Steep-Slope Assembly Testing of Clay and Concrete Tile Roofs

WITH AND WITHOUT COOL PIGMENT

Part II of II

By William A. Miller, PhD, PE

This is the second of a two-part series. The first part, published in December, 2006, showed the effect of cool color pigments on the solar reflectances of clay and concrete tile roofs. The conclusion herein describes the effectiveness of cool color pigments on clay and concrete tiles through field test results and conclusions. The study was done for the California Energy Commission (CEC) and is published with its approval. An abbreviated report from the study was delivered at the RCI Foundation's 2005 Cool Roofing Symposium in Atlanta.

The multiple hazard protection provided by concrete and clay tile from fire and wind and the superior aesthetics and durability of tile are making these roof materials the preference of homeowners in western and some southern states. Thermal performance data collected from the attic test assembly at Oak Ridge National Laboratories (ORNL) show tile to be an energy-efficient roof product because of the venting occurring on the underside of the tile and because of the increase in solar reflectance achieved by cool color pigments.

Venting of attic spaces and its effect on heat transmission, moisture, and condensation have been studied at reasonable length, but little has been studied with regard to the venting and flow patterns observed in the inclined channel created by tile roofs. 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 procedures and the associated flow within the attic space. Though work is scarce on heat transfer within the narrow air channel in counter-batten installations, insight can be gained from the work done on attic ventilation and on experimental studies of heat transfer in inclined ducts. Ozsunar *et al.* (2001) studied the effects of inclination on convection within a large-aspect ratio duct heated from below. Beal and Chandra (1995) studied heat transfer through direct-nailed and counter-batten tile roofs compared to direct-nailed asphalt shingles. Tile in general reduced heat transmission by 39% for the direct-nailed roof and by 48% for the counter-batten roof.

These reported energy savings are attributed in part to thermally driven airflow within the air channel formed by the underside of the tile and the roof deck. The airflow is driven by buoyancy and/or wind-driven forces. The air channel also provides an improvement in the insulating effect of the roofing system. Measuring and correctly modeling the heat flow on the underside of a tile roof are key hurdles for predicting the roof's thermal performance. The heat transfer can switch from conduction to single-cell convection to Bénard cell convection, dependent on the aspect ratio made by the underside of the tile and the roof deck, slope of the roof, and weather. The coexistence and competition of the various modes of heat transfer require experimental measurements and numerical simulations.

INSTRUMENTATION FOR ATTIC ASSEMBLY

Surface and underside temperatures of the tile, temperatures of the roof deck on both sides of the oriented strand board (OSB), and heat flux transmitted through the roof deck are directly measured and electronically recorded by a data acquisition system (DAS).

All roof decks have a 2-inch-square by 0.18-inch-deep routed slot with a heat flux transducer (HFT) inserted to measure the heat flow crossing the deck. Each HFT was placed in a guard made of the same OSB material used in construction and calibrated using a FOX 670 Heat Flow Meter Apparatus to correct for shunting effects (i.e., distortion due to three-dimensional heat flow). Attic cavities also have an instrumented area in the ceiling for measuring the heat flows into the conditioned space.

The ceiling consists of a metal deck, a 1-inch-thick piece of wood fiberboard lying on the metal deck, and a 1/2-inch-thick piece of wood fiberboard placed atop the 1-inch

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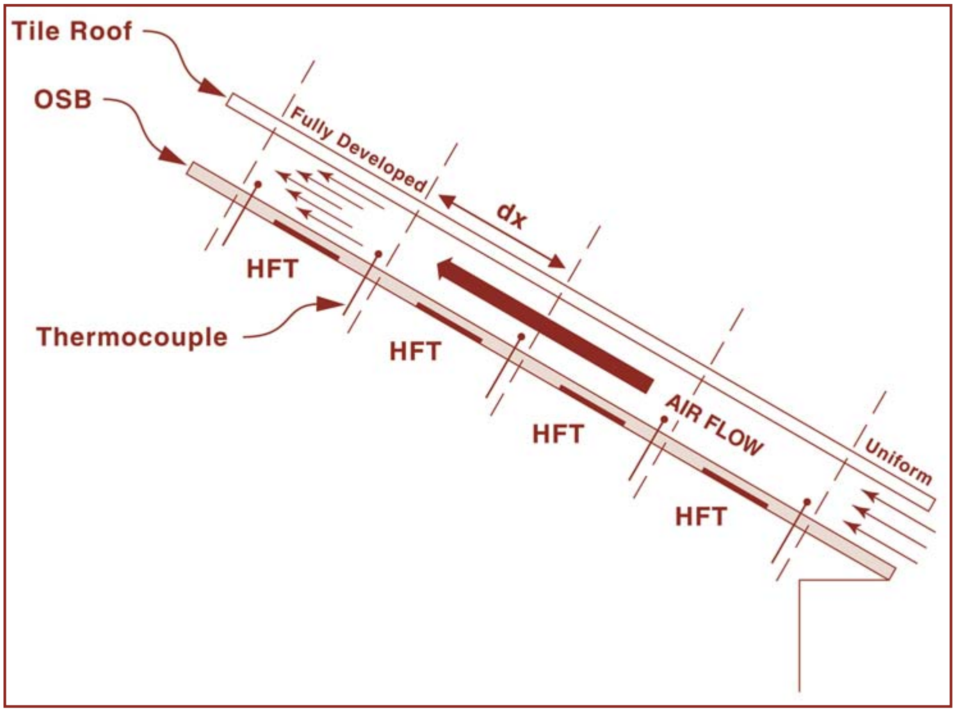

