A Compilation of Home Energy Assessments for Cool Roofs, Above-Sheathing Ventilation, Radiant Barriers, and Other Attic Strategies

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ABSTRACT

A combined experimental and analytical study documented the thermal performance of cool roofs in combination with other roof and attic strategies. Cool-colored roofs are a first line of defense against heat transfer penetrating the conditioned space. However, radiant barriers, above-sheathing ventilation, low-emittance (low-e) surfaces in an inclined air space above the roof deck, insulation, and conventional and advanced thermal masses (i.e., phase-change materials) are all possible candidates that can enhance cool roof and attic performance. Field data and benchmarked computer simulations are reviewed to better understand energy and economic trade-offs in a variety of climates.

INTRODUCTION

A steep-slope roof and attic test stand, the Envelope Systems Research Apparatus (ESRA), was used to field test and document the heat transfer crossing the roof decks of cool-colored roofs separately or in combination with other energy-saving strategies. All attic assemblies were equipped with heat flux transducers (HFTs) embedded in the roof deck and in the attic floor. A Fox 670 heat flux apparatus was used to calibrate each HFT in a guard made of the same material used in construction to correct for shunting effects (i.e., distortion due to three-dimensional heat flow (ASTM 2006). Salient features of the ESRA and additional details of the roof and attic assemblies are provided by Miller (2006). A commercially available asphalt shingle with a solar reflectance of 0.093 and thermal emittance of 0.89, abbreviated herein as SR10E89, was the control for comparing the thermal performances of the prototype roof systems. Solar reflectance was measured using the ASTM C 1549 protocol (ASTM 2009). Thermal emittance was measured using the ASTM C 1371 protocol (ASTM 2004a).

The field data were used to validate the attic simulation model in ASTM C 1340 (ASTM 2004b). Ceiling insulation in the test assemblies was purposely set low, at R_{US}-5.1 h·ft^2·°F/Btu (R_{SI}-0.9 m^2·K/W), to help reduce the experimental uncertainty in measured heat flux. Hence, the discussions of field data will focus on the measured heat flux crossing the roof deck of the attic, and simulations will provide results for computed heat flux crossing the attic floor and the subsequent energy consumption associated with attics having code-compliant levels of insulation.

CLAY AND CONCRETE TILE FIELD DATA

Concrete and clay tile roof and attic assemblies were field-tested on the ESRA to assess the effects of cool-colored roofs, thermal mass, and placement of batten and double-batten systems under the tile (Figure 1). A clay tile was manufactured with cool-colored pigments; its measured solar reflectance was 0.54 and its thermal emittance was 0.90 (SR54E90). Two medium-profile concrete tiles were coated in the field with pigments boosting solar reflectance from 0.08 for the conventionally painted tile to 0.40 for the coated tile. Salient features of the different tile roofs are provided in the appendix (Figure A1).

Medium-Profile Tile

Three medium-profile concrete tile roofs were configured: 1) direct to the roof deck and the tile painted with a

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(a) (b) (c)

Figure 1 *Field-testing of clay and concrete tile roofs on the ESRA. Test roofs are, starting from the far right:*

- *medium-profile concrete on double battens (SR10E93)*
- *medium-profile concrete direct to deck (SR37E93), infrared reflective (IRR) coating*
- *medium-profile concrete on battens (SR37E93), IRR coating*
- *flat concrete tile direct to deck (SR13E83)*
- *high-profile concrete tile on battens, terra-cotta (SR34E83)*
- *high-profile concrete tile spray foam to deck, splotchy terra-cotta (SR26E86)*
- *high-profile concrete tile direct to EPS foam, splotchy terra-cotta (SR26E86)*
- *high-profile clay tile direct to EPS foam (SR54E90), IRR pigments*

cool-colored pigmented coating (SR37E93), 2) on battens (1 × 1 in. [0.03 × 0.04 m] nominal lumber) with cool-colored pigments (SR37E93), and 3) on double battens (1 × 1 nominal lumber) with tile having conventional color pigments (SR10E93). All three medium-profile tiles exhibited less heat transfer across the roof deck compared to the flat tile (SR13E83) mounted directly to the deck during field tests on the ESRA. Most important, though, is the observation that as the cool-colored tile is further offset from the deck, the roof's thermal performance improves due to above-sheathing ventilation (ASV). The medium-profile tile with conventional color pigments and on double battens (1.5 in. [0.038 m]) showed deck heat transfer very similar to that of the cool-colored tile attached directly to the deck. The finding agrees in trend with similar work by Beal and Chandra (1995), who field-tested two identical medium-profile concrete tile roofs; one tile roof was direct-nailed and the other was offset mounted about 1.5 in. (0.038 m) above the deck. Beal and Chandra (1995) measured an 11% reduction in the daytime heat flux penetrating the concrete tile roof on double battens compared to the adjacent direct-nailed tile roof.

High-Profile Tile

A high-profile tile with conventional terra-cotta color pigments (SR34E83) was tested on nominal 1 × 1 wood battens. The terra-cotta tile slightly outperformed all medium-profile tile configurations (Figure 2). Two more roofs—one with high-profile concrete tile having a splotchy terra-cotta finish (SR26E86) and the other with a high-profile clay tile with cool-colored pigments (SR54E90)—were each placed on 1.25 in. (0.032 m) of expanded polystyrene (EPS) insulation[1] adhered to the deck using a spray polyurethane adhesive.[2] The additional R_{US}-4.8 (R_{SI}-0.85) of EPS insulation under the high-profile splotchy terra-cotta tile helped drop peak-day heat transfer by 85% of that measured for the control shingle roof. Further drops in deck heat transfer were observed with the clay tile because its solar reflectance was double that of the splotchy terra-cotta tile. In fact, the heat transfer crossing the deck of the clay tile roof was the lowest observed of all tested tile roofs: deck heat flow dropped by 90% of that measured around solar noon for the control shingle roof on the hot August day of measurement (Figure 2).

Computations using AtticSim (Wilkes 1991a) deduced that the high-profile clay tile placed on 1.25 in. (0.032 m) of EPS insulation is about R_{US}-8.9 (R_{SI}-1.6), of which ASV is estimated at about R_{US}-2.7 (R_{SI}-0.48), or roughly 30% of the total resistance of the R_{US}-8.9 (R_{SI}-1.6) deck. In contrast, the asphalt shingle roof deck (i.e., the control roof) is about R_{US}-1.8 (R_{SI}-0.32).

METAL ROOFING FIELD DATA

Miller et al. (2006) field-tested stone-coated metal roofs on adjacent attic test assemblies on the ESRA similar to the assemblies used for testing tile. A conventional dark-gray stone-coated metal shake (SR08E90) and a light-gray metal shake (SR26E90) were tested on identical double-batten constructions (air space of 0.75 in. [0.019 m]). The dark-gray metal shake and the control shingle have almost identical solar reflectance and thermal emittance characteristics, yet the heat flow crossing the roof deck of the dark-gray shake was just 70% of

1. The EPS foam has a density of 0.94 lb per cubic foot (15 kg/m^3).

2. The roof system is commercially available and received Florida Building Code approval (Trinity Evaluation 02768.03.06-R2, Revision 2: 10/31/2008).

the heat flow crossing the roof deck of the control shingle (Figure 3). The 30% reduction in heat flow was caused by the thermal resistance of the air space due to convection occurring in the air space and in part by the low-emittance (low-e) of the underside of the stone-coated roof shake (emittance being 0.35).

