

THE IMPACT OF ABOVE-SHEATHING VENTILATION ON THE THERMAL AND MOISTURE PERFORMANCE OF STEEP-SLOPE RESIDENTIAL ROOFS AND ATTICS

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ABSTRACT

Field studies were conducted on several attic assemblies having stone-coated metal shake roofs with and without infrared blocking color pigments (IrBCPs) and with and without above-sheathing ventilation. The combination of increased solar reflectance and above-sheathing ventilation reduced the heat flow penetrating the attic floor by 70% as compared with the heat flow penetrating the attic floor of a roof with conventional asphalt shingles. The venting strategy also eliminated the heating penalty associated with a reflective roof as compared with that of a dark heat-absorbing shingle roof.

KEYWORDS

Moisture and humidity; attic ventilation case studies; monitoring and analysis of energy data; data project case studies; building envelope issues; glazing; residential housing design; institutional, government, and utility energy policy; energy conservation; Rebuild America program

INTRODUCTION

Infrared blocking color pigments (IrBCPs) that are dark in color but highly reflective in the near-infrared (NIR) spectrum were a serendipitous by-product of research conducted for the U.S. Department of Defense. Military camouflage was tailored to match the reflectance of foliage in the visible and the NIR spectra. The chlorophyll in plants strongly absorbs in the non-green parts of the visible spectrum, giving the leaf a dark green color with high reflectance elsewhere in the solar spectrum (Kipling 1970). In the NIR the chlorophyll in foliage naturally boosts the reflectance of a plant's leaf from 0.1 to about 0.9; this enhanced reflectance explains why a dark green leaf remains cool on a hot summer day.

Tailoring color pigments to produce high NIR reflectance similar to that of chlorophyll provides an excellent opportunity for passive energy savings for exterior residential surfaces such as roofs exposed to the sun's irradiance. For example, a calcinated mixture of the black pigment chromic oxide (Cr_2O_3) and ferric oxide (Fe_2O_3) increases the solar

reflectance of a standard black pigment from 0.05 to 0.26 (Sliwinski, Pipoly and Blonski 2001). Further details about identifying and characterizing dark yet highly reflective color pigments and calculating their potential energy benefits are discussed in Miller et al. (2004); Akbari et al. (2004); and Levinson, Berdahl, and Akbari (2004a–b).

Above-sheathing ventilation of a roof cover can also provide thermal benefits for comfort cooling. Residential roof tests by Beal and Chandra (1995) demonstrated a 45% reduction in the daytime heat flux penetrating a counter-batten concrete tile roof as compared with a direct-nailed shingle roof. Parker, Sonne, and Sherwin (2002) observed that a barrel-shaped terra-cotta concrete tile with moderate solar reflectance reduced a test home's annual cooling load by about 8% of the base load measured for an identical adjacent home with an asphalt shingle roof. These reported energy savings are attributable in part to a thermally driven airflow occurring above the sheathing within the air channel formed by the underside of the tile and the roof deck; this airflow is referred to in this paper as *above-sheathing ventilation*. The airflow is driven by buoyancy and/or wind forces. The air channel also provides an improvement in the insulating effect of the roofing system. Though few studies are available on heat transfer within the narrow air channel in counter-batten installations, insight can be gained from the work done on attic ventilation and from experimental studies of heat transfer in inclined ducts. Ozsunar, Baskaya, and Sivrioglu (2001) studied the effects of inclination on convection within a large-aspect-ratio duct heated from below.

To examine the effects of "cool color" pigments in combination with above-sheathing ventilation, a steep-slope roof assembly was constructed for field testing and documenting the energy savings and durability of stone-coated metal roofs with shake and S-mission profiles. Stone-coated metal is made from pre-primed 26-gauge galvanized steel that is coated with a layer of stone chips (Figure 1). An acrylic base coat and an overglaze are applied to seal the product.

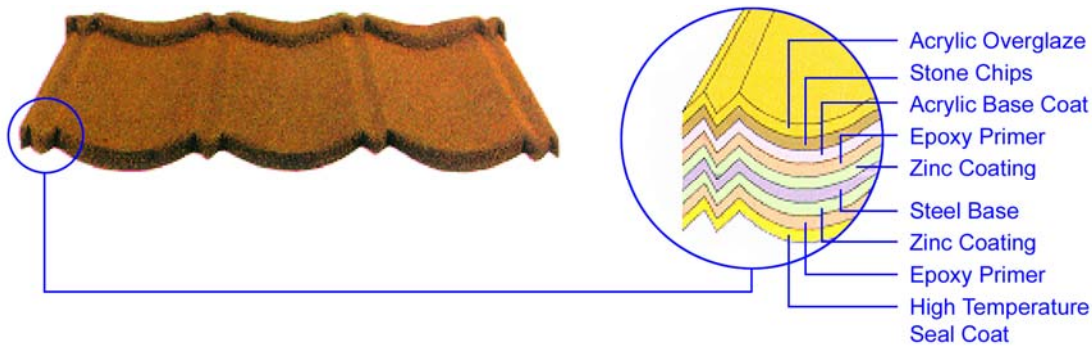


Figure 1. The construction of a commercially available stone-coated metal roof product.

