A Study of the Energy-Saving Potential of Metal Roofs Incorporating Dynamic Insulation Systems

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ABSTRACT

This article presents various metal roof configurations that were tested at Oak Ridge National Laboratory in Tennessee, U.S. between 2009 and 2013, and describes their potential for reducing the attic-generated space-conditioning loads. These roofs contained different combinations of phase-change material, rigid insulation, low emittance surface, and above-sheathing ventilation with standing-seam metal panels on top. These roofs were designed to be installed on existing roofs' decks, or on top of asphalt shingles for retrofit construction.

All the tested roofs showed the potential for substantial energy savings compared to an asphalt shingle roof, which was used as a control for comparison. The roofs were constructed on a series of adjacent attics separated at the gables using thick foam insulation. The attics were built on top of a conditioned room. All attics were vented at the soffit and ridge. The test roofs and attics were instrumented with an array of thermocouples. Heat flux transducers were installed in the roof deck and attic floor (ceiling) to measure the heat flows through the roof and between the attic and conditioned space below. Temperature and heat flux data were collected during the heating, cooling and swing seasons over a three-year period. Data from previous years of testing have been published. Here, data from the latest roof configurations being tested in year three of the project are presented. All test roofs were highly effective in reducing the heat flows through the roof and ceiling, and in reducing the diurnal attic-temperature fluctuations.

INTRODUCTION

This article describes phase three of a study that began in 2009 to evaluate the energy benefits of a sustainable reroofing technology utilizing standing-seam metal roofing panels combined with energy efficient features like above-sheathing ventilation (ASV), phase-change material (PCM) and rigid insulation board. The data from phases one and two have been previously published and reported (Kosny et al. 2011; Biswas et al. 2011; Biswas and Childs 2012; Kosny et al. 2012). Based on previous data analysis and discussions within the research group, additional test roofs were installed in May 2012 to test new configurations and further investigate different components of the dynamic insulation systems.

It has been well-documented that roofs and attics experience higher temperature fluctuations than other building envelope components. A study by Huang et al. found roofs contributed 12%–14% of the heating and cooling loads in residential buildings (1999). A great deal of research has been devoted to reducing the roof and attic-generated space-conditioning loads. Parker et al. compared the heat transfer through direct-nailed and counter-batten tile roofs to an asphalt shingle roof and found 50% reductions in heat transfer (1995). Akbari et al. found that a roof surface with high solar reflectance and high thermal emittance resulted in cooling energy savings in moderate and hot climates (2004). Miller and Kosny studied prototype roof designs that combined strategies like infrared reflective roofs, radiant barriers, ASV, low emittance (low-e) surfaces, insulation, and thermal mass to regulate the attic temperature and reduce the ceiling heat transfer (2007). Attic radiant barriers have shown the pote5ntial for reducing radiation heat exchange across roof cavities and attic spaces (Medina 2010). In addition to the aforementioned technologies, PCMs

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are increasingly being investigated for use in building envelopes, including roofs for thermal storage, and a consequent reduction in space-conditioning loads. Zalba et al. (2003), Sharma et al. (2009) and Xin et al. (2009) have provided detailed reviews of the thermal storage systems incorporating PCMs, including those for building envelope applications.

The current test roofs combined PCM, fiberglass insulation, a low-e surface, and ASV in different configurations to evaluate their potential in reducing the heating and cooling loads in buildings. In addition to the steady thermal resistance of the fiberglass insulation, these roofs utilize the dynamic effects of the PCM, ASV airflow, and the low-e surface to reduce the heat flow through the roof. The roofs were designed and built by a collaboration between Metal Construction Association (MCA), CertainTeed Corporation, Phase Change Energy Solutions, and Oak Ridge National Laboratory (ORNL). MCA is a North American trade association of metal building manufacturers, builders, and material suppliers; CertainTeed is a manufacturer of thermal insulation and building envelope materials; and Phase Change Energy Solutions manufactured the PCM.

The current dynamic roofs were designed such that they can be installed in new construction or on top of existing roofs. According to a 2002 report, asphalt shingles covered more than 85% of the residential roofing area in the U.S (Dodge 2002). Reroofing at the end of their service lives generates an estimated 6.8 million tons of waste asphalt shingles per year in the U.S., requiring large disposal areas (Sengoz and Topal 2005). Using the present dynamic roofing systems for reroofing and retrofitting applications precludes the asphalt shingle waste generation, in addition to improving the energy efficiency of the building.

