# DRAFT PAPER

# Experimental Analysis of the Natural Convection Effects Observed within the Closed Cavity of Tile Roofs

by

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## ABSTRACT

A field study is in progress to demonstrate and document the thermal benefits of clay and concrete tile roofs. The reflectance and emittance of the tile roofs, the bulk air temperatures underneath the tiles, the deck temperatures and the deck heat flux at specific distances from the roof's soffit to its ridge are being measured on an outdoor attic test assembly. The attic assembly has roof sections with direct nailed, batten and counter-batten tile systems. Field data are reviewed to better understand the synergism observed from the tile's solar reflectance and the venting occurring between the roof deck and the underside of the tile roof.

## INTRODUCTION

The Tile Roof Institute (TRI) and the Oak Ridge National Laboratory (ORNL) are working together to quantify and report the potential energy savings for concrete and clay tile roofs. TRI and its affiliate members are keenly interested in specifying tile roofs as cool roof products and they want to know the effect of the tile's solar reflectance and the effect of venting the underside of a tile roof. Parker, Sonne and Sherwin (2002) demonstrated that a Florida home with a "white reflective" barrell-shaped concrete tile roof reduced the annual cooling energy by 22% of the energy consumed by an identical and adjacent home having an asphalt shingle roof. The cost savings due to the reduced use of comfort cooling energy was about $120 or about 6.7¢ per square foot per year.

The venting of the underside of a tile roof also provides 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 tile roof as compared to a direct nailed shingle roof. Parker, Sonne and Sherwin (2002) observed in their study that a moderate solar reflectance terra cotta barrell-shaped tile reduced the home's annual cooling load by about 8% of the base load measured for an identical home with asphalt shingle roof that was adjacent the home with terra cotta tile. These reported energy savings are in part attributed to the venting occurring on the underside of the tile roofs although it is difficult to quantify this benefit.

The reduced heat flow occurs because of a thermally driven airflow within the air gap formed by the tile and the roof deck. Here wood furring strips, "battens," are laid vertically (soffit-to-ridge) against the roof deck, and a second, counter-batten is sometimes laid horizontally across the vertical battens (Fig. 1). The bottom surface of the inclined channel is formed by the roof decking and is relatively flat and smooth. The underside of the roofing tiles establish the upper surface of the inclined vent, and the tile's overlap is designed to be porous to alleviate the underside air pressure and minimize wind uplift on the tiles (Fig. 1). The design may further complicate solution of the heat transfer because an accurate prediction of the airflow is required to predict the heat transfer crossing the roof boundary.

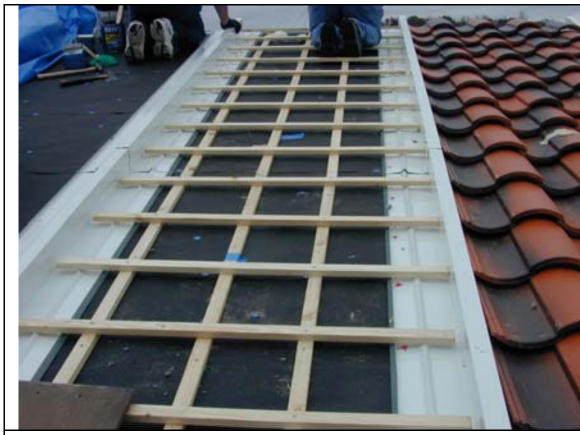

Figure 1. Batten and counter-batten assembly showing inclined air cavity for the slate tile roof.

The airflow in th einclined vent is driven by both buoyancy and wind driven forces. The air gap also provides an improvement in the insulating effect of the roofing system. However, measuring and correctly modeling the heat flow within the vent cavity of a tile roof is a key hurdle for predicting the roof's thermal performance. The heat transfer within the channel can switch from conduction to single-cell convection to Bénard cell convection dependent on the channel's aspect ratio, the roof slope and the season of the year. The coexistence and competition of the various modes of heat transfer requires experimental measurements and numerical simulations.

Therefore a combined experimental and analytical approach is in progress with field data just coming available, some of which we are reporting to show the potential energy savings for residential homes having concrete and clay tile roofs.

## FIELD DEMONSTRATION

Members of TRI installed clay and concrete tile on a fully instrumented attic test assembly at the ORNL campus (Fig. 2). High-profile clay and concrete tile, low-profile concrete and a concrete slate tile are direct nailed to the roof deck, installed on batten or on batten and counter-batten systems. The sixth lane (see furthermost left lane in Fig. 2) has a standard production asphalt shingle roof for comparing energy savings. The tile roofs are approximately 4 feet wide with 16 feet of footprint. Table 1 lists the salient features of the concrete and clay tiles being field tested on the Envelope Systems Research Apparatus (ESRA). All tiles whether direct nailed or installed on battens have a venting occurring up along the height from soffitt to ridge and transversely along the width of the test roofs. Parapet partitions with channel flashing were installed between lanes to limit any transverse airflows to within a given test roof and not between test roofs (Fig. 1).