Figure II-1 – Instrumentation used on the underside of the tile roofs for measuring the heat transfer driven by thermally induced airflows.

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.

Tile roofs are traditionally offset from the roof deck, and the convection heat transfer in this space may be mixed, being a combination of forced and natural convection heat transfer. Data on the mixed-convection phenomena are sparse because buoyancy effects can cause oscillations in the inertia flow field, which make convergent numerical solutions difficult to obtain. Therefore, the effect of above-sheathing ventilation is a key measurement issue that required added instrumentation.

The S-Mission clay tile and flat-profile "slate" roofs have thermocouples and HFTs at four stations starting at the soffitt and spaced evenly about 4 feet apart up to the ridge to measure the bulk air temperatures and the heat flux near the underside of the tile (*Figure II-1*). These measurements are used to gauge the convective heat transfer within the air channel made by the underside of the tile and the roof deck. On a typical warm, sunny day, heat from the sun will penetrate the tile roof and will cause a net inflow of heat into the air channel. A portion of this heat is conducted into the attic space. Penetration of heat into the attic as measured by the HFTs is defined as positive heat flow. Heat leaving the attic or conditioned space is defined as negative heat transfer.

COOLING SEASON FIELD PERFORMANCE

Clay S-Mission tile (SR54E90), S-Mission concrete tile spot adhered with foam (SR26E86), and S-Mission concrete tile on battens (SR34E83) had the least amount of heat penetrating into their respective roof decks (*Figure II-2*). Roof heat flux data are for two consecutive days of exposure during August 2004 in East Tennessee's hot and humid climate. All three tiles have venting occurring along the underside of the tile's barrel from soffitt to ridge; however, the ridge vent is closed to simulate conventional installations in the western states.

Of these three roof systems, the clay tile (SR54E90) had the lowest heat flux through the deck, due primarily to the tile's high solar reflectance and above-sheathing ventilation. The clay tile reduced the peak heat flow through the roof deck at solar noon to about 30% of that through the deck of the attic covered with an asphalt shingle roof. Subsequently, the heat penetrating the ceiling of the attic assembly with clay tiles was reduced to about 40% of that entering through the ceiling of the attic assembly with asphalt shingles[1].

The solar reflectance and thermal emittance of the flat-profile "slate" roof (SR13E83) and the medium-profile tile (SR10E93) are very similar to that of the asphalt shingle (SR10E89), but the heat transfer through the roof and ceiling of the attic with the "slate" roof and the medium-profile tile roof are only half that measured for the asphalt shingle roof. The reduction must be due to buoyancy and wind-force effects occurring in the inclined air channel that dissipates heat away from the deck. The "slate" tiles are attached to batten and counter-batten strips, which form the inclined air channel that is about 1-1/2 inches deep. The medium-profile tile forms its own half-cylindrical channel of about 0.5-inch radius.