Increasing solar reflectance from 0.08 to 0.26 caused the heat flow crossing the roof deck of the light-gray shake to be less than the heat flow crossing the deck of the dark-gray stone-coated shake (Figure 3). Miller et al. (2006) also determined that the heat flow removed by ASV of the hotter dark-gray stone coated shake is more than double that removed by the light-gray shake. The hotter dark-gray stone-coated shake causes greater buoyancy-induced airflows; therefore, the ventilation scheme is somewhat self-regulating. The darker the roof, the hotter the roof and the greater is the buoyant flow that carries heat away from the attic space. The stone-coated metal

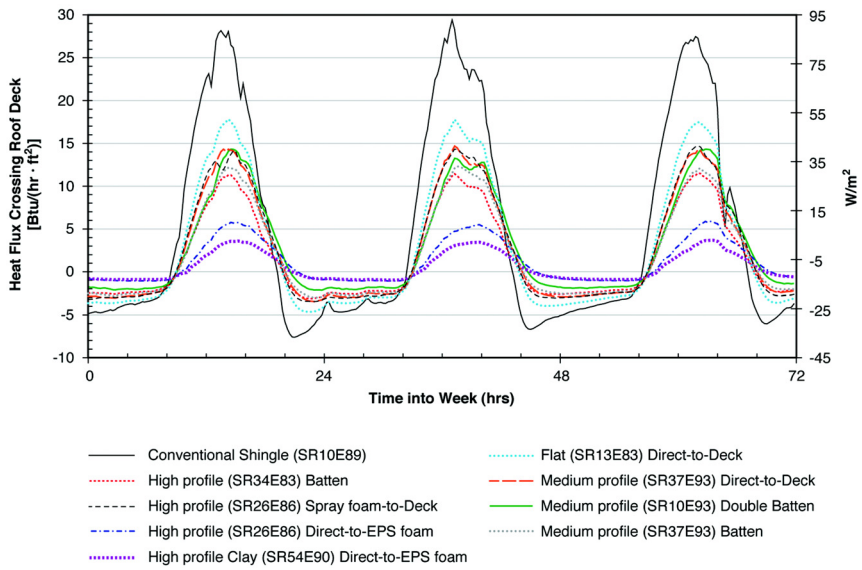

Figure 2 *Field data for the heat flow crossing the roof deck for attic assemblies having concrete and clay tile roofs. August 2007 data benchmarked against AtticSim.*

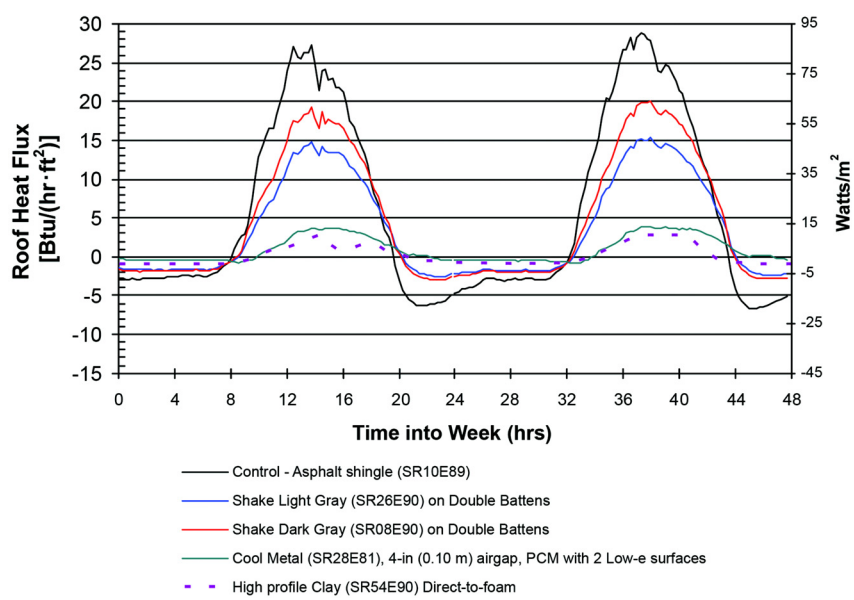

Figure 3 *Heat flow measured crossing the roof deck of a direct-nailed shingle roof and stone-coated metal roofs with and without cool color pigments. Metal roofs installed on 1.5 × 1.5 in. (0.038 × 0.038 m) double-battens. The July 2005 field data are benchmarked against AtticSim.*

lacks the mass of a concrete tile, implying that ASV and/or the effective thermal resistance of the air space significantly affect the amount of heat penetrating into the attic.

ASHRAE (2005) provides empirical data for the effective thermal resistance of plane and closed air spaces. A 0.75 in. (0.0191 m) plane and closed air space inclined at 45° with the horizontal has R_{US}-0.85 (R_{SI}-0.15). The air space for the metal roofs was ventilated at the eave and the ridge and therefore has a slightly higher thermal resistance, estimated by AtticSim (Wilkes 1991a) at R_{US}-2 (R_{SI}-0.36).

Miller and Kosny (2008) showed that a standing seam painted metal roof (SR28E81) having a 4 in. (0.102 m) air space with two low-e surfaces facing each other across the space yielded almost identical heat transfer through the roof deck as that observed for the best-performing clay tile assembly shown in Figure 2 and compared to the standing seam metal assembly in Figure 3. The painted metal roof had two different fabric sheathings that contained about 0.125 lb of phase-change material (PCM) per square foot of roof deck (0.61 kg/m^2 of PCMs) (Figure 4).

The PCMs and the inclined air space with low-e surfaces acted as a buffer against heat loss during the winter. For three consecutive winter evenings, the surface and sheathing temperatures of the control shingle roof dropped below the outdoor air temperature as a result of night-sky radiation. Measurements of the surface temperatures of the painted metal roof indicated that it had the coldest nighttime temperature (Figure 5); however, its sheathing temperature never dropped below the outdoor air temperature for the three consecutive winter nights in January 2007.

Hence, the design is retarding the loss of heat from the roof deck of the metal roof and attic assembly because of the air space, the low-e surfaces, and the PCM that releases heat stored during the daytime. Subsequently, the prototype roof assembly significantly decreased variations in the attic air temperature, resulting in warmer nighttime temperatures during the winter and cooler daytime temperatures during the summer.

Miller and Kosny (2008) suggest that an open air space above the sheathing may be an excellent design strategy for reducing roof heat gains and losses. Miller et al. (2007) benchmarked AtticSim (Wilkes 1991a) against the field data and made seasonal simulations for Sacramento, CA, to determine the energy benefits of ASV for air spaces from 1 to 4 in. (0.025