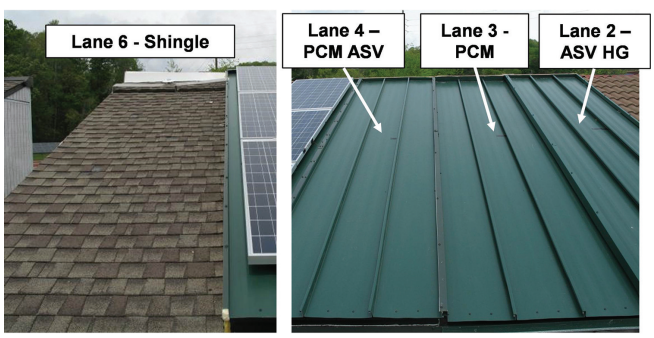

Figure 1 *Control asphalt shingle roof (left) and the test roofs (right).*

DESCRIPTION OF TEST ROOFS

These test roofs were built on side by side attics on the Envelope Research Systems Apparatus (ESRA) facility in Oak Ridge, Tennessee. The attics are thermally isolated from each other by using foam insulation at the gable ends and are vented at the soffit and ridge. A conventional asphalt shingle roof was used as a control to evaluate the energy benefits of the test roofs. Further details of the attic construction are provided by Miller (2006).

Figure 1 shows the attic roofs located on the ESRA facility. Three test roofs are described in this article and will be referred to as Lane 2 ASV HG (heat gain), Lane 3 PCM and Lane 4 PCM ASV. Lane 6 Shingle is the control roof built with asphalt shingles on the roof deck (Kosny et al. 2012). The three test roofs were constructed with different configurations of rigid fiberglass insulation, PCM, and air gap (ASV) under the metal panels, as shown in Figure 2. Figure 2 also shows how the roof assemblies were instrumented to measure the temperature distribution and heat flow through the oriented strand board (OSB) deck into and out of the attic.

Lane 4 consisted of rigid fiberglass insulation on the OSB roof deck, followed by a layer of macro-encapsulated biobased PCM and the standing-seam metal panels on top. The metal panels were placed on top of metal subpurlins that provided an air gap of about 5.1 cm over the PCM layer; the air gap was vented both at the ridge and the eave providing ASV (Miller and Kosny 2007). The fiberglass insulation is about 2.5 cm thick and has a thermal resistance of 0.76 $m^2 \cdot K/W$. The PCM was packed in arrays of plastic cells of dimensions 4.4 × 4.4 × 1.3 cm with 1.3 cm spacing (air pockets in plastic cells represented about 20% of the total volume). The nominal heat storage capacity of the PCM packed in the plastic film pouches is about 560 kJ/m^2 of the roof area. The PCM has nominal melting and freezing temperatures of about 30°C and 26°C, respec-

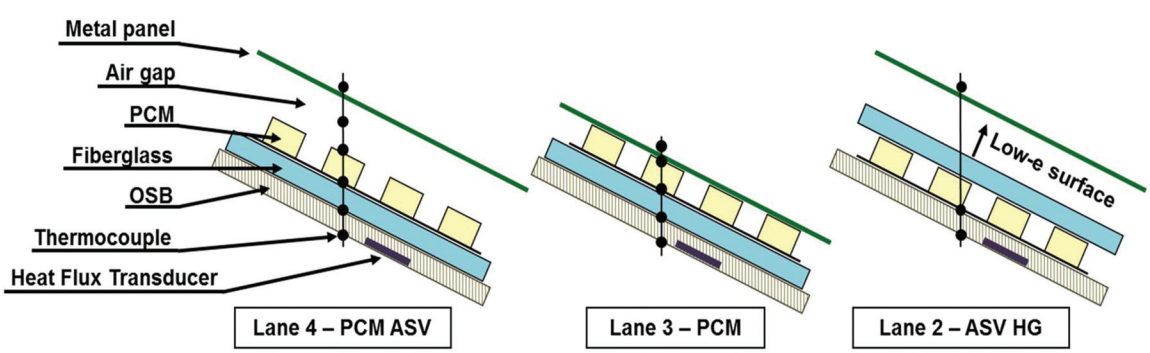

Figure 2 *Test roof configuration schematics.*

tively. The melting-phase transition enthalpy of the PCM is about 190 J/g.

Lane 3 was constructed with the same rigid fiberglass insulation on the roof deck, followed by the PCM layer, but did not contain any air gap above the PCM layer. It should be noted that the 1.3 cm spacing between the air channels still provided some ASV in this roof.

The fiberglass board in Lane 2 contained a reflective-foil facing that introduces a low-e surface which acts to reflect the incoming solar radiation and helps reduce daytime cooling loads. This roof was similar to the one studied during Phase 1 of this project (Biswas et al. 2011; Kosny et al. 2012), except for the absence of laminated photovoltaics. In addition to the thermocouples shown in Figure 2, Lane 2 was instrumented with two thermocouples, each in the air gap close to the ridge and the eave sections. The intent was to try and quantify the heat gain in the buoyant airflow generated in the air gap by natural convection (hence the nomenclature ASV HG).

