Next-Generation Roofs and Attics for Homes

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ABSTRACT

Prototype residential roof and attic assemblies were constructed and field tested in a mixed-humid U.S. climate. Summer field data showed that at peak day irradiance the heat transfer penetrating the roof deck dropped almost 90% compared with heat transfer for a conventional roof and attic assembly. The prototype assemblies exhibited attic air temperatures that did not exceed the peak day outdoor air temperature. The assemblies use a combination of strategies: infrared reflective cool roofs, radiant barriers, above-sheathing ventilation, low-emittance surfaces, insulation, and thermal mass to reduce the attic air temperature and thus the heat transfer into the home. Field results were benchmarked against an attic computer tool and simulations indicated that retrofitting pre-1980 construction with prototype roof systems and improving ductwork by reducing air leakage and heat transfer to existing ducts in attics could yield annual savings of about $200. In the hot, dry southeastern region of California, the combined ceiling and duct annual load drops by 23% of that computed for a code-compliant roof and attic assembly.

Introduction

In moderate and hot climates, a roof surface with high solar reflectance and high thermal emittance was shown by Akbari et al. (2004) and by Parker and Sherwin (1998) to reduce the exterior temperature and produce savings in comfort cooling. The intent herein is to further develop the next generation of roofs and attics, which may include strategies of radiant barriers, above-sheathing ventilation[1], low-emittance (low-e) surfaces in the air space, insulation, and conventional and advanced thermal mass (i.e., phase change materials [PCMs]) that complement the thermal performance of cool roofs. Experience gleaned in testing different PCMs by Kośny et al. (2007a) helped determine the amount and placement of PCMs tested in the prototype roof and attic assemblies. In parallel, the attic design tool ASTM C 1340 (2004) was reformulated for above-sheathing ventilation and validated against the field data (Miller et al. 2007). The code, dubbed AtticSim II, predicts the heat transfer crossing the air space and is usable for judging the effectiveness of several design strategies in various climates, as well as the effects of the strategies on duct losses. Typical construction places ductwork within the attic, which can literally triple the loads for the attic assembly for moderately leaky ducts (Petrie et al. [2004] and Parker, Fairey, and Gu [1993]). Petrie et al. (1998) validated the duct algorithm in ASTM C 1340 against experimental data for an attic assembly tested first without and then with a radiant barrier attached to the underside of the roof deck. Validations showed the duct algorithm predicted the duct air change (inlet-to-outlet of the supply duct) within ±0.3°F (±0.2°C) over all tests housing an insulated duct system.

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[1] Air space above the sheathing in which buoyancy-induced airflow occurs from the eave to the roof ridge.

Whole-building energy simulations using Energy Plus are also discussed to demonstrate the potential energy savings in homes equipped with PCM-enhanced attic insulation. A one-story house was simulated for the climate of Bakersfield, California, to assess adding PCM-enhanced blown cellulose to the attic floor. ASTM C518 tests demonstrated that adding 30% paraffinic hydrocarbon PCM to cellulose fibers had no negative impact on the R-value of the insulation. The 30% paraffinic hydrocarbon PCM also passed the ASTM C1149 smoldering combustion test; it did not compromise the fire resistance of cellulose-PCM blend insulation (Kośny et al. 2007b).

Field Study

A steep-slope roof and attic test stand, the Envelope Systems Research Apparatus (ESRA), was used for field testing and documenting the heat transfer crossing the roof decks of cool color roofs separately or in combination with other energy saving strategies. 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 solar reflectance of 0.093 and thermal emittance of 0.89 (SR093E89)[2] was the control for comparing the thermal performance of the prototype roof systems.

All 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 as used in construction to correct for shunting effects (i.e., distortion due to three-dimensional heat flow). The HFT for measuring ceiling heat flow is embedded between the two pieces of wood fiberboard. The ceiling insulation was set low at R_{US}-5.1 h·ft^2·°F/Btu [R_{SI}-0.9 m^2·K/W] to minimize the experimental uncertainty of the measured heat flow crossing the attic floor. The field data were then used to validate the attic simulation model. Therefore, the discussions of field data will focus on heat crossing the roof deck of the attic, and simulations will provide results for energy consumption of attics with code-compliant levels of insulation.

Clay and Concrete Tile Field Data

Miller et al. (2005a) observed that tiles with high profiles allowed the least amount of heat to penetrate into their roof decks. Venting occurred along the underside of the barrel of the tiles from soffit to ridge. Miller et al. (2005b) designed a procedure using tracer gas techniques outlined in ASTM E 741 (ASTM 2000) and measured at solar noon buoyancy-induced airflows ranging from about 12 to 40 ft^3/min (0.0056 to 0.0188 m^3/s). The high- profile tile had the highest measured airflow.

Of the high-profile roof tiles, the clay tile (SR54E90) had the lowest heat flux crossing the deck; subsequently, the heat penetrating the deck around solar noon was 70% less than that entering through the deck of the attic assembly with asphalt shingles (Miller et al. 2005a). The solar reflectance and thermal emittance of a flat concrete tile (SR13E83) and a medium-profile concrete tile (SR10E93) are very similar to that of the control shingle (SR093E89); but the heat transfer through the roof of the attic assemblies for the flat-tile and the medium-profile tile roofs was half that for the asphalt shingle roof. The flat tile was installed on double battens; the

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[2] SRxx is the solar reflectance; "Eyy" is the thermal emittance. Thus, labeling a roof as SR093E89 indicates that it has a solar reflectance of 0.093 and a thermal emittance of 0.89.

medium-profile tile was attached directly to the deck. The reduction in heat transfer is due in part to the thermal mass of the tile and in part to the thermal resistance across the air space and to the thermally induced convection.

