The Trade-Off between Solar Reflectance and Above-Sheathing Ventilation for Metal Roofs on Residential and Commercial Buildings

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ABSTRACT

An alternative to white and cool-color roofs that meets prescriptive requirements for steep-slope (residential and non-residential) and low-slope (non-residential) roofing has been documented. Roofs fitted with an inclined air space above the sheathing (herein termed above-sheathing ventilation or ASV) performed as well as, if not better than, high-reflectance, high-emittance roofs fastened directly to the deck. Field measurements demonstrated the benefit of roofs designed with ASV. A computer tool was benchmarked against the field data. Testing and benchmarks were conducted at roofs inclined at 18.34°; the roof span from soffit to ridge was 18.7 ft (5.7 m). The tool was then exercised to compute the solar reflectance needed by a roof equipped with ASV to exhibit the same annual cooling load as that for a direct-to-deck cool-color roof. A painted metal roof with an air space height of 0.75 in. (0.019 m) and spanning 18.7 ft (5.7 m) up the roof incline of 18.34° needed only a 0.10 solar reflectance to exhibit the same annual cooling load as a direct-to-deck cool-color metal roof (solar reflectance of 0.25). This held for all eight ASHRAE climate zones complying with ASHRAE/IES Standard 90.1 (2007a). A dark heat-absorbing roof fitted with 1.5 in. (0.038 m) air space spanning 18.7 ft (5.7 m) and inclined at 18.34° was shown to have a seasonal cooling load equivalent to that of a conventional direct-to-deck cool-color metal roof. Computations for retrofit application based on ASHRAE/IES Standard 90.1 (1980) showed that ASV air spaces of either 0.75 or 1.5 in. (0.019 or 0.038 m) would permit black roofs to have annual cooling loads equivalent to the direct-to-deck cool roof. Results are encouraging, and a parametric study of roof slope and ASV aspect ratio is needed for developing guidelines applicable to all steep- and low-slope roof applications.

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 Parker and Sherwin (1998) to reduce the exterior temperature and produce savings in comfort cooling. Akbari and Levinson (2008), in a compilation of cool roof studies conducted for non-residential low-slope buildings, observed summertime daily air-conditioning savings ranging from 10% to 30%, though some reported data showed values as low as 2% and as high as 40%. Their findings clearly show that cool roofs can be a viable strategy for reducing energy consumption; therefore, many U.S. states have implemented prescriptive requirements for cool roofs in their energy codes based on ASHRAE Standard/IES Standard 90.1 (2007a), ASHRAE Standard 90.2 (2007b), or the International Energy Conservation Code (2009).

California's building code regulations, referred to here as 2008 Title 24, specify either prescriptive requirements or a whole-building performance approach for demonstrating the energy-efficiency compliance of buildings in California (CEC 2008). The performance approach allows the building owner to simulate the energy use of a proposed building with an approved whole-building model. Alternatively, the prescriptive approach requires that each building component meet or surpass the respective component requirements

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in 2008 Title 24, which prescribes the initial solar reflectance (SR) of steep-slope residential and non-residential cool roofs. Aged solar reflectance must equal 0.15 and emittance must be greater than or equal to 0.75 for residential roofing.

While industry agrees with many of the cool roof guidelines, there is concern among roof manufacturers that the strong emphasis on cool roofs ignores other viable construction practices such as above-sheathing ventilation (ASV). Therefore, this paper demonstrates the benefits of ASV through both field and computer verification. Field tests were conducted on the Envelope Systems Research Apparatus (ESRA). The data were used to benchmark the computer tool AtticSim (Version 13).[1] The computer tool uses overall energy balances to calculate the heat flows and temperatures on the external and internal surfaces of the attic. The tool can predict the temperature difference across the air space of an ASV system and was validated against field data. The validated code was exercised to simulate roofs having a pitch of 18.34°, the same pitch as validated against the ESRA field measurements. AtticSim simulated the performance of roofs installed directly to the deck as compared to roofs fitted with ASV. Results of the simulations are described to show that roofs equipped with ASV can meet existing prescriptions for cool roofs.

ABOVE-SHEATHING VENTILATION–FIELD DATA AND COMPUTER BENCHMARKS

Several steep-slope roofs and attics were installed on top of the ESRA, located on the campus of the Buildings Technology Research Integration Center at Oak Ridge National Laboratory. Stone-coated metal and standing-seam metal roofs were equipped with ridge and soffit vents for ventilating the attic. The ratio of the vent opening area to attic floor area was 1 to 300. Miller (2006) field tested stone-coated metal products with shake profiles to observe and quantify the effect of ASV (Figure 1a). Stone-coated metal is made of 26-gauge Zincalume (pre-primed 55% Al-Zn hot-dip-coated steel). It is coated with a layer of stone chips sealed by an acrylic base coat and over-glazed.

Standing-seam metal roofs (green color in Figure 1a) were also field tested to document the effects of offset metal roofs as compared to metal fastened directly to the roof deck. The metal panels snap-lock together and have a straight pan profile. Panels are 24 gauge galvanized steel painted with a polyvinylidene fluoride (PVDF) finish that contains infrared-reflective paint pigments. Solar reflectance of the painted metal is about 0.30 and is warranted for 35 years.

The distance (L) from the soffit to ridge is 18.7 ft (5.7 m) for the roofs pictured in Figure 1a, and the inclination of the roofs is 18.43°. The double-batten arrangement (Figure 1b) provides an air space of height (W) equal to 0.75 in. (0.019 m). Therefore, the aspect ratio (L/W) for the stone-coated metal roof is about 300:1. Air space heights of 0.75 and 4.0 in. (0.019 and 0.1 m) were field tested in the standing-seam metal roofs (Figure 1a) yielding aspect ratios of 300:1 and 56:1, respectively.