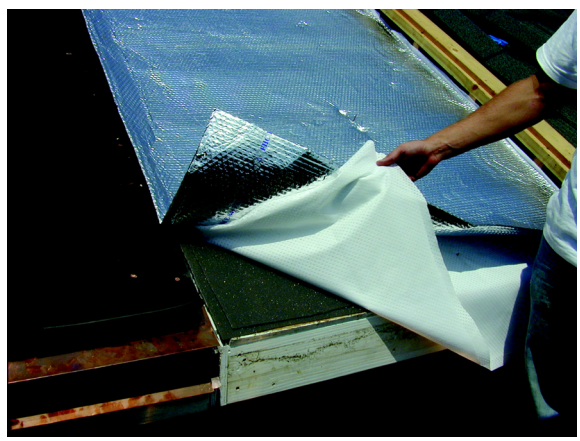

Figure 4 *PCM fabrics placed above roof deck.*

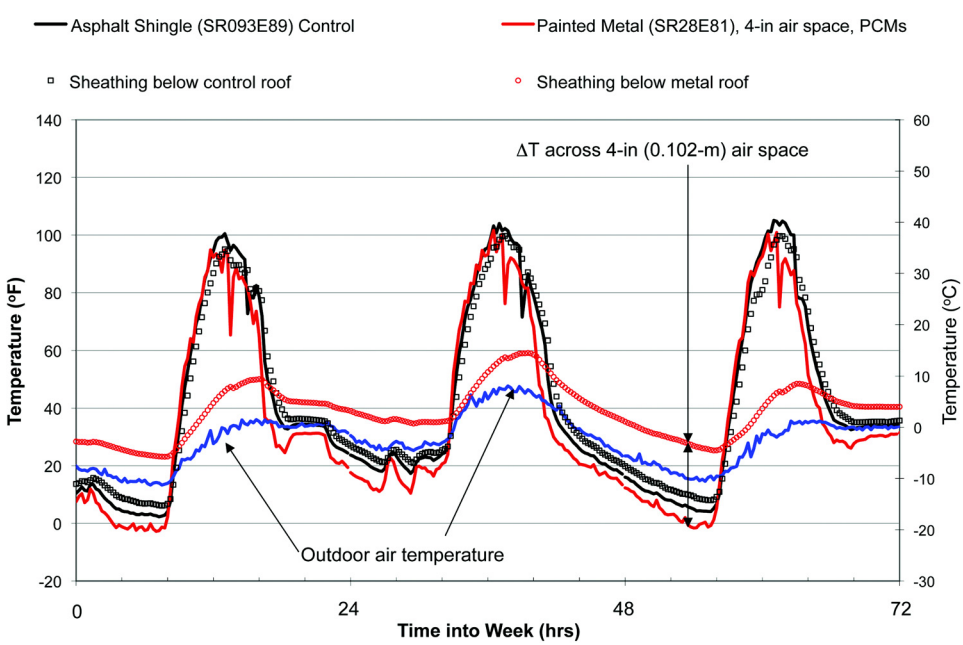

Figure 5 *Temperatures of the roof sheathing and the underside of the roof cover for three consecutive winter days. Data for January 2007.*

to 0.102 m) in height. Sacramento, which has 1202 cooling degree-days with 65°F (18.3°C) base (CDD_{65}) and 2697 heating degree-days with 65°F (18.3°C) base (HDD_{65}), was simulated using California code-compliant levels of ceiling and duct insulation. A radiant barrier was also assumed in the simulations based on Title 24 requirements (CEC 2005).

The integrated heat flows over the heating and cooling season (Table 1) show that the cool-colored metal roofs have less heat loss during the winter and less heat gain during the summer than that computed for a direct-nailed shingle roof (shaded row in Table 1). Increasing the height of the air space reduces heat transfer for both the ceiling and the duct. The benefits seen for the ductwork occur because the air space helps maintain a more moderate attic air temperature throughout the year, reducing convection heat transfer from the ducts. The painted metal roof with a 4 in. (0.102 m) air space shows winter losses 9% less and summer gains 37.6% less than the ceiling heat flows computed for the direct-nailed case (Table 1). Similarly, duct losses dropped by 7% (heating) and 27% (cooling) from the base case duct system (shaded row in Table 1). Therefore, implementing ASV helps negate the heating penalty associated with cool roofs. The air space is an insulating buffer against heat loss to the night sky in the winter and provides natural ventilation in the summer.

For a retrofit application where the air handler and ductwork are operating in the attic, the prototype roof assembly would help improve the efficiency of the HVAC equipment while also lessening heat gains and losses from ductwork.

Asphalt Shingle Assemblies

Shingle roofs are by far the least-expensive roofing option, as evident by the predominance of these roofs across the country (Dodge 2002). Three roofs that have the same style of architectural shingle and the same solar reflectance and thermal emittance were field-tested with and without a radiant barrier. The radiant barrier used in one assembly was a perforated, foil-faced oriented strand board (OSB) with the foil facing into the attic. The other attic assembly used EPS insulation that is profiled to fit between roof rafters (Figure 6). It is foil faced on

Table 1. Heating and Cooling Load for Ceiling and Air-Conditioning Duct Simulated in Sacramento, CA, for a Roof and Attic Assembly with R_{US}-38 (R_{SI}-6.7) Ceiling Insulation and R_{US}-6 (R_{SI}-1) Duct Insulation

Roof System	SR/TE[1]	ASV[2] Air Space	Ceiling Load,[3] kBtu/yr[4]		Air-Conditioning Duct Load,[3] kBtu/yr[4]	
			Heating	Cooling	Heating	Cooling
Asphalt shingle	0.25/0.75	Direct-nailed	–1,714	274	–4,782	1,575
Painted metal[5]	0.28/0.81	1-in (0.025-m)	–1,572	187	–4,488	1,234
Painted metal[5]	0.28/0.81	2-in (0.051-m)	–1,563	181	–4,470	1,199
Painted metal[5]	0.28/0.81	4-in (0.102-m)	–1,557	171	–4,452	1,147

Note: Duct leakage is assumed to be 4% of the supply flow. Simulation does not include PCMs.
[1] SR = solar reflectance, TE = thermal emittance.
[2] Air space for above-sheathing ventilation (ASV) fitted with one low-e surface.
[3] Loads based on attic footprint of 1261 ft^2 (117.2 m^2).
[4] Millijoules per year = 1.055·kBtu/yr.
[5] Standing-seam painted metal roof with cool-colored pigments.

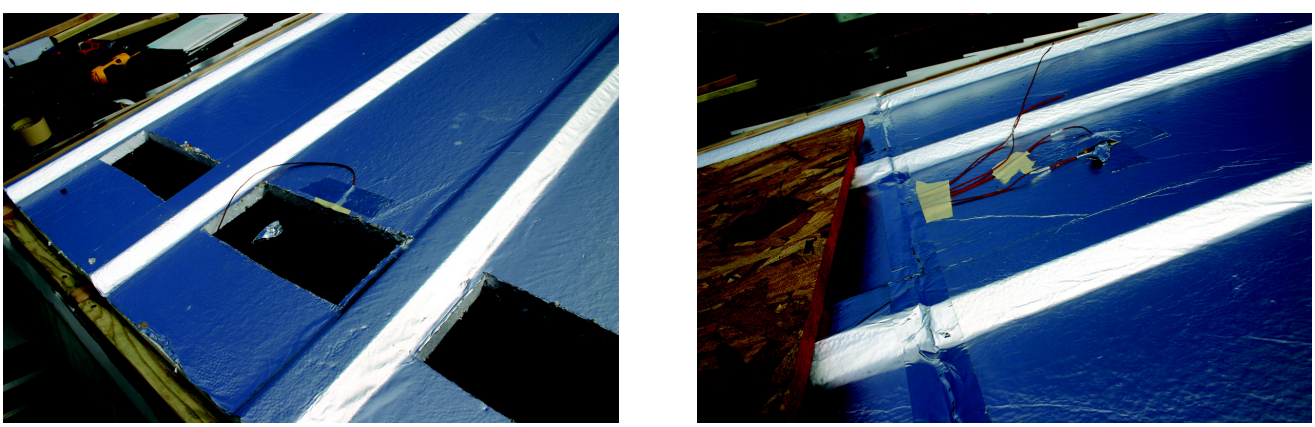

Figure 6 *Setup of a prototype roof for new construction shows the EPS with vent slots and a perforated foil-faced OSB deck laying on top of the EPS to create an air gap. The slots in the EPS provide a passageway for air from the soffit vents and also from the attic space.*

both sides to serve as a radiant barrier facing into the attic and as a low-e surface facing into the inclined air space. It has application for both new and retrofit construction. The EPS insulation is profiled to provide a 1 in. (0.0254 m) air space. An OSB with a foil facing is placed on top of the insulation to provide an additional low-e surface. A slot is cut near the eave just above the soffit vent to provide makeup air from the soffit vent and attic plenum (Figure 6). Buoyant air moves up the inclined air space and creates a negative pressure at the eave, which pulls cool makeup air from the soffit and attic to enhance thermal performance in the inclined air space. The design puts the opening to the air space within the soffit enclosure, which helps block any burning embers from entering the space and thereby improves the fire protection design of the roof.