ATTIC CONSTRUCTION AND INSTRUMENTATION

Figure 3 shows the typical attic construction and instrumentation on the ESRA facility. The attics are built on top of a conditioned basement. The basic roof construction consists of a weather barrier (moisture shield) on top of a 1.6 cm OSB deck. The asphalt shingles (in Lane 6, the control roof) or other test roof components are installed on top of the roof deck. The attic floor or ceiling consists of two wooden fiberboards on top of a corrugated metal sheet. No ceiling insulation was used in this study. However, during phase one of this study, R-6.7 $m^2 \cdot K/W$ ceiling insulation was installed in all attics (Biswas et al. 2011; Kosny et al. 2012). In phase three, the ceiling insulation was removed to check the energy-saving impact of the prototype roofs in retrofit applications where the original attic is poorly insulated or missing insulation.

Type T copper-constantan thermocouples are placed within the attic, roof assembly, and the ceiling, as shown in Figure 3. These are in addition to the thermocouples shown in Figure 2 and the ones added to the ASV air gap in Lane 2. Heat flux transducers (HFT), with an accuracy of ±5% and a sensitivity of 5.7 $(W/m^2)/mV$, measure the heat flows through the ceiling and the roof deck. The HFTs were calibrated using a heat flow meter apparatus while sandwiched by the same materials as in the roof deck and the ceiling, respectively. The heat flow towards the conditioned space is defined as positive (heat flow into the attic from the roof and heat flow into the conditioned basement from the attic), and vice versa.

In addition to the attic instrumentation, an on-site weather station was installed that measures the solar irradiance on the sloped roofs, longwave radiation beyond 3 micrometers (μm), ambient dry bulb temperature, ambient air relative humidity, etc.

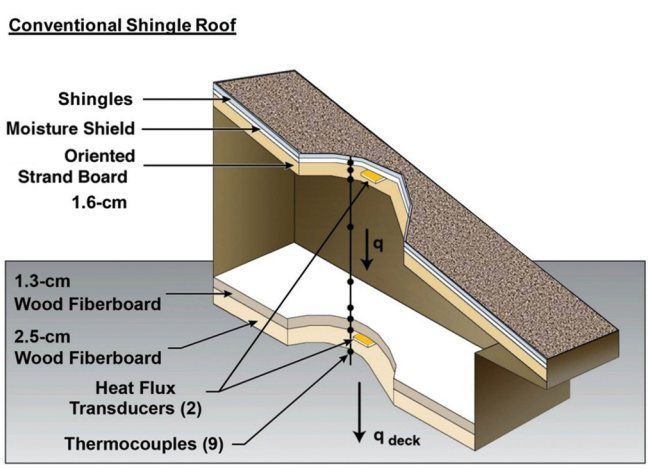

Figure 3 *Typical ESRA attic instrumentation.*

RESULTS AND DISCUSSION

In the following sections, data from the test attics are presented and discussed. The temperature and heat flux data were averaged over 15 minute periods and stored in weekly data files. Here, data collected during summer, fall, and winter of 2012–2013 are shown. Specifically, the evaluation period extends from May 30, 2012 to January 1, 2013.

Roof Surface Temperatures

Figure 4 shows the temperature variations during two typical summer days and two typical winter days. Also shown is the outdoor ambient temperature during those days. The maximum roof surface temperatures rose well above the outdoor temperature due to the daytime solar irradiance. At night, radiation losses to the sky (especially in the absence of cloud cover) lower the roof temperatures below the ambient. No significant differences were observed in the different metal panel and asphalt shingle roof temperatures. The recorded roof surface temperatures of Lane 3 (PCM) were lower than the other roofs during the winter days shown in Figure 4. It was later discovered that the Lane 3 roof thermocouple detached from the roof surface and was measuring the air temperature above the roof. Once fixed, Lane 3 roof temperatures were similar to the other roofs.

PCM Behavior

The PCM used in the present experiment was tested using a differential scanning calorimeter (DSC). The phase-change characteristics of the PCM are shown in Figure 5. The heating and cooling rate used in the DSC tests was 0.3°C per minute, and the resulting melting and freezing thresholds were observed to be 25.7°C and 27.2°C, respectively.

Figures 6 and 7 show the temperatures above and below the PCM layer during the typical summer and winter days in Lane 4. The roof design studied in Phase 1 of this project was very effective in regulating the attic temperature and reducing the ceiling heat flows, but temperature data indicated that the PCM remained frozen and was inactive throughout the winter period (Biswas et al. 2011; Kosny et al. 2012). In the current design of Lane 4, the PCM is placed on top of the fiberglass insulation.

As indicated by the temperature separation between the top and bottom of the Lane 4 PCM layer in Figures 6 and 7, the PCM did undergo both melting and freezing during both summer and winter periods, as described by Kosny et al. (2012). Figure 8 shows the weekly maximum and minimum temperatures across the PCM layer in both Lane 3 and Lane 4 roofs, compared to the phase-change onset temperatures from the DSC tests. The weekly minimum temperatures always remained below the freezing threshold temperature, and the maximum temperatures were always above the melting threshold. Thus, on a weekly basis, the PCM in both Lane 3 and Lane 4 can be expected to have been active during both summer and winter periods. It should be noted that DSC heating rate of 0.3°C per minute is higher than the temperature change rates in actual building envelopes. The data shown in Figures 6 and 7 revealed a temperature rise rate of about 0.1°C per minute at the PCM layer. At lower heating rates, the melting threshold can be expected to be lower than 25.7°C and the freezing threshold higher than 27.2°C (Castellón 2008), making the observed temperature in Lane 3 and Lane 4 even more conducive to melting and freezing of the PCM.