Stone-Coated Metal Field Measurements

Miller, Wilson, and Karagiozis (2006) field tested dark-gray stone-coated metal shakes having a solar reflectance of 0.08 and thermal emittance of 0.89 (abbreviated SR08E90) and light-gray metal shakes (SR26E90). Both were tested on identical double-batten constructions (air space of ¾ in. [0.019 m], Figure 1b). The dark-gray metal shake and the control shingle have almost identical solar reflectance and thermal emittance, yet the peak heat flow crossing the roof deck from the dark-gray shake was just 70% of the heat flow crossing the roof deck of the control

[1] AtticSim Version 13 originated from the ASTM C1340 (2004) protocol. Version 13 contains revisions for above-sheathing ventilation benchmarked by Miller et al. (2007) and attic ventilation as developed by Ken Childs.

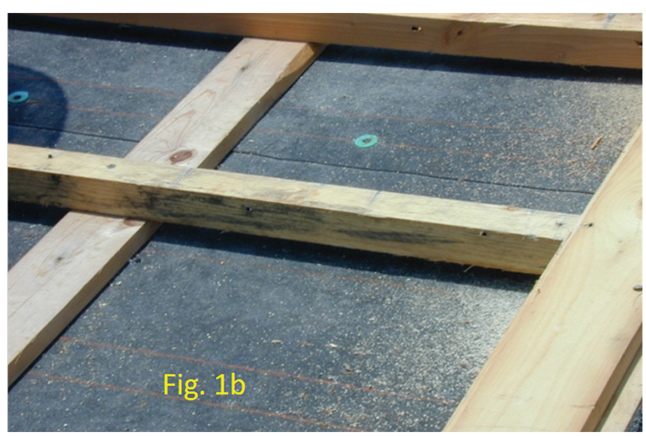

Figure 1 *(a) Roofs offset-mounted from the roof deck for ASV or fastened directly to the roof deck on the Envelope Systems Research Apparatus. (b) Stone-coated metal offset from the roof deck using double battens.*

shingle (Figure 2). The 30% lower heat flow was caused in part by the thermal mass of the double battens, the thermal resistance of the air space, and the low emittance (0.35) of the bare metal underside of the stone-coated roof shake.

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 shake (Figure 2). Miller, Wilson, and Karagiozis (2006) also determined that the heat flow diverted away from the attic by ASV of the hotter dark-gray shake is more than double that removed by the light-gray shake.

The hotter dark-gray roof causes greater buoyancy-induced airflows; therefore, the ventilation scheme is somewhat self-regulating. The darker the roof, the hotter the roof, so there is greater buoyancy to carry heat away from the attic. For the data shown in Figure 2, the surface temperature of the asphalt shingle peaks at 165.6°F (74.2°C). Buoyancy-driven airflow in the inclined air space cooled the dark-gray stone-coated metal shake 10°F (5.6°C) below that of the shingle; the dark shake had a peak temperature of 155.5°F (68.6°C). The addition of cool-color pigments further dropped the surface temperature of the light-gray shake to 151.3°F (66.3°C). Temperature profiles measured from the soffit to ridge at four discrete cross sections of the roof deck for the light-gray shake reveal the benefit of the inclined air space (Figure 3). Heat flow crossing the roof deck was measured with heat flux transducers (HFTs) embedded into the underside of the OSB deck (Figure 3). The HFTs show a linear but slight increase in heat flow, which is also reflected in the temperature trends observed in the oriented strand board (OSB) and inclined air space. The temperature difference from air to underside of OSB increases with length (Figure 3). This causes the increase in heat transfer observed in the HFTs from soffit to ridge.

The air space temperature was 124°F (51.1°C) after 4 ft (1.2 m) of travel up the roof (Figure 3). However, after another 12 ft (3.6 m) of travel,[2] its temperature rose to 138°F (58.9°C). Slight increases are observed in the top side temperature of the OSB (Figure 3); however, the thermal buoyancy in the air space keeps the OSB cooler than that of the direct-nailed shingle roof. The OSB for the shingle roof was 138°F (58.9°C) at a 10 ft (3.05 m) station. In contrast, the OSB for the light-gray shake was 116°F (46.7°C) at a similar location.

STANDING-SEAM PAINTED METAL FIELD MEASUREMENTS

Field tests (Figure 4) revealed that the control asphalt shingle (solar reflectance of 0.09 and thermal emittance of 0.89, abbreviated SR09E89), had heat flows crossing the deck similar to those of a metal roof applied directly to the deck. The cool-color painted metal (solar reflectance of 0.28 and thermal emittance of 0.81, abbreviated SR28E81) had similar deck heat flows to the shingle roof. The results are due in part to the higher thermal resistance of the shingle and its higher thermal mass. Shingles overlap and the added bulk causes the shingle to perform better than painted metal if both systems have the same solar reflectance and thermal emittance.

Two painted metal roofs were offset about 0.75 in. (0.019 m) from the roof deck. One of the two roofs had its underside painted with conventional backer[3] paint. The other metal roof was painted with a low-emittance coating for im-

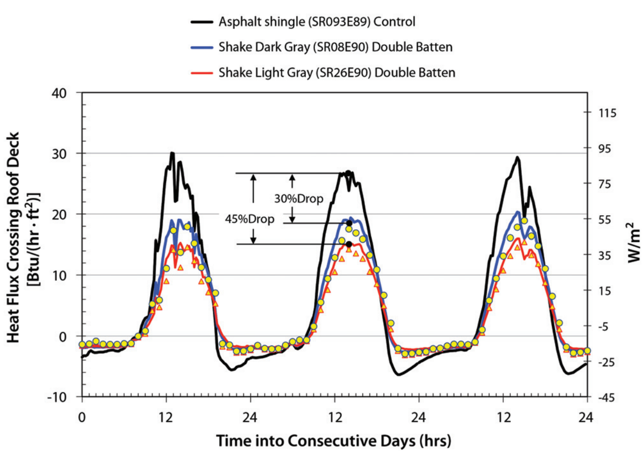

Figure 2 *Heat flow measured crossing the roof deck of a direct-nailed shingle roof and stone-coated metal roofs with and without cool-color pigments. Stone-coated metal roofs were installed on 1½ × 1½ in. (0.038 × 0.038 m) double battens. The open symbols represent AtticSim benchmarks against the field data for the dark-gray shakes (open circles) and light-gray shakes (open triangles).*

