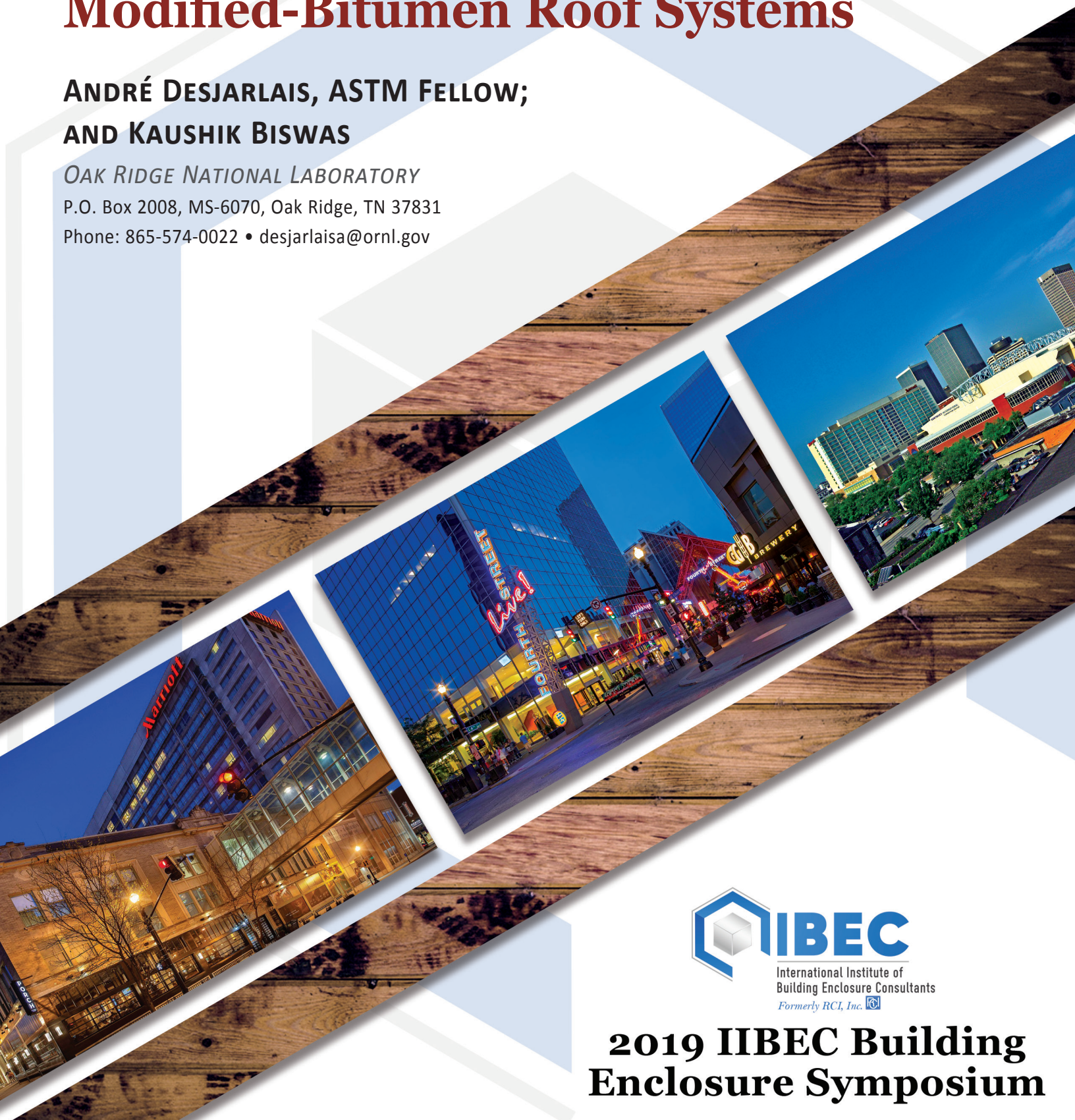


Re-examining the Energy Efficiency of Built-Up Roofing and Modified-Bitumen Roof Systems

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ABSTRACT

Built-up roofing (BUR) and modified-bitumen (mod-bit) roofing systems represent some of the longest-lasting roofing systems available for low-slope roofing. Over the past 20 years, the emergence of cool roofing and its enactment into multiple building codes in many cases has eliminated this roofing option from consideration because these systems typically do not have the required levels of solar reflectance.

Since BUR and mod-bit systems are typically ballasted with aggregate for ultraviolet (UV) protection of the asphalt, they are much heavier than their counterparts. With areal densities from 7–10 lb/ft², the role of thermal inertia could have a significant contribution to the energy savings of the building enclosure. Since the late 1980s, ASHRAE Standard 90.1 has given an energy credit to wall systems that have thermal mass. In the early 2000s, research has demonstrated that ballasted roofing systems are more energy efficient than their light-weight counterparts given equivalent applications. Aggregate is also available in a wide range of colors that can enhance BUR and mod-bit systems in reflecting solar load.