FORMULATING STONE-COATED METALS WITH IRBCPs

Weathered Timber is a commercially available stone-coated metal product that has a solar reflectance of 0.06. To improve its solar reflectance, several granular-coated products of a given color were evaluated for the importance of the size of the aggregate, the type of cool paint pigment, and the effect of applying the paint pigments to the primer/binder adhesive holding the aggregate in place. Pigment testing showed that adding cool pigments to the base granite adhesive increased the solar reflectance only 0.03 reflectance points over an adhesive with conventional pigment. The results reveal that little irradiance penetrates the multiple finishing layers of the stone-coated metal (Figure 2).

Blending a Weathered Timber color with individual granules with a somewhat lighter and more reflective color and then coating the stone chips with a clear acrylic overglaze increased the solar reflectance from 0.06 to about 0.19 (second bar from left in Figure 2). The acrylic overglaze is typically applied as a final coating and gives the stone granules a semigloss appearance. The acrylic finish bonds to the granules and encapsulates them with a coating that enhances the panel’s resistance to physical damage.

When cool pigments were added to the granules and to the acrylic base coat adhesive, the solar reflectance again increased, to 0.22. The addition of cool pigments to the overglaze (right-hand bar in Figure 2) further increased the solar reflectance

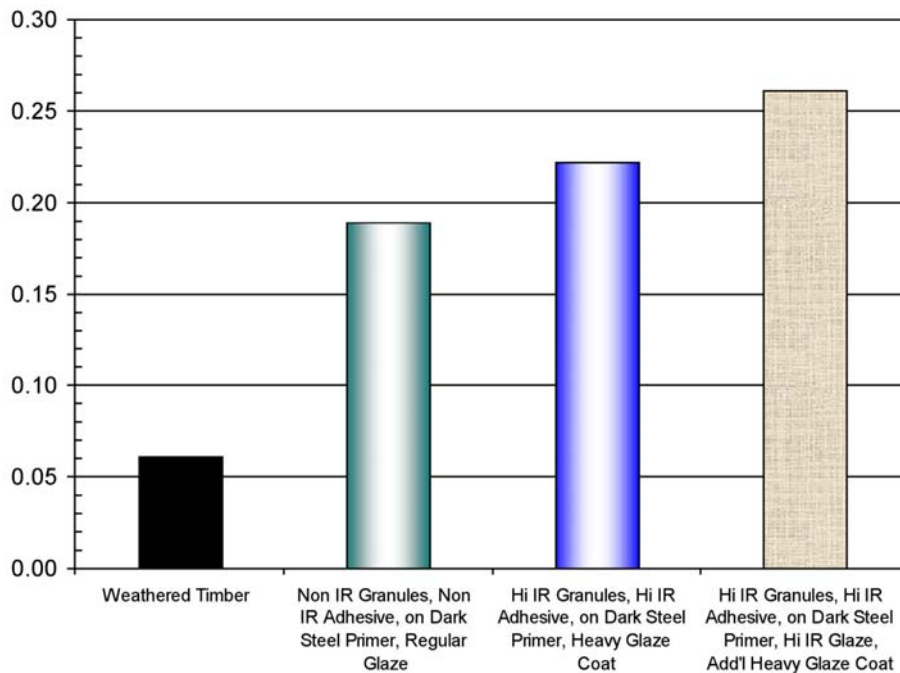


Figure 2. Improvements in solar reflectance of stone-coated metal through application of IRBCPs and acrylic overglaze.

above 0.25, which is the threshold set for steep-slope roofing for an ENERGY STAR rating. Given these results for improving solar reflectance, prototype stone-coated metal shakes and tiles meeting the 0.25 reflectance threshold were installed on an assembly of steep-slope attics and field-tested for a full year.

STEEP-SLOPE ATTIC ASSEMBLY

Light-gray and dark-gray stone-coated metal shakes (solar reflectances of 0.26 and 0.08, respectively) were installed on batten and counter-batten systems and field-tested against a control asphalt shingle roof assembly. The steep-slope assembly and characteristics of the shingles are summarized in Table 1. The stone-coated shake facsimile roofs were offset from the roof deck using a batten and counter-batten system made of 1 × 4 in. counter-battens nailed to the roof deck from soffit to ridge, and 2 × 2 in. battens placed above the counter-battens and nailed to the deck (Figure 3). The batten and counter-batten construction provides a unique inclined air channel running from the soffit to the ridge. The bottom surface of the air channel is formed by the sheathing. The top surface is created by the underside of the stone-coated metal and is broken at regular intervals by the 2 × 2 in. batten wood furring strip (into which the shakes are fastened). Each test roof has its own attic cavity with 5 in. of expanded polystyrene insulation installed between adjacent cavities to reduce the heat leakage

between cavities so that each attic assembly and test roof can be tested as a stand-alone assembly.

A painted metal shake with a polyvinylidene fluoride (PVDF) base coat and two S-mission-profile stone-coated metal roofs were also tested (Figure 4); however, the discussion here will focus on the dark- and light-gray stone-coated metal roofs. Details about the metal shake with PVDF base coat and the S-mission profiles are provided in Miller (2006).