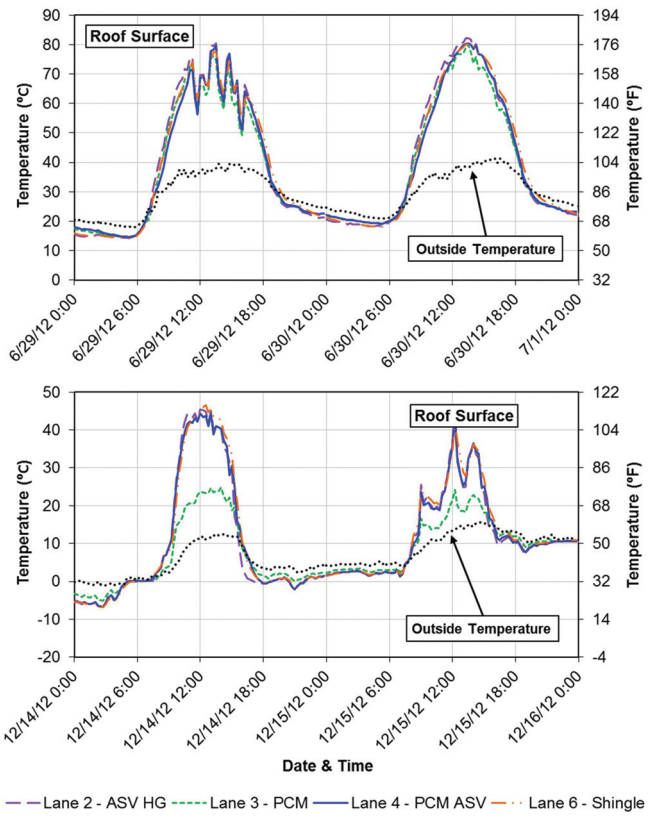

Figure 4 *Roof surface-temperature variations.*

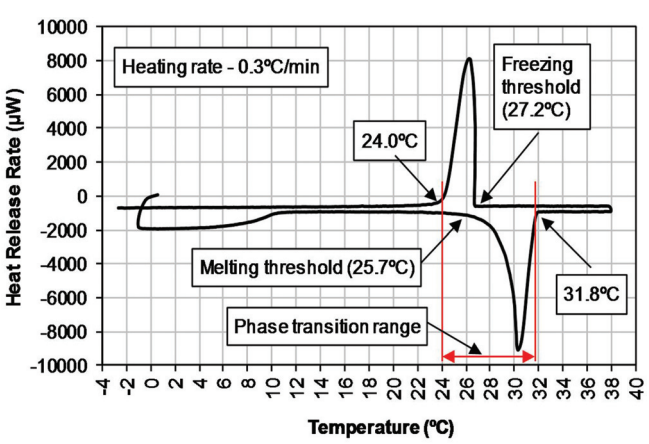

Figure 5 *Heat flow data of the PCM from differential scanning calorimetry (Kosny et al. 2012).*

Summer Performance

This section presents temperature and heat flux data from a summer week (June 27–July 3, 2012) when highest peak outdoor temperatures were observed and the overall summer