This paper reports on a series of in-situ experiments that were designed to measure the energy performance of BUR and mod-bit roofing systems. These data were then used to calibrate a transient thermal model for roofs and to generalize the findings to the range of climates found in the United States. Comparisons of their energy performance are then made to other traditional low-slope roofing systems.

SPEAKER

ANDRÉ DESJARLAIS, ASTM FELLOW



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ROOF TYPES AND CONSTRUCTION

A field test was performed on the Oak Ridge National Laboratory's (ORNL's) Roof Thermal Research Apparatus (RTRA) in Oak Ridge, TN. The



Figure 1 – Test roof sections on the Roof Thermal Research Apparatus.

RTRA is a single story, conditioned building that exposes side-by-side roof and wall assemblies to natural weathering. The RTRA was constructed in the late 1980s for documenting the effects of long-term exposure of small, low-sloped roof test sections to the East Tennessee climate. The RTRA has four 4 x 8 ft. openings in its roof to house instrumented low-slope roof test sections, with the option of dividing each test section into multiple areas. Figure 1 shows the roof of the RTRA containing the test sections.

These openings can accommodate test roofs with state-of-the-art and prototype building enclosure technologies for evalua-

tion under real building and weather conditions. Test roofs are usually instrumented with temperature, relative humidity, and heat flow sensors. The data are collected and monitored over several months, and even years, to evaluate the long-term performance of building enclosure systems and technologies.

Figure 2 shows the different test roofs being evaluated in this paper. Both the BUR and mod-bit roofs were divided into two sections—each containing aggregate of a different color and with different solar reflectance (SR). The measured reflectance of each roof section is shown on the figure.

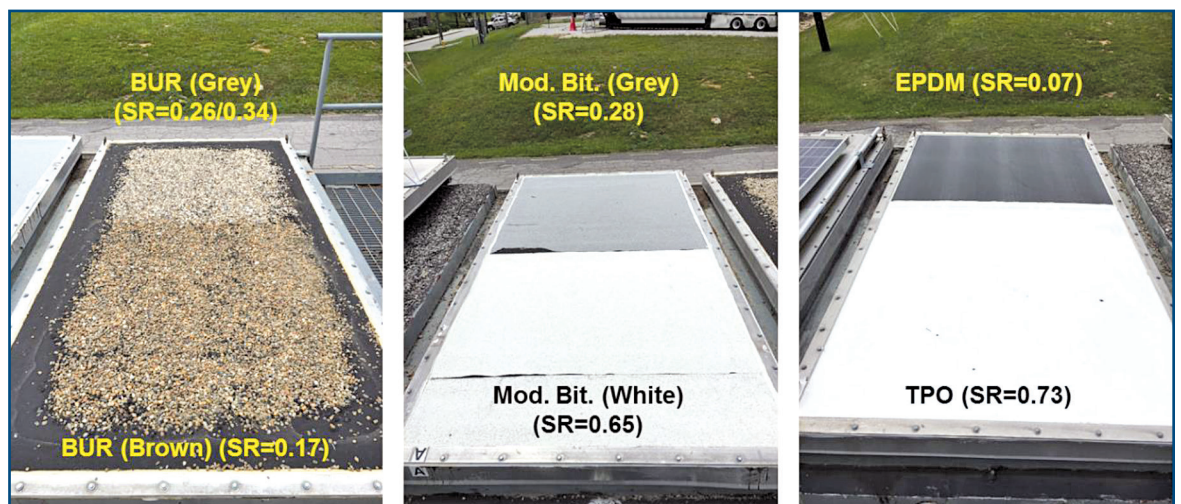


Figure 2 – BUR and mod-bit roofs; also shown are EPDM and TPO roofs that were used as control roofs.

The aggregate on the gray BUR section was replaced during the test period, and the solar reflectance before and after are listed. Two additional test roofs were installed and monitored—one containing an ethylene propylene diene monomer (EPDM) membrane, and another containing a thermoplastic polyolefin (TPO) single-ply roofing membrane. These test roofs were used as low-mass controls.

Figure 3 schematically shows the cross section and components of the test roof (excluding the surface aggregates), as well as the instrumentation utilized to monitor the roofs. The roofs were all built on a steel deck with two layers of polyisocyanurate (polyiso) insulation, followed by a wood