It is very interesting that these two dark tile systems (SR13E83 and SR10E91), as compared to the shingle roof (SR10E89), significantly reduce the heat penetrating their respective ceilings. The data in *Figure II-2* clearly show the benefit derived from venting the roof deck based solely on the direct comparison of the percent reduction of peak loads (i.e., ~45% reduction for the SR13E83 or SR10E93 and a 70% reduction for the SR54E90 tile as compared to the shingle roof). Proportioning the heat reduction due solely to venting (SR10E93 vs. SR10E89) to the heat reduction due to solar reflectance and venting (R54E90 vs. SR10E89): (*Equation 1*)

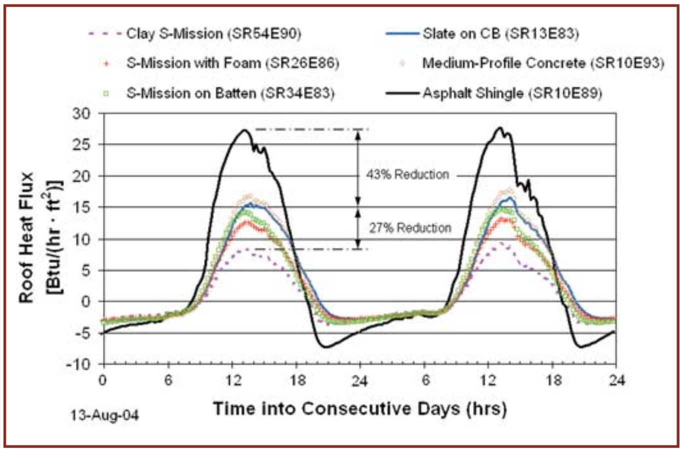

Figure II-2 – Heat penetrating the tile roof of each attic assembly on the ESRA. The ridge vent was closed.

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$$\overbrace{\frac{45\% \text{ due to venting}}{70\% \text{ due to venting and SR}}}^{\text{heat reduction}} \cdot \left[SR554_{\text{Clay Tile}} - SR10_{\text{Shingles}}\right]$$

Equation 1

yields a venting benefit at solar noon that is equivalent to roughly 30 points of surface reflectance![2] Hence, the data at peak loading imply that above-sheathing ventilation can be a “cool roofing” option.

A full month of field data for August 2004 was reduced to better observe the seasonal trends in roof heat transfer for the tile and asphalt shingle roofs. Data for the HFTs embedded in the south-facing roof deck and the ceiling of each attic assembly were integrated over the daylight hours (red bars in *Figure II-3*), nighttime hours (gray bars in *Figure II-3*), and the 24-hour cycle for HFTs embedded in the ceiling (blue bars in *Figure II-3*) and summed for the month. Hence, the red and gray bars represent, respectively, the total daytime heat gain and nighttime loss crossing the roof deck during August 2004 exposure. The blue bars represent the total heat transfer into the conditioned space measured from the HFT embedded in the ceiling of each attic assembly.

Results for the unvented attics show that the heat gain entering the asphalt shingle roof is almost double that observed for the medium-profile (SR10E93) and the flat-profile “slate” (SR10E83) concrete roofs. Therefore, the effect of venting the underside of the medium-profile and “slate” tile roofs based on proportioning roof heat transfer (*Equation 1*) equates to about 24 points of solar reflectance for the month of August 2004. In other words, an SR34E93 roof with no deck venting would have about the same roof heat transfer as the vented tile (SR10E93) roof.

Again, the S-Mission tile roofs have the least amount of heat penetrating the roof deck, with the clay tile (SR54E90) showing best performance. About 4,100 Btu/ft^2 of roof surface penetrated the shingle roof as compared to only 1,127 Btu/ft^2 for the clay tile roof, representing a 72% reduction in roof heat transfer. This, in turn, leads to the reduction in heat transfer observed crossing the ceiling of the two attic assemblies. The