Effect of cool colors, thermal mass and batten arrangement. The Tile Roofing Institute (TRI) and its affiliates reconfigured the tile roof and attic assemblies on the ESRA to further assess the effects of cool color roofs, thermal mass, and placement of batten and double-batten systems under the tile. The double batten arrangement used for the flat tile (SR13E83) was removed and the tile[3] attached directly to the deck to judge the effect of the tile's thermal mass. Data for a hot August week (Fig. 1) show that the heat transfer for conventionally pigmented flat tile laid directly on the deck was only about 45% that measured for the control shingle. Previous tests of the same tile placed on double battens (offset 1.5 in [0.038 m]) showed similar rankings among the various tile roofs (Miller et al. 2005a). A recent field study by Wilcox (2007) elevated similar flat concrete tiles already on 1 by 2-in. battens an additional ⅜ in (0.0093 m) above the roof deck based on recommendations from TRI (2002, 6, 20). Wilcox's results with the additional ⅜-in (0.0093-m) air space showed no improvement over the original batten system. Results herein imply that the thermal mass of the flat-tile roof predominates, and the tile may need be elevated further than 1½ in (0.38 m) off the deck for convection to have more effect.

Three medium-profile concrete tile roofs were configured: (1) direct to the roof deck and tile painted with an infrared reflective cool color pigmented coating (SR37E93); (2) on battens (1 by 1-in. nominal lumber) with cool color pigments (SR37E93); and (3) on double battens (1 by 1-in. nominal lumber) with tile having conventional color pigments (SR10E93). The cool color medium-profile tile on battens showed slightly lower heat transfer across the deck. All three medium-profile tiles showed less heat transfer across the roof deck than with the flat tile (Fig. 1). Most important, though, is the observation that as the cool color tile is moved further away from the deck (i.e., lain directly on the deck compared with offset from deck using batten (0.75 in [0.019 m], the roof's thermal performance improves. 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 color 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 1½ 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 with the adjacent direct-nailed tile roof.

High-profile tile. A high-profile tile with conventional terra-cotta color pigments (SR34E83) was tested on battens (1 by 1-in. nominal lumber). The terra-cotta tile slightly out-performed all medium-profile tile configurations. Two 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 color pigments (SR54E90)—were each placed on 1¼ in. (0.032 m) of extruded polystyrene (EPS) insulation adhered to the deck using a spray polyurethane adhesive. The additional R_{US}-6.25 (R_{SI}-1.1) 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. Doubling the solar

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[3] The underside of the flat tile is hollow, and the placement of tile allows for a small but closed air space formed by overlapping tile.

reflectance from 0.26 to 0.54 further improved roof performance. 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 this hot day (Fig.1)!

Figure 1. Field Data of the Heat Flow Crossing the Roof Deck for Attic Assemblies Having Concrete and Clay Tile Roofs; Data Benchmarked against AtticSim II.
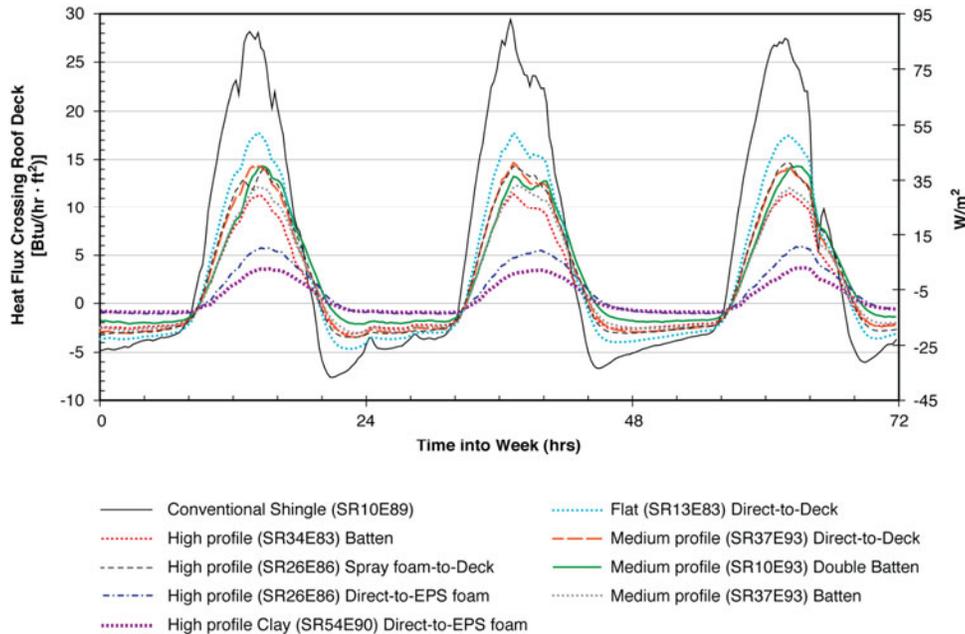
Stone-Coated Metal Roofs

Miller, Wilson, and Karagiozis (2006) field tested stone-coated metal roofs on adjacent attic test assemblies similar to the assemblies used for testing tile. A conventional dark-gray stone-coated metal shake (SR08E90) and a light-gray shake (SR26E90) were tested on identical double-batten constructions (air space of ¾-in. [0.019-m]). The dark-gray metal shake and the asphalt 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 the heat flow crossing the roof deck of the control shingle (Fig. 2). The 30% reduction in heat flow was caused by the thermal resistance of the air space, by convection occurring in the air space, and in part by the low-e (emittance) of the underside of the stone-coated roof shake. Thermal emittance was determined to be 0.35 for the bare metal underside of the shake roof.