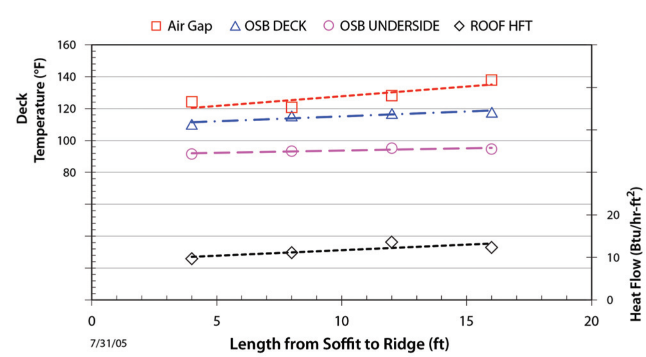

Figure 3 *Temperatures in the inclined air space, the oriented strand board (OSB) facing the metal shake, the OSB facing into the attic, and the roof deck heat flux are measured at discrete locations from soffit to ridge of the light-gray stone-coated metal shake. Measurements made at 12:00 PM EDST.*

2. Measurement location is within 2 ft (0.61 m) of ridge vent; total roof length is about 18.7 ft (5.7 m).

proved radiation control. Field tests showed that the painted metal roof with 0.75 in. (0.019 m) air space and backer paint on its underside had almost the same deck heat flow as observed for a direct-to-deck metal roof that had an EPS[4] insert (Figure 4). The finding implies that the 0.75 in. (0.019 m) air space is roughly equivalent to a thermal resistance of R_{US}-1 (R_{SI}-0.18). Adding the low-e undercoat dropped daytime heat flows below that of the roof with backer paint (Figure 4) and resulted in deck heat flows almost identical to another metal roof with 2 in. (0.51 m) of air space (not shown in Figure 4). ASV air spaces of 2 in. (0.51 m) and 4 in. (0.10 m) were also compared to the cool metal with EPS insulation inserted between the pan and the deck. Field data showed that both air gaps reduced deck heat flows below that observed for the metal roof with EPS insert having R_{US}-1 (R_{SI}-0.18) thermal resistance.

AtticSim Benchmarks to Stone-Coated Metal and Standing-Seam Metal Field Data

Wilkes (1991), Petrie et al. (2004), and Miller et al. (2007) all demonstrated AtticSim's ability to accurately predict the surface temperature and ceiling heat flow for attic assemblies with direct-nailed roof products. The AtticSim model can account for different insulation R-values and 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 are provided by Wilkes (1991). Miller et al. (2007) modified the code for inclusion of ASV.

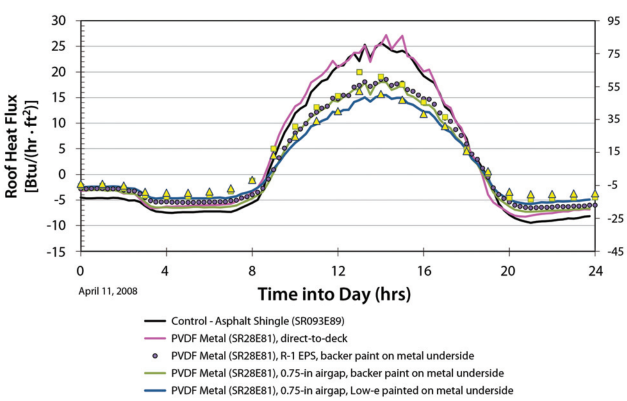

Figure 4 *Heat flow crossing the roof deck of cool-color standing-seam painted metal roofs. Open symbols (circle and triangle) represent AtticSim benchmarks against the PVDF metal roofs with 0.75 in. (0.019 m) air space.*

3. Prepainted metal roofing uses backer paint on the interior surface of metal panels to provide additional corrosion resistance, scratch resistance, and aesthetics where the underside is seen in open purlin structures.

4. EPS is expanded polystyrene insulation that is R_{US}-1 for its thickness of ¼ in. (0.071 m).

He describes tracer gas tests that were used to benchmark AtticSim's ability to predict the natural convection airflow in the ASV inclined air space. Herein, the code was also benchmarked against the stone-coated metal data (Figure 2), the standing seal metal data (Figure 4), and ASHRAE (2005) data for a closed air space. The code was then exercised to predict the benefit of opening the air space in terms of the effective R-value (shown later in Table 1).

Stone-Coated Metal. Weather data[5] from a station adjacent the ESRA was read by the AtticSim code and used to simulate the dark-gray and light-gray stone-coated metal roofs (refer back to Figure 2). The code accounted for the effects of ASV and predicted the heat transfer crossing the roof deck of the dark-gray shake within ±15% of measures made with HFTs embedded in the roof deck (view open circles with yellow highlight). AtticSim also predicted the heat flux crossing the roof deck of the light-gray shake and closely followed the trends in measured heat flux. These results are surprisingly good because the ASV algorithm does not account for the thermal mass of the double battens or for the radiation view factors among all battens and roof deck. It simply computes the radiation exchange between two parallel plates of finite dimension.