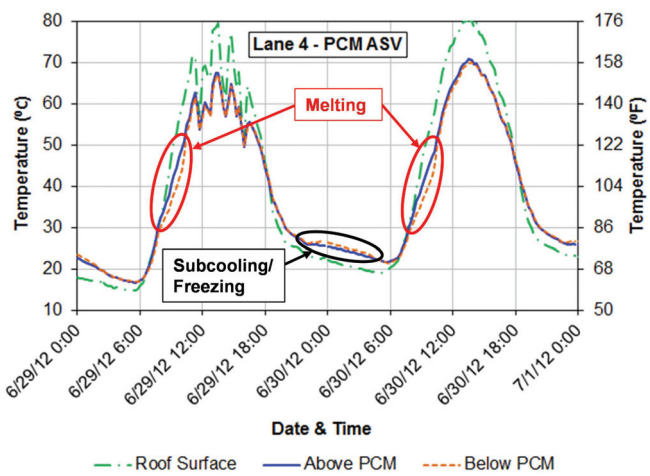

Figure 6 *Summer PCM behavior.*

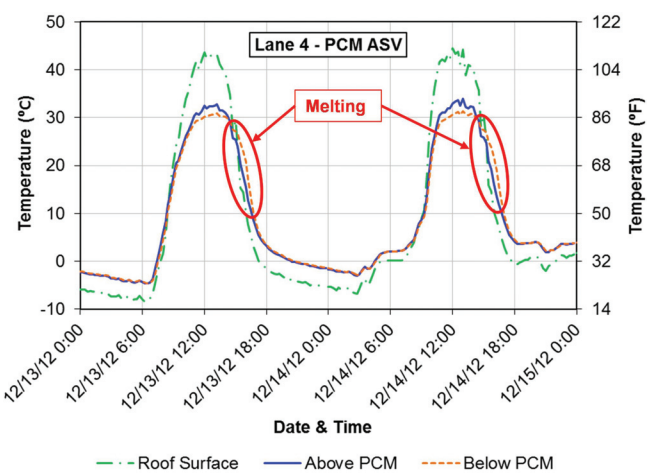

Figure 7 *Winter PCM behavior.*

period (defined as June –September 30, 2012). Figure 9 shows the variation of the roof heat flux during the summer week. Compared to the control (Lane 6), the ASV HG roof reduced the peak daytime heat gain by about 90% while PCM and PCM ASV roofs reduced the peak heat gain by 80%. Due to the melting of PCM (and the proximity of the PCM to the roof HFT) on some days, the roof HFT in the ASV HG roof actually showed a reversal of heat flow direction (negative heat flow) during the afternoons.

Figure 10 shows the attic temperatures during the summer week. All test lanes were effective in lowering the diurnal fluctuations on the attic temperature, and reduced the peak daytime temperatures. The ASV HG attic experienced the lowest peak temperatures, about 9.9°C lower than peak control attic temperatures during this week; the PCM and PCM ASV peak-attic temperatures were 7.6°C and 8.3°C lower than the control.

From a space-conditioning perspective, it is most interesting to examine the ceiling heat flux, which directly impacts the heating and cooling loads. Figure 11 shows the weekly ceiling heat-flux variations in the different attics. Again, all the test roofs were highly effective in reducing the ceiling heat gains compared to the asphalt shingle roof. During this week, on average, the peak ceiling heat gains in the different attics were 7.0 W/m^2 (ASV HG), 7.3 W/m^2 (PCM), 7.7 W/m^2 (PCM ASV), and 18.2 W/m^2 (Shingle).

To further evaluate the performance of the test roofs over the entire cooling period, the attic temperatures and the ceiling heat flows were averaged over June 1–September 30, 2012. The averaging (referred to as bin-averaging) was done over corresponding 15-minute periods of each day, and the resulting average data are shown over a 24-hour period in Figures 12 and