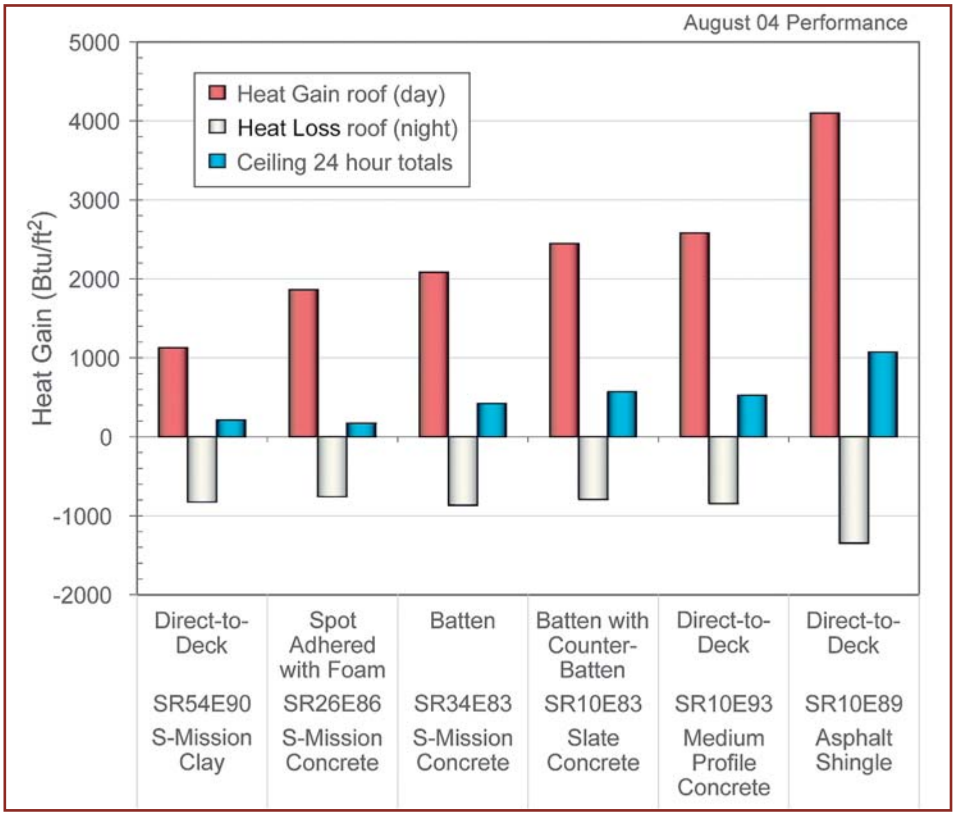

Figure II-3 – S-Mission tile reduced the integrated daytime roof heat gain by 50 to 75% of the gain for the asphalt shingle roof.


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The Achilles heel of all cool roof systems is, therefore, the heating penalty that offsets the energy and cost savings associated with the cooling benefit of the reflective roof system.

heat transfer penetrating the ceiling of the attic with clay tile was about 75% less than that measured for the heat penetrating the ceiling of the attic with an asphalt shingle roof.

It is also interesting to observe that all the tile roofs have less heat loss to the ambient sky as compared to the direct-nailed asphalt shingle roof (*Figure II-3*). The effect is due in part to above-sheathing ventilation and in part to the thermal mass of the tile. Parker, Sonne, and Sherwin (2002) showed that a white, galvanized metal roof slightly outperformed a white, S-shaped concrete tile roof because the thermal mass of the tile retained more heat that the air-conditioner had to temper earlier in the day than the house with a painted metal roof. However, in more moderate climates, this thermal mass effect is a benefit and will be discussed in the next section on heating seasonal performance.

Beal and Chandra (1995) showed that S-Mission tile on battens reduced the heat penetrating the ceiling by an additional 11% as compared to the same tile of the same color direct-nailed to the deck. Subsequently, above-sheathing venting of the tile roofs appears just as important as is the boost in solar reflectance for reducing the heat gain into the attic and conditioned space.

EFFECTS OF OPENING THE RIDGE VENT

As early as 1942, the Federal Housing Administration (FHA) set a 1:300 requirement (i.e., area of soffitt and ridge vent openings to attic footprint) for convective cooling of the attic air and for minimizing condensation on the underside of roof sheathing as a preventative maintenance measure (FHA 1942). However, the importance of convection cooling of the attic air is controversial. The ridge vents for the tile and asphalt shingle roofs were opened for the summer of 2005 to observe the effects of attic ventilation and, more importantly, the effect of unrestricted airflow within the inclined air gap made by the underside of the tile roofs. Two summer days with very similar outdoor air temperatures and solar irradiance were selected. On one day, the ridge vent was closed; on the other day, it was kept open (*Figure II-4*). The soffitt vent was open for both summer days of field-testing.

Opening the ridge vent reduced the bulk air temperature within the inclined air channel for the “slate” (SR10E83) tile and also for the clay (SR54E90) tile (*Figure II-4*). At solar noon, the bulk air temperature near the underside of the “slate” tile was 10˚F cooler than that observed for the same tile with the ridge vent closed during the previous summer. The effect for the S-Mission clay was about a 5˚F drop in the bulk air temperature for the two different summer days with very similar weather.