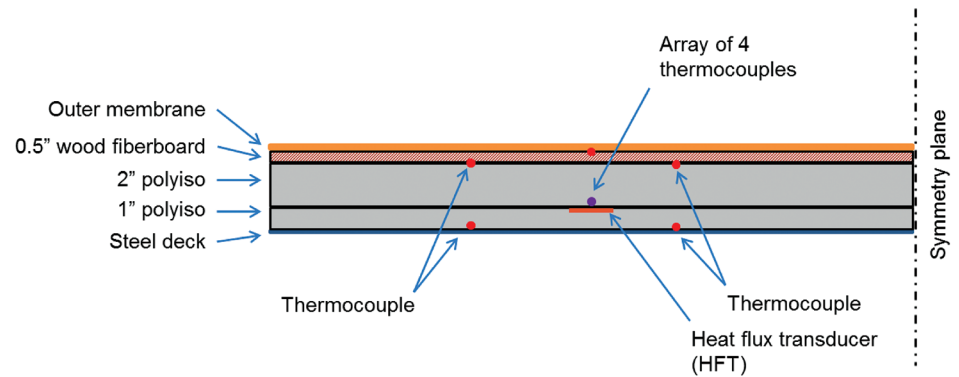


Figure 3 – Roof components and instrumentation.

fiberboard cover board and the roof membranes. Aggregates on the BUR and mod-bit roofs are not shown in Figure 3. The solar

reflectance of the roof surfaces was measured using a solar reflectometer by Devices and Services Company¹ in accordance with ASTM C1549.²

EXPERIMENTAL DATA

Figure 4 shows the hourly temperatures during a summer week at the different locations within the BUR with the gray aggregate. “Deck” means the bottom steel deck, “HFT A-D” represents the array of four thermocouples (T/C) near the HFT (above the 1-in. polyiso layer), “Top ISO” means the top surface of the 2-in. polyiso layer, and “Cover” means the top of the wood fiberboard.

Figure 5 and Figure 6 compare the outer roof surface temperatures (top of the cover board) and the heat fluxes through the roofs for a week during the summer. The EPDM roof experienced the highest surface temperatures and heat fluxes due to the lowest solar reflectance and no thermal mass. On the other end of the spectrum, with the lowest surface temperature and heat flux were the TPO and mod-bit (white) roofs due to high solar reflectance (TPO) and thermal

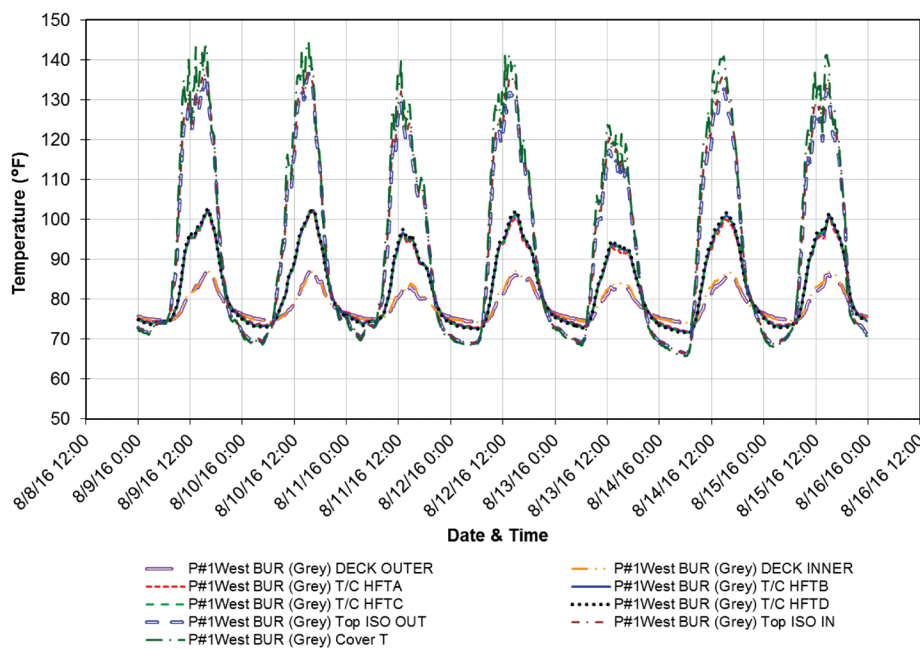


Figure 4 – Temperatures at different locations within the BUR with gray aggregate.

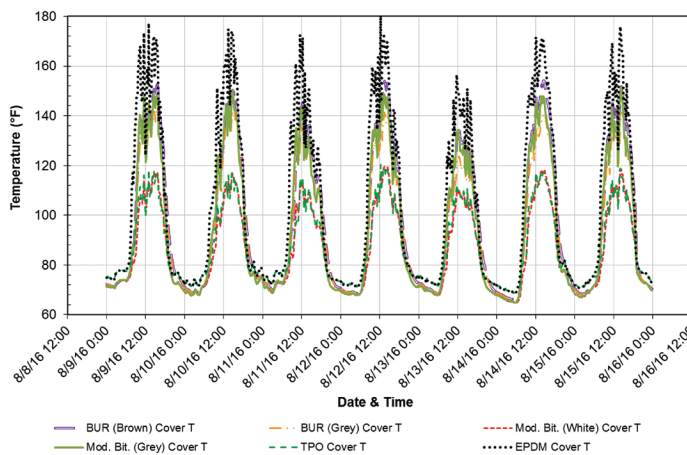


Figure 5 – Comparison of outside surface temperatures on the different roofs.