Instrumentation for Attic Assembly

The roof surface temperature, the air temperature in the inclined air gap, the temperatures of the roof deck on both sides of the oriented strand board (OSB), and the heat flux transmitted through the roof deck were directly measured and recorded by a data acquisition system (DAS). All roof decks have a 2-in.-square by 0.18-in.-deep routed slot with a heat flux transducer (HFT) inserted to measure the heat flow crossing the roof deck. Each HFT was placed in a guard made of the same OSB material used in construction and was calibrated using a FOX 670 heat flowmeter to correct for shunting effects (i.e., distortion due to three-dimensional heat flow). The assemblies also have an instrumented area in the attic floor (i.e., ceiling) for measuring the heat flows into the conditioned space. The attic floor consists of a metal deck, a 1-in.-thick piece of wood fiberboard

Table 1. Stone-coated metal shakes field tested on the steep-slope attic assembly

Profile	Color	Pigment	Surface	Underside	Attachment	Above-sheathing ventilation ^a
<i>Lane 6: Control asphalt shingle (SR093E89)</i>						
Shingle ^b	Dark-gray	Conventional	Aggregate	NA	Direct-to-deck	No
<i>Lane 7: Shk-LG-IRRagg-Upt-CB (SR246E90)</i>						
Shake	Light-gray	IrBCP	Aggregate	Unpainted	Batten and counter-batten ^c	Yes
<i>Lane 8: Shk-DG-CNVagg-Upt-CB (SR08E90)</i>						
Shake	Dark-gray	Conventional	Aggregate	Unpainted	Batten and counter-batten	Yes
<i>Lane 9: Shk-LG-IRRagg-Pt-CB (SR25E90)</i>						
Shake	Light-gray	IrBCP	Aggregate	Painted	Batten and counter-batten	Yes
<i>Lane 12: Shk-LG-IRRagg-Upt-DDk (SR25E90)</i>						
Shake	Light-gray	IrBCP	Aggregate	Unpainted	Direct to deck	Yes

^aAll lanes have soffit and ridge venting. ^bBaseline conditions. ^cBattens are 2 × 2 in. wood run along roof width. Counter-battens are 1 × 4 in. and run from soffit to ridge (see Figure 3).



Figure 3. Roof deck construction with battens and counter-battens.



Figure 4. South-facing steep-slope attic assemblies placed atop the roof testing facility.

lying on the metal deck, and a ½-in.-thick piece of wood fiberboard placed atop the 1-in.-thick piece. The HFT for measuring ceiling heat flow is embedded between the two pieces of wood fiberboard. It was also calibrated in a guard made of wood fiberboard before being placed in field service.

FIELD RESULTS

The ridge vents for the stone-coated metal and asphalt shingle roofs were opened to observe the effects of attic ventilation and, more importantly, the effect of unrestricted airflow within the inclined air gap formed under the stone-coated metal roofs. The effects of venting of attic spaces on heat transmission and moisture have been studied at some length, but little has been done to analyze the venting and flow patterns observed in the inclined channel created by batten and counter-batten deck constructions. Rose (1995) gives an overview of the evolution of attic venting, and Romero and Brenner (1998) instrumented a test building for the study of ridge venting and the associated flow within the attic space. Beal and Chandra (1995) studied heat transfer through direct-nailed tile roofs and counter-batten tile roofs as compared with heat transfer through direct-nailed asphalt shingle roofs. Relative to the asphalt shingles, tile reduced heat transmission by 39% in the direct-nailed configuration and by 48% for the counter-batten configuration.

A commercially available asphalt shingle with a solar reflectance of 0.093 and a thermal emittance of 0.89 (SR093E89) was selected as the control for comparing the thermal performance of the metal

products. (The control is shown in lane 6 from the right in Figure 4.) Another conventional shake, a dark-gray stone-coated metal (SR08E90), was also used for field testing. This shake has a solar reflectance and a thermal emittance almost identical to that of the control asphalt shingle. The asphalt shingle, however, was directly nailed to the roof deck, with no venting along its underside, while the dark-gray shake was attached to the batten and counter-batten arrangement. Both assemblies were equipped with attic ventilation through soffit and ridge vents. Thus, a comparison of the two test roofs can provide insight into the effects of above-sheathing ventilation. The light-gray stone-coated shake (SR246E90) had the same batten and counter-batten construction as the dark-gray shake. The light gray shake has a solar reflectance of 0.25 and thermal emittance of 0.90; its unpainted underside has a thermal emittance of 0.35. A comparison of the two stone-coated roofs reveals the benefits of IRR pigments in combination with above-sheathing ventilation.

Summer Field Exposure

A clear, cloudless summer day was selected to display the separate and combined effects of IrBCPs and above-sheathing ventilation as compared with the asphalt shingle roof. Venting the underside of the dark-gray stone-coated metal shake caused significant reductions in the heat flow crossing the deck during solar noon, as seen in Figure 5. The daytime values for deck heat flows for the 7-day period around August 2 are provided in Table 2. The interior walls of each attic assembly were insulated