The conventionally pigmented asphalt shingle (SR11E89) with a foil-faced OSB radiant barrier dropped the peak day heat transfer by 20% of that measured for the control shingle (SR10E89) (Figure 7a). The only difference between the two shingled roofs and their attic assemblies was the addition of the foil-faced OSB radiant barrier. The surface temperatures of shingles were very similar; the control shingle roof reached a high of 160°F (71°C) at solar noon, and the other shingle roofs with radiant barriers were slightly higher but were within two or three degrees. However, the underside temperature of the foil-faced OSB was 15°F (8.3°C) hotter than the underside deck temperature for the control (Figure 7b), because the foil prevented the transfer of thermal radiation into the attic space.

By comparison, the attic assembly with the profiled and foil-faced EPS radiant barrier was 32°F (17.8°C) cooler than the control shingle roof around solar noon; it was 50°F (27.8°C) cooler than the foil-faced OSB (Figure 7b). The reduced temperature (which is measured at the underside of the foil-faced EPS insulation) is the result of the ASV that carries heat away from the deck by natural convection to the ridge vent, the low-e surfaces in the air space, and the EPS insulation. Therefore, because heat transfers to the attic floor primarily by convection and radiation, the cooler temperatures for the EPS radiant barrier reduce the heat transfer crossing the attic floor (Figure 7a). Performance of the prototype shingle roof is very similar to that observed for the best prototype painted metal roof and the high-profile clay tile with EPS foam. Their attic air temperatures did not exceed the outdoor air temperatures throughout the summer.

THERMAL SIMULATIONS FOR A RESIDENTIAL ATTIC

Wilkes (1991a) formulated and validated an attic simulation tool known as AtticSim. The ability to simulate ASV was formulated by Miller et al. (2007) and validated against the field data for tile, stone-coated metal, standing-seam metal, and asphalt shingle roofs with and without ASV and with and without cool colors. Miller et al. (2010) show the benchmarking of AtticSim against the various field data acquired on the ESRA.

On command, AtticSim reads the percentage of time between 0% and 100% that a duct system operates during each hour of the simulation. To estimate typical run times for a duct system, Energy Plus, the annual whole-building energy-estimating program, was run for a small residence in each climate. Desjarlais et al. (2004) provide details of the modeled building, which was a 1261 ft^2 (117 m^2) single- story residence. The conditioning system consisted of an electric air conditioner and a natural gas furnace. An algorithm in Energy Plus sized each system to meet the peak loads during cooling and heating for each climate. Hourly run times for cooling and heating and the subsequent hourly indoor air temperatures for the house in hot and cold climates were obtained from hourly reports generated by the Energy Plus system simulation and read by AtticSim to better estimate the roof and attic loads (Tables 2–6) as coupled to the building envelope.

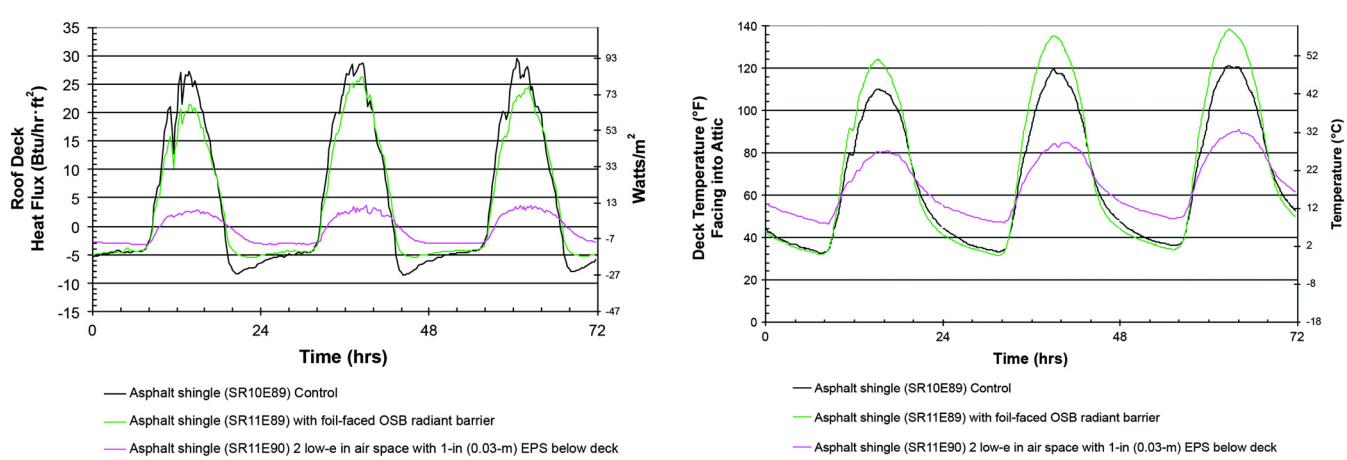

Figure 7 *(a) The measured heat flux crossing the roof deck and (b) temperature measured on the underside of the roof deck.*

A clean radiant barrier was modeled on all interior attic surfaces with the exception of the attic floor, which was modeled with Title 24 (CEC 2005) or ASHRAE (2005) code levels of insulation. Wilkes (1991b) modeled radiant barriers placed on the attic floor and attached to the roof deck and gable ends of the attic. He observed that applying the radiant barrier to the underside roof deck and to the gable ends yielded savings very similar to a horizontally placed "clean" radiant barrier. Simulations therefore assumed that radiant barriers applied to the roof deck and gables had a thermal emittance set at 0.05. The approach eliminates the effect of dust accumulation on the horizontally positioned radiant barrier, which Wilkes (1991a) showed lost performance as emittance increased due to dust accumulation.

Annual Loads for Pre- and Post-1980 Attic Construction

Simulations for pre- and post-1980 roof and attic constructions were made for the hot, dry southeastern region of El Centro in California, the moderate climate of Sacramento, CA, and the cold, windy climate of Chicago, IL. An attic with a 1261 ft^2 (117 m^2) footprint, a roof pitch of 18°, and air-conditioning ducts was modeled. The supply ducts contained six branches off the main branch; the surface area was set at 304 ft^2 (28.7 m^2). The return duct with 176 ft^2 (16.4 m^2) of surface area was also placed in the attic. Both post-1980 and pre-1980 construction often placed the HVAC system and ductwork in the attic.

The time-dependent valuation (TDV) protocol was used for El Centro and Sacramento to compute source energy based on performance data for air-conditioning units tested in northern and central California (CEC 1999). The energy efficiency ratio of the air-conditioning unit was used at each hour of a weather database (CEC 1992) along with hourly TDV energy factors to convert attic heat transfer to source energy of natural gas in British thermal units of natural gas (Btu_{NG}). Eley (2002) describes the procedure used to calculate TDV costs. Weather data from typical meteorological years was used for computing roof and attic performance for Chicago, IL (NREL 1995).

The results for pre-1980 construction (Tables 2, 3, and 4) and for new construction (Tables 5 and 6) provide a progression in construction that shows the energy and cost savings as specific roof and attic strategies are augmented in the design. Please note that replacing an asphalt shingle roof with a tile roof has structural implications, which must be reviewed a priori replacement to comply with building code requirements.

Hot Climate—Pre-1980 Construction. F.W. Dodge (2002) reported that about 85% of homes in the United States have replaced existing worn-out roofs with asphalt shingles. Because cool-colored shingles are relatively new, the old shingles that need to be replaced are dark heat absorbers with a solar reflectance of about 0.05 and a thermal emittance of about 0.90. The attics of these homes, which were built around 1980, have R_{US}-19 (R_{SI}-3.3) or less insulation on the attic floor and at best R_{US}-4.2 (R_{SI}-0.74) insulation wrapped around leaky ducts operating in the attic. Air leakage of the ductwork is unknown; however, for demonstration purposes, simulations assumed air losses of 14% of supply airflow for uninspected ductwork (CEC 2005). In many homes, the ductwork increases air conditioner energy use by roughly 18% for moderately leaky ducts in a well-insulated attic (Cummings et al. 1990; Parker et al. 1993).