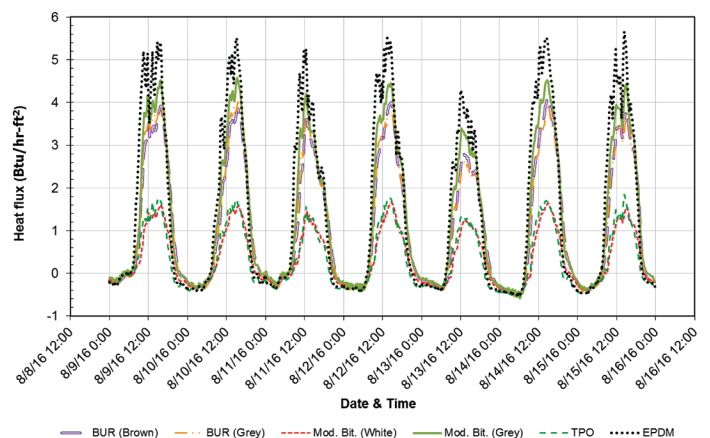


Figure 6 – Comparison of heat fluxes through the different roofs.

mass (mod-bit roof). The other roofs, with thermal mass and intermediate/low SR, were in between these datasets.

Figures 7-9 show bin-averaged outer surface temperatures and heat fluxes from the different roofs during two summer and one winter periods. Bin averaging means averaging the hourly readings of each corresponding hour (midnight to 1 AM, 1 to 2 AM, and so on) from the number of days used for averaging. Summer period A ranged from June 28 to August 8, 2016; the winter period ranged from December 20, 2016, to January 30, 2017; and summer period B ranged from May 16 to June 19, 2017.

The aggregate on the BUR (gray) was changed between summer period A and the winter period; the solar reflectance before the change was 0.26, and it was 0.33 after the change. Similar to the weekly data shown earlier, the EPDM roof exhibited the highest bin-averaged peak surface temperatures and heat fluxes, while the TPO and mod-bit (white) roofs showed the lowest peak surface temperatures and heat fluxes. During winter, the mod-bit (white) roof showed the minimum night time heat losses (Figure 8).

Changing the aggregate on the BUR (gray) had a discernible impact on its performance. During summer period A, the BUR (gray) roof showed significantly higher average peak surface temperature and heat flux compared to the TPO roof: 27.6°F and 2.4 Btu/hr-ft², respectively. During summer period B, the difference reduced to 2.1°F and 0.4 Btu/hr-ft².

SIMULATIONS USING STAR AND MODEL VALIDATION

Simplified Transient Analysis of Roofs (STAR)³ was used to simulate the test roofs to compare their performance on an annual basis under different climate conditions. Prior to performing the annual simulations, models of the roofs using STAR were created to match the test wall geometries, and the results were compared against measured data for model validation.

STAR is a one-dimensional, finite-difference heat conduction model. For boundary conditions, the model can use either specified temperatures at the exterior and interior surfaces or outdoor weather data and indoor conditions. The outdoor weather data include solar incidence, ambient temperature, wind conditions, radiation exchange with the sky, etc. The convective

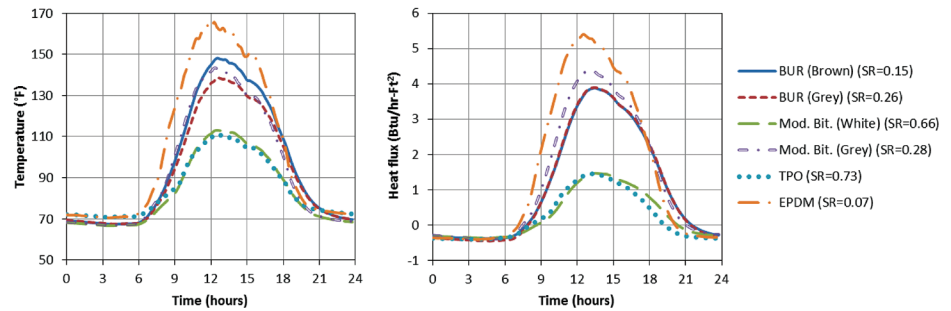


Figure 7 - Bin-averaged hourly surface temperatures and heat fluxes - summer period A.

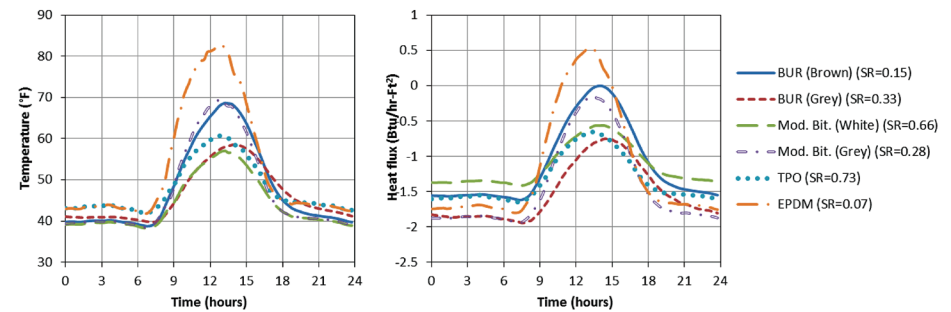


Figure 8 - Bin-averaged hourly surface temperatures and heat fluxes - winter period.