**Table 1. Clay and concrete tile placed on the ESRA.**

| Roof Cover | Roof System | Reflectance Emittance |
|---|---|---|
| | | SR*xx*E*yy*[1] |
| S-Mission clay | Direct to Deck | SR54E90 |
| Low-Profile concrete | Direct to Deck | SR10E93 |
| S-Mission concrete | Direct to Deck with foam | SR26E86 |
| Flat concrete | Counter Batten | SR13E83 |
| S-Mission concrete | Batten | SR34E83 |
| Asphalt Shingle | Direct to Deck | SR10E89 |

[1]SR*xx* states the solar reflectance of a new sample. E*yy* defines the thermal emittance of the new sample. As example, the asphalt-shingle roof is labeled SR10E89; its freshly manufactured surface properties are therefore 0.10-reflectance and 0.89-emittance.

Each test roof has its own attic cavity that has 11 inches of expanded polystyrene insulation installed between adjacent cavities. This reduces the heat leakage between cavities to less than 0.5% of the solar flux incident at solar noon on a test roof. Therefore, each lane can be tested as a stand-alone entity. Salient features of the ESRA facility are fully discussed by Miller et al. (2002).

Roof surface temperature, oriented strand board (OSB) temperature on both the upper and lower surfaces, and the heat flux transmitted through the roof deck are directly measured. Prior to installing the HFTs, they were placed in a guard made of the same 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). Thermocouples are also stationed from the soffitt to the ridge to measure the bulk air temperatures in the air channel. The 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-in. thick piece of wood fiberboard 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.

## REFLECTANCE AND EMITTANCE OF TILE

The solar reflectance and the thermal emittance of a roof surface are important surface properties affecting the roof temperature, which in turn drives the heat flow through the roof. The solar reflectance ($\rho$) determines the fraction of radiation incident from all directions that is diffusely reflected by the surface. The thermal emittance ($\varepsilon$) describes how well the surface radiates energy away from itself as compared to a blackbody operating at the same roof temperature.

Solar reflectance measures of the clay and concrete tile roofs exposed at ORNL are collected quarterly; these data are shown in Figure 3. Each tile roof is identified by the R*xx*E*yy* nomenclature described in Table 1. After 1 year of exposure, the S-Mission tiles

(SR54E90, SR26E86 and SR34E83) show little drop in solar reflectance. The low-profile concrete (SR10E93) and the slate (SR13E83) tiles actually show slight increases in solar reflectance as does the asphalt shingle roof due to the accumulation of air-borne contaminants. Dusts tend to lighten these darker colors. Data for clay tile are also available for field exposure testing in three of the sixteen climatic zones of California. The clay samples are identical to those tested at ORNL. They show a loss of solar reflectance that occurs because of climatic soiling. The worst soiling observed occurs in the urban area of Colton and the desert area of El Centro (Fig. 4). However, the crisp and clear alpine climate of McArthur shows the lowest loss of solar reflectance because less contaminants pollute the air. Roof slope appears to affect the loss of solar reflectance (Fig. 4). Testing at the slope of 8-in of rise per 12-in of run (33.7º slope) has less reflectance loss as compared to testing at 2-in of rise per 12-in of run (9.5º) for all three exposure sites (Fig. 4). Precipitation is not believed to be the dominant player, especially when one considers that El Centro has less than 2-in of annual rainfall! Rather wind may be causing the differences in loss of solar reflectance as roof slope changes from 9.5º to 33.7º. The results in Fig 3 and 4 also show that exposure testing differed between the western and mid-eastern climates of the U.S. Samples from the two regions show California has more air-borne dusts than does Tennessee, which causes the greater loss of reflectance in California.

The clay tile (SR54E90) tested at ORNL and California exceeds the solar reflectance of all the other tile (Fig. 3) because it contains complex inorganic color pigments that boosts its reflectance in the infrared spectrum. A slurry coating process is used to add color to the surface of a clay tile. Once coated the clay is kiln-fired, and the firing temperature, the atmosphere and the pigments affect the final color and solar reflectance Akbari, Levinson and Berdahl (2004). The complex inorganic color pigments, termed here as Cool Roof Color Materials (CRCMs), are of paramount importance and will literally revolutionize the roofing industry. The energy and cost savings reported by Parker, Sonne and Sherwin (2002) for white reflective concrete tile is promising; however, in the residential market, the issues of aesthetics and durability will limit the acceptance of “white” residential roofing. To homeowners, dark roofs simply look better than their counterpart, a highly reflective “white” roof. What the public does not know, however, is that the aesthetically pleasing dark roof can be made to reflect like a “white” roof in the near infrared spectrum. Miller et. al (2004), Akbari et. al (2004) and Levinson, Berdahl and Akbari. (2004a and 2004b) provide further details about the potential energy benefits and identification and characterization of dark yet highly reflective color pigments.