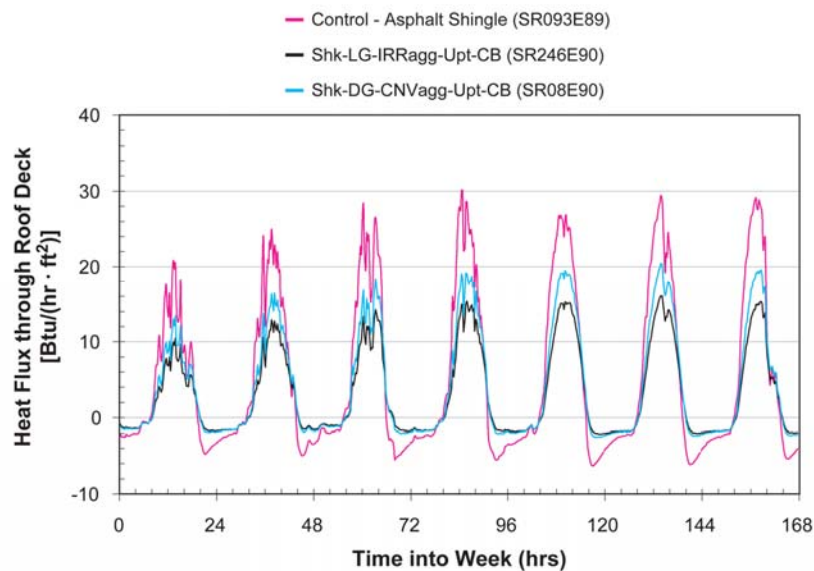


Figure 5. The effect of above-sheathing ventilation and solar reflectance for two stone-coated metal roofs compared with a direct-nailed shingle roof.

Table 2. Roof deck and attic floor heat flows (Btu/ft²) integrated over the daylight hours for a week of data taken in July 2005

	Control shingle (SR093E89)	Shk-LG-IRRagg-Upt- CB (SR246E90)	Shk-DG-CNVagg-Upt- CB (SR08E90)
Roof deck	1216.4	670.3	853.9
Attic floor	326.6	95.5	112.2
Q _{Attic vent}	889.7	574.8	741.8
Q _{Deck vent}		1280.6	2703.8

Note: Heat flows are corrected for projected attic floor area. Daylight is defined as the period when the solar flux normal to roof exceeds 30 Btu/hr-ft².

with at least 5 in. of foam insulation. Given the measurements of heat flow crossing the roof deck and the attic floor, the amount of heat removed by attic ventilation and above-sheathing ventilation can be approximated by the following energy balances:

$$Q_{\text{Attic vent}} = \frac{Q_{\text{Roof Deck}}^{\text{HFT}}}{\text{COS}(\theta)} - Q_{\text{Attic floor}}^{\text{HFT}} \quad (1)$$

and

$$Q_{\text{Deck vent}} = \frac{Q_{\text{Solar Abs}} - Q_{\text{Mass}} - Q_{\text{Roof Deck}}^{\text{HFT}}}{\text{COS}(\theta)}, \quad (2)$$

where

$$Q_{\text{Solar Abs}} = I_{\text{Solar}} (1 - \rho_{\text{SR}}) - \dot{h} (T_{\text{S}} - T_{\text{OD Air}}) - \varepsilon \sigma (T_{\text{S}}^4 - T_{\text{Sky}}^4)$$

$$Q_{\text{Mass}} = \Delta \rho C_p \frac{\partial T}{\partial t} \quad (\text{thermal mass of roof cover and OSB decking included in } Q_{\text{Mass}})$$

$$Q_{\text{Attic floor}}^{\text{HFT}} = \text{heat flux transducer (HFT) embedded in attic floor}$$

$$Q_{\text{Roof deck}}^{\text{HFT}} = \text{heat flux transducer (HFT) embedded in roof deck}$$

The dark-gray stone-coated metal shakes and the asphalt shingles have almost identical reflectance and emittance characteristics, yet the heat flow crossing the roof deck of the dark-gray shake is just 70% of the heat flow crossing the roof deck of the asphalt control shingle (Table 2). The 30% reduction in heat flow is due to above-sheathing ventilation despite the slight decrease in attic ventilation occurring under the dark-gray shake.

Above-sheathing ventilation ($Q_{\text{Deck vent}}$) of the dark-gray shake is nearly four times larger than its attic ventilation ($Q_{\text{Attic vent}}$). Thus, above-sheathing ventilation of the dark-gray shake lowers the heat content of the attic and the interior surface temperatures, which in turn means that lower amounts of heat penetrate the attic's floor. As result, venting (above-sheathing and attic soffit and ridge) reduced the heat flow through the attic floor by about 65% of the heat flow crossing the floor of the attic assembly (326.6 vs 112.2 Btu/ft² of attic floor) with the conventional asphalt shingle roof.

The light gray shake (SR246E90) and the dark gray shake (SR08E90) have identical batten and counter-batten constructions and low underside emittance values (0.35). Both have soffit and ridge vents supporting attic ventilation. The 0.17 increase in the solar reflectance caused the heat flow crossing the roof deck of the light-gray shake to be less than the heat flow crossing the roof deck of the dark-gray stone-coated shake. The reduction is about 15% of the heat crossing the deck of the control shingle roof (Table 2). The 30% reduction due to above-sheathing ventilation of the dark stone-coated shake (previously discussed) can be added to the 15% reduction due to IrBCPs to yield a total of a 45% reduction in heat flow due to both above-sheathing ventilation and increased solar reflectance. The combined results (Figure 5) observed using both IrBCPs and above-sheathing ventilation show that ventilating the deck is just as important as the boost in solar reflectance and may be the stronger player in reducing the heat gain to the attic assembly. It should be noted that the heat flow due to above-sheathing ventilation of the hotter dark-gray shake is more than double the amount of heat flow swept away from the deck of the light-gray shake (Table 2). The hotter dark-gray shake induces greater buoyancy-induced

airflows, and therefore above-sheathing ventilation is somewhat self-regulating and offsets the effect of the darker, less reflective color.