The roof and attic of a home built around 1980 (shaded row in Table 2) is compared to retrofit roof systems also simulated with an uninspected duct ("nn Duct" having a 14% loss of supply airflow). Simulations listed above the thin line of Table 2 demark roof replacement work as compared with work

Table 2. Annual Ceiling and Air-Conditioning Duct Heat Transfer and TDV Energy Costs for Pre-1980 Attic Construction Simulated for El Centro, CA (CA Climate Zone 15)

Roof SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2]		Duct System		Load Due to Roof and Attic		TDV Source Energy[4] Costs	
		R-Value	RB (TE)	R-Value	Air Leakage	Cooling, kWh/sq	Heat, Therms/sq	$NPV over 30 yrs	PV$ per yr per sq
0.05 / 0.90	NA	19	0.9	4.2	14%	320.7	2.9	$20,687	$84
0.25 / 0.90	NA	19	0.9	4.2	14%	306.3	3.0	$19,821	$80
0.28 / 0.81	1 in. air space	19	0.9	4.2	14%	283.6	2.6	$18,188	$74
0.54 / 0.90	High profile[3]	19	0.9	4.2	14%	271.8	2.	$17,483	$71
0.54 / 0.90	High profile[3]	19	0.05	4.2	14%	228.3	2.7	$14,804	$60
0.54 / 0.90	High profile[3]	38	0.05	4.2	14%	219.0	1.9	$13,909	$56
0.54 / 0.90	High profile[3]	38	0.05	8	4%	107.0	4.8	$7741	$31

SR = solar reflectance, TE = thermal emittance, RB = radiant barrier, NPV = net present value over 30-year forecast, PV = present value.
[1] Air space fitted with one low-e surface.
[2] Annual loads based on attic footprint of 1261 ft^2 (117.2 m^2).
[3] High-profile clay tile spray-adhered to 1.25 in. (0.32 m) EPS foam; spray foam adhered EPS to roof deck.
[4] TDV source energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.244/$kBtu_{NG}$. Annual cost is computed using a 3% discount rate over 30 years.

Table 3. Annual Ceiling and Air-Conditioning Duct Heat Transfer and TDV Energy Costs for Pre-1980 Attic Construction Simulated for Sacramento, CA (CA Climate Zone 12)

Roof SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2]		Duct System		Load Due to Roof and Attic		TDV Source Energy[4] Costs	
		R-Value	RB (TE)	R-Value	Air Leakage	Cooling, kWh/sq	Heat, Therms/sq	$NPV over 30 yrs	PV$ per yr per sq
0.05 / 0.90	NA	19	0.90	4.2	14%	109.8	6.8	$9195	$37
0.25 / 0.90	NA	19	0.90	4.2	14%	103.0	7.1	$8844	$36
0.28 / 0.81	1 in. air space	19	0.90	4.2	14%	90.8	6.6	$7915	$32
0.54 / 0.90	High profile[3]	19	0.90	4.2	14%	85.9	6.9	$7689	$31
0.54 / 0.90	High profile[3]	19	0.05	4.2	14%	65.2	7.6	$6639	$27
0.54 / 0.90	High profile[3]	38	0.05	4.2	14%	63.6	5.2	$5748	$23
0.54 / 0.90	High profile[3]	38	0.05	6	4%	28.7	6.0	$3745	$15

SR = solar reflectance, TE = thermal emittance, RB = radiant barrier, NPV = net present value over 30-year forecast, PV = present value.
[1] Air space fitted with one low-e surface.
[2] Annual loads based on attic footprint of 1261 ft^2 (117.2 m^2).
[3] High-profile clay tile spray-adhered to 1.25 in. (0.32 m) EPS foam; spray foam adhered EPS to roof deck.
[4] TDV source energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.244/kBtu$_{NG}$. Annual cost is computed using a 3% discount rate over 30 years.

done within the attic for installing radiant barriers and fixing leaky ducts. Homeowners are probably more willing to make cool-colored roofs, ASV, low-e surfaces, and insulations placed above the roof deck critical components of a proactive roof maintenance program; most would prefer to contract a crew to work on the roof rather than have workers enter the dwelling and work in an attic.

Retrofitting a roof with cool-colored shingles (SR25E75) drops roof and attic cooling energy by 4.5% of that used by the base roof (SR05E75); savings for the cool-colored shingles are about $4/year per square[3] ($43/year per 100 m^2). The cost premium (Mullenax 2010) for cool-colored shingles is projected at about $50/sq ($535/100 m^2). Therefore, the roof with new cool-colored shingles can pay for itself in roughly 6 to 12 years. If a newly installed roof has a 1 in. (0.0254 m) air space and a solar reflectance similar to that of the cool-colored shingle, then the consumed cooling energy drops by 11.6% of the base. Selecting a cool-colored clay tile roof (SR54E90) with 1.25 in. (0.032 m) of EPS foam placed under the clay tile results in a 15.3% drop in consumed roof and attic energy. Therefore, conducting work on the roof (without encroaching on the home) yields savings of about $13/year per square ($140/year per 100 m^2). Further improvements require working within the attic (rows below the thin line in Table 2).

Adding a radiant barrier[4] yields a 28.2% drop in energy consumed when combined with a clay tile roof that has 1.25 in. (0.032 m) of EPS foam above the deck. If the R-value of ceiling insulation is increased from R_{US}-19 to R_{US}-38 (R_{SI}-3.3 to R_{SI}-6.7) instead of installing the radiant barrier, then the cooling energy drops by 21% of that used by the control roof and attic assembly. Therefore, installing a radiant barrier has about the same effect as doubling the ceiling insulation from R_{US}-19 to R_{US}-38 (R_{SI}-3.3 to R_{SI}-6.7). If the homeowner elects to revamp the attic by installing a radiant barrier, repairing leaky ductwork, and adding more ceiling insulation, then a 67% drop in consumed energy can be realized, yielding an estimated savings of $53/year per square for the hot climate of El Centro (see bottom in Table 2). Clearly, the ductwork in the attic is a major contributor to the energy losses in a building envelope.

Moderate Climate—Pre-1980 Construction. Sacramento has a moderate climate with about 30% of its cooling load attributable to comfort conditioning as estimated by its 1202 CDD_{65} and 2697 HDD_{65}. Replacing a 0.05 solar reflective roof in Sacramento with a cool-colored shingle (0.25 solar reflective) results in a 6.2% drop in demand for cooling energy. However, the more reflective roof incurs a 3% increase in heating energy consumed (Table 3). A new metal roof, which has reflectance and emittance similar to those of a cool-colored shingle roof but includes a 1 in. (0.0254 m) ventilated air space above the deck, demonstrated a 18% drop in cooling energy as compared to the base SR05E75 roof. Heat losses drop, resulting in a 3.2% reduction in heating energy.

The air space serves as an insulating layer in the winter and retards heat losses because it has an effective insulating value of R_{US}-1.0 (R_{SI}-0.17). The cool-colored clay tile roof (SR54E90) with 1.25 in. (0.032 m) of EPS foam placed above the roof deck also performs well in Sacramento. Summer cooling energy drops by 22% of the base energy consumption of the SR05E75 roof and attic, and the 1.25 in. (0.032 m) of EPS foam (R_{US}-4.8 [R_{SI}-0.85]) helps eliminate any heating

3. *Square* (sq) represents 100 ft^2 (9.29 m^2).

4. Simulation assumed the radiant barrier was attached to the underside of the roof rafters and to the gable ends of the attic. Modeling did not account for any natural convention between the radiant barrier and the underside of the roof deck.

penalty from the very reflective cool-colored tile roof. The incremental savings for the more reflective roof, ASV, and added insulation above the deck is about $6 per year per square of the attic footprint (PV$ of $37 for the control versus $31 for the prototype roof assembly; see Table 3). Therefore, a deeper retrofit approach is needed that requires renovations within the attic as well as the roof.