Coating tile with CRCMs has been successfully demonstrated by American Rooftile Coatings who applied their COOL TILE IR COATING™ to several samples of concrete tiles of different colors (Fig. 5). The solar reflectance for all colors tested exceeded 0.40. Most dramatic is the effect of the dark colors. The black coating increased the solar reflectance from 0.04 to 0.41, while the chocolate brown coating increased from 0.12 to 0.41, a 250% increase in solar reflectance! Because solar heat gain is proportional to solar absorptance, the COOL TILE IR COATING™ reduces the solar heat gain roughly 33% of the standard color, which is very promising. The coating application is a significant advancement for concrete tile because the alternative is to add the CRCMs to the cement and sand mixture, which requires too much pigment and makes the product too expensive. The coating can certainly help tile roof products pass the Environmental Protection Agency's Energy Star 0.25 solar reflectance criterion as well as California's Title 24 pending criterion  for steep-slope roofing.

The thermal emittance of the clay and concrete tile has not changed much after 2 years of exposure in California. It remains relative constant at about 0.85.

## EXPERIMENTAL RESULTS

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 the western and some southern states. Thermal performance data collected from the attic test assembly at ORNL shows tile to be an energy efficient roof product. The clay S-Mission tile (SR54E90), the S-Mission tile attached with foam (SR26E86) and the S-Mission tile on battens (SR34E83) had the least amount of heat penetrating into their respective ceilings; each reduced the peak load at solar noon about 70% of the energy penetrating through the ceiling of the attic covered with an asphalt shingle roof (Fig. 6). The data are for a week of exposure during August 2004 in East Tennessee's hot and humid climate. Of these three roof systems the clay tile (SR54E90) had the lowest ceiling heat flux due primarily due to its high solar reflectance. All three tiles have a venting occurring along the underside of the tile's barrel from soffitt to ridge.

The solar reflectance and emittance of the slate roof (SR13E83) and the low-profile tile (SR10E93) are very similar to that of the asphalt shingle (SR10E89) but the heat transfer through the ceiling for the attic with the slate roof and the low-profile tile roof are only half that measured for the asphalt shingle roof (Fig. 6). 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 tile are attached to batten and counter-batten strips, which form a vent cavity that is about 1½-in deep. The low-profile tile forms its own half-cylindrical channel of about 0.5-in 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 of Figure 6 clearly shows the benefit derived from venting the roof deck based solely on the direct comparison of the percent reduction of peak loads (i.e. 50% reduction for the SR13E83 or SR10E93 and a 70% reduction for the SR54E90 tile as compared to the shingle roof). By proportioning the heat reduction due solely to venting [SR10E93 vs SR10E89] to the heat reduction due to solar reflectance and venting [SR54E90 vs SR10E89] :

$$\overbrace{\frac{\text{50\% due to venting}}{\text{70\% due to venting and SR}}}^{\text{heat reduction}} \cdot \left[ SR54_{\text{Clay Tile}} - SR10_{\text{Shingle}} \right]$$

the benefit of venting at solar noon equivalences to roughly 30 points of surface reflectance! Hence the data at peak loading implies that "cool roofing" credits are obtainable through venting the underside of a tile or similarly constructed roof system. The data also clearly shows the synergism gained by both the solar reflectance of CRCMs (Fig. 6) and the deck venting utilized by all tile roofs.

Demonstration homes located in Fair Oaks, California are also under field study to further document the effects of CRCMs and roof venting, Akbari et. al (2004). A pair of homes are adjacent to one another, and have the same identical floor plan and roof orientation. Both homes have the same low-profile tile with chocolate brown color (SR10E93) as being tested on the ESRA at ORNL; however, one of the two homes was coated with CRCMs and has a measured solar reflectance of about 0.41 (see the chocolate brown color tile in Figure 5). The field data shows that the higher reflectance roof reduced the attic temperature about 5 to 15ºF around solar noon. The reduction in attic temperature is a direct result of the reduction in heat penetrating the roof. Heat flux transducers embedded in the west facing roofs of both homes show that the roof with Cool Tile IR Coating™ had less heat penetrating the roof as compared to the roof with standard color tile. As result, there is a lower temperature driving force from attic to the conditioned space and therefore the heat penetrating the ceiling at solar noon is reduced about 70% of that measured for the standard production tile roof (Fig. 7). Integrating the heat flows over the three-day daytime period shows a 25% reduction in the heat load that is due solely to the higher reflectance of the low-profile tile. Therefore CRCMs and roof venting are key strategies for providing cool roof products that can reduce whole house energy consumption.