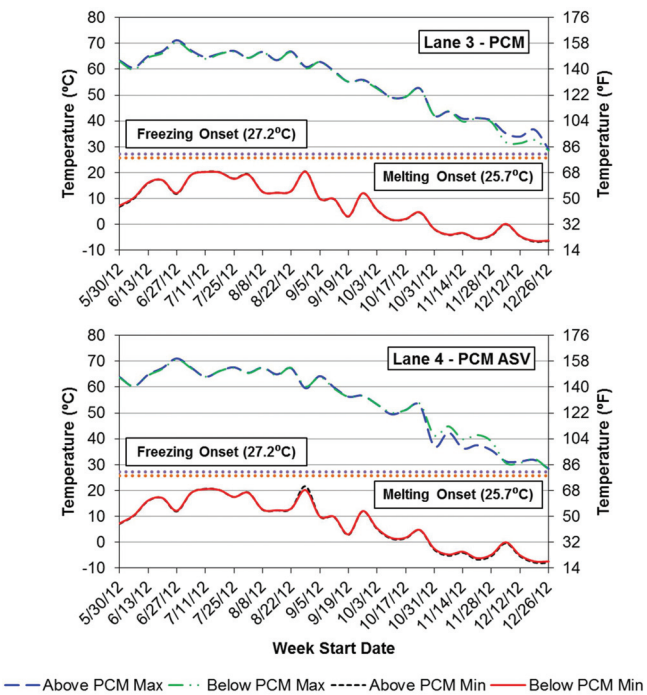

Figure 8 *Weekly maximum and minimum PCM surface temperatures.*

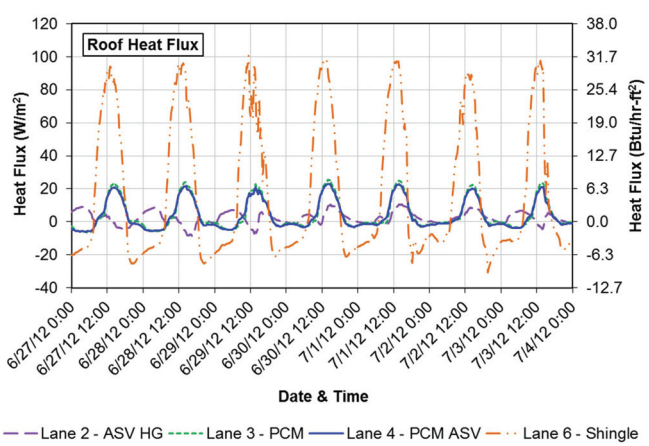

Figure 9 *Summer roof heat-flux variation.*

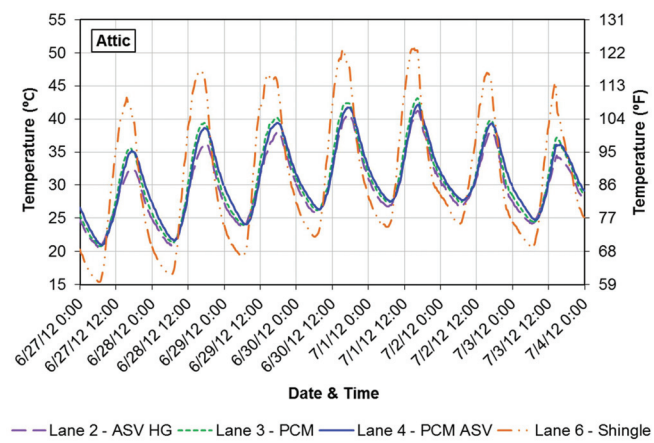

Figure 10 *Summer attic-temperature variation.*

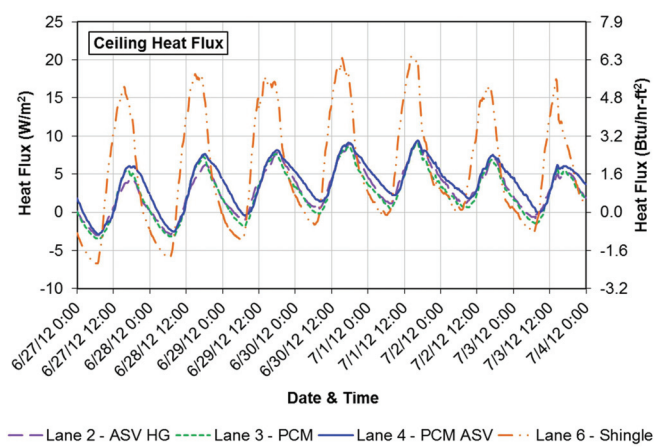

Figure 11 *Summer ceiling heat-flux variation.*

13. Bin-averaged outside temperatures are also shown in Figure 12.

The peak average-attic temperatures in the test lanes were 31.7°C (ASV HG), 33.9°C (PCM), and 33.6°C (PCM ASV), compared to 39.7°C in the asphalt shingle attic. Further, a delay of about 2–2.5 h was observed in occurrence of the peak temperature in the test attics compared to the asphalt shingle attic, which allows the benefit of peak-load shifting for utilities. Further, space-conditioning equipment have higher efficiency at lower ambient temperatures, which results in less energy usage to meet the loads with the peak shifting. The averaged ceiling heat flows showed a similar trend as the attic temperatures, with a delay of about 2–2.5 hours in the occurrence of the peak-ceiling heat flow. The peak-ceiling heat flows in the test attics were 3.6 W/m^2 (ASV HG), 4.2 W/m^2 (PCM), 5.0 W/m^2 (PCM ASV), and 12.2 W/m^2 (Shingle). The average-ceiling heat flows in the PCM ASV lane were consistently higher than the PCM lane. This is surprising, since the PCM ASV lane showed lower attic temperatures than the PCM lane between the hours of about 9:00–18:00, which includes the peak attic-temperature period. This could be the result of some uncertainty in the HFT measurements, and needs to be further investigated.