Winter Field Exposure

Cool roofs have received much positive trade press, and some state and federal support for installations where comfort cooling is the dominant building energy load. In mixed climates with both significant heating and cooling loads, the wintertime effect reduces the energy benefit because the desirable roof heat gain in winter is diminished somewhat by the higher solar reflectance of the roof. The Achilles heel of all cool roof systems continues to be the heating penalty that offsets the energy and cost savings associated with the cooling benefit of the reflective roof system. The colder the climate the greater the penalty, and the trade-off between climate and reflective roofs limits their penetration of the market in predominantly heating load climates. However, field data for the stone-coated metal roofs tested in East Tennessee's moderate climate are showing that the metal's above-sheathing ventilation negates the heating penalty associated with its IrBCP cool roof.

Data for a January week with clear skies, shown in Figure 6, illustrate the wintertime thermal performance of stone-coated metal roofs compared with that of a dark, heat-absorbing asphalt shingle roof. The ridge vents for these test sections were open, and both attic and above-sheathing ventilation

were available for this week of January, which had an average daytime ambient air temperature of 36°F. At solar noon for each of the 7 days, the attic assembly with asphalt shingles (SR093E89) absorbed more solar radiation than either of the two more reflective stone-coated metal roofs (18 vs. 10 Btu/hr·ft²; see Figure 6). However, the nighttime losses for the direct-nailed asphalt shingle roof were significantly larger than losses for the attics with above-sheathing ventilation of the shake roofs (the abscissa in Figure 6 shows midnight as multiples of 24). The heat loss from the shingle roof at night was roughly twice that escaping from the two light-gray roofs or from the dark-gray shake roof, all with batten and counter-batten construction. The underside of the second light-gray stone-coated metal was painted to show the effect of thermal emittance, which increased from 0.34 (unpainted) to 0.85 (when painted). The higher underside emittance resulted in larger nighttime heat losses from the roof deck. Therefore, the air gap appears to be serving as an insulating layer that forces radiative and convective heat transfer from the roof deck to the metal roof's underside, as compared with the direct conduction path through relatively highly conductive solids in the case of the asphalt shingle roof. From about 8:00 p.m. through about 6:00 a.m. all the stone-coated metal roofs lose less heat to the night sky than does the asphalt shingle roof. The temperature of the stone-coated metal is colder at night than that of the shingle, yet the deck temperature for the stone-coated metal roof (with

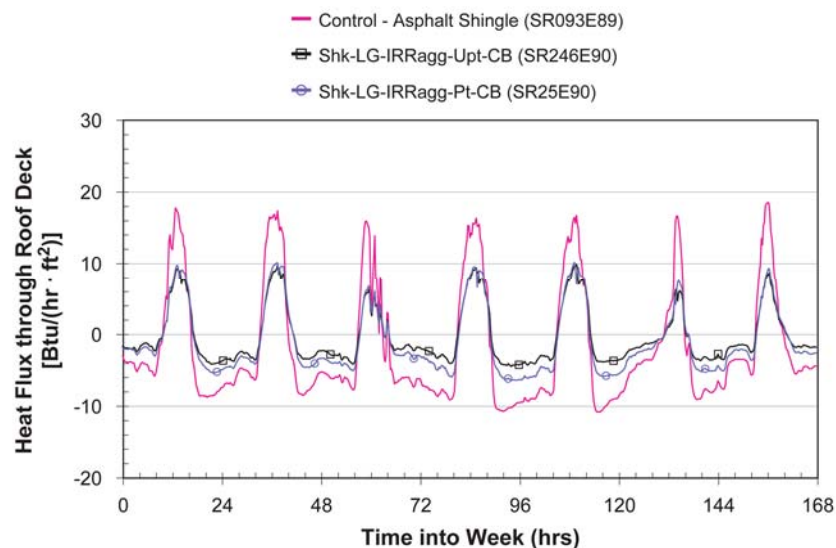


Figure 6. Heat flow measured through the roof deck for stone-coated metal shake and asphalt shingle roof during a week in January 2005. The one light-gray stone-coated metal roof [Shk-LG-IRRagg-Pt-CB(SR25E90)] has a painted underside to show the effect of thermal emittance within the air gap.

above-sheathing ventilation) is warmer than the deck temperature for the direct-nailed shingle roof.

Results integrated over the week of January data shown in Figure 6 indicate that the above-sheathing ventilation of the stone-coated metal roofs counterbalances the heating penalty associated with cool roofing for the moderate climate of Tennessee (Table 3). The asphalt shingle roof gains through its deck about 476 Btu/ft² of attic floor during the daylight hours for the week of January data. The light-gray stone-coated metal roofs gain only half as much heat because of their higher solar reflectance (0.25 vs. 0.09). During the evening hours, however, the heat lost through radiative cooling of the roof decks for the stone-coated metal roofs is 50% less than that lost from the asphalt shingle roof. In fact, during the evening hours the insulation air layer reduced the heat loss from the stone-coated metal roofs to the point that the heat loss from the attic floor was less than the loss from that of the control shingle (−562 Btu/ft² of attic floor for the shingle roof vs. −453 and −429 Btu/ft² for the stone-coated metal roofs). These data represent a very important finding because they show that stone-coated metal roofs negate the heating penalty associated with a cool roof in Tennessee's moderate climate (3662 HDD₆₅ and 1366 CDD₆₅).