The AtticSim algorithm for ASV assumes an inclined air space (gap height of W) that runs from the soffit to the ridge (length of L). Note, however, that the aspect ratios used by experimentalists to derive convective heat transfer correlations from which the convection heat transfer coefficient is computed and used to calculate heat transfer crossing the air space in AtticSim are only of the order 50 to 1. AtticSim uses the correlation by Azevedo (1984) for an open inclined channel with aspect ratios ranging from 10:1 to 22:1. For a closed air space with the warmer surface below the colder surface, the ASV algorithm uses Holland's (1976) inclined closed cavity correlation. Holland's correlation was developed from an experimental facility with aspect ratio of 48:1. During summer exposure, the roof cover is hotter than the roof deck, and a lighter air layer hugs the underside of the roof cover as it travels up the roof; it is naturally above the denser air layer in contact with the cooler bottom surface of the air space (i.e., OSB deck). Arnold et al. (1974) and ElSherbiny et al. (1984) offer a correlation that is based on an adaptation of heat transfer in a vertical closed cavity useful for aspect ratios exceeding 5. Hence the benchmarks reported herein are very important and verify the applicability of the multiplicity of correlations used in the ASV algorithm within AtticSim because the correlations are based on aspect ratios different than found in roof applications.

Standing-Seam Metal. AtticSim also predicted the heat transfer crossing the roof deck of standing-seam metal roofs fitted with a 0.75 in. (0.019 m) air space. Here the in-

5. A local weather station provided outdoor temperature, relative humidity, wind speed and direction, irradiance, and night-sky radiation for use in validating the AtticSim code.

clined channel was clear of any obstructions inside the cavity, and therefore AtticSim's predictions are well within 10% of heat flux measurements depicted in Figure 4. The open squares with yellow highlight (Figure 4) represent the heat flow crossing the OSB deck of the PVDF metal having backer paint on its underside and 0.75 in. (0.019 m) of air space. Note that the open circles with brown highlight represent the heat flow through the roof deck where R_{US}-1 (R_{SI}-0.18) EPS insulation was sandwiched between the metal and OSB. The field data and AtticSim predictions are very consistent and prove the code is capable of accurately calculating the heat transfer crossing roof decks equipped with ASV. The triangle symbols highlighted in yellow represent simulations results for a PVDF metal roof with 0.75 in. (0.019 m) of air space but with the underside of the metal painted with a low-emittance paint (Figure 4). The results show AtticSim's ability to capture the physics of the combined convection and radiation heat transfer occurring in an ASV inclined air space.

The AtticSim code was also validated for a case having an aspect ratio of 55:1 (e.g., standing-seam metal roof with inclined air space of 4 in. [0.032 m]). The standing-seam metal roof was equipped with thermocouples measuring temperatures of the air space and roof deck at several discrete locations up the roof (similar to that shown in Figure 3). The thermocouples in the air space (four discrete locations) were averaged and plotted against AtticSim estimates. AtticSim is designed to compute overall heat balances for the various surfaces of the attic. Results in Figure 5 prove AtticSim is capable of accurately predicting the average air temperature in an ASV inclined air space.

***ASHRAE Handbook—Fundamentals* Data.** The *ASHRAE Handbook—Fundamentals* (2005) lists data for the thermal resistance of an inclined and closed air space. The data accounts for the effects of aspect ratio, slope, and convection and radiation heat transfer occurring within the air space. ASV results computed by AtticSim for a closed cavity are in excellent agreement with ASHRAE data (Table 1).

For the case of a painted metal roof with 0.75 in. (0.019 m) of open air space and a span of 18.7 ft (5.7 m), AtticSim predicts R_{US}-0.91 (R_{SI}-0.16) for a 0.75 in. (0.019 m) air space spanning 18.7 ft (5.7 m). The Table 1 result is within 10% of the experimentally derived result in Figure 4 for the SR28E81 metal roof with R_{US}-1 (R_{SI}-0.17) of expanded polystyrene insulation between the sheathing and metal pan. Increasing the air space from 0.75 in. (0.019 m) to 4 in. (0.10 m) caused a 40% jump in the thermal resistance of the open air space. However, including a low-emittance surface (E = 0.05) caused the air space resistance to jump by a factor of 6 as compared to the open cavity with effective emittance of 0.82 (Table 1). ASHRAE (2005) documents similar effects of emittance in an inclined but closed air space.

METHODOLOGY USED FOR SR AND ASV TRADE-OFF

AtticSim and Energy Plus were coupled through parallel simulations to compute the heat transfer through ceilings under attics. Simulations were made for the ASHRAE climate zones and for Sacramento, California (Table 2). An attic of 1539 ft^2 (143 m^2)[6] with a roof pitch of 18.34° was modeled with cool-color stone-coated metal, standing-seam metal, and asphalt shingle; solar reflectance of the cool roofs was set at 0.25 and 0.40. Simulations assumed supply and return air-conditioning ducts (cylindrical metal) installed in the attic. The supply duct surface area was set at 304 ft^2 (28.7 m^2). The surface area of the return duct exposed in the unconditioned attic was assumed to be 176 ft^2 (16.4 m^2). Energy Plus estimated the hourly indoor air temperature and hourly run times for a SEER 13 air conditioner as it cooled the home; heating assumed an 85% efficient gas furnace. The Home Energy Rating System (HERS) Building Energy Simulation Test (BESTEST) served as the simulated home (NREL 1995). It is used as a standard for evaluating the credibility of software used by HERS to predict energy use in homes.

Energy Plus computed hourly values of the mass flow rate of air in the duct system and the bulk air temperature entering the ducts for all climates listed in Table 2. Hourly values of duct flow rate, duct air leakage, bulk air temperature, percentage "on" time of the HVAC, and indoor air temperature were written to auxiliary files and read by AtticSim for computing the roof and attic load as coupled to the home simulated in the various ASHRAE climate zones. Low-slope simulations assumed the HVAC in the conditioned space.