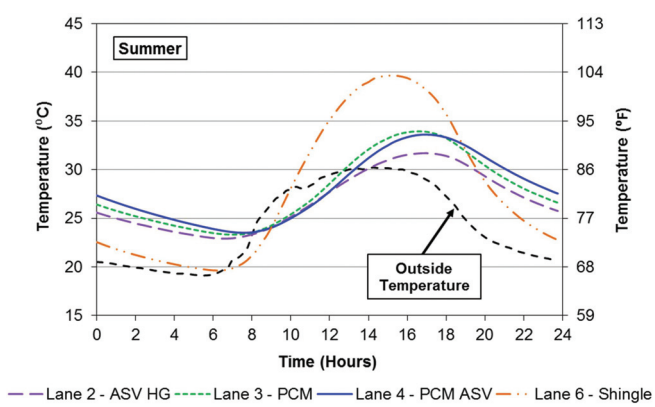

Figure 12 *Bin-averaged summer attic temperatures.*

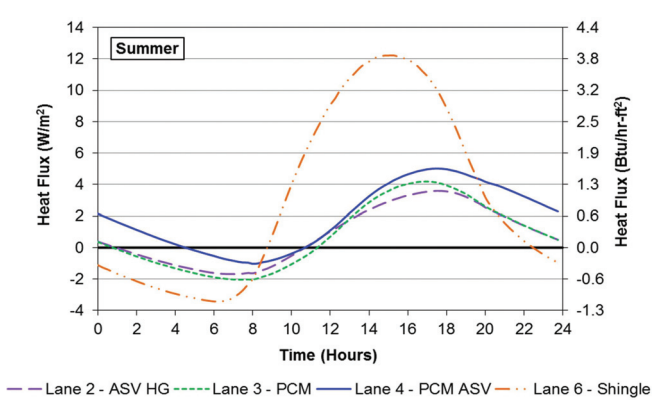

Figure 13 *Bin-averaged summer ceiling heat flows.*

Winter Performance

Here, temperature and heat flux data from a typical winter week (December 12–18, 2012) and the overall winter period (defined as November 1, 2012–January 1, 2013) are shown. Figure 14 shows the weekly variation of the roof heat flux. All test roofs (Lane 2 ASV HG, Lane 3 PCM, and Lane 4 PCM ASV) significantly reduced both the daytime heat gains and nighttime losses compared to the control asphalt shingle roof. The reductions in daytime heat gain could potentially result in a heating penalty in winter for these test roofs. However, all the attics with the dynamic test roofs remained warmer than the control attic, except during certain periods of peak solar irradiance (Figure 15). The PCM ASV roof performed the best in maintaining a warmer attic, with minimum temperatures about 6.1°C higher than the asphalt shingle attic; the minimum PCM and ASV HG attic temperatures were 4.2°C and 3.1°C higher than the control.

Figure 16 shows the weekly ceiling heat flows during the winter week. The test roofs reduced the ceiling heat loss significantly. During this week, the heat flows were predominantly out of the conditioned space. The asphalt shingle attic

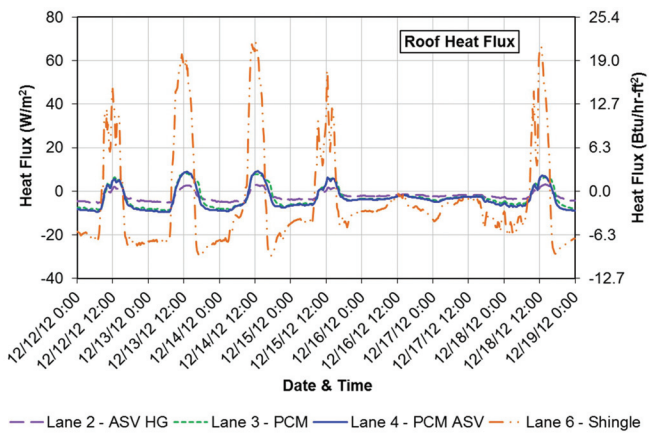

Figure 14 *Winter roof heat-flux variation.*

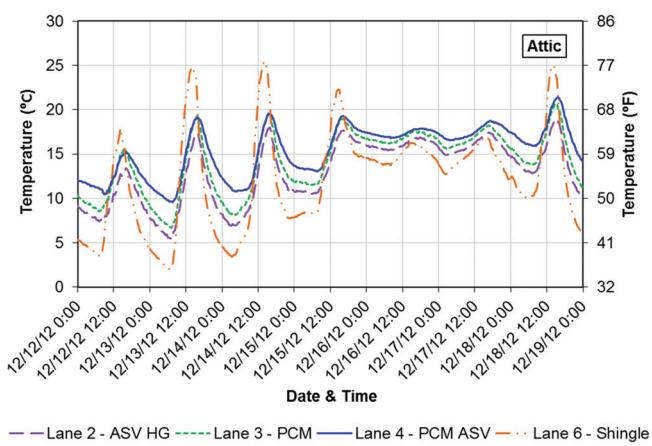

Figure 15 *Winter attic-temperature variation.*

added some heat to the conditioned space for brief daytime periods. On average, the peak nighttime ceiling losses for the different attics were 10.8 W/m^2 (ASV HG), 9.6 W/m^2 (PCM), 9.1 W/m^2 (PCM ASV), and 14.4 W/m^2 (Shingle). Note that the negative signs have been omitted, since heat loss indicates heat flow out of the conditioned space.

To evaluate the performance of the test roofs over the entire heating period, the bin-averaged attic temperatures and the ceiling heat flows from November 1, 2012–January 1, 2013 are shown in Figures 17 and 18. During winter, the PCM ASV attic stayed warmer than both the ASV HG and PCM lanes. The asphalt shingle attic had warmer daytime temperatures due to the solar heat gain, but lower nighttime temperatures than the test lanes. The minimum average-attic temperatures in the test lanes were 10.9°C (ASV HG), 12.0°C (PCM), and 14.0°C (PCM ASV), compared to 7.9°C in the asphalt shingle attic. The minimum ceiling heat flows (heat loss) were 10.7 W/m^2 (ASV HG), 9.6 W/m^2 (PCM), 9.1 W/m^2 (PCM ASV), and 14.4 W/m^2 (Shingle).