## PHYSICS OF THE HEAT FLOW IN THE INCLINED CHANNEL

The transfer of heat across the roof tile and roof deck has similar physics to the problem associated with the heat transfer across the inclined air channel that is formed by roof mounted solar collectors. Comprehensive reviews of both experimental and theoretical results are available in the literature, Hollands et al. (1976), Arnold, Catton and Edwards (1976) and most recently Brinkworth (2000) studied this situation as applied to flat-plate photovoltaic cladding.

All residential roofs are sloped and make an angle θ with the horizontal plane that ranges from 2-in of rise per 12-in of run (9.5º slope) to a steep-sloped roof of 45º. During winter exposure, a roof deck is warmer than the tile and in the inclined air channel the heated surface is positioned below the cooler tile surface much like the solar panel application studied by Hollands et al. (1976). Here a more dense air layer near the tile overlays a lighter air adjacent the roof deck (see θ = 0, Fig. 8). Hollands observed that the

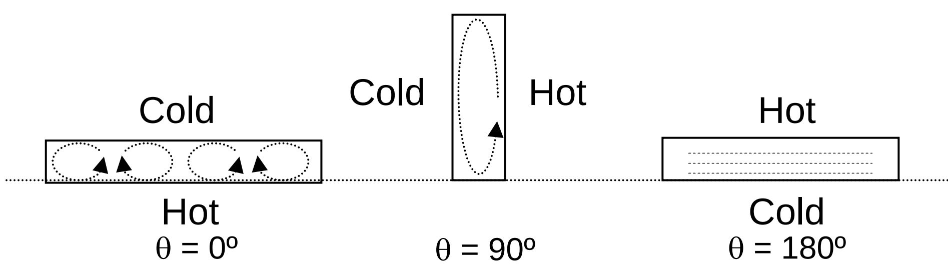


Figure 8. Heat transfer phenomena occurring in the inclined air channel.

heat transfer across the air channel can switch from conduction to single-cell convection to Bénard cell convection dependent on the strength of a non-dimensional prameter called the Rayleigh ($Ra_L$) Number. For Rayleigh Numbers less than 1708/Cos(θ) there is no naturally induced airflow within the cavity, and the heat transfer occurs exclusively by conduction. However, a flow of air occurs if buoyancy forces overcome the resistance imposed by the viscous forces. As the flow increases due to buoyancy, the heat transfer within the channel switches to Bénard cell convection, which has hexagonal cells with flow ascending in the center and descending along the sides of the air channel (see $\theta = 0$, Fig. 8). Arnold, Catton and Edwards (1976) observed that the channel's aspect ratio and the slope of the solar panel (for our application a roof) had a major impact on the flow and heat transfer within the air channel. They observed that if the channel were rotated from $\theta = 180^{o}$ (summer exposure for a roof) all the way to $\theta = 0^{o}$ (winter exposure), the heat transfer rises to a maximum at $\theta = 90^{o}$ and then as $\theta$ decreases below 90º the heat transfer rate first decreases and passes through a local minimum at $\theta^*$ (Bejan 1984). However as $\theta$ decreases below $\theta^*$ the heat transfer rate again rises because of the inception of Bénard cell convection. Arnold, Catton and Edwards (1976) also observed that the aspect ratio of the channel changed the critical angle $\theta^*$ where the heat transfer across the channel was minimal. The information may be very useful for designing tile to limit ice daming in predominantly cold climates.

During summer exposure, the tile is hotter than the roof deck and Bénard cell convection does not occur within the inclined channel because the lighter air layer is now atop the denser air layer near the roof deck. The air heated by the underside of the tile tends to rise and natural convection begins within a boundary layer formed along the underside of the tile ($\theta = 180$, Fig. 8). Brinkworth (2000) studied this situation as applied to flat-plate photovoltaic cladding, and it is this configuration and heat transfer mechanism that is evident in the field experiments shown for the ESRA tile roof systems.

## NUMERICAL SIMULATIONS

Computer simulations for thermally induced airflow and heat transfer across an inclined air channel were conducted for several different constant temperature wall boundary conditions and several different inclinations with the horizontal plane to better understand the strength of natural convection forces occurring within the heated channel. The channel was modeled for four conditions (Table 2) with the top plate always held at a higher temperature than the bottom plate to simulate summer exposure of the tile roof. The aspect ratio of the duct was fixed at 0.01.

Table 2. Channel inclinations and temperature gradients used in simulations.

| Channel Inclination | Top plate to bottom plate $\Delta T$ (ºF) |
|---|---|
| 0° | 27 |
| 5° | 27 |
| 30° | 27 |
| 5° | 9 |

The bottom and the two side surfaces of the channel were held at 68°F, and the top surface was held at 68° + $\Delta T$ listed in Table 2. All channel surfaces were assumed smooth and solid. The smulations in Figure 9 and 10 are plotted in terms of the isotherms (constant temperature lines shown in color) and streamlines (lines of constant velocity).