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 (Fig. 2). Miller, Wilson, and Karagiozis (2006) also determined that the heat flow removed by above-sheathing ventilation of the hotter dark-gray shake is more than double that removed by the light-gray shake. The hotter dark-gray shake causes greater buoyancy-induced airflows; therefore, the ventilation scheme is somewhat self-regulating; it offsets the effect of the darker, less reflective color. The stone-coated metal does not have the mass of a concrete tile, which further suggests that above-sheathing ventilation and/or the effective thermal resistance of

the air space has significant effects on the amount of heat penetrating into the attic. ASHRAE (2005) provides empirical data for the effective thermal resistance of plane air spaces. A ¾-in. (0.0191-m) plane air space inclined at 45° with the horizontal has an R_{US}-0.85 (R_{SI}-0.15)[4].

Figure 2. 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 1½ by 1½-in. (0.038 by 0.038-m) Double-Battens. The Field Data are Benchmarked against AtticSim II.
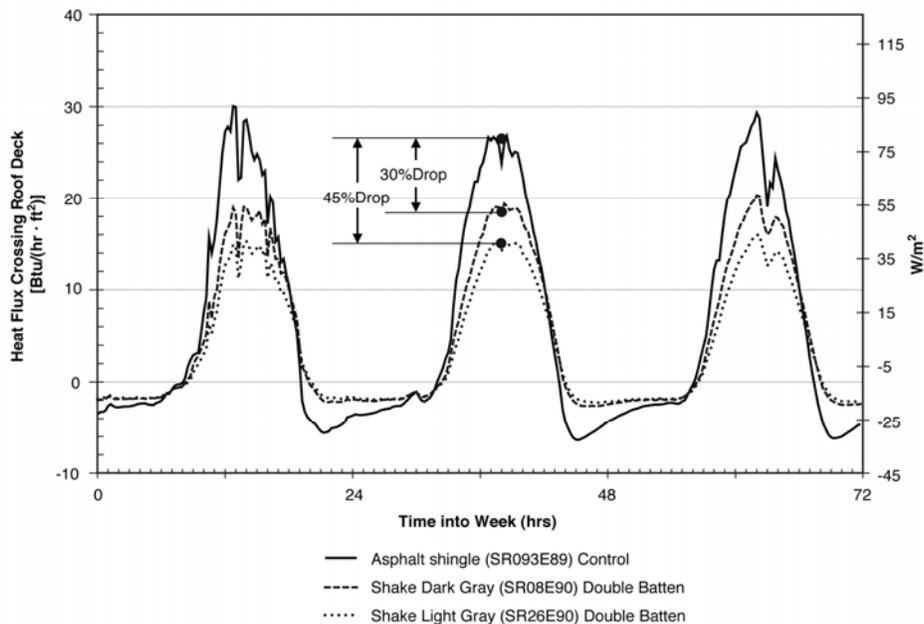
Comparing design strategies. The Metal Construction Association and its affiliates conducted additional field tests with standing-seam painted metal roofs. Asphalt shingle roofs with and without a radiant barrier, and the best-performing tile attached directly to the deck and to EPS foam, with the foam adhered to the deck, are also shown to illustrate the comparative performance of the different roof systems (Fig. 3).

A conventionally pigmented asphalt shingle (SR11E89) with an attic radiant barrier dropped the peak day heat transfer by 20% of that measured for the control shingle (SR093E89). The only difference between the two shingle roofs and their attic assemblies was the addition of a radiant barrier. It is of interest that the stone-coated metal roof (SR08E89) with ¾-in. air space (0.019 m) and a moderately low-e surface works about as well as the assembly with a radiant barrier (Fig. 3). The air space was therefore increased to 2 and 4 in. (0.051 and 0.102 m) and tested on standing-seam metal roofs painted with cool color pigments (SR28E81). A patented metal Z-batten (Cooper 2002) was used to offset mount the metal roofs from the roof decks. The air spaces of both assemblies were fitted with low-e surfaces. The 2-in. (0.051-m) air space had

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[4] An effective emittance of 0.82 was assumed with a mean temperature of 90°F (32.2°C) having a 10°F (5.6°C) temperature gradient for heat flows moving downward across the air space.

just one low-e surface facing up toward the metal pan, whereas the 4-in. (0.102-m) air space was fitted with two low-e surfaces attached along the solid boundaries of the air space.

Figure 3. Peak Day Heat Flux Crossing the Roof Deck of Asphalt Shingle, Stone-Coated Metal, and Next-Generation Roofs Field Tested on the ESRA.

Asphalt Shingle (SR093E89) Control
Asphalt Shingle (SR11E89) Radiant Barrier
Dark Gray Shake (SR08E90) Double Batten, Low-e
Panted Metal (SR28E81), 2-in Airspace, 1-Low-e
Clay High profile (SR54E90) Direct nailed
Painted Metal (SR28E81), 4-in Airspace, PCM, 2-Low-e
High profile Clay (SR54E90) Direct-to-EPS Foam
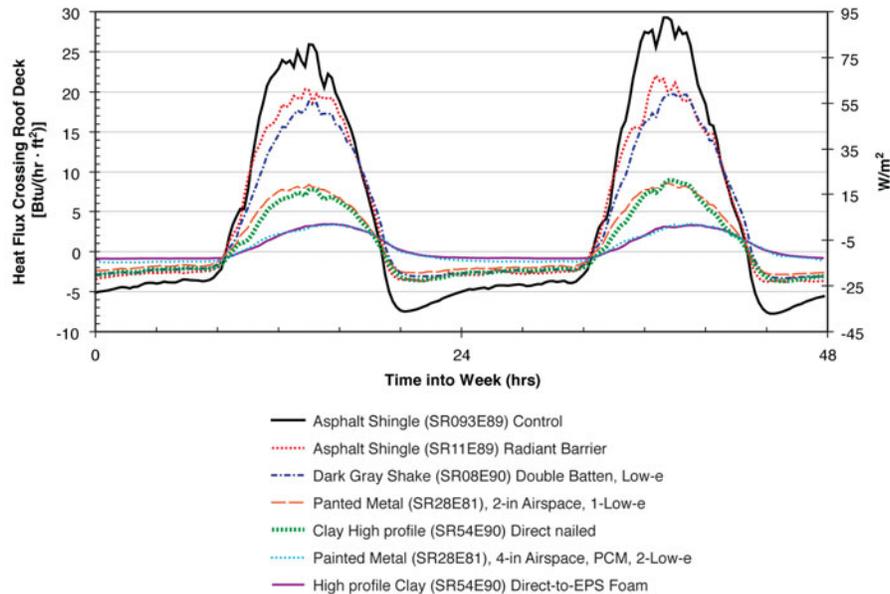
The cool color painted metal roof with 2-in. (0.051-m) air space showed a 70% drop in peak day heat transfer, very similar to the drop observed for the best-performing high-profile cool color clay tile roof (Fig. 3). The solar reflectance of the cool color painted metal is roughly half that of the cool color clay tile; therefore, the air space and low-e surface in the metal assembly must be compensating for the effect of the higher solar reflectance and higher thermal mass of the clay tile (Fig. 3).