“Slate” tiles are laid one atop another and have little clearance for the seepage of air between overlapped tile. The S-Mission tiles are designed to be porous to minimize wind uplift forces (*Figure II-4*). Therefore, the clay tile allowed more leakage of air by naturally induced thermal gradiants between overlapped tiles than observed for

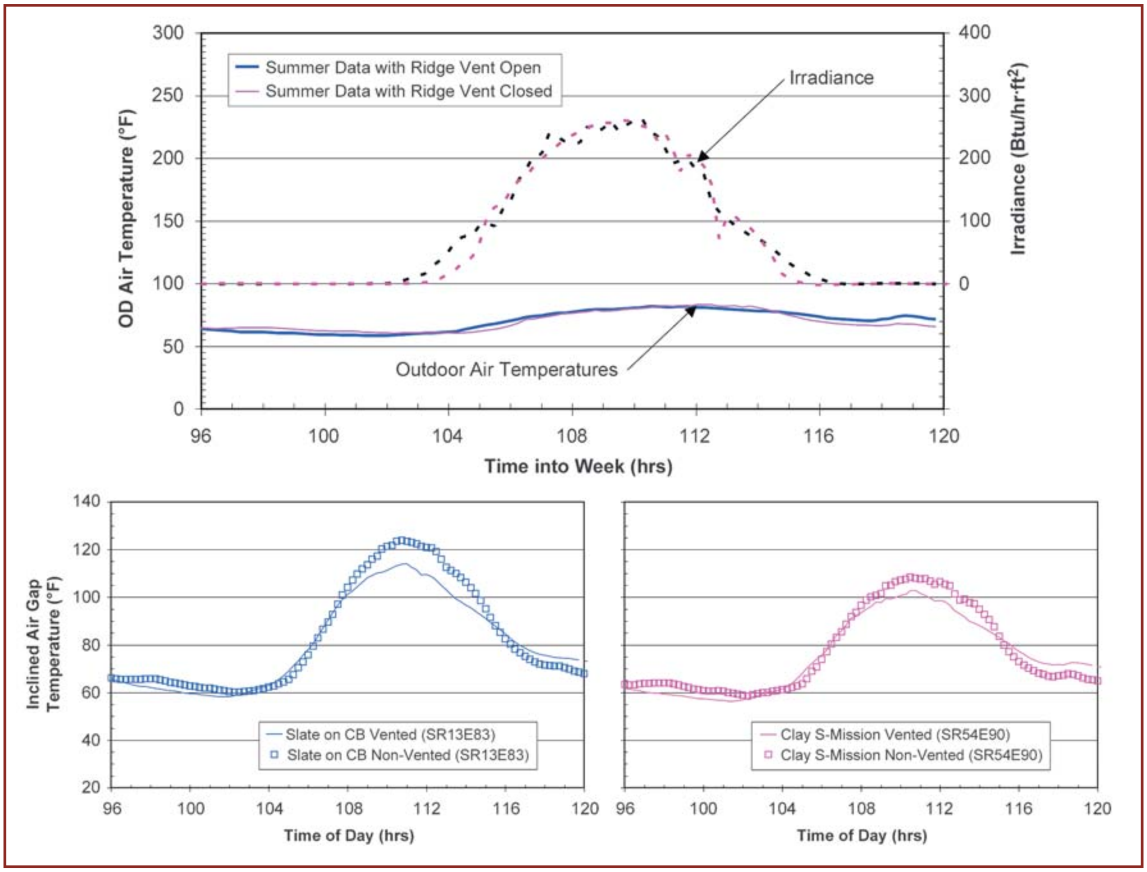

Figure II-4 – Bulk air temperatures underneath the S-Mission clay and the concrete “slate” tile for two different summer days; one with the ridge vent open and the other with the ridge vent closed.

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the "slate" tile system. As a result, opening the ridge vent caused a more significant drop in heat flow crossing the roof deck for the "slate" tile roof than for the clay tile roof (*Figure II-4*). The results imply that opening the ridge caused more heat to be exhausted out the ridge for both the S-Mission clay and the "slate" tile systems.