The results depicted in Figure 9a show that with no inclination, natural convection flow does not occur within the channel. Rather a plume of heated air forms above the heated top surface. Becaise no net airflow occurs within the channel, the heat transfer across the two plates is conduction dominated. For case (b in Figure 9) with only 5 degrees of inclination and the top plate held just 2ºF above the lower plate, there is seen a distinct flow moving within a boundary layer on the underside of the top plate. The flow field is laminar, which is most probably the same flow occurring in the inclined air channels of the tiles being field tested on the ESRA. These simulations indicate that naturally induced flow can be expected at very low inclination angles and very low temperature differences, well below those experienced in roofing systems. The induced flow causes a net flow from soffitt to ridge that carries heat away from the attic. Parker, et al. (2001) tested the white tile roof at 5-in of rise per 12-in run (35º slope). They measured during July exposure a temperature gradient from the tile to the roof deck of about 14ºF, (Fig. 10). A numerical simulation is superimposed onto the roof for the slope and $\Delta T$ observed by Parker et al. (2001) to again help show the strength of the natural convection flows. The flow patterns are similar to those described in Fig. 8; however, the exit jet is more in line with the duct axis indicating the momentum of the flow has increased (see Fig. 10). Hence the numerical results help to qualitatively show that the venting occurring on the underside of the tile roof can be very significant for dissipating heat away from the roof deck, making the tile roof system cooler than conventional direct nailed systems.

The numerical results do not take into account the effect of a forced flow component, which may aid or oppose the naturally induced flow. Mixed convection (forced convection driven by wind effects that are accompanied by buoyancy effects) is an additional confounding variable that must be mathematically described a priori the prediction of the heat transfer across the roof deck. The key to the problem is to accurately predict the airflow within the cavity. Once known, the portions of heat penetrating the roof deck and that convected away through the ridge vent can be derived from energy balances.

## CONCLUSION

The tile roofs exposed to East Tennessee’s climate maintained their solar reflectance during the full year of exposure. Dust and urban pollution in California’s urban areas are soiling the materials more so than in the less populated sections of the state, and the loss of reflectance is most sever for samples exposed at the slope of 2-in of rise per 12-in of run. Increasing the slope reduced the soiling because the dust is probably blown off by the strong California winds.

The addition of complex inorganic pigments to clay and concrete tile significantly increased the solar reflectance and reduced the heat penetrating into the conditioned space. Applying a coating with CRCMs to low-profile concrete tile reduced the heat penetrating the ceiling of a demonstration home by about 70% of that measured for an identical home with the same standard production low-profile tile.

The venting occurring beneath a tile roof and the addition of CRCMs yields a synergistic improvement in the thermal performance of clay and concrete tile roofs. Field data collected at peak loading for clay and concrete tile roofs at ORNL demonstrate that venting roughly equivalences to about 30 points of solar reflectance. Therefore venting offers a significant 50% reduction in the heat penetrating the conditioned space as compared to direct nailed roof systems that are in direct contact to the roof deck.

The combination of tile venting and improved solar reflectance offers excellent credits that clay and concrete tile can claim for “Cool Roof” steep-slope roof products as specified by the EPA and many state energy offices.

Numerical simulations of the inclined air channel formed by tile roof systems demonstrated that naturally induced flow can be expected at very low roof slopes and very low temperature differences, well below those experienced in roofing systems.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

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Figure 2. Clay and concrete tile being field tested on the steep-slope attic assembly at ORNL.