The metal roof and attic assembly having a 4-in. (0.102-m) air space was also fitted with PCM. Two different fabrics, impregnated with 10 lb (4.5-kg) of PCMs, were placed on the sheathing and covered by one of the two low-e surfaces. The second low-e surface was draped over the metal Z-batten. One PCM melts between 78 and 82°F (25.6 and 27.8°C) and the other at about 90°F (32.2°C). The PCM with a lower phase-change temperature was placed nearest the deck. Results again show a continued drop in heat transfer crossing the roof deck. Increasing the air space from 2 to 4 in. (0.051 to 0.102 m) and adding PCM caused an additional 10% drop compared with the assembly with a 2-in. air space (Fig. 3). Overall, the peak day heat transfer was reduced by about 90% compared with that measured for the control shingle roof. Further, the performance of the cool color metal roof with a 4-in. (0.102-m) air space, low-e surfaces, and PCM is almost identical to that of the cool color clay tile (SR54E90) adhered to EPS foam board having R_{US}-6.25 (R_{SI}-1.1). The attic air temperature of these two roofs never exceeded the peak day outdoor air temperature! During the month of August, the control shingle assembly had attic air temperatures reaching as high as 120°F (48.9°C) when the outdoor air peaked at 96°F (35.6°C). Hence, the two prototype roof and attic assemblies with their lower peak day attic air

temperatures (93°F [33.9°C] versus 120°F [48.9°C] for the control assembly) have another advantage—less heat gain to the conditioned air in air-conditioning ducts installed in hot attics.

Winter Field Tests of the Prototype Roof and Attics

On a national basis, residential homes use more energy for heating than for cooling (EIA 1997). During winter nights, field data show that night sky temperatures were much lower than the surface temperatures of the test roofs, a situation that drives radiation heat loss to the sky. The surface temperatures of the control shingle and painted metal roof systems measured at night in January 2007 were about the same, and they dropped below the outdoor air temperature (Fig. 4). The sheathing temperature just below the control shingle roof was also observed to drop below that of the outdoor air. However, the painted metal roof assembly (1) was warmer than the control shingle; and (2) over the course of three consecutive winter nights, its temperature (top of roof deck forming the bottom surface of the air space) never fell below the outdoor air temperature (Fig. 4). Therefore, the metal roof and attic assembly incurs less heat loss because of the air space, the low-e surfaces, and the PCM that releases heat stored during the daytime.

Figure 4. Temperatures of the Roof Sheathing and the Underside of the Roof Cover for Three Consecutive Winter Days. Data for January 2007.
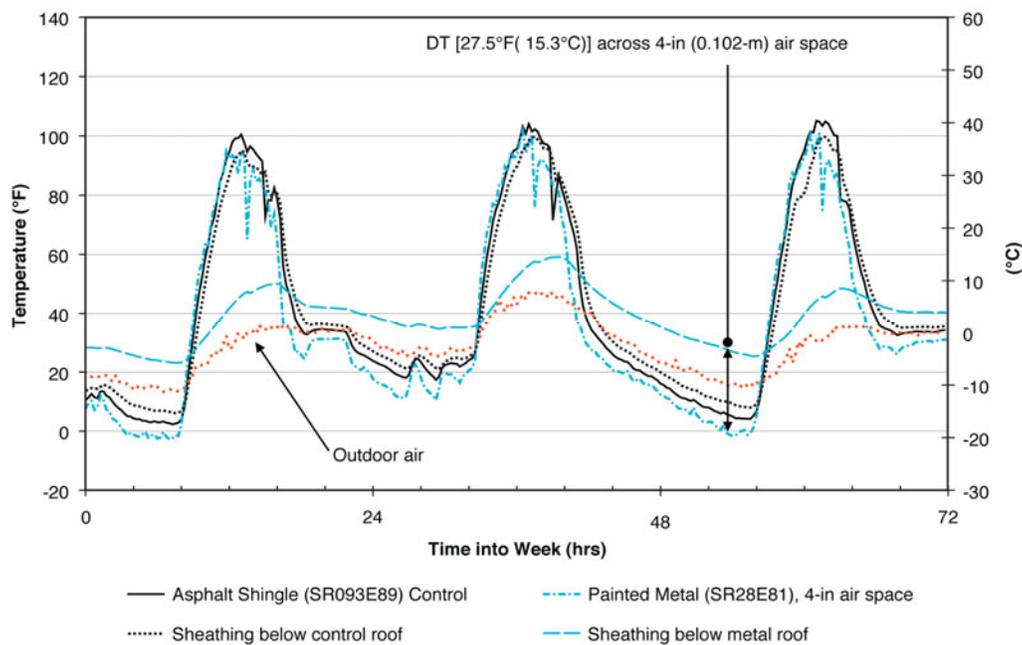
The measured heat flux crossing the roof decks during January 2007 shows that the asphalt shingle (SR093E89) gains the most heat during the day but loses the most heat at night (Fig. 5). At night, the painted metal roofs lose only about half as much heat as the shingle roof (SR093E89). Since this application has a 2-in. and 4-in. (0.051- and 0.102-m) air space, the effective R-value is about R_{US}-0.78 (R_{SI}-0.14). The metal roof with a 2-in. air space and one low-e surface shows slightly larger heat losses than the metal roof with a 4-in. (0.051-m) air space (Fig. 5).