The addition of a radiant barrier on the underside of the roof rafters and also the gable ends of the attic (Title 24 prescribes a radiant barrier in several California climates, including zone 12) further improves performance of the roof and attic assembly (CEC 2005). Cooling energy consumption drops from 85.9 to 65.2 kWh/sq (925 to 702 kWh/100 m^2), resulting in a 40% reduction as compared with energy use of the base SR05E75 roof assembly (Table 3). The addition of the radiant barrier causes the heat load to slightly increase by about 10% of the base case (Table 3).

A building owner might ask whether it would be more economical to retrofit the attic with a radiant barrier or to add more insulation to the attic floor already covered with R_{US}-19 (R_{SI}-3.3) levels of insulation. Although not shown in Table 3, if the building owner opted to not put in a radiant barrier but instead added R_{US}-19 (R_{SI}-3.3) to the existing level of insulation, the cooling energy increases from 65.2 kWh per square to 79.3 kWh per square, which is about a 12% increase of the energy used by the control roof and attic. In comparison, a 41% reduction of the control energy consumption occurs if the radiant barrier is installed rather than the added insulation. BNI (2008) cost data estimate that adding R_{US}-19 (R_{SI}-3.3) of blown fiber insulation would cost about $104/sq ($1,120/100 m^2) of attic footprint. The radiant barrier foil costs about $15 per square of material, and the labor to attach the foil directly to the underside of roof rafters is estimated at $25/sq ($269/100 m^2) of coverage. Therefore, retrofitting the attic with a radiant barrier would cost about $40/sq ($430/100 m^2) of attic footprint as compared to $104/sq ($1120/100 m^2) for the additional R_{US}-19 (R_{SI}-3.3) of blown fiber insulation.

Incorporating both a radiant barrier and additional attic floor insulation to bring the ceiling insulation in compliance with Title 24 (R_{US}-38 [R_{SI}-6.7]) decreases the demand for cooling energy by 42% and for heating energy by 24% of the base case roof for the very reflective clay tile roof assembly (see the next to last row in Table 3). Finally, if the owner opts to also correct duct leakage and increase duct insulation to comply with the Title 24 code, then the use of cooling energy drops by 74% and of heating energy drops by 12% of the control levels.

Cold Climate—Pre-1980 Construction. The cold climate of Chicago in winter has 6139 HDD_{65} but also a considerable cooling load in summer estimated at 2895 CDD_{65}. The situation in Chicago is reviewed to observe benefits of cool-colored roofing in cold-climate application when adapted by other roof and attic strategies. Once again, the replacement of a 0.05 solar reflective roof in Chicago with a 0.25 solar reflective roof results in a 5.7% drop in cooling energy use and a 2% increase in heating energy use (Table 4). If an offset mounted roof of similar solar reflectance and thermal emittance as the cool-colored roof were installed (1 in. [0.0254 m] air space above the deck), then estimates show cooling savings increase to 16% of the base SR05E75 roof energy requirements while heat losses are the same as the control.

Table 4. Annual Ceiling and Air-Conditioning Duct Heat Transfer and Energy Costs for Pre-1980 Attic Construction Simulated for Chicago, IL

Roof SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2]		Duct System		Load Due to Roof and Attic		TDV Source Energy[4] Costs	
		R-Value	RB (TE)	R-Value	Air Leakage	Cooling, kWh/sq	Heat, Therms/sq	$NPV over 30 yrs	PV$ per yr per sq
0.05 / 0.90	NA	19	0.90	4.2	14%	47.6	17.0	$683	$35
0.25 / 0.90	NA	19	0.90	4.2	14%	44.9	17.3	$685	$35
0.28 / 0.81	1 in. air space	19	0.90	4.2	14%	40.1	17.0	$660	$34
0.54 / 0.90	High profile[3]	19	0.90	4.2	14%	38.1	17.3	$661	$34
0.54 / 0.90	High profile[3]	19	0.05	4.2	14%	29.0	18.5	$669	$34
0.54 / 0.90	High profile[3]	38	0.05	4.2	14%	28.6	13.8	$521	$27
0.54 / 0.90	High profile[3]	38	0.05	8	4%	18.1	11.6	$417	$21

SR = solar reflectance, TE = thermal emittance, RB = radiant barrier, NPV = net present value over 30-year forecast, PV = present value.
[1] Air space fitted with one low-e surface.
[2] Annual loads based on attic footprint of 1261 ft^2 (117.2 m^2).
[3] High-profile clay tile spray-adhered to 1.25 in. (0.32 m) EPS foam; spray foam adhered EPS to roof deck.
[4] TDV source energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.244/kBtu$_{NG}$. Annual cost is computed using a 3% discount rate over 30 years.

Table 5. Annual Ceiling and Air-Conditioning Duct Heat Transfer and TDV Energy Costs for New Roof and Attics Simulated for El Centro, CA (CA Climate Zone 15)

Roof SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2]		Duct System		Load Due to Roof and Attic		TDV Source Energy[5] Costs	
		R-Value	RB (TE)	R-Value	Air Leakage	Cooling, kWh/sq	Heat, Therms/sq	$NPV over 30 yrs	PV$ per yr per sq
0.10 / 0.90	NA	38	0.90	8	4%	150.4	5.1	$10,545	$43
0.10 / 0.90	NA	38	0.05	8	4%	130.7	5.0	$9330	$38
0.25 / 0.90	NA	38	0.05	8	4%	125.3	5.1	$9008	$36
0.28 / 0.81	1 in. airspace	38	0.05	8	4%	114.2	4.7	$8159	$33
0.54 / 0.90	High profile[3]	38	0.05	8	4%	107.0	4.8	$7751	$31
0.54 / 0.90	High profile[3]	38	0.05	NA	NA	10.4	0.7	$788	$3
0.54 / 0.90	High profile[3,4]	38	0.05	NA	NA	10.7	0.7	$813	$3

SR = solar reflectance, TE = thermal emittance, RB = radiant barrier, NPV = net present value over 30-year forecast, PV = present value.
[1] Air space fitted with one low-e surface.
[2] Annual loads based on attic footprint of 1261 ft^2 (117.2 m^2).
[3] High-profile clay tile spray-adhered to 1.25 in. (0.32 m) EPS foam; spray foam adhered EPS to roof deck.
[4] Attic sealed with dynamic ventilation occurring only from 3:00 to 5:00 p.m. during hours of peak irradiation.
[5] TDV source energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.244/kBtu $_{NG}$. Annual cost is computed using a 3% discount rate over 30 years.

As stated previously, the air space serves as an insulating layer in the winter and retards heat losses because it has an effective R_{US}-1.0 (R_{SI}-0.17). The cool-colored clay tile roof (SR54E90) with 1.25 in. (0.032 m) of EPS foam placed above the roof deck performs well in Chicago. Summer cooling energy drops by 20% of the base SR05E75 roof, and the 1.25 in. (0.032 m) of EPS foam (R_{US}-4.8 [R_{SI}-0.85]) causes heating losses resulting from the 0.54 solar reflective tile to increase only 2% of the control roof (SR05E75). In other words, the penalty associated with a coolcolored roof is almost eliminated in this predominantly heating climate. However, the incremental savings for the more reflective roof, ASV, and added insulation above the deck is only $1 per year per square of attic footprint (PV$ of $35 for the control vs. $34 for the prototype roof assembly, as shown in Table 4). Therefore, a cost-effective cold-climate house design will require renovations within the attic as well as on the roof.