The roof heat transfer for metal roofs with ASV was computed for the cooling and heating season and compared with data for a painted cool-color metal roof with a prescrip-

6. Footprint of 57 ft by 27 ft wide (17.4 m by 8.2 m).

Table 1. R-Value for an Inclined Air Space Computed by AtticSim and Compared to ASHRAE (2005) for the Case of a Closed Air Space. AtticSim Also Computed the Thermal Resistance for an Open Cavity

Air Space for 4-in-12 Pitch Roof	ASHRAE[1] (2005) (Closed Air Space)	AtticSim Simulation[1] (Closed Air Space)	AtticSim Simulation (Open Air Space)	AtticSim Simulation (Low-ε Surface in Open Air Space)
0.75 in. (0.019 m)	0.70	0.68	0.91	5.32
4.00 in. (0.10 m)	0.74	0.77	1.30	8.74

[1]An effective emittance of 0.82 was assumed with a mean temperature of 133°F (56.1°C) having 11°F (6.1°C) temperature gradient for heat flows moving downward across the air space.

tive requirement of 0.25 solar reflectance. The base case roof was fastened directly to the roof deck.

The ceiling insulation was set to comply with ASHRAE/IES Standard 90.1 for low-slope commercial roofing (ASHRAE 2007a) and with ASHRAE Standard 90.2 for steep-slope commercial and residential homes (ASHRAE 2007b). For retrofit practice, the ceiling and duct insulation were assumed to comply with thermal resistance levels published in ASHRAE 90 (1980), Table 2. Air leakage of the ductwork is unknown; however, for demonstration purposes, simulations assumed air losses of 10% of supply airflow for existing homes built to ASHRAE 90 (1980) code and 4% leakage for inspected, well-installed ductwork (Cummings et al. 1990; CEC 2008).

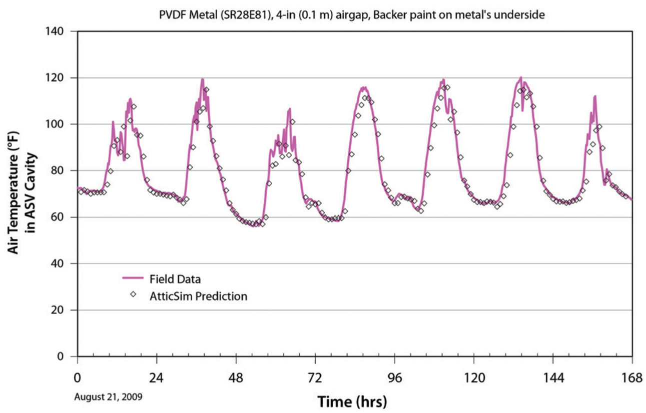

Figure 5 *AtticSim's prediction of the average air temperature in an inclined cavity of a standing-seam metal roof offset from the roof deck by 4 in. (0.032 m). Aspect ratio (L/W) of 48:1.*

TASKS REQUIRED TO JUDGE THE SR TRADE-OFF WITH ASV

Simulations were completed to judge the trade-off between solar reflectance and ASV for both low- and steep-slope roof assemblies. The ceiling heat transfer was computed over the cooling season for direct-to-deck cool roofs and for roofs equipped with ASV. Aspect ratio for the ASV roofs was 240:1 for a 0.75 in. (0.019 m) air gap and about 115:1 for a 1.5 in. (0.038 m) air space. Attic ventilation was set to 1:300. Computations assumed weathered reflectance values consistent with the 2008 Title 24 guidelines. However, PVDF painted metal and stone-coated metal roofs are very fade resistant and lose less than 10% of their original solar reflectance even after 30 years of weathering (Berdahl et al. 2006, Miller et al. 2010). AtticSim was exercised for the following tasks:

Task 1: Determine the solar reflectance needed for a steep-slope (18.34°) roof with ASV (min ¾ in. of continuous air space) to match load of an SR-0.25 (0.15 weathered) cool roof

Task 2: Determine the solar reflectance needed in a steep-slope (18.34°) roof with ASV (min ¾ in. of continuous air space) to match load of an SR-0.40 roof (0.25 weathered) fastened directly to deck

Task 3: Determine the solar reflectance needed in a low-slope (9.5°) roof with ASV to match load of an SR-0.65 (0.50 weathered) cool roof fastened directly to deck

Table 2. Trade-Off of ASV with Solar Reflectance for Low- and Steep-Slope Roofs in ASHRAE Climate Zones and California Climate Zone 12

ASHRAE Climate Zones					ASHRAE Standard 90.2 Residential Code				ASHRAE/IES Standard 90.1 Commercial Code			
					ASHRAE Standard 90.2		ASHRAE Standard 90-80		ASHRAE/IES Standard 90.1 New		ASHRAE Standard 90-80	
Zone	City	State	HDD_{65}	CDD_{65}	Ceiling	Duct[1]	Ceiling	Duct[2]	Ceiling	Duct	Ceiling	Duct
1	Miami	FL	222	9368	30	8	20	5.5	15	NA	10	NA
2	Austin	TX	1481	7435	30	8	20	5.5	20	NA	10	NA
3	Atlanta	GA	2614	4814	30	8	20	5.5	20	NA	10	NA
4	Baltimore	MD	4731	3598	38	8	21	5.5	20	NA	11.8	NA
5	Chicago	IL	6139	2895	43	8	24	5.5	20	NA	13.3	NA
6	Minneapolis	MN	7787	2513	49	8	29	5.5	20	NA	16.4	NA
7	Fargo	ND	10052	1332	49	8	30	5.5	20	NA	16.7	NA
8	Fairbanks	AK	2697	1040	52	8	33	5.5	20	NA	19.6	NA
12	Sacramento	CA	2697	1202	38	6	20	5.5	20	NA	10	NA

[1]Inspected duct system "iiDuct" having 4% air leakage.
[2]Existing duct system "kkDuct" assumed 10% air leakage. ASHRAE 90-80 does not address leakage.