Figure 5. Heat Flux Crossing the Roof Deck of the Direct-Nailed Asphalt Shingle Roof and the Cool Color Painted Metal Roof Offset 4 in. (0.102 m) from the Roof Deck; Field Data Benchmarked against AtticSim II
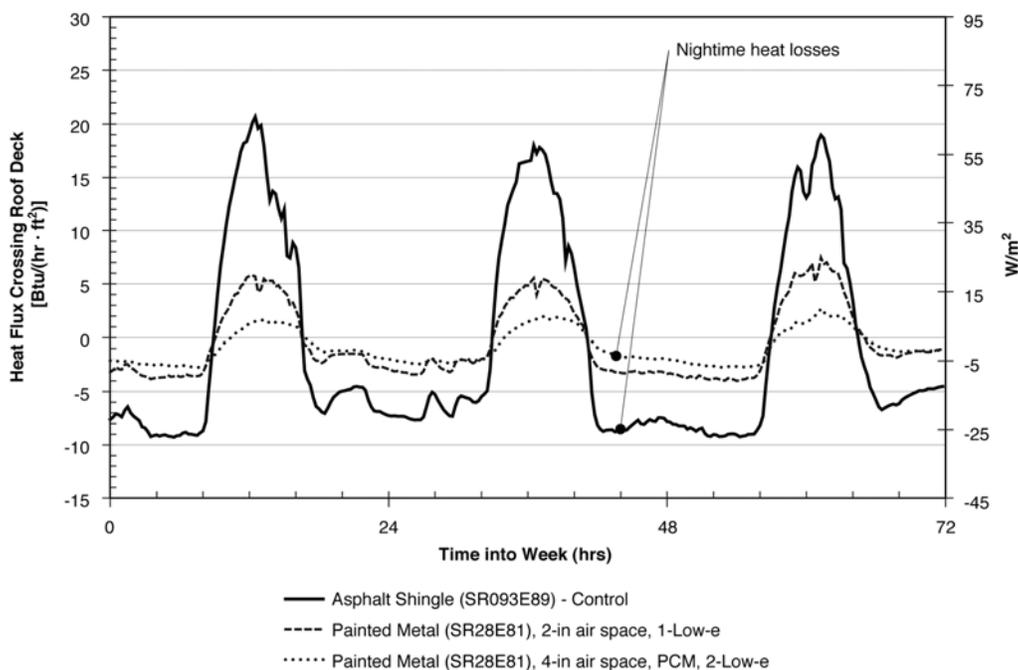
Cooling benefit versus winter penalty. The field data suggest that an open air space above the sheathing may be an excellent design strategy for reducing roof heat gains and losses. Miller et al. (2007) benchmarked AtticSim II against the field data. Seasonal simulations were made using AtticSim II to determine the energy benefits of above-sheathing ventilation for air spaces from 1 to 4 in. (0.025 to 0.102 m) in height. Sacramento, which has 1202 CDD_{65} and 2697 HDD_{65}, was simulated using California code-compliant levels of ceiling and duct insulation. A radiant barrier was also assumed in the simulations (Table 1).

The integrated heat flows over the heating and cooling season (Table 1) show that the cool color metal roofs have less heat loss during the winter and less heat gain during the summer than computed for a direct-nailed shingle roof (row highlighted in yellow). 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 (row highlighted in yellow, Table 1). Therefore, implementing above-sheathing ventilation negates 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.

Table 1. Heating & Cooling Load for Ceiling & Air-Conditioning Duct Simulated in Sacramento, CA for a Roof & Attic Assembly with R_{US}-38 (R_{SI}-6.7) Ceiling Insulation 7 R_{US}-6 (R_{SI}-1) Duct Insulation. Duct leakage Is Assumed to Be 4% of the Supply Flow.

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

[1] Air space for above sheathing ventilation (ASV) fitted with one low-emittance surface.
[2] Loads based on attic footprint of 1261 square feet (117.2 m²).
[3] Standing-seam painted metal roof with cool color pigments.

Thermal Simulations for a Residential Attic

Wilkes (1991) formulated and validated an attic simulation tool entitled "AtticSim." He published the tool as an ASTM standard (ASTM 2004) for estimating heat transfer through ceilings under attics containing radiant barriers. The model can account for different insulation R-values and has an algorithm for predicting the effect of air-conditioning ducts placed in the attic, as reported by Petrie et al. (1998) and described in ASTM C 1340 (2004). Salient features of AtticSim (including the source code) are provided by Wilkes (1991).

The ability to simulate above-sheathing ventilation 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 above-sheathing ventilation and with and without cool colors. AtticSim II yielded predictions within ±3°F (1.7°C) of field measures for surface temperatures and integrated ceiling and deck heat fluxes within ±10% of field measures when exercised for the case of above-sheathing ventilation.

Annual Loads for Pre- and Post- 1980 Attic Construction

Simulations were made for Sacramento (central basin area), Burbank (densely populated west coast area), and El Centro (hot, dry southeastern region). An attic of 1261 ft² (117.2 m²) with a roof pitch[5] of 18° was modeled that had air-conditioning ducts in the attic. The supply ducts contained six branches off the main branch; the surface area was set at 304 ft² (28.7 m²). The return duct with 176 ft² (16.4 m²) of surface area was also placed in the attic.