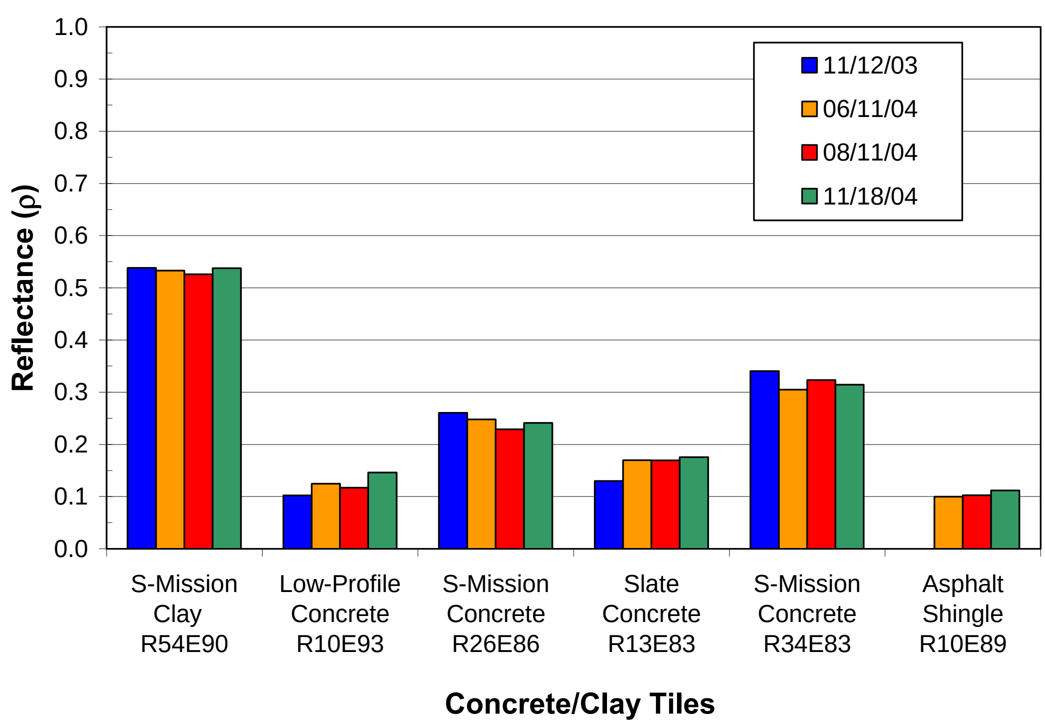


Figure 3. Solar reflectance measurements for the tile exposed on the attic assembly at ORNL.

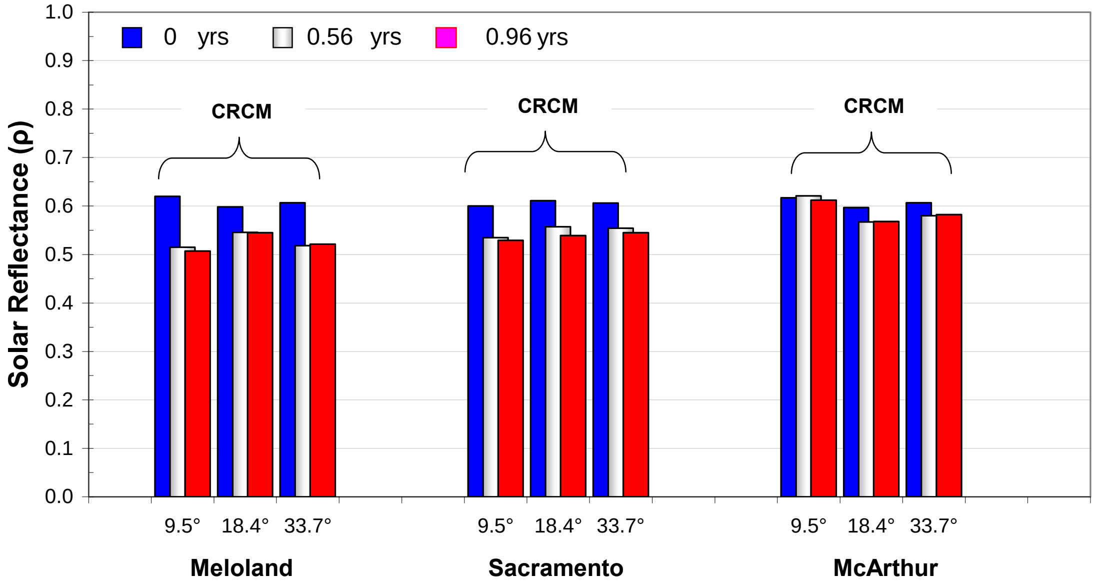


Figure 4. Clay tile field tested on exposure racks in California at the slopes of 9.5º, 18.4º and 33.7º which represent roof slopes settings of 2-in, 4-in and 8-in of rise per 12-in of run.

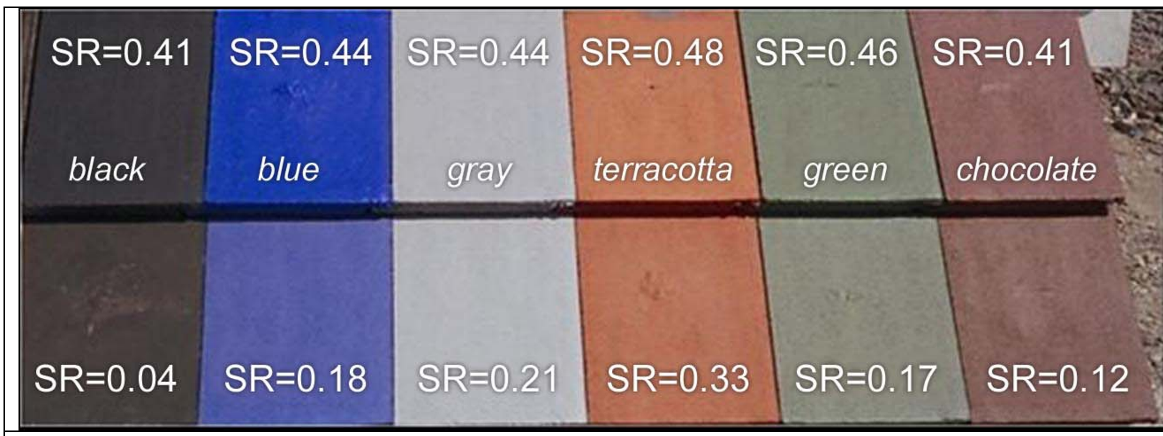


Figure 5. Solar reflectance of concrete tile roofs with CRCMs (top row) and without CRCMs (bottom row). The COOL TILE IR COATING™ technology was developed by Joe Riley of American Rooftile Coating.