When compared with the SR05E75 control assembly, a radiant barrier installed inside the attic yields a 39% drop in cooling energy but a 9% increase in heating energy use when combined with the clay tile roof with 1.25 in. (0.032 m) of EPS foam above the deck. Again, if the R-value of ceiling insulation is increased from R_{US}-19 to R_{US}-38 (R_{SI}-3.3 to R_{SI}-6.7) but no radiant barrier is installed, then the cooling energy drops by 25% and the heating energy drops by 25% of the energy used in the control roof and attic assembly. In the winter adding R_{US}-19 (R_{SI}-3.3) more insulation to the ceiling is superior to installing a radiant barrier to the attic. The combination of radiant barrier and R_{US}-38 (R_{SI}-6.7) insulation causes the computed heating energy to drop by 40% of that used by the control assembly; the incremental savings are about $8/yr per square ($86/100 m^2). The costs are $35/yr per square for the base vs $27/yr per square for the addition of both the radiant barrier and of more R_{US}-19 (R_{SI}-3.3) insulation. Electing to revamp the attic by installing a radiant barrier, repairing leaky ductwork, and adding more ceiling insulation results in a 73% drop in cooling energy and a 31% drop in heating energy, yielding a computed $14/yr per square ($150/100 m^2) savings over the control roof and attic assembly (see the shaded row versus the last row in Table 4).

Hot Climate—New Construction. For new construction the control assembly is a direct nailed asphalt shingle roof having solar reflectance of 0.10 and thermal emittance of 0.90 (SR10E90). The attic plenum was simulated with R_{US}-38 (R_{SI}-6.7) code-compliant levels of insulation on the attic floor and R_{US}-8 (R_{SI}-1.4)[5] around cylindrical metal ducts (CEC 2005). Air leakage was set at 4% of supply airflow for the six branches of the air-conditioning ducts (Table 5).

Using a radiant barrier on all interior surfaces of the attic plenum (except the attic floor) caused the annual cooling energy attributable to the roof and attic to drop about 13% of that computed for the control shingle roof (Table 5). Applying a foil directly to the underside of roof rafters or draping it over the roof rafters incurs labor charges estimated at $25/sq ($269/100 m^2) of coverage, and the foil costs about $15/sq ($162.4/100 m^2) of material. Therefore, a draped foil or foil applied to the underside of the rafters feasibly pays for itself in about five to eight years (view energy costs of $43 versus $38 per year per square (Table 5).[6] Increasing the solar reflectance of the shingle from 0.10 to 0.25 with inclusion of the radiant barrier resulted in an additional 3.5% drop in cooling

5. Duct R-value is based on the outside diameter of the insulation, not the duct diameter.

energy, or a total of 16.7% drop as compared to the control. Hence, inclusion of the radiant barrier and cool shingle roof can pay for itself in 8 to 11 years. Next, a painted metal roof (SR28E81) with cool-colored pigments was simulated for steep-slope roofs fitted with a 1 in. (0.0254 m) air space above the sheathing (Table 5). A low-e surface was assumed in the air space and a radiant barrier was assumed on the underside of the roof deck. Energy attributable to the roof and attic drops an additional 6% due primarily to ASV; total cooling energy drop is 24% of the base roof and attic assembly.

The best-performing tile, a clay tile roof (SR54E90), was simulated with the tile spray-adhered to 1.25 in. (0.032 m) of EPS foam and the foam spray-adhered to the roof deck. A low-e surface was not assumed above the sheathing; however, an attic radiant barrier was assumed as required by code (CEC 2005). The clay tile's solar reflectance of 0.54 is near the highest reflectance achievable for a nonwhite appearance. Levinson et al. (2007) indicated that coated steel and glazed clay tile products painted with cool pigments can achieve near-infrared solar reflectance up to 0.50 and 0.75, respectively, resulting in a solar reflectance limit of about 0.50. The infrared reflective high-profile tile with EPS foam board (R_{US}-4.8 [R_{SI}-0.85]) placed above the deck dropped roof and attic cooling energy 29% of the control shingle assembly. Estimates put the cost of energy savings at about \$12/yr per square[7] (\$129/100 m^2) (Table 5). It is expected that the prototype roof with PCM and air space above the deck would have similar performance as computed for the clay tile roof (see Figure 2 from Miller and Kosny [2008] showing identical trends for the two prototypes).

The computed ceiling and duct loads for the above discussed cases (Table 5) indicated that the annual duct loads are at least double the ceiling load. The losses from the ductwork predominate. Placing ductwork in an attic simplifies construction but exacerbates building energy use. Thus, for new construction, Title 24 encourages ductwork be placed in the conditioned space (CEC 2005). If the ducts must be in the attic, then at least eliminate duct leakage using mastic, which effectively seals metal, flexible, and fibrous ductwork. However, placing the ductwork in the conditioned space yields significantly higher energy savings. Removing ductwork from the attic helps drop the roof and attic annual load for the clay tile with 1.25 in. (0.032 m) of EPS foam by 93% of the annual load for the SR10E75 base assembly! The annual energy savings are about \$40/yr per square (\$430/100 m^2) for this cool-colored tile roof with 1.25 in. (0.032 m) of EPS foam placed on the deck and with the ducts in the conditioned space. This would yield estimated heating and cooling savings of about \$600/yr for an attic of 1500 ft^2 (140 m^2) footprint exposed in the hot climate of El Centro. An additional simulation was made assuming a dynamically ventilated attic plenum. The attic was power venting simulated only from 3:00 to 5:00 p.m., during periods of peak attic air temperature. Results showed marginal improvements in the performance of the attic (see last row in Table 5), which is consistent with the study conducted by Rudd et al. (1996).

Cold Climate—New Construction. The annual load attributed to the roof and attic for the SR10E75 control was 23.2 kWh/sq (250 kWh/100 m^2) cooling energy and 22.8 Therms/sq (1.136E06 kJ/100 m^2) heating energy (Table 6). Installing a radiant barrier[8] in the attic of the SR10E75 shingle roof resulted in a 22% drop in cooling energy use and a 2% increase in heating energy use attributed to the roof and attic with inspected ductwork. The addition of a cool-colored shingle reduced cooling energy demand but resulted in a slight increase in demand for heating energy, as did the radiant barrier. However, the results imply that the combination of a cool-colored shingle roof with a radiant barrier in this cold climate drops the annual attic load; cool roof shingles and the radiant barrier were not counterproductive (Table 6). The same was also true for installing a cool roof with a radiant barrier and creating an inclined air space above the sheathing. Cooling energy use is reduced by 39% and the heating penalty is 1% of the direct-to-deck control having solar reflectance of 0.10.

Installing the clay tile roof (SR54E90) with spray-adhered 1.25 in. (0.032 m) of EPS foam further dropped cooling energy by 45% of the SR10E75 base energy levels; however, the added EPS insulation had only a slight effect on the heating load, which is actually quite good because the highly solar reflective roof would cause a heating penalty without the EPS foam. In Chicago, placing the ductwork in the conditioned space with the clay tile roof and EPS insulation on the deck almost eliminated the cooling load; it computed at only 0.5 kWh/yr per square, a 97% drop from the base case. Heating energy consumption dropped by 80% of the base. Applying a dynamic ventilation scheme had some effect on the cooling load but had little effect on the heating. Hence, the combination of schemes, which includes placing the ductwork in the conditioned space, dropped cooling energy about 98% and heating energy by 78% of the base case and yields a \$32 premium per year per square (\$344/100 m^2) for the cold climate of Chicago, IL.

CONCLUSIONS

Field results demonstrated that a combination of strategies including cool-colored roofs, above-sheathing ventilation, conventional insulation, and thermal mass all helped reduce the heat transfer crossing the roof deck; however, the

6. An original equipment manufacturer charges about \$5/sq (\$53.8/100 m^2) more for a foil-faced OSB as compared to the conventional OSB. The foil-faced OSB is an excellent choice for a radiant barrier because there are no incremental labor charges. However, the foil-faced OSB case was not modeled in this report.