Cooling and heating season roof heat transfer were computed and compared with data for two different bases: (1) new-construction homes, where the requirement of 0.25 solar reflectance[6] and 0.75 thermal emittance (SR25E75) is the base (CEC 2005); and (2) pre-1980 homes, where 0.05-solar reflectance and 0.90-thermal emittance is the base. The time-dependent valuation (TDV)[7] protocol was used to compute source energy based on performance data for

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[5] Roof pitch of 18° is equivalent to 4-in. (0.102-m) rise per 12-in. (0.305-m) run
[6] The California Energy Commission's Title 24 building standards has set the minimal prescriptive solar reflectance at 0.20; however, asphalt shingles, holding about 85% of the roofing market, can exploit cool color pigments and reach solar reflectance values of about 0.25.
[7] Time-dependent valuation (TDV) methodology computes the energy used at a site and consumed by power generation and transmission in delivering the energy to the site. TDV assigns a higher value to the savings of an energy measure that is very efficient during hot summer peak demand compared with late evening off-periods.

air-conditioning units[8] tested in northern and central California (CEC 1999). The energy efficiency ratio (EER) of the air-conditioning unit was used at each hour of a weather database[9] (CEC 1992) along with hourly TDV values to convert attic heat transfer to energy in units of Btu of natural gas (Btu_{NG}). Eley (2002) describes the procedure used to calculate TDV costs.

New construction. Painted metal roofs (SR28E81) with cool color pigments were simulated for steep-slope roofs fitted with a 1-in. (0.0254-m) and 4-in. (0.102-m) air space above the sheathing (Table 2). A low-e surface was assumed in the air space and a radiant barrier was assumed on the underside of the roof deck. The best-performing tile, a clay tile roof (SR54E90), was simulated with the tile nailed directly to the deck and spray-adhered to 1¼-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 for the clay tile simulations; however, an attic radiant barrier was assumed as required by code. The clay tile's solar reflectance of 0.54 is near the highest solar reflectance achievable for a nonwhite roof, which people generally prefer over the lighter white roof. Levinson et al. (2006) 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 attic plenum was simulated with code-compliant levels of insulation on the attic floor and 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 2).

Table 2. Annual Ceiling and Air-Conditioning Duct Heat Transfer and TDV Energy Cost for New (2005 Title 24) Attic Construction

City	Climate Zone	SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2]		Duct System		Annual Load (kBtu per yr)		TDV Energy[4] Costs	
				R-value	RB (TE)	R-Value	Air Leakage	Ceiling	Duct	$NPV over 30-yrs	PV$ per yr
Burbank	09	0.25 / 0.75	NA	30	0.05	6	4%	1,305	3,082	$1,266	$65
		0.28 / 0.81	1-in airspace	30	0.05	6	4%	1,162	2,425	$912	$47
		0.28 / 0.81	4-in airspace	30	0.05	6	4%	1,018	2,538	$976	$50
		0.25 / 0.75	NA	30	0.05	6	0%	1,316	2,574	$1,079	$55
Sacramento	12	0.25 / 0.75	NA	38	0.05	6	4%	1,988	6,356	$1,921	$98
		0.28 / 0.81	1-in airspace	38	0.05	6	4%	1,758	5,722	$1,655	$84
		0.28 / 0.81	4-in airspace	38	0.05	6	4%	1,729	5,599	$1,603	$82
		0.25 / 0.75	NA	38	0.05	6	0%	2,018	5,305	$1,636	$83
El_Centro	15	0.25 / 0.75	NA	38	0.05	8	4%	2,324	7,442	$3,528	$180
		0.28 / 0.81	1-in airspace	38	0.05	8	4%	1,950	6,354	$2,922	$149
		0.28 / 0.81	4-in airspace	38	0.05	8	4%	1,882	6,152	$2,819	$144
		0.54 / 0.90	High profile	38	0.05	8	4%	1,858	6,037	$2,771	$141
		0.54 / 0.90	High profile[3]	38	0.05	8	4%	1,751	5,744	$2,618	$134
		0.54 / 0.90	High profile[3]	38	0.05	NA	NA	2,159	0	$665	$34
		0.25 / 0.75	NA	38	0.05	8	0%	2,396	5,338	$2,649	$135

[1] Air space fitted with one low-emittance surface. [2] Annual loads based on attic footprint of 1261 square feet (117.2 m²).

[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 energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.145 per $kBtu_{NG}$. Annual cost computed using 3% discount rate over 30-yrs.

The ceiling and duct loads for all cases shown in Table 2 show that the annual ceiling loads are 25% of the combined load. The losses from the ductwork predominate. Placing ductwork in an attic simplifies construction but exacerbates building energy use. Thus, it should be encouraged in new construction to eliminate duct leakage using mastic, which effectively seals metal, flexible, and fibrous ductwork. Eliminating duct air leakage (4% reduced to 0%

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[8] Field data yielded an SEER of 8.3 for Sacramento, 8.4 for Burbank, and 7.8 for the hotter climate of El Centro.

[9] The weather database contains 16 weather files, one for each of the 16 climate zones of California. Each file contains 8760 hours (one year) of metered weather data (CEC 1992).

leakage) for the SR25E75 roof and attic (yellow versus gray highlighted rows, Table 2) yields savings comparable to the best roof systems simulated in Table 2.

In Burbank, the roof and attic assembly with a 4-in. (0.102-m) air space dropped the combined annual ceiling and duct heat transfer by 19% of that measured for the SR25E75 roof and attic assembly (yellow highlighted rows, Table 2). In Sacramento, roughly 12% savings are estimated, and in El Centro the savings are about 18% of those computed for the SR25E75 assembly. The increased solar reflectance and the thermal mass of the clay tile with 1¼ in. (0.032 m) of EPS foam further improved roof and attic performance. In El Centro, the combined ceiling and duct load dropped 23% from that computed for the SR25E75 roof and attic assembly (Table 2). If the ductwork is placed in the conditioned space, then the total reduction in roof and attic annual load for the clay tile with 1¼ in. (0.032 m) of EPS foam (green-shaded row, Table 2) drops 78% of the annual load for the SR25E75 assembly (yellow-shaded row, Table 2)!