Three simulations per climate zone were needed (Figure 6) to develop the solar reflectance labels in Figures 7 and 8. As an example, simulations were conducted for a given climate zone (say Atlanta, which represents ASHRAE Climate Zone 3). Cumulative cooling and heating loads were written to an external file for the case of a roof fastened directly to the roof deck. A second run was made for an SR-0.25 roof fitted with ASV; its cooling and heating loads were also written to the external file. The third run read the data from the external file and used an interpolating scheme in AtticSim to adjust the solar reflectance of the roof with ASV until its annual cooling load matched the annual cooling load of the cool metal roof fastened directly to the deck. These are the solar reflectance labels shown in Figures 7 and 8.

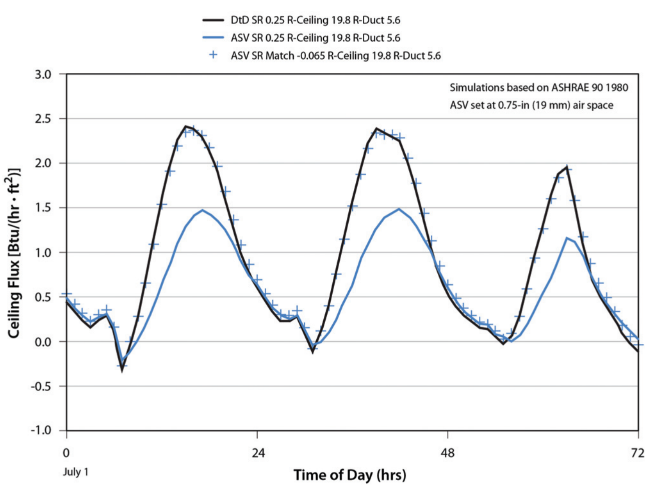

Figure 6 *Simulations showing (on the line defined by the + symbols) the match of ceiling load between a direct-to-deck cool metal roof and a roof fitted with ASV. AtticSim matched the loads by adjusting the solar reflectance of the ASV roof.*

A check of the procedure is shown in Figure 6 for three contiguous July days. The direct-to-deck cool metal roof having solar reflectance of 0.25 has a peak-day heat flow crossing the attic floor that is about 40% higher than the load for a cool roof fitted with ASV (Figure 6). By adjusting the solar reflectance of the roof with ASV, its seasonal load is made about equal to the load for the direct-to-deck base roof. (See control roof black line comparison to the ASV roof with adjusted SR defined by + symbols in Figure 6.)

Task 1. AtticSim/Energy Plus computed the heat flux crossing the ceiling below a cool metal roof that was attached directly to the deck (Figure 7). The solar reflectance of a cool metal roof fitted with ASV was modified until its seasonal cooling load matched the computed load for the conventional direct-to-deck cool roof assembly. New construction (Figure 7) and retrofit practice (Figure 8) were compared to the base, a cool-color painted metal attached directly to the deck.

A painted metal roof with 0.75 in. (0.019 m) air space spanning 14.2 ft (4.3 m) from soffit to ridge needed only a 0.10 solar reflectance to have the same annual cooling load as a direct-to-deck cool-color metal roof based on ASHRAE Standard 90.2 (2007) code. Increasing the air space to 1.5 in. (0.038 m) for the same span caused the required solar reflectance to drop to almost the equivalent of a black roof. In other words, a roof fitted with 1.5 in. (0.038 m) of ASV spanning 14.2 ft (4.3 m) can be black and still have a seasonal cooling load within 0.05% of the conventionally constructed cool-color metal roof. The finding was also observed for stone-coated metal roofing. The stone-coated metal with an air space equal to or exceeding 0.75 in. (0.019 m) can be black and still have a seasonal cooling load that is less than that of a cool metal (SR-0.25) roof fastened directly to the roof deck.

Computations based on existing construction using ASHRAE Standard 90 (1980) were very eye opening

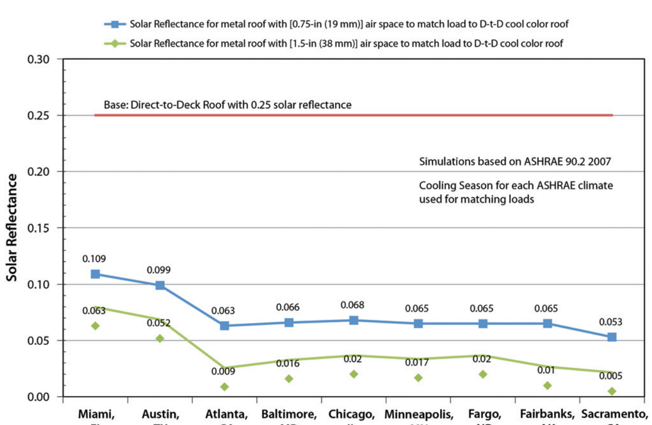

Figure 7 *Solar reflectance needed for a standing-seam metal roof with ASV (new product on new construction) to match the cooling load of a cool roof fastened directly to the roof deck.*

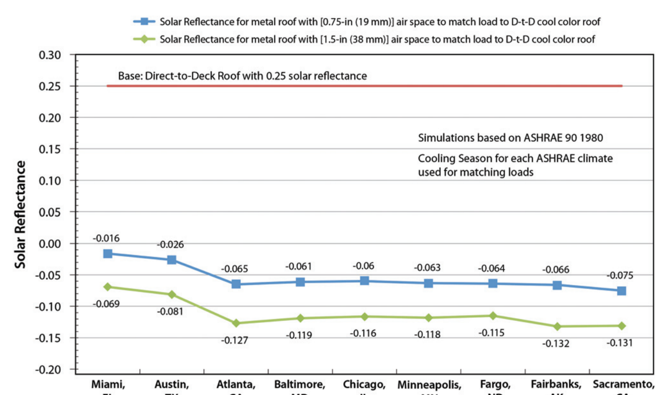

Figure 8 *Solar reflectance needed for a standing-seam metal roof with ASV (new product on existing construction) to match the cooling load of a cool roof fastened directly to the roof deck.*

(Figure 8). For several simulations, iterations yielded a negative solar reflectance to match loads, which is unrealistic because the lowest achievable solar reflectance is zero for a perfectly black absorber. Therefore, the negative values imply that the ASV roof can be black and still perform better than a direct-to-deck cool metal roof having a solar reflectance of 0.25.