7. In Table 5, compare base at \$32 to energy cost of high-profile tile at \$18/yr per square.

8. Radiant barrier simulated is a draped foil or a foil attached to the underside of the rafters. The foil is also assumed on the gable ends of the attic.

Table 6. Annual Ceiling and Air-Conditioning Duct Heat Transfer and Non-TDV Energy Costs for New Roof and Attic Construction Simulated for Chicago, IL

Roof SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2]		Duct System		Load Due to Roof and Attic		TDV Source Energy[5] Costs	
		R-Value	RB (TE)	R-Value	Air Leakage	Cooling, kWh/sq	Heat, Therms/sq	$NPV over 30 yrs	PV$ per yr per sq
0.10 / 0.75	NA	38	0.90	8	4%	23.2	22.8	$782	$40
0.10 / 0.75	NA	38	0.05	8	4%	17.9	23.3	$779	$40
0.25 / 0.75	NA	38	0.05	8	4%	16.8	23.4	$779	$40
0.28 / 0.81	1-in airspace	38	0.05	8	4%	14.2	23.0	$759	$39
0.54 / 0.90	High profile[3]	38	0.05	8	4%	12.8	23.2	$759	$39
0.54 / 0.90	High profile[3]	38	0.05	NA	NA	0.5	4.8	$149	$8
0.54 / 0.90	High profile[3,4]	38	0.05	NA	NA	0.4	4.8	$150	$8

SR = solar reflectance, TE = thermal emittance, RB = radiant barrier, NPV = net present value over 30-year forecast, PV = present value.
[1] Air space fitted with one low-e surface.
[2] Annual loads based on attic footprint of 1261 ft^2 (117.2 m^2).
[3] High-profile clay tile spray-adhered to 1.25 in. (0.32 m) EPS foam; spray foam adhered EPS to roof deck.
[4] Attic sealed with dynamic ventilation occurring only from 3:00 to 5:00 p.m. during hours of peak irradiation.
[5] TDV source energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.244/kBtu $_{NG}$. Annual cost is computed using a 3% discount rate over 30 years.

combination of strategies are not necessarily additive, nor are the strategies synergistic. Cool-colored roofs are a first line of defense against heat transfer penetrating the conditioned space and show positive benefits even with R_{US}-4.8 (R_{SI}-0.85) of EPS foam board placed above the deck. The clay tile roof placed on 1.25 in. (0.032 m) of EPS foam or a painted metal roof offset from the roof deck 4 in. (0.102 m) and fitted with phase-change material dropped the peak-day heat transfer by 90% of that measured for the control shingle roof having 0.093 solar reflectance and 0.89 thermal emittance.

Simulation results clearly show that placement of ductwork in the conditioned space is crucial for best performance of the building envelope. Improvements to ductwork should be a priority in any retrofit program. Radiant barriers showed excellent performance in hot climates. The strategy resulted in the greatest drops in roof and attic energy consumption. Energy use for cooling was reduced by 20% to 30% of that consumed by a conventional roof and attic in a hot climate and showed marginal gains in heating-predominant climates. The combination of cool-colored roofs and a radiant barrier and/or above-sheathing ventilation reduced the heating penalty associated with the cool-colored roof.

Therefore, the marketing of cool-colored roof materials can penetrate into predominantly heating load climates provided that the cool-colored roof is made part of a proactive roof and attic design that includes such strategies as above-sheathing ventilation with a low-emittance surface in the air space, above-deck insulation, radiant barriers, and/or added ceiling insulation.

ACKNOWLEDGMENTS

Funding for this project was provided by the Department of Energy Building Technology program and by the California Energy Commission's Public Interest Energy Research program through the U.S. Department of Energy under contract DE-AC03-76SF00098. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

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APPENDIX—
CLAY AND CONCRETE TILE SALIENT FEATURES

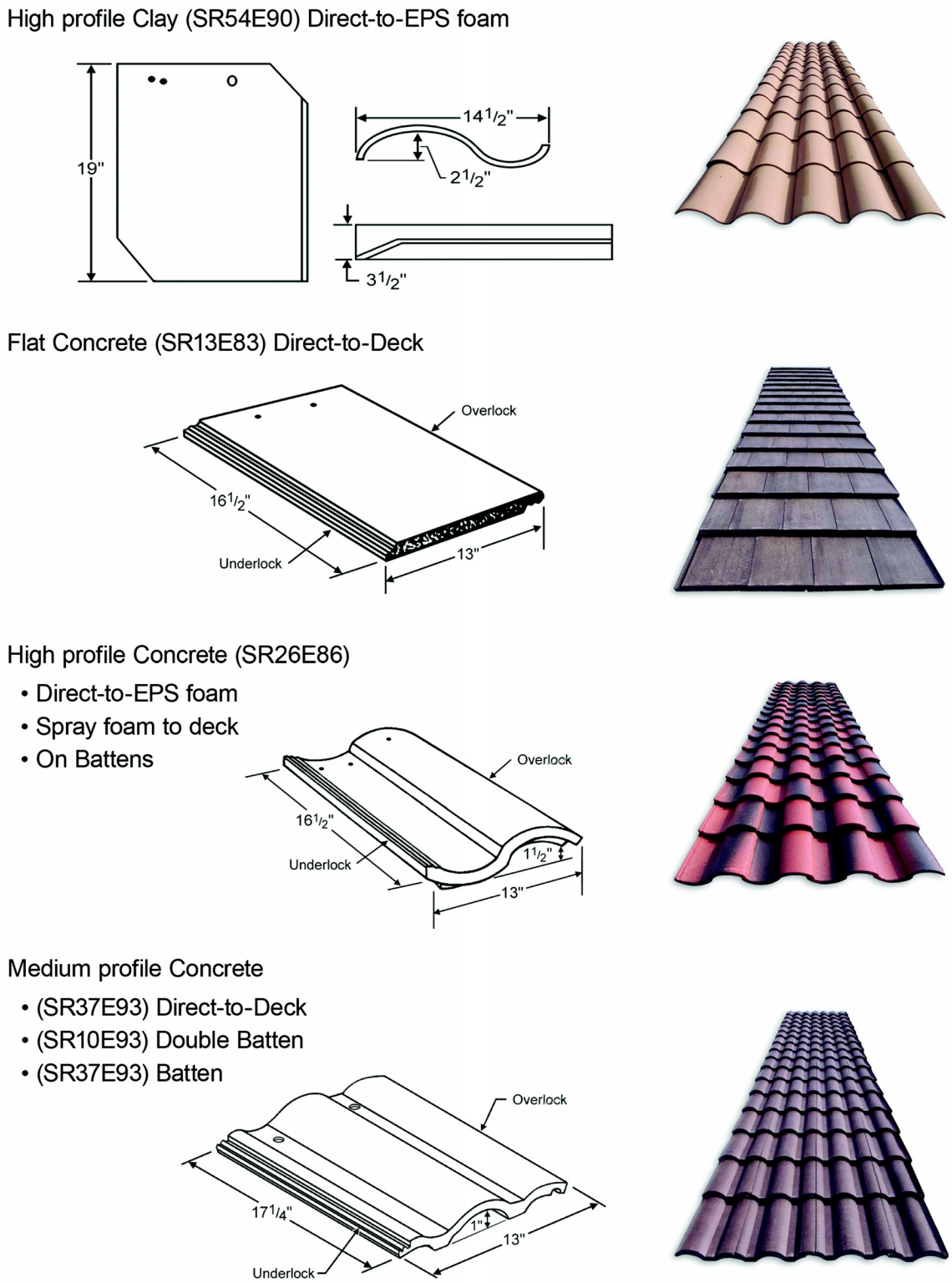

Figure A1 *Clay and concrete tile features and dimensional specifications.*