The annual energy savings[10] for the cool color roof with a 4-in. (0.102-m) air space is about \$36 in El Centro and \$16 in Sacramento compared with the SR25E75 assembly. If modifications to eliminate leakage from ductwork are included, yearly savings increase to about \$81 in El Centro. If the ducting is placed in the conditioned space and a cool color tile roof with 1¼ in. (0.032 m) of EPS foam is placed on the deck, savings jump to \$146 per year.

Pre-1990 construction. F.W. Dodge (2002) reported that about 75% of single-family homes in the Pacific region have replaced existing worn-out roofs with asphalt shingles. Because cool color reflective shingles are relatively new, the replacement shingles are dark heat absorbers with about 0.05 solar reflectance and 0.90 thermal emittance. The attics of these homes (built around 1980 to 1990) have R-19 or less insulation on the attic floor and at best R-4.2 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). The roof and attic of a home built before 1990 (gray highlighted rows, Table 3) was simulated with an uninspected duct (14% air loss) and an inspected duct (4% air loss) to compute savings for repairing ductwork and compare them with retrofitting a new prototype roof. 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).

Reducing duct air leakage from 14% to 4% resulted in about a 25% drop in annual heat load from the ceiling and ducts (gray-highlighted rows, Table 3). In comparison, if a homeowner in Burbank left the ductwork untouched but replaced his existing roof with a metal roof having a 4-in. (0.102-m) air space, the annual load drops by about 17% of the load computed for the SR05E90 base with leaky ducts (Table 3).

In Sacramento and El Centro, the reductions in annual load are, respectively, 10% and 16% of the load calculated for the per-1980 base case. Similar results were observed for installing a cool color clay tile roof (SR54E90) attached directly to the deck. If 1¼ in. (0.032 m) of EPS foam is placed under the clay tile (tan-highlighted row Table 3), then the annual ceiling and duct load drops by 17% of the base case (SR05E90) in El Centro. Renovating the ducts for the assembly with a clay tile roof and EPS foam (green-highlighted row, Table 3) yields a

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[10] Energy costs are estimated using a TDV weighting for space cooling electricity and space heating natural gas. A nominal natural gas cost for residential consumption of \$0.145 per $kBtu_{NG}$ is assumed based on a 30-year forecast. Annual energy costs are discounted using a 3% real (inflation-adjusted) rate over the 30-year forecast.

combined 43% drop in roof and attic loads. Renovations included R-8 insulation wrapped around the ducts and air leakage reduced from 14 to 4%.

Table 3. Annual Ceiling and Air-Conditioning Duct Heat Transfer and TDV Energy Cost for Pre-1980 Attic Construction

City	Climate Zone	SR / TE	Above-Sheathing Ventilation[1]	Attic Plenum[2] R-value	Attic Plenum[2] RB (TE)	Duct System R-Value	Duct System Air Leakage	Annual Load (kBtu per yr) Ceiling	Annual Load (kBtu per yr) Duct	TDV Energy[4] Costs $NPV over 30-yrs	TDV Energy[4] Costs PV$ per yr
Burbank	09	0.05 / 0.9	NA	19	NA	4.2	14%	3,137	5,620	$2,630	$134
		0.28 / 0.81	1-in airspace	19	NA	4.2	14%	2,410	5,081	$2,186	$112
		0.28 / 0.81	4-in airspace	19	NA	4.2	14%	2,307	4,937	$2,102	$107
		0.05 / 0.9	NA	19	NA	6	4%	3,202	3,649	$2,004	$102
Sacramento	12	0.05 / 0.9	NA	19	NA	4.2	14%	5,198	11,946	$4,076	$208
		0.28 / 0.81	1-in airspace	19	NA	4.2	14%	4,500	11,156	$3,590	$183
		0.28 / 0.81	4-in airspace	19	NA	4.2	14%	4,399	10,973	$3,498	$178
		0.05 / 0.9	NA	19	NA	6	4%	5,378	7,341	$3,016	$154
El_Centro	15	0.05 / 0.9	NA	19	NA	4.2	14%	6,141	16,518	$8,459	$432
		0.28 / 0.81	1-in airspace	19	NA	4.2	14%	5,114	14,554	$7,233	$369
		0.28 / 0.81	4-in airspace	19	NA	4.2	14%	4,932	14,178	$7,017	$358
		0.54 / 0.90	High profile	19	NA	4.2	14%	5,000	13,972	$6,942	$354
		0.54 / 0.90	High profile[3]	19	NA	4.2	14%	4,897	13,872	$6,867	$350
		0.54 / 0.90	High profile[3]	19	NA	8	4%	5,116	7,812	$4,579	$234
		0.05 / 0.9	NA	19	NA	8	4%	6,342	9,173	$5,608	$286

[1] Air space fitted with one low-emittance surface. [2] Annual loads based on attic footprint of 1261 square feet (117.2 m²).

[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 energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.145 per kBtu NG. Annual cost computed using 3% discount rate over 30-yrs.

Whole-Building Energy Simulations of PCM-Enhanced Residential Attic

Energy Plus is a whole building simulation tool sanctioned by the Department of Energy for estimating building energy consumption. It includes routines for predicting the effect of PCMs exhibiting variable thermal storage capacities in building materials. The feature was exploited for simulating PCMs-enhanced attic insulation added to a 1400-ft^2 (150-m^2) single-story ranch house operating in Bakersfield CA. A direct nailed asphalt shingle roof was modeled with an assumed solar reflectance of 0.09 and thermal emittance of 0.90. Additional salient features of the ranch style house are provided by Kośny et al. (2007b).