The improved summer performance coupled with the reduced heat losses during the winter show that infrared reflective metal roofs negate the heating penalty associated with a cool roof. Offset-mounting the stone-coated metal roofs provides a synergistic effect (improved cooling performance and reduced

winter heat losses) that the metal roof industry can exploit for marketing its products in predominately heating climates.

ABOVE-SHEATHING VENTILATION

Light-gray stone-coated shakes were direct-nailed to the roof deck to further quantify the effect of above-sheathing ventilation. Direct nailing the light-gray stone-coated metal shakes increased the heat transfer entering the roof deck as compared with the light-gray shake on battens and counter-battens (Figure 7). As already stated, offset-mounting the light-gray stone-coated metal shakes from the roof deck and increasing the solar reflectance from 0.093 to 0.25 caused a 45% drop in the heat flux entering the roof deck. Attaching the stone-coated metal shakes directly to the deck diminished the benefit by about 14% (Table 4), and rather than a 45% reduction, about a 30% reduction was measured because of the effect of solar reflectance and the smaller air pocket created between the direct nailed shakes and the decking. In addition, the offset-mounted stone-coated metal with above-sheathing ventilation lost less heat during the evening hours than the other stone-coated metal attached directly to the roof deck (Figure 7). Hence results show that an open free-flowing channel is the best configuration for reducing the roof heat gain and for minimizing roof heat loss.

Measurements were made of the airflow underneath two different stone-coated shake roofs both on batten and counter-batten systems. We designed a procedure using tracer gas techniques outlined in ASTM E 741 (ASTM 2000) and also by Lagus et al. (1988). The procedure, outlined by

Table 3. Roof deck and attic floor heat flows (Btu/ft²) integrated over the daylight and nighttime hours for a week of data taken in January 2005

	Control shingle (SR093E89)	Shk-LG-IRRagg-Upt-CB (SR246E90)	Shk-LG-IRRagg-Pt-CB (SR246E90)
<i>Heat flows during daylight hours</i>			
Roof deck	476.2	257.3	223.7
Attic floor	−166.0	−195.8	−185.9
<i>Heat flows during nighttime hours</i>			
Roof deck	−768.1	−313.3	−392.1
Attic floor	−562.0	−452.8	−428.9

Note: Heat flows are corrected for projected attic floor area. Daylight is defined as the period when the solar flux normal to roof exceeds 30 Btu/hr-ft². Similarly, nighttime is defined as the period when the solar flux normal to roof is less than 30 Btu/hr-ft². Entering heat is defined as a positive heat gain.

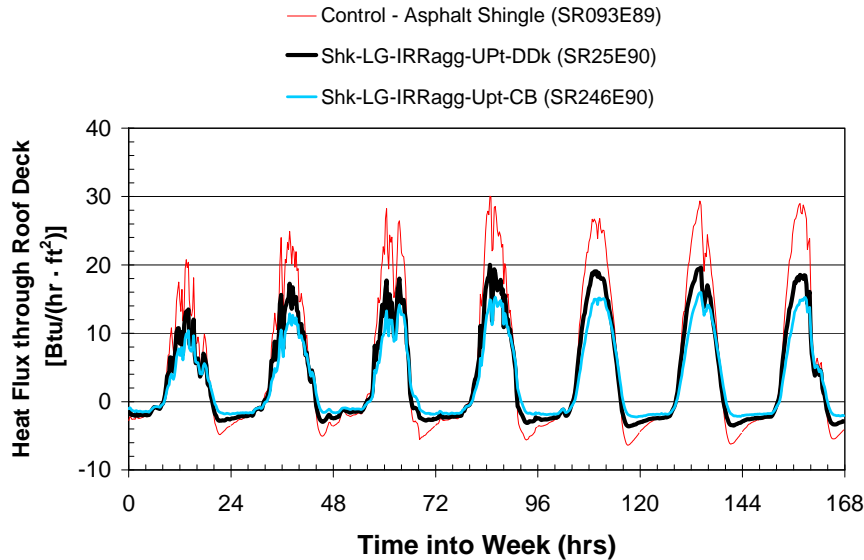


Figure 7. Stone-coated metal roof nailed directly to the roof deck show increased heat flows as compared to the stone-coated roof with batten and counter-batten construction.

Table 4. Deck heat flow for direct-to-deck attachment of stone-coated metal roofs as compared to batten and counter-batten construction (Btu/ft²)

	Control shingle (SR093E89)	Shk-LG-IRRagg-Upt-CB (SR246E90)	Shk-LG-IRRagg-Upt- DDk (SR25E90)
Roof deck	1216.4	670.3	834.6

Note: Heat flows are corrected for projected attic floor area. Daylight is defined as the period when the solar flux normal to roof exceeds 30 Btu/hr·ft².

Miller (2006), required monitoring the decay rate of the tracer gas CO₂ with time using the following equation, derived from a continuity balance for the concentration of CO₂:

$$\dot{V}_{\text{Air}} = -\frac{\text{VOL}_{\text{Channel}}}{t} \text{LN} \left[\frac{C(t) - C_{\infty}}{C_i - C_{\infty}} \right] \quad \text{Equation (3)}$$

We injected the gas into the vent gap of the soffit and saturated the cavity with about 20,000 ppmv of CO₂ gas. After a substantial buildup of concentration registered on a monitor (20,000 ppmv of CO₂), the gas injection was stopped, and the concentration was recorded at timed intervals. All measurements were made around solar noon, when the two roofs were at their highest temperatures and thus had the highest heat flows penetrating the attic.