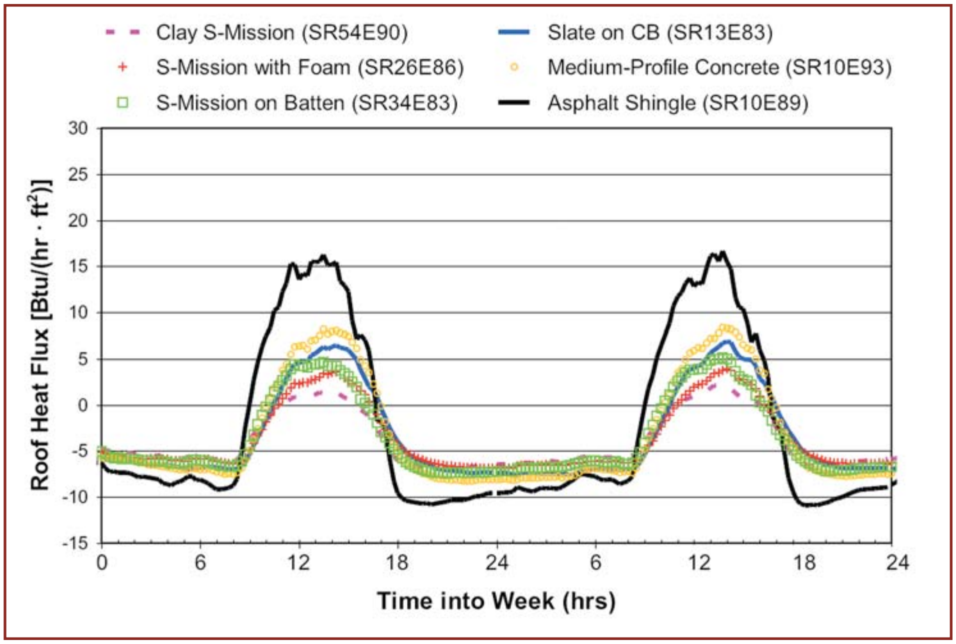

Figure II-5 – Roof deck heat flow for two consecutive days in January 2005; the ridge vent was closed.

HEATING SEASON FIELD PERFORMANCE

Cool roofs have received much positive trade press, as well as some state and federal support for installation 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 is, therefore, 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. The trade-off between climate and reflective roofs limits their penetration into predominantly heating-load climates. However, field data for the tile roofs tested in East Tennessee's climate are showing that the tiles' mass and above-sheathing venting are negating the heating penalty associated with cool roofs.

Results from two consecutive days with clear January skies are displayed in *Figure II-5* to review the thermal performance of the clay and concrete tile roofs compared to that of the dark, heat-absorbing, asphalt shingle roof. The ridge vents for these tests

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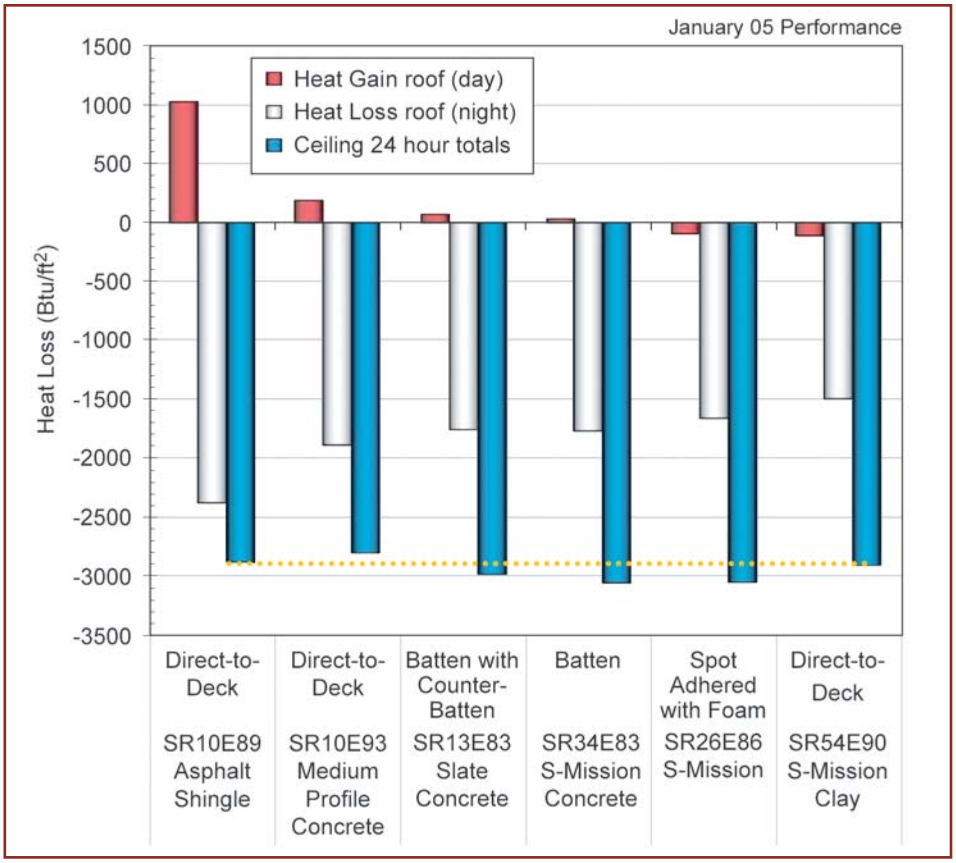