Energy Plus simulations for the ranch style house were conducted for R-values of attic insulation ranging from R_{US}-12 through R_{US}-50 (R_{SI}-2.1 through R_{SI}-8.8). The house was also modeled with R_{US}-38 (R_{SI}-6.7) attic insulation that contained 20% by weight microencapsulated PCM. The melting temperature of the PCM was simulated between 78°F and 82°F (25.6 and 27.8°C). Differential Scanning Calorimeter (DSC) tests results developed by Kośny et al. 2006 and Kośny et al. 2007b were used in Energy Plus to compute the fusion enthalpy of the PCM as function of the materials bulk temperature.

Results of the simulations for the climate of Bakersfield, CA are plotted in Figure 6 to depict the relationship between R-value of the conventional attic insulation and whole building energy consumption. Similarly, the whole building energy consumption for the case with R_{US}-38 (R_{SI}-6.7) PCM-enhanced attic insulation is shown to illustrate the potential benefits of PCMs (Fig. 6). The R_{US}-38 (R_{SI}-6.7) roof containing PCM-enhanced insulation generates significant whole building energy savings as compared to the same level of conventional insulation. Roughly 2 GJ (556 kWh per year) are saved by adding the 20% by weight PCM to the attic insulation. The annual cost of this energy savings is estimated at $70 using the EIA (2006) state wide cost of electricity; it being 12.82¢ per kWh.

The simulation results also demonstrate that conventional attic insulation must be about R_{US}-75 (R_{SI}-13.2) for the home to consume the same annual whole house energy compared to the

home with R_{US}-38 (R_{SI}-6.7) attic insulation with PCM-enhancement. Therefore, in terms of a "Dynamic Attic R-value Equivalent" (Fig. 6) and BNI (2008, 61) cost data, about $1.30 per square foot of attic footprint [i.e., $1830 for the 1400 ft^2 (150-m^2) ranch style home] would be spent to increase the thermal resistance of conventional blown-in fiberglass insulation from R_{US}-38 to R_{US}-75 (R_{SI}-6.7 to R_{SI}-13.2).

Figure 6. Relationship between Attic R-Value and Whole Building Energy Consumption for a 1400-ft^2 (150-m^2) Single-Story Ranch House in Bakersfield, California
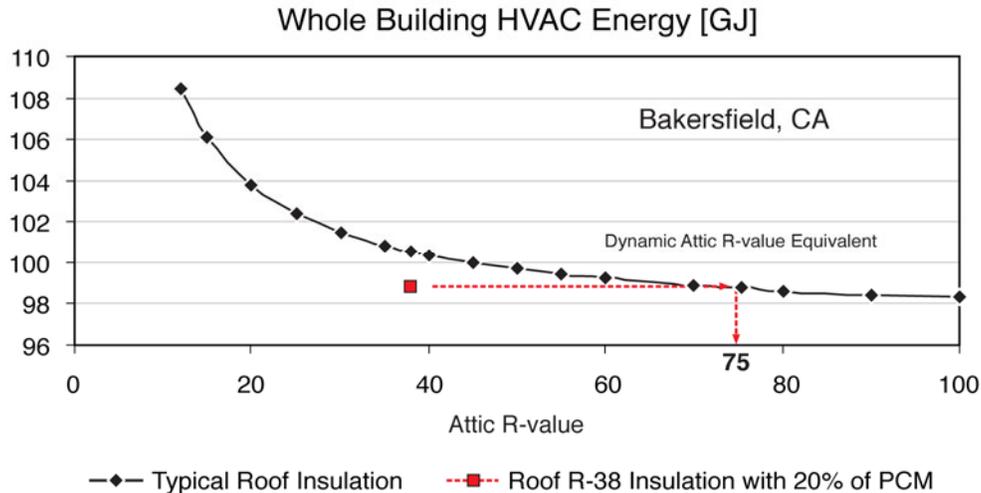
Conclusions

Field results demonstrated that a combination of strategies including cool color roofs, above-sheathing ventilation, conventional insulation and thermal mass all helped reduce the heat transfer crossing the roof deck; however, the combination of strategies are not necessarily additive nor are the strategies synergistic. The clay tile roof placed on 1¼-in (0.032-m) of EPS foam or a painted metal roof (SR28E81) offset from the roof deck 4-in (0.102-m) and fitted with PCMs dropped the annual load due to ceiling and duct heat gains/losses by 23% of that computed for the SR25E75 code compliant roof and attic assembly. If in addition the ducts are placed in the conditioned space, the annual ceiling and duct load drops 78% of the SR25E75 case.

Simulation results clearly show that improvements to ductwork should be a priority in any retrofit program. The estimated heat flow reductions for the prototype retrofit roofs are comparable to the savings realized for duct renovations.

Whole building simulations demonstrated that a low-cost insulation opportunity exists with PCM-enhanced blown insulations. Energy Plus simulations for Bakersfield CA showed that R_{US}-38 (R_{SI}-6.7) with 20% by weight PCM insulation performs as well as R_{US}-75 (R_{SI}-13.2) conventional attic insulation. Additional study is needed to develop PCM building products and to generate cost data for making economic decisions for these PCM products.

Recommendations

In southern California, homeowner associations are selecting new roof products and replacing all existing roofs in an individual association with the same product. The major incentive for the California homeowner is reduced home insurance rates for fire protection. However, moderate savings are also realized from installing new roofs that integrate cool roofs, above-sheathing ventilation with a low-e surface in the air space, insulation, and thermal mass. What utilities and building owners need is annual performance metrics prioritizing retrofit choices. Further collaborative study and assessment by utilities and research institutions is needed to develop a portfolio of the best available materials and construction methods that, through rebate incentives, reduce energy bills sufficiently and justify for the homeowner the economics of higher up-front material and installation costs.

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