CONCLUSION AND FUTURE WORK

This article presents various metal roof configurations that were tested at the ESRA facility of ORNL during summer, fall, and winter of 2012–2013, and describes their potential for reducing the attic-generated space-conditioning loads. These roofs contained different combinations of PCM, rigid insulation, low-e surface, and above-sheathing ventilation, with standing-seam metal panels on top. Three test roofs were constructed and are referred to as the ASV HG roof, PCM roof and PCM ASV roof. These roofs were built on side by side test lanes, and compared to a control Shingle roof containing asphalt shingles on OSB roof deck. All three test roofs showed the potential for substantial energy savings compared to the asphalt shingle roof. They were highly effective in reducing the heat flows through the roof and ceiling, and in reducing the diurnal attic-temperature fluctuations. The ASV HG roof showed the best performance during the cooling period, while the PCM ASV roof performed the best during the heating season.

It should be noted that the present work does not seek to compare metal and asphalt shingle roofs *per se*. Rather, the intent was to evaluate the energy-saving potential of roofs containing rigid insulation and dynamic features like PCM, ASV and low-e surface with respect to a conventional shingle roof, which is the most common roof-type in the United States. The metal roofs in this study also possess different surface optical properties from shingle roofs, which also contributes to the thermal performance differences.

The data generated from these test lanes are useful in evaluating their performance in the field. However, these results are limited to the current test setup and the specific climate zone. In order to evaluate these roofs in different climate zones and for different construction types, numerical modeling is important. The data from these tests are invaluable for validating such energy models.

ACKNOWLEDGMENTS

The authors would like to thank Joe Harter and Derrick Fowler (ATAS International, Inc.), Sam Yuan (CertainTeed) and Pete Horvath (Phase Change Energy Solutions) for their contributions. The technical assistance of Phillip Childs and

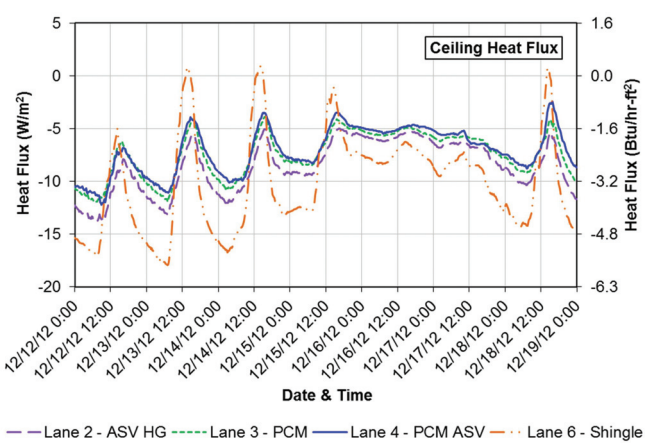

Figure 16 *Winter ceiling heat-flux variation.*

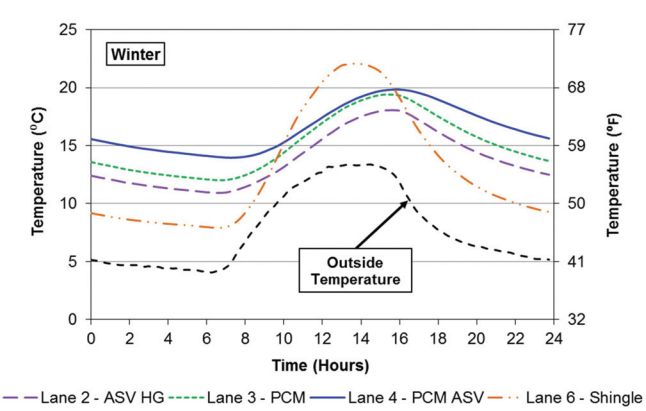

Figure 17 *Bin-averaged winter attic temperatures.*

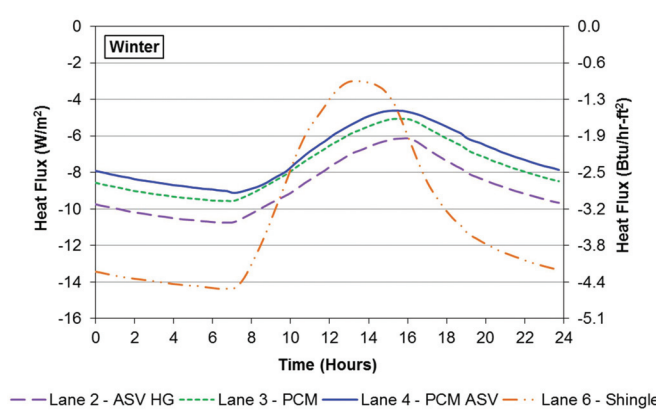

Figure 18 *Bin-averaged winter ceiling heat flows.*

Jerald Atchley (ORNL) in setting up the data acquisition systems is gratefully acknowledged.

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