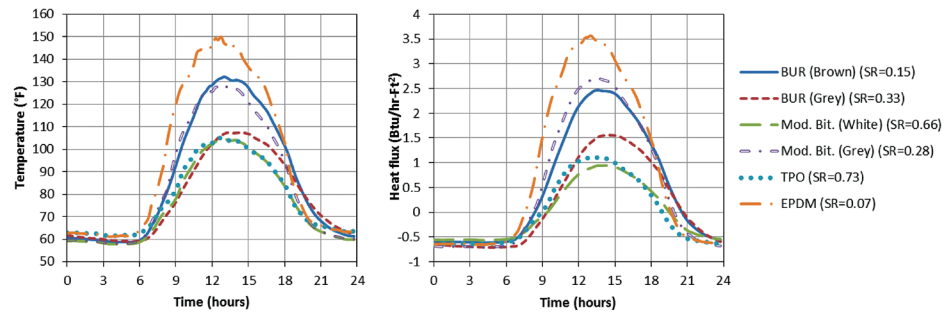


Figure 9 - Bin-averaged hourly surface temperatures and heat fluxes - summer period B.

heat transfer at the outdoor and indoor surfaces are calculated using correlations from the literature.

For validation study, the STAR model consisted of the 1/2-in. wood fiberboard and the two layers of polyiso insulation, as seen in Figure 3. The temperatures at the top of the fiberboard and the bottom of the 1-in. polyiso insulation were used as the bound-

ary conditions. The calculated temperatures and heat fluxes at the intermediate locations were compared against measurements. Table 1 lists the layers and material properties that were used in the simulations. The properties are based on literature and ORNL measurements of conductivity according to ASTM C518.⁴

The validation simulations were done for

| Layer | Thickness (inches) | Conductivity (Btu-in/hr-ft ² -°F) | Specific heat (Btu/lb-°F) | Density (lbs/ft ³) |
|-----------------|--------------------|--|---------------------------|--------------------------------|
| Wood fiberboard | 0.5 | 0.338 | 0.450 | 15.6 |
| Polyiso (1) | 2.0 | 0.178 | 0.374 | 1.50 |
| Polyiso (2) | 1.0 | 0.178 | 0.374 | 1.50 |

Table 1 - Material properties used in the validation models.

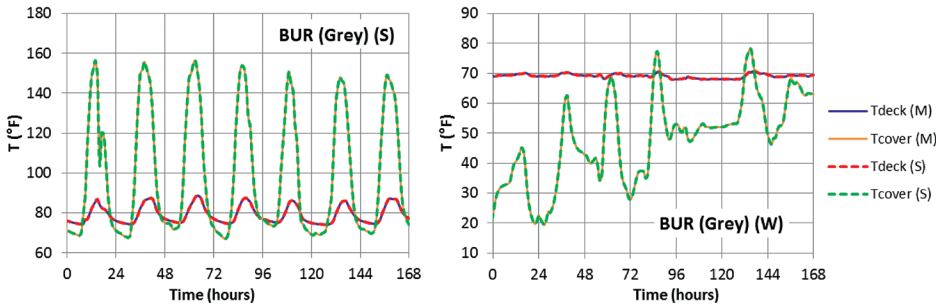


Figure 10 – Measured (M) and STAR output (S) of boundary temperatures.

seven-day periods during summer (between July 19 and 25, 2016) and winter (between December 20 and 26, 2016). Figure 10 shows the boundary temperatures used in the BUR (gray) model, “S” and “W” indicate the summer and winter periods. Also shown are the STAR outputs of the boundary conditions, to ensure that the boundary temperatures were being incorporated correctly in the models.

Figures 11 and 12 show the comparison of measured and calculated temperatures and heat fluxes from the EPDM roof. In general, the calculated tempera-

tures at the interfaces were in excellent agreement with the measurements, within 1–2°F of the peaks and valleys in the measured temperature profiles.

| Component | Material | Thickness | Thermal conductivity | Specific heat | Density |
|-----------------|------------------|-----------|-------------------------------|---------------|---------------------|
| | | inches | Btu-in/hr-ft ² -°F | Btu/lb-°F | lbs/ft ³ |
| Aggregate* | Stone | 0.50 | 10.0 | 0.21 | 105 |
| Roof membrane | Black EPDM | 0.06 | 1.1 | 0.24 | 86 |
| | White TPO | 0.06 | 1.1 | 0.24 | 86 |
| | Modified bitumen | 0.76 | 2.0 | 0.36 | 70 |
| | Built-up roof | 0.38 | 1.15 | 0.35 | 70 |
| Wood fiberboard | Wood fiberboard | 0.50 | 0.34 | 0.45 | 15.6 |
| Insulation | Polyiso | ** | 0.18 | 0.38 | 1.5 |
| Steel deck | 22-gauge steel | 0.028 | 312 | 0.11 | 502 |

* Mod-bit and BUR roofs only

** Based on climate zone

Table 2 – Modeled roofs – components and material properties.