For retrofit work, the offset-mounted metal roof could be black and still have the same annual cooling load as the cool metal direct-to-deck base case! The data suggest that offset-mounted standing-seam and stone-coated metal products can qualify as cool roof systems.

Task 2 is a continuation of the work in Task 1 with the exception that the solar reflectance of the cool roof is increased from 0.25 to 0.40. Pending legislation has suggested increasing the solar reflectance of roof products to as high as 0.40. Levinson et al. (2006) indicated that coated steel and glazed clay-tile products painted with cool pigments can achieve near-infrared solar reflectance of up to 0.50 and 0.75, respectively, resulting in a solar reflectance limit of about 0.50. We conducted the computations based on ASHRAE Standard 90.2 (2007) code to document the solar reflectance needed in an ASV metal roof to match the cooling load for a 0.40 solar reflective roof of conventional direct-to-deck construction (Figure 9). Again the roof slope is 18.34°, and the roof span from soffit to ridge is 14.2 ft (4.3 m).

Simulations for the hot climates surrounding Miami and Austin resulted in the highest solar reflectance needed by an offset-mounted roof to have the same seasonal cooling load as the 0.40 high-reflectance, direct-to-deck metal roof. Atlanta has 4814 CDD_{65} but also sees 2614 HDD_{65}, double that of Austin and 11 times that of Miami. From Atlanta on through the colder climates such as Baltimore, Chicago, and Minneapolis, the solar reflectance of a painted roof offset 0.75 in. (0.019 m) needs to be about 0.26 to have the same cooling load as the direct-to-deck base roof with high solar reflectance of 0.40. The stone-coated metal roof needs a solar reflectance of only 0.11 in Atlanta and the colder climates.

A standing-seam cool roof (0.25 SR) that has a 1.5 in. (0.038 m) air space spanning 14.2 ft (4.3 m) has about the same annual cooling load as the direct-to-deck, 0.40 high-reflectance roof assembly (Figure 9). The stone-coated metal with an air space of 1.5 in. (0.038 m) needs a solar reflectance of only about 0.1 in hot climates and 0.05 in cold climates to match the cooling load for a 0.40-SR cool roof that is fastened directly to the deck.

Task 3. AtticSim/Energy Plus computed the heat flux for a low-slope (9.5°), SR-0.65 (0.50 weathered) roof and compared it to the load for a roof fitted with a 2 in. (0.051 m) air space spanning 14.2 ft (4.3 m). Simulations investigated all climate zones listed in Table 2. The code determined the heat flux for the low-slope roof with 0.65 SR (0.50 weathered) and matched its seasonal cooling load to the offset-mounted assembly by altering the solar reflectance of the ASV system. Results for ASHRAE/IES Standard 90.1 (2007) and ASHRAE Standard 90 (1980) are listed respectively in Tables 3 and 4.

The ASV roof must have a solar reflectance greater than 0.55 for all climates zones (Table 3) in order to have the same

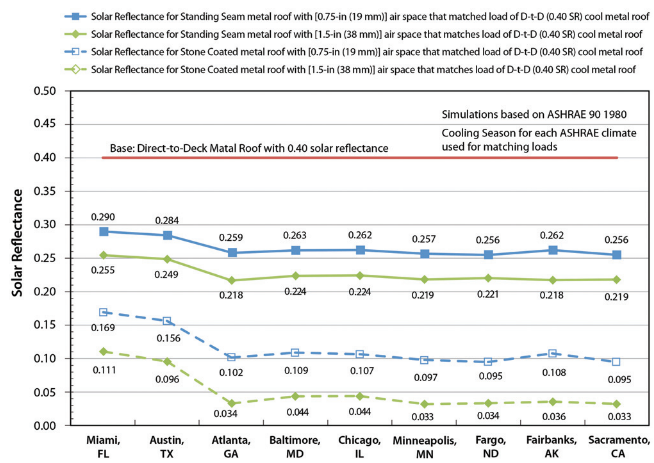

Figure 9 *Solar reflectance needed for a standing-seam metal roof with ASV (new product on existing construction) to match the cooling load for an SR-0.40 metal roof fastened directly to the roof deck.*

Table 3. Solar Reflectance Needed for a Painted Metal Roof Fitted with ASV to Match the Cooling Load of an SR-0.65 (SR-0.55 Aged) Cool White Roof Mounted Directly to Roof Deck (ASHRAE Standard/IES 90.1 [2007] Code)

Task 1C	Miami, FL	Austin, TX	Atlanta, GA	Baltimore, MD	Chicago, IL	Minneapolis, MN	Fargo, ND	Fairbanks, AK	Sacrament, CO
HDD_{65}	222	1481	2614	4731	6139	7787	10052	13940	2697
CDD_{65}	9368	7435	4814	3598	2895	2513	1332	1040	1202
R_{US} Ceiling	15	20	20	20	20	20	20	20	20
Direct-to-Deck	Solar reflectance needed by roof with inclined air space set at 2 in. (50.8 mm)								
New Product (SR 0.65)	0.577	0.572	0.546	0.543	0.539	0.535	0.526	0.547	0.529
Aged Product (SR 0.55)	0.399	0.392	0.356	0.356	0.351	0.347	0.340	0.354	0.337

Table 4. Solar Reflectance Needed for a Painted Metal Roof with ASV to Match the Cooling Load of an SR-0.65 (SR-0.55 Aged) Cool White Roof Mounted Directly to the Roof Deck (ASHRAE 90 [1980] Code)