Figure II-6 – Integrated heat flow measured through the roof deck for all tile and shingle roofs during the month of January 2005.

were closed, and the average ambient air temperature for these two January days was 32˚F. At solar noon, the roof deck of the attic with asphalt shingles (SR10E89) absorbed about 15 Btu/h/ft^2 of solar flux, which is almost twice that absorbed by the medium-profile (SR10E93) or flat-profile (SR13E83) roofs. The attic assemblies with S-Mission clay and concrete tile showed marginal heat gains, with the clay tile showing almost no gain even at solar noon. However, from about 8 p.m. through about 6 a.m., all the tile roofs lose less heat to the night sky than does the asphalt shingle roof (*Figure 16*). The tile reach peak day temperatures ranging from 92˚F for the SR34E83 S-Mission concrete to 75˚F for the S-Mission clay tile (SR54E90). The shingle reaches about 105˚F peak temperature. But during the night, the tiles are all warmer than the shingles because of the thermal mass of the tile and because the air channel formed on the underside of the tile adds a radiative resistance to night-sky radiations losses as compared to the direct-nailed shingle.

Results integrated over the month of January 2005, as done similarly for August 2004, show that the above-sheathing ventilation and thermal mass of the tile roofs nearly counterbalances the heating penalty associated with cool roofing for the moderate climate of Tennessee (*Figure II-6*). Again, venting the underside of the tile plays a part in the results. The asphalt shingle roof gains about 1,000 Btu/ft^2 of roof deck during all January days, while the tile roofs show little gain, and some, a loss of heat from the roof deck. However, during the evening hours, the thermal mass and possibly the tiles' air channel have reduced the heat loss from the roof to the point that the heat loss from the ceiling of all roofs is about the same (see blue bars in *Figure II-6*).

These data are very promising because the tile roofs are negating the heating penalty associated with cool roofs in Tennessee's moderate climate, having 3662 HDD$_{65}$ and 1366 CDD$_{65}$. The fact that the SR54E90 and SR26E86 tile roofs actually lost heat during the January days implies that the radiative resistance afforded by the inclined air gap on the tiles' underside is the primary driver (rather than the mass of the tile) causing the reduction in nighttime heat losses.

CONCLUSIONS

Clay and concrete tile roofs are energy-efficient, cool roof products as verified by field results obtained for East Tennessee's climate. The combination of improved solar reflectance afforded by cool color pigments and above-sheathing ventilation reduced the noontime heat flow crossing the roof deck of the clay tile roof by 70% of the flow crossing the conventional shingle roof, which in turn reduced the heat entering the conditioned space to 60% of the heat flow penetrating the ceiling of the attic assembly with a shingle roof. The flat and medium-profile concrete roofs, having nearly the same surface properties as the conventional shingle, reduced the deck heat flow ~45% of that crossing the shingle roof because of above-sheathing ventilation.

Proportioning the reduction in deck heat flows due to above-sheathing ventilation to the reducton due to cool color pigments and above-sheathing ventilation indicates that the latter is equivalent to about 30 points of solar reflectance. In other words, the "slate" tile (SR13E83) on battens and counter-battens is equivalent to a direct-nailed concrete "slate" roof system with solar reflectance of 0.43 and thermal emittance of 0.83. The results imply that above-sheathing ventilation of a tile roof is just as important as is the boost in solar reflectance for reducing the heat gain into the conditioned space.

Opening the ridge vent of the attics to allow both attic and above-sheathing ventilation caused more heat to be exhausted out the ridge for both the S-Mission clay and the flat-profile "slate" tile systems and therefore further improved the performance of the two tile roofs. The effect was more pronounced for the "slate" tile than observed for the S-Mission tile because the slate tile has less air leakage between tiles.