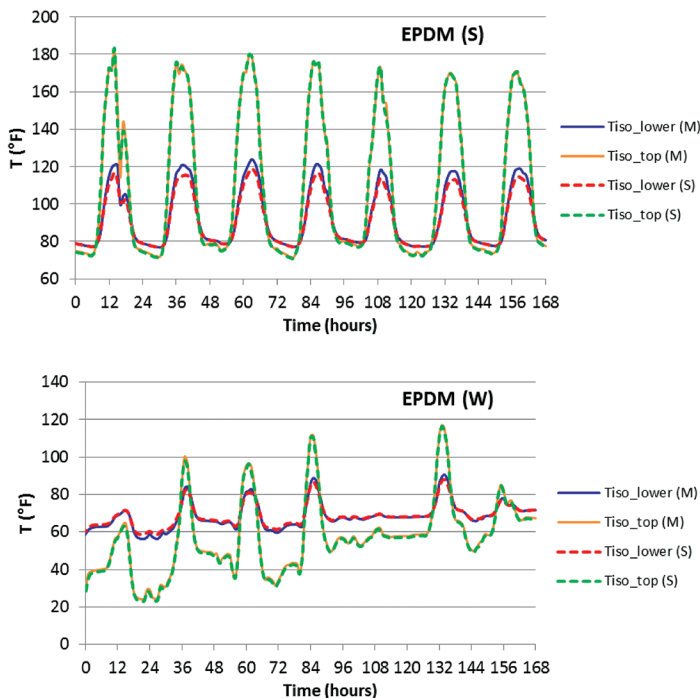


Figure 11 – Measured (M) and calculated (S) temperatures at the interfaces of the EPDM roof.

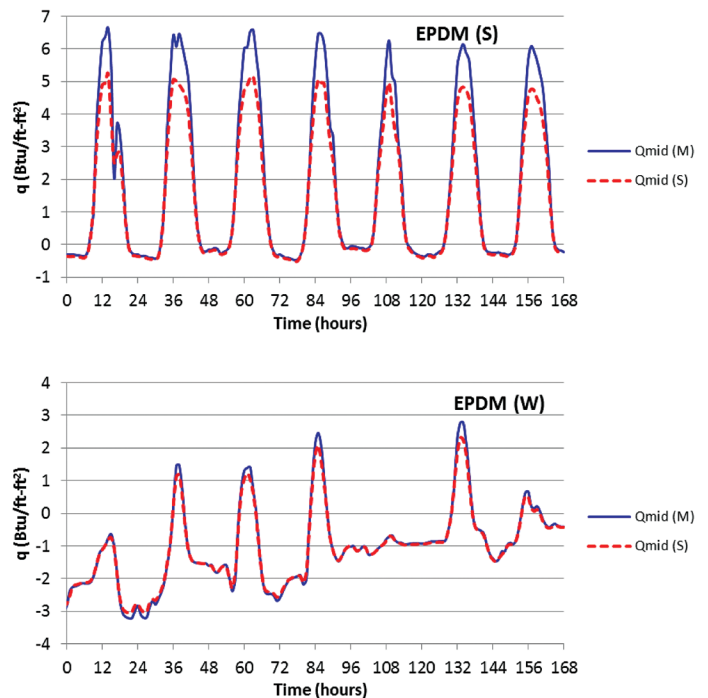


Figure 12 – Measured (M) and calculated (S) heat fluxes through the EPDM roof.

Higher discrepancies were observed between the measured and calculated heat fluxes. The simulation model had difficulty in capturing the summer peak heat fluxes. However, the model did well in predicting the average weekly heat flux.

ANNUAL SIMULATIONS

Following the validation simulations, STAR was used to calculate the annual performance of a variety of different roofs in terms of heating and cooling loads. Eight cities—one in each ASHRAE climate zone—were chosen for the annual modeling using typical meteorological year (TMY) weather data.⁵ Table 2 lists the roof configurations

and material properties of the different layers used for the annual simulations. *Table 3* lists the cities and the thickness of the insulation for each city, based on the code-mandated minimum insulation thermal resistance (R-value). The R-values are based on the 2015 International Energy Conservation Code, table C402.1.3 assuming insulation entirely above roof deck.⁶ The material properties are based on literature, primarily the *ASHRAE Handbook of Fundamentals*.⁷

The mod-bit roof and BUR contained five layers, while the EPDM and TPO roofs contained four layers (no aggregate layer). Two mod-bit roofs were modeled with solar reflectances of the aggregate layer of 0.65 (white) and 0.28 (gray), and two BURs were modeled with an aggregate layer solar reflectances of 0.34 (white) and 0.17 (brown). The solar reflectance of the EPDM and TPO roofs were 0.067 and 0.73, respectively.