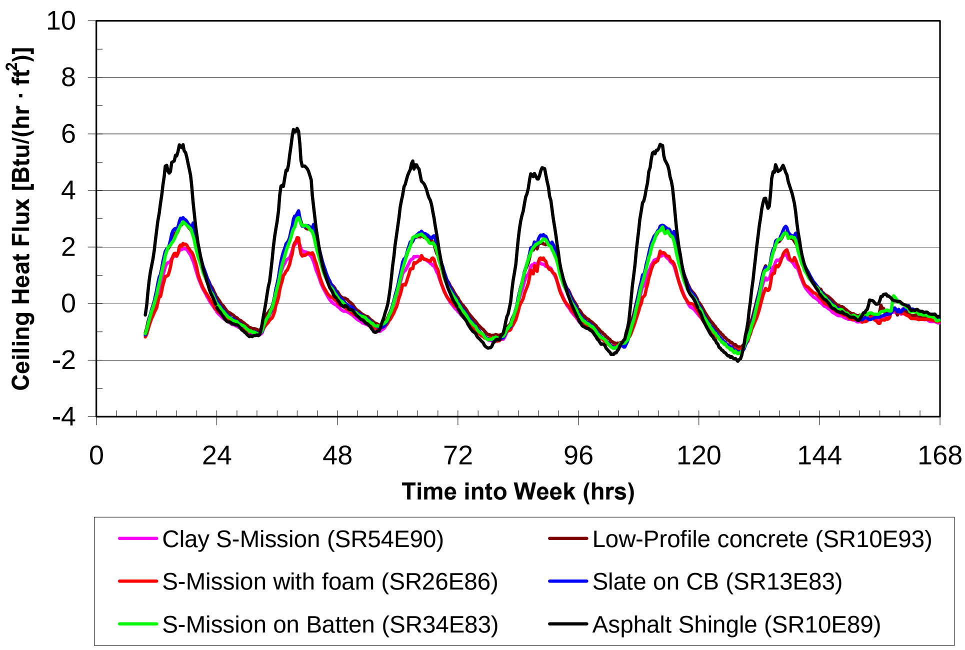


Figure 6. Heat penetrating the ceiling of each attic assembly being field tested on the ESRA.

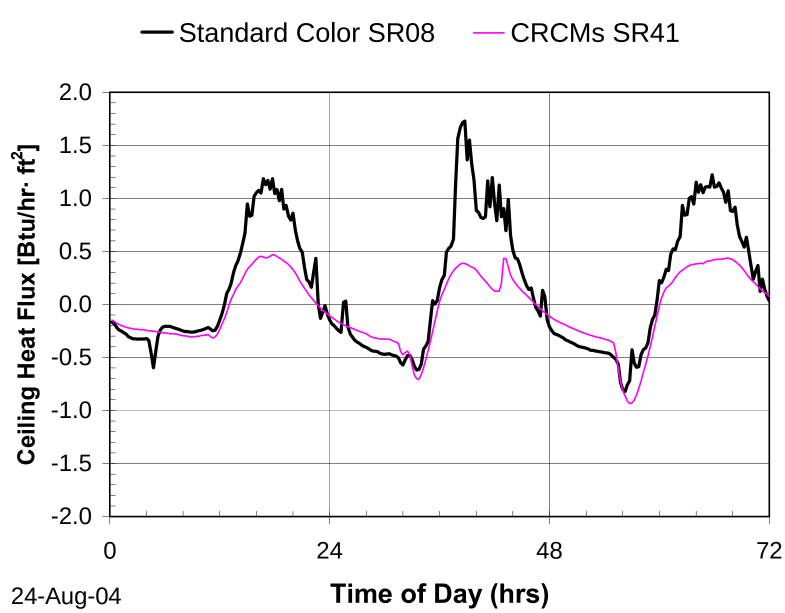


Figure 7. The heat penetrating the ceiling of two homes having identical footprint and orientation in Fair Oaks CA. Roofs are the same as the low-profile concrete tile tested at ORNL.

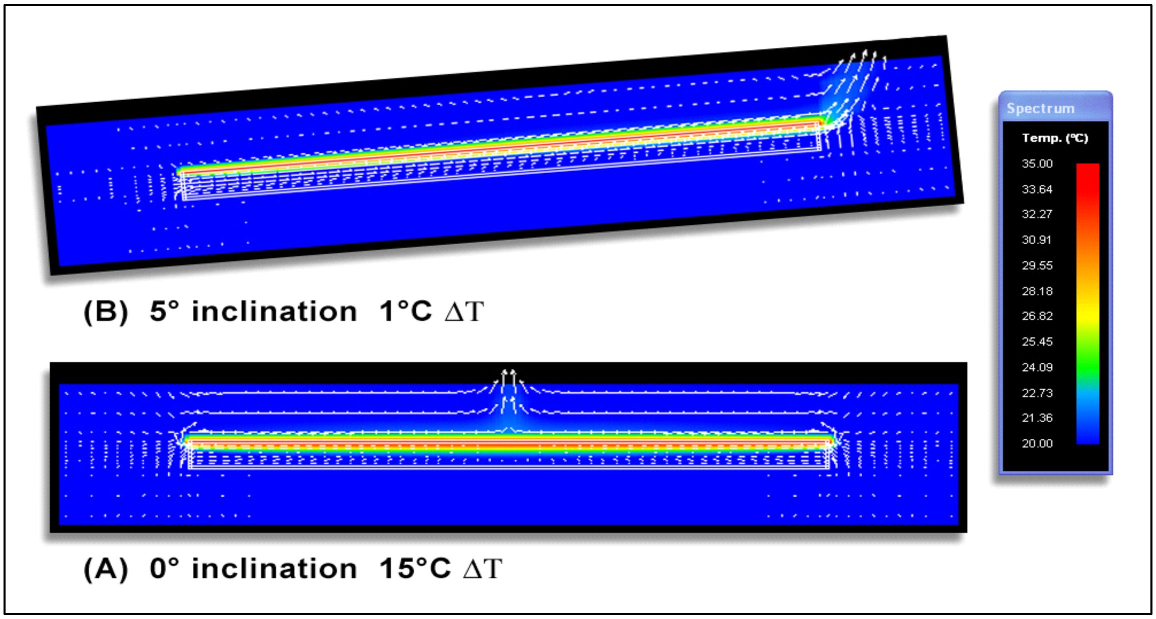


Figure 9. Naturally induced flow observed at low inclinations and at low temperature gradients from the top plate to the lower plate.

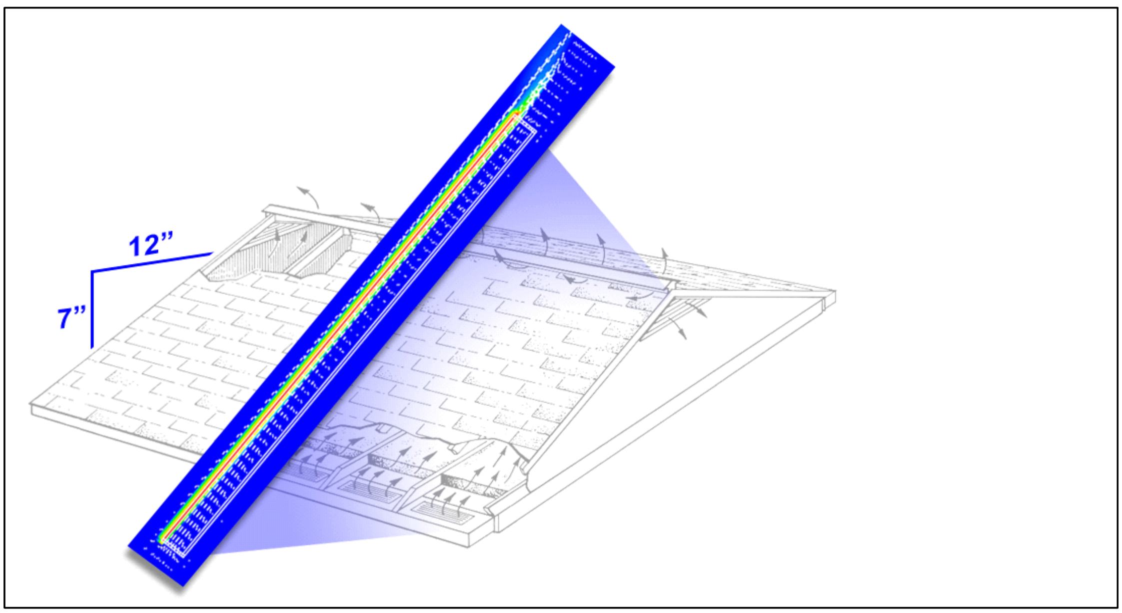


Figure 10. Naturally induced flow observed at typical roof slope and temperature gradients observed in the work of Parker, Sonne and Sherwin (2002).