-8, 4% Leak	$10.08	$22.22	$37.58	$44.00	$300.0	> 70

[1] ASHRAE 90.2-2007 [8].

[2] Energy Information Agency (2008)

[3] Costs based on EIA 2008 data for electricity and natural gas.

[4] Pre-1990 Home: ASHRAE 90-1980 code. Duct in attic; leakage rate 10% of supply flow.

[5] Pre-1990 Home: ASHRAE 90-1980 code. No Duct in attic.

Renovating the ductwork and sealing the attic floor can save about \$87 per year in Miami, \$165 per year in Austin and about \$240 per year in Atlanta (see Table 2). The cost of the renovation is about \$50 per square, and the savings pay for the renovation in 9 years for a home in Miami, in 5 years in Austin, in 3 years in Atlanta and 2½ years in Baltimore. If one opts to not renovate the ducts but rather just add insulation up to code level [R_{US}-30 (R_{SI}-5.3)] the annual savings per 100 square feet (square) are just \$20 in Miami, \$32 in Austin, \$44 in Atlanta and \$67 in Baltimore. Material and labor costs estimated by the Building News Index (BNI) [20] are \$65 per square for the added R_{US}-10 (R_{SI}-1.8) insulation in the hot climates, and \$103 in Baltimore[4]. So adding R_{US}-10 (R_{SI}-1.8) will pay for itself in 52 years in Miami, 32 years in Austin and in 23 years in Atlanta. Adding R_{US}-19 (R_{SI}-3.3) in Baltimore yielded payback in 23 years.

Of the four retrofit options; adding insulation (Table 2, option 1), installing a radiant barrier (option 2), installing above sheathing ventilation (option 3) or replacing shingles with cool color products (option 4) — adding insulation is the best choice followed by the installation of a radiant barrier. The inclined air space in itself or replacing asphalt shingles with a cool color shingle as part of roof maintenance (no other renovations) yields payback periods exceeding 75 years, Table 2.

Installing the insulated and ventilated roof design and repairing the ducts and sealing the attic saves energy (see Table 2). Savings for the insulated and ventilated roof deck are very close to those computed for a sealed attic, if both systems have IECC code levels of insulation; however, present practice removes the insulation from the attic floor of the sealed attic. So to mimic sealed attic practice, the simulations listed in Table 2 for a sealed attic assumed R_{US}-5 (R_{SI}-0.9) insulation left on the attic floor. A sprayed-on

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[4] Code level of insulation is R_{US}-38 in Baltimore and simulations assumed adding R_{US}-19.

open cell foam was also assumed installed between 2 × 6 rafters supporting the roof deck. The material and labor cost for sealing an attic is estimated at about \$0.78 per square foot per inch depth of foam [R_{US}-4 (R_{SI}-0.70)]; a 2-in. depth costs \$1.29 per square foot [20] and [21]. Therefore, to fill the cavity made by 2 × 6 rafters would cost about \$3 per square foot of coverage[5] for a 5½-in. (0.14-m) depth of foam [R_{US}-22 (R_{SI}-3.9)]. Sealing the attic therefore yields paybacks in excess of 70 years. However, payback for the insulated and ventilated roof deck is 30 years in Miami, 18 years in Austin and 14 years in Atlanta. In Baltimore the payback is estimated at 11 years for the insulated and ventilated roof deck as compared to a 68 year payback for sealing the attic with open cell spray foam.

If one follows the BA lead and removes the duct from the attic, then the BA benchmark or the ventilated and insulated roof in conjunction with the elimination of duct losses can pay for itself in 10 to 15 years. To accomplish the job dictates removal of the ducts, and installation of a new ductless HVAC system such as the wall-mounted, mini-split heat pumps that are becoming more and more popular. A 2-ton mini-split system costs about \$3,500 for equipment and the labor. The labor and material costs for installing an added R_{US}-10 (R_{SI}-1.8) of insulation, for sealing the attic floor, for installing the ventilated and insulated roof deck and for the mini-split heat pump costs about \$360 per square of attic footprint. Implementing these measures for the 1539 square feet (143 m^2) home would save from \$220 per year in Miami to \$520 in Atlanta and yield paybacks of about 26 years in Miami, 11 years in Atlanta, and 9 years in Baltimore. The estimates are conservative because the SEER of the mini-split heat

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[5] A field study conducted by ORNL and TVA showed costs of about \$3.50 per square foot [22].

pumps is about 22, which is considerably higher than that of a SEER 13 heat pump used in simulation. In other words, one can renovate his or her roof and attic and feasibly pay for a new HVAC over its expected life.

Conclusions

The most cost-effective retrofits for an attic are repairing the leaks through the attic floor and in the HVAC ducts. Adding insulation from R_{US}-20 (R_{SI}-8.8) to ASHRAE 90.2 code showed payback in Baltimore (about 24 years) and exceeded 20 years for all hot climates. Installing a radiant barrier showed a payback of about 40 years. The addition of a cool color roof saves little energy for homes having code levels of insulation. Unless cool color shingles, above sheathing ventilation and or radiant barriers are installed in a systems approach or in conjunction with other attic renovations (e.g. ductwork) a viable payback will not be realized for the energy conscious homeowner. The ventilated and insulated roof retrofit on a pre-1980 home can provide a 10 to 30 year payback on investment. The sealed attic assembly does not yield a payback less than 70 years.

However, homeowners are probably more willing to make a system approach that exploits cool color roofs, above-sheathing ventilation, low-e surfaces and insulations placed above the roof deck as a critical component of a proactive roof maintenance program; preference being to contract a crew to work on the roof rather than enter the dwelling to work in the attic. The ventilated and insulated roof assembly can be used with almost all types of roof products. Its implementation can match the energy consumed by the BA benchmark without having to fill the attic with insulation to R_{US}-50 (R_{SI}-8.8) levels.

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