Using the TMY3 weather data, including solar irradiance, radiation exchange with the surroundings, wind speed and direction, and ambient temperature and humidity, the heat gains and losses at the interior surface of the roofs were calculated.

Figures 13 and *14* show the calculated monthly heat gains and losses from the different roofs under Miami (hot) and Minneapolis (cold) climate conditions, respectively. The heat gains in the hot, cooling-dominated climate zone are in the following descending order: EPDM > BUR (brown) > mod-bit (gray) > BUR (white) > mod-bit (white) > TPO. Clearly, the surface solar reflectance has a major impact on the heat gains through the roof. The roofs in a descending order of total annual heat gains matches the descending order of the surface solar reflectance.

As expected, the monthly heat losses are higher than heat gains in the cold, heating-dominated climate of Minneapolis, in the following descending order: TPO > mod-bit (white) > BUR (white) > mod-bit (gray) > EPDM > BUR (brown). In a cold climate, higher surface solar reflectance has an adverse impact on the heat losses, due to lower solar gains that would offset the losses due to lower ambient temperature. For heat losses, thermal mass also seems to be an important consideration. EPDM had the lowest solar reflectance (0.07) of all roofs but had a higher total annual heat loss than BUR (brown), which had a solar reflectance of 0.17 but had some thermal mass due to the aggregate layer.

Tables 4 and *5* show the calculated total annual heat gains and losses from the different roofs and in the different climate zones. The roof types have been listed in increasing order of surface solar reflectance. As expected, the annual heat gains decrease with increasing surface solar reflectance.

The calculated heat losses generally increase with increasing solar reflectance, but again, thermal mass also seems to play a significant role in the performance of the roofs. In all climate zones, the calculated heat losses through the BUR (brown) were lower than EPDM, even though EPDM has a lower solar reflectance, presumably due to the stone layer on the BUR acting as added thermal mass. In some climate zones, the other mod-bit and BUR roofs also had lower heat losses than the EPDM roof.

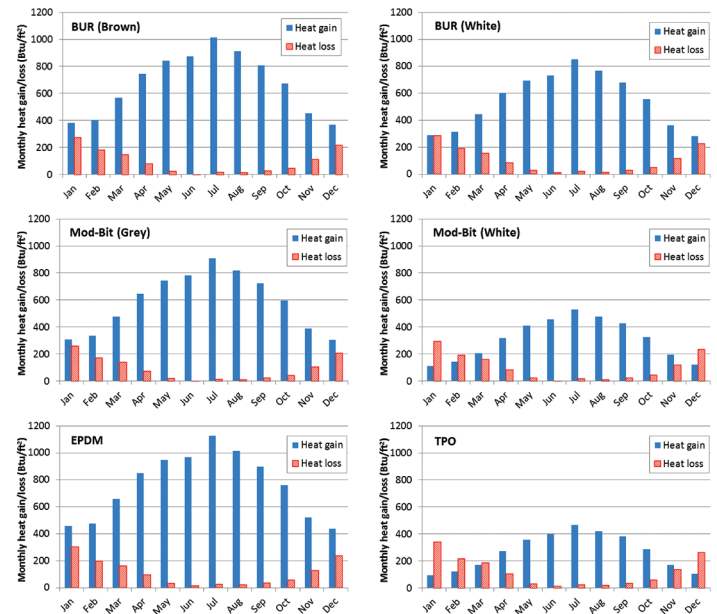


Figure 13 – Comparison of calculated heat gains and losses through the different roofs under Miami weather conditions.

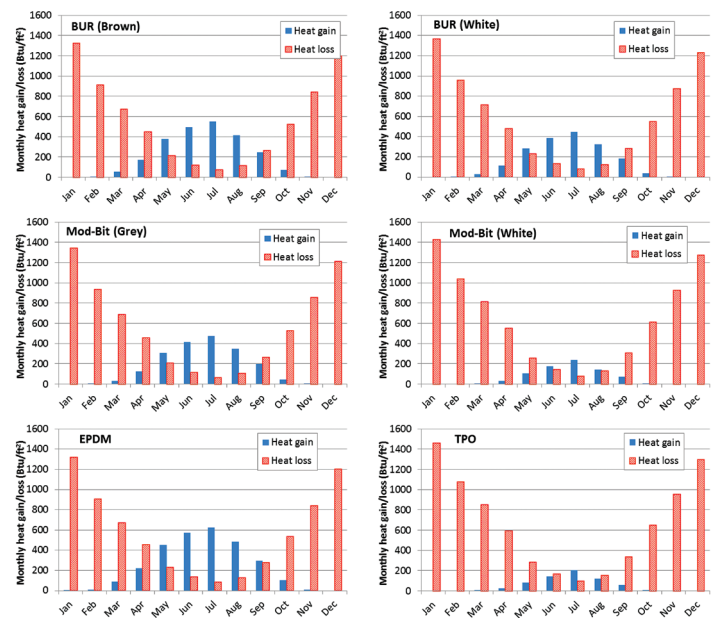


Figure 14 – Comparison of calculated heat gains and losses through the different roofs under Minneapolis weather conditions.