Data for the two stone-coated metal shakes were collected (Table 5); the calculated airflows were about 18 cfm. The average velocity was about 0.3 ft/s. Based on an integral technique for the case of a natural convection flow induced by a constant solar flux, the average velocity would be about 0.8 ft/sec after 14 ft of travel up a smooth, inclined channel. Therefore, the measured data is within reason of theory. The uncertainty of measurement for the tracer gas technique, calculated on the basis of a first-order error analysis, is estimated at about ±25% of the measurement.

The above-sheathing ventilation flow of about 18 cfm also helps assist with the removal of unwanted moisture. Moisture is a prevalent issue in all aspects of building design. As discussed in the following section, above-sheathing ventilation would remove both heat and moisture for the roof deck.

Table 5. Airflow rate and bulk velocity measured under the two stone-coated metal shake roofs using tracer gas techniques

	Light-gray shake on batten and counter-batten	Light-gray shake on batten and counter-batten (fascia vent)
Volume (V_{Channel} in ³) ^a	6673	6673
Airflow (cfm)	16.3	17.7
Av. velocity (V_{air} ft/s)	0.26	0.28

^aBased on measured cross-sectional area of shake and distance from one CO₂ metering station to another.

MOISTURE REMOVAL BENEFIT

To better understand hygrothermal performance, a moisture engineering analysis was performed on the roof system depicted in Figure 3. The roof system was simplified for inclusion in the 2-D MOISTURE-EXPERT model (Karagiozis 2001), that has shown good agreement in ventilated wall systems.

A series of simulations were performed to provide a preliminary scoping study on the potential for reducing moisture-related problems in the roofing systems. The simulations were performed using hygrothermal material properties available in the open literature. Material properties employed in the analysis were the sorption and suction isotherms, vapor permeability as a function of relative humidity, the liquid transport coefficients for moisture uptake and for moisture redistribution, the moisture-dependent thermal conductivity, and the effective heat capacity. Approximations by taking material data from the open literature will not impact the results from this preliminary analysis, as the intention was to compare the performances of a ventilated versus a nonventilated roof system.

The following modes of heat and moisture transport were included:

- Vapor diffusion through all porous roof construction materials
- Liquid transport through all porous roof construction materials
- Air convection transport for both thermal and moisture components
- Moisture storage in all roof construction materials
- Radiative transport with nighttime sky conditions
- Radiative transport within the air gap provided by the stone coated metal roof

- Condensation and evaporation processes and freeze and thawing processes with the associated latent heat exchanges

In the simulation analysis, the exterior and interior environmental loads were assumed for the climatic conditions of Knoxville, Tennessee. The proposed ASHRAE SPC 160P, “Design Criteria for Moisture Control,” were employed for both the exterior and interior hygrothermal loading conditions. All simulations were initiated using two times the equilibrium moisture content (EMC) at 80% relative humidity. Both the ventilated and nonventilated cases were simulated for a period of 2 years.

A snapshot of the moisture content in the sheathing board is given in Figure 8. The simulation period started October 1, 2005, one of the more difficult periods of the year to dry out. Above-sheathing ventilation accelerated the removal of unwanted moisture and reduced the moisture content of the OSB well below that of the OSB in an unvented cavity (Figure 8). Ventilating the roof deck dried the OSB within 200 days to safe moisture limits in which fungal growth would not typically occur. In comparison, the unvented roof deck required an additional 100 days to reach safe moisture content.

The number of air exchanges occurring within the ventilated cavity (Figure 9) tells the story. Air exchange rates are displayed for the assumed air changes per hour (ACH), which are dependent on both temperature and wind pressure flows acting along the roof ventilation cavity. Roughly 20–100 ACH are prevalent about 80% of the time during the 2-year simulation runs. The incidence of 60 ACH (the maximum air exchange rate) was observed to occur roughly 25% of the time. Therefore, the potential moisture removal benefits

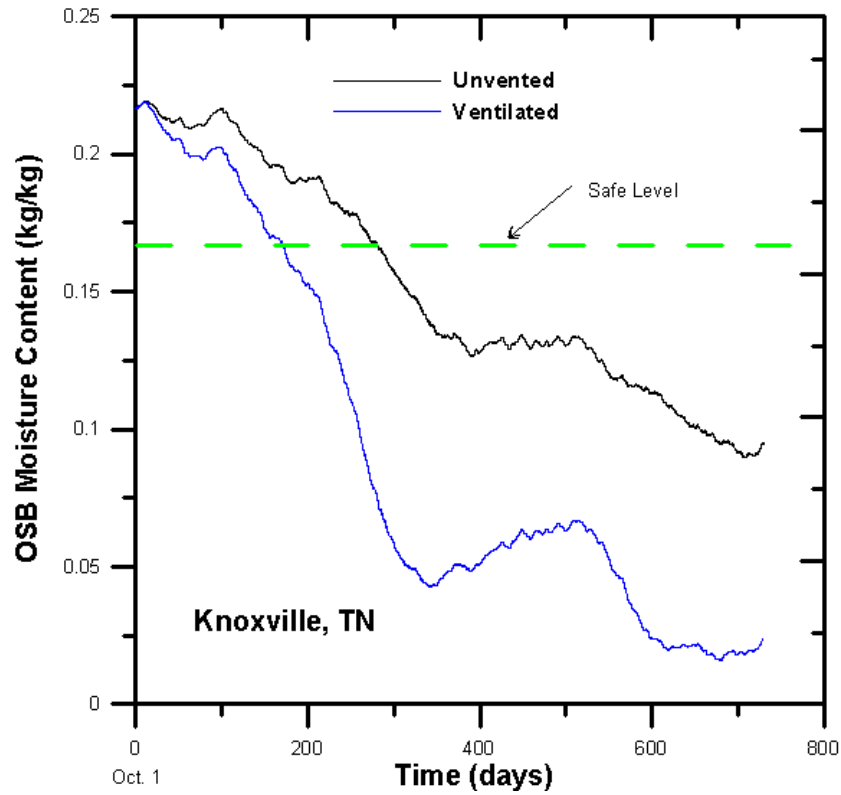


Figure 8. Comparison of moisture content of OSB layer as a function of ventilation strategy (ventilated vs. unvented) for a 2-year period.

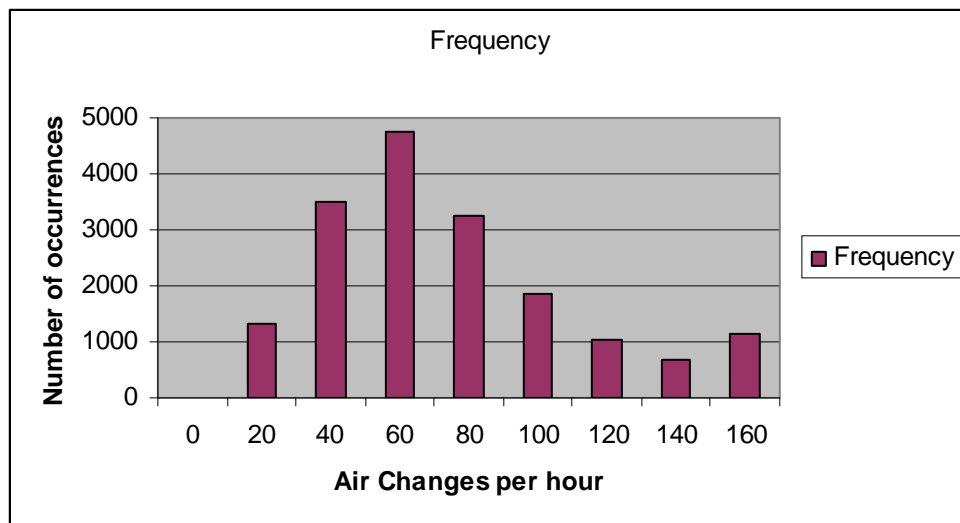


Figure 9. Period of time during 2-year simulation for cavity air changes per hour (wind- and temperature-dependent).

afforded by above-sheathing ventilation are evident from the vented compared to the unvented simulations.

CONCLUSIONS

Field results show that the combination of improved solar reflectance afforded by IrBCPs and above-sheathing ventilation make stone-coated metal roofs energy-efficient. The light-gray stone-coated metal shakes offset-mounted with a batten and counter-batten system reduced the heat transfer penetrating the roof deck by about 45% compared with the heat penetrating the deck of an attic covered with an asphalt shingle roof. About 15% of the reduction was due to IrBCPs, and another 30% was due to above-sheathing ventilation. The combined effects of solar reflectance and above-sheathing ventilation supported a 70% reduction in the heat flow penetrating the ceiling into the conditioned space. Above-sheathing ventilation of the stone-coated metal roofs is just as important as the boost in solar reflectance for reducing the heat gain into the attic and conditioned space.

Above-sheathing ventilation improves the summer performance of the attic assembly and also reduces the heat losses by night-sky radiation during the winter. The reduction in night-sky radiation helps negate the heating penalty associated with the stone-coated metal cool roofs. Offset-mounting the infrared reflective stone-coated metal roofing provides a synergistic seasonal effect by improving cooling performance and reducing winter heat losses. Therefore, cool roofs using IrBCPs can be effectively utilized in more predominately heating climates provided the deck provides above-sheathing ventilation.

The roof employing above-sheathing ventilation has shown superior performance when compared with the unvented roof system in thermal and in hygrothermal performance. This preliminary analysis demonstrates the potential for ventilation to be employed in cool roofs using IrBCPs. More research could develop the pressure boundary dynamics for a number of roofing applications that could allow these roofs to be moisture-optimized.

ACKNOWLEDGMENTS

Funding for this project was provided by the U.S. Department of Energy under the supervision of Marc LaFrance of the Building Technologies Program. The IrBCP project team members are André Desjarlais, William Miller, Tom Petrie, Jan Kosny and Achilles Karagiozis, all of ORNL's Buildings Envelope Program. The Metal

Construction Association and its affiliate members provided the stone-coated shake and S-mission roofs used in testing. Metro Roof Products constructed the attic assemblies and provided valuable assistance in installing the roofs on the steep-slope assemblies. The financial support of the Metal Construction Association and the guidance of Metro Roof Products are greatly appreciated.

The metal roofing manufacturers and pigment (colorant) manufacturers selected appropriate color pigments. They applied them to stone-coated metal shakes and S-mission tile, and field-tested the prototypes on a steep-slope roof assembly for one year, collecting summer and winter exposure of the stone-coated metal products.

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