Task 1C	Miami, FL	Austin, TX	Atlanta, GA	Baltimore, MD	Chicago, IL	Minneapolis, MN	Fargo, ND	Fairbanks, AK	Sacrament, CO
HDD_{65}	222	1481	2614	4731	6139	7787	10052	13940	2697
CDD_{65}	9368	7435	4814	3598	2895	2513	1332	1040	1202
R_{US} Ceiling	10	10	10	11.8	13.3	16.4	16.7	19.6	10
Direct-to-Deck	Solar reflectance needed by roof with inclined air space set at 2 in. (50.8 mm)								
New Product (SR 0.65)	0.565	0.557	0.537	0.536	0.536	0.535	0.526	0.547	0.529
Aged Product (SR 0.55)	0.386	0.375	0.346	0.347	0.347	0.347	0.340	0.354	0.333

cooling load as new product fastened directly to the roof deck and having a roof solar reflectance of 0.65. For aged product, the solar reflectance needed to match loads is less than the prescriptive code of 0.55. As an example, in Miami a 0.40 solar reflectance is needed for a roof with 2 in. (0.051 m) of air space to match the load of an SR-0.55 (aged) roof that is fastened directly to the roof deck. In Chicago, an SR-0.35 roof with 2 in. (0.051 m) of air space has the same cooling load as the 0.55 direct-to-deck assembly.

Generally the results for existing construction based on the ASHRAE Standard 90 (1980) code are very similar to those computed for the new 2007 code (Table 3 compared to Table 4). However, the annual loads are very different between the two cases because, for example, Chicago called for R_{US}-20 (R_{SI}-3.5) ceiling insulation in 2007 while in 1980 ASHRAE specified R_{US}-13.3 (R_{SI}-2.3).

CONCLUSION

Field tests were conducted to examine the effects of cool-color pigments on standing-seam metal roofs and stone-coated metal roofs attached directly to the roof deck or fitted with ASV. Results show that light-gray stone-coated metal shakes with ASV reduced the peak day heat transfer penetrating the roof deck by about 45% compared to the heat penetrating the deck of an attic covered with an asphalt shingle roof.

Field data also indicated that the measured summertime deck heat flows for an asphalt shingle roof having solar reflectance of 0.09 and thermal emittance of 0.89 was about the same as that measured for a cool-color standing-seam metal roof having a higher solar reflectance of 0.28 and thermal emittance of 0.85. Both roof assemblies were attached directly to the deck. Therefore AtticSim/Energy Plus simulations based on equal cool roof reflectance for the two systems revealed that the asphalt shingle yielded better performance if both roofs were direct-to-deck applications. As result, simulations were conducted using a painted metal fixed directly to the roof deck as the base to best show the trade-off between solar reflectance and ASV.

Simulations to determine the solar reflectance and ASV trade-off were conducted at the same roof slope (18.34°) as field tested on the ESRA and benchmarked by AtticSim against the field data. It is expected that the steeper the pitch of the roof, the greater will be the buoyancy-driven convection within the air space, and, therefore, the trade-off between solar reflectance and ASV will be more and more weighted toward ASV as roof slope increases. However, additional simulations conducted at steeper roof pitch and different roof spans (implying different aspect ratios) are needed to qualify potential code requirements for ASV as applied to steep- and low-slope roofs.

A standing-seam metal roof with 0.75 in. (0.019 m) air space with span of 14.2 ft (4.3 m) needs only a 0.10 solar reflectance to have the same annual cooling load as a direct-to-deck cool-color metal roof. A standing-seam metal roof fitted with 1.5 in. (0.038 m) of ASV or a stone-coated metal fitted with 0.75 in. (0.019 m) of air space (spanning 14.2 ft [4.3 m]) can both be black and still have a seasonal cooling load within 0.05% of the conventionally constructed cool-color metal roof (solar reflectance of 0.25). Computations for retrofit application based on ASHRAE Standard 90 (1980) showed ASV air spaces of 0.75 and 1.5 in. (0.019 and 0.038 m) would permit black roofs to have cooling loads equivalent to the direct-to-deck cool roof.

The hot climates of Miami and Austin require solar reflectance of 0.30 and 0.29 respectively for an ASV standing-seam metal roof (0.75 in. [0.019 m] air space spanning 14.2 ft [4.3 m]) to have the same seasonal cooling load as the 0.40 solar reflective direct-to-deck metal roof. For climates colder than Atlanta, the required solar reflectance for the ASV assemblies remain relatively level. Therefore, a cool-color roof (solar reflectance of 0.25) fitted with at least 0.75 in. (0.019 m) of ASV performs as well as a 0.40 reflective roof attached directly to the roof deck. The stone-coated metal with an air space of 1.5 in. (0.038 m) need only have a solar reflectance of about 0.10 to match the cooling load for a 0.40 solar reflective cool roof that is fastened directly to the deck.

A low-slope painted metal roof with 2.0 in. (0.051 m) of air space must have a solar reflectance slightly above 0.55 for all climate zones to match 0.65 direct to deck. Roof span was span was 14.2 ft (4.3 m). For aged product the solar reflectance needed to match load is less than the prescriptive code of 0.55. The results for existing construction based on the

ASHRAE Standard 90 (1980) code are very similar to those computed for the current 2007 code.

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ABBREVIATIONS, NOMENCLATURE, AND SUBSCRIPTS

air	=	air within inclined channel
ASV	=	above-sheathing ventilation
C_{DD}	=	cooling degree days based on 65°F
E	=	thermal emittance
EPS	=	expanded polystyrene insulation
H_{DD}	=	heating degree days based on 65°F
HFT	=	heat flux transducer
IR	=	infrared spectrum
L	=	length of roof from soffit to ridge
L/W	=	aspect ratio
PVDF	=	polyvinylidene fluoride
R_{SI}	=	thermal resistance ($m^2 \cdot °C/W$)
R_{US}	=	thermal resistance ($h \cdot ft^2 \cdot °F/Btu$)
sky	=	sky temperature
solar	=	irradiance
SR	=	solar reflectance
T	=	temperature
W	=	height of inclined air space

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