| ASHRAE Climate Zone | City | Thickness | R-value |
|---------------------|-----------------|-----------|----------------------------|
| | | Inches | hr-ft ² -°F/Btu |
| 1 | Miami, FL | 3.59 | 20 |
| 2 | Houston, TX | 4.49 | 25 |
| 3 | Atlanta, GA | 4.49 | 25 |
| 4 | Baltimore, MD | 5.39 | 30 |
| 5 | Chicago, IL | 5.39 | 30 |
| 6 | Minneapolis, MN | 5.39 | 30 |
| 7 | Fargo, ND | 6.28 | 35 |
| 8 | Fairbanks, AK | 6.28 | 35 |

Table 3 – List of cities and corresponding insulation R-value and thickness.

| Roof Type | SR | Miami | Houston | Atlanta | Baltimore | Chicago | Minneapolis | Fargo | Fairbanks |
|-----------------|------|-------|---------|---------|-----------|---------|-------------|-------|-----------|
| EPDM | 0.07 | 9111 | 6490 | 5724 | 3684 | 3070 | 2859 | 2248 | 1329 |
| BUR (brown) | 0.17 | 8034 | 5649 | 4898 | 3127 | 2579 | 2384 | 1871 | 1045 |
| Mod-Bit (gray) | 0.28 | 7020 | 4850 | 4110 | 2600 | 2119 | 1942 | 1515 | 780 |
| BUR (white) | 0.34 | 6575 | 4558 | 3840 | 2420 | 1970 | 1798 | 1399 | 703 |
| Mod-Bit (white) | 0.65 | 3722 | 2467 | 1875 | 1140 | 876 | 768 | 565 | 163 |
| TPO | 0.73 | 3241 | 2165 | 1598 | 960 | 734 | 631 | 456 | 112 |

Table 4 – Calculated total annual heat gains (Btu/ft²).

| Roof Type | SR | Miami | Houston | Atlanta | Baltimore | Chicago | Minneapolis | Fargo | Fairbanks |
|-----------------|------|-------|---------|---------|-----------|---------|-------------|-------|-----------|
| EPDM | 0.07 | 1294 | 2758 | 3979 | 4555 | 5803 | 6775 | 6842 | 9966 |
| BUR (Brown) | 0.17 | 1169 | 2585 | 3831 | 4486 | 5763 | 6739 | 6814 | 9924 |
| Mod-Bit (Gray) | 0.28 | 1087 | 2497 | 3789 | 4513 | 5822 | 6815 | 6888 | 10013 |
| BUR (White) | 0.34 | 1203 | 2684 | 3994 | 4699 | 6006 | 7006 | 7064 | 10173 |
| Mod-Bit (White) | 0.65 | 1229 | 2889 | 4399 | 5188 | 6539 | 7598 | 7597 | 10780 |
| TPO | 0.73 | 1451 | 3243 | 4787 | 5532 | 6887 | 7963 | 7936 | 11141 |

Table 5 – Calculated total annual heat losses (Btu/ft²).

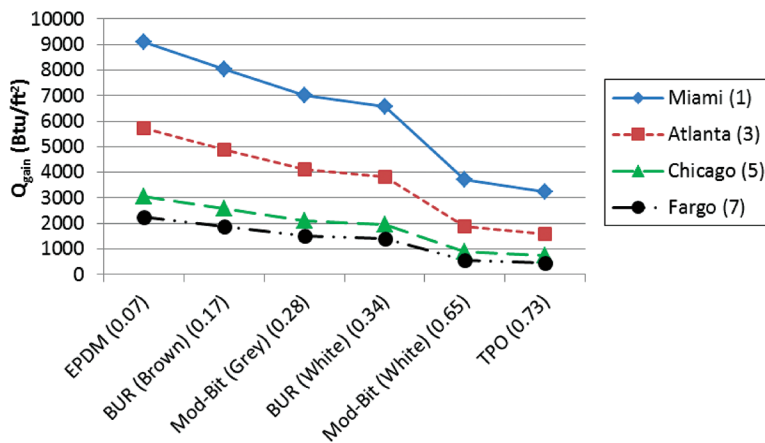


Figure 15 – Comparison of calculated annual heat gains in climate zones 1, 3, 5 and 7.