Summer heat flows for the month of July 2005 were integrated over the daylight and nighttime hours to show seasonal performance of the various roof systems (*Table II-1*). The ridge vent was open for attic and for above-sheathing ventilation for all test roofs during July 2005. The best-performing roofs were the direct-nailed S-Mission clay tile and the S-Mission concrete tile spot adhered with foam. Both roofs caused a 50% reduction in the heat penetrating through the ceiling over the full July month. The maximum attic air temperatures for July show the attic of the conventional shingle roof is about 10 to 15˚F warmer than any of the other tile roofs because of

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Test Roof	SR & TE	Roof Deck Construction	Attic Air (°F)		Roof Deck Heat Flux (Btu/ft^2)		Ceiling Heat Flux (Btu/ft^2)
			Average	Max	Daytime	Nighttime	24-Hour
Asphalt Shingle	SR10E89	Direct-to-Deck	88.7	116.4	4921	-1085	1999
Slate Concrete	SR13E83	Batten and Counter-batten	84.8	106.4	2915	-543	1366
S-Mission Concrete	SR34E83	Batten	83.7	103.6	2611	-666	1351
Medium Profile Concrete	SR10E93	Direct-to-Deck	84.3	105.5	3172	-522	1200
S-Mission Concrete	SR26E86	Spot Adhered with Foam	83.6	103.2	2316	-603	956
S-Mission Clay	SR54E90	Direct-to-Deck	83.3	101.6	1540	-649	873

Table II-1 – July 2005 attic temperatures and cumulative heat flows through the roof deck and ceiling of the attic assemblies having both ridge and above-sheathing ventilation.

the heat flow crossing the roof deck of the respective tile, which was 35 to 70% less than that crossing the shingle roof (*Table II-1*).

During January 2005's winter exposure (*Table 3*), above-sheathing ventilation has reduced the heat loss from the tile roofs to the point that it is less than the loss for the asphalt shingle roof. The tile roofs are negating the heating penalty associated with a cool roof in Tennessee's moderate climate, having 3,662 HDD$_{65}$ and 1,366 CDD$_{65}$. The improved summer performance (*Table II-1*), coupled with the reduced heat losses during the winter (*Table II-2*), show that tile roofs can benefit from Cool Roof Color Materials, while at the same time negate the heating penalty associated with a cool roof. Therefore, above-sheathing ventilation of tile roofs provides tile manufacturers with the opportunity to market high NIR-reflectance tile in more predominant heating-load climates.

The inclined air channel formed by the tile and the roof deck provides an additional radiative resistance to night-sky heat losses from the tile as compared to the direct-nailed shingle roof. Two of the tile roofs – the clay tile and the S-Mission concrete tile roof spot-adhered to the deck – have no net heat gain during the daylight hours for the January exposure (*Table II-2*). Therefore, the reduction in night-sky radiation is due more to the decoupling of conduction prevalent in the direct-nailed shingle roof rather than to the thermal mass of the concrete and clay tile roofs. The air channel forces the heat flow from the roof deck to radiate across the air channel rather than conduct from the roof deck through to the surface of the shingle roof.

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EDITOR'S NOTE: More extensive explanation of venting the underside of tile roofs and the ATTICSIM Model is available by contacting the author at wml@ornl.gov.

Test Roof	SR & TE	Roof Deck Construction	Nighttime Attic Air (°F)		Roof Deck Heat Flux (Btu/ft^2)		Ceiling Heat Flux (Btu/ft^2)
			Average	Min	Daytime	Nighttime	24-Hour
Medium Profile Concrete	SR10E93	Direct-to-Deck	52.8	31.9	185	-1890	-2803
Asphalt Shingle	SR10E89	Direct-to-Deck	49.9	25.6	1024	-2376	-2879
S-Mission Clay	SR54E90	Direct-to-Deck	46.7	25.5	-110	-1499	-2906
Slate Concrete	SR13E83	Batten and Counter-batten	52.5	31.4	69	-1761	-2983
S-Mission	SR26E86	Spot Adhered with Foam	51.1	29.5	-94	-1664	-3054
S-Mission Concrete	SR34E83	Batten	50.1	26.0	30	-1772	-3055

Table II-2 – January 2005 attic temperatures and cumulative heat flows through the roof deck and ceiling of the attic assemblies with the ridge closed to attic and above-sheathing ventilation.

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[1] The tile roof has much more thermal mass than the shingle roof. This may also be responsible for a significant fraction of peak flux reduction.

[2] The ridge vent for the asphalt shingle roof was also closed for the August 2004 comparison to clay and concrete tile roofs field-tested on the ESRA.

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Dr. Miller is a specialist with 25 years of experience in vapor compression refrigeration systems, absorption heat, and mass transfer and building science technologies. He has a PhD in mechanical engineering and works for the Engineering Science and Technology Division of the Oak Ridge National Laboratory. He has conducted cool roof studies for the California Energy Commission, SPRI, and a consortium of metal industries to quantify the energy savings and affordable cost premiums for highly reflective roof products as compared to dark, absorptive roof systems. He has expertise in finite difference heat conduction for application to forced convection, natural convection, and mixed convection finite-difference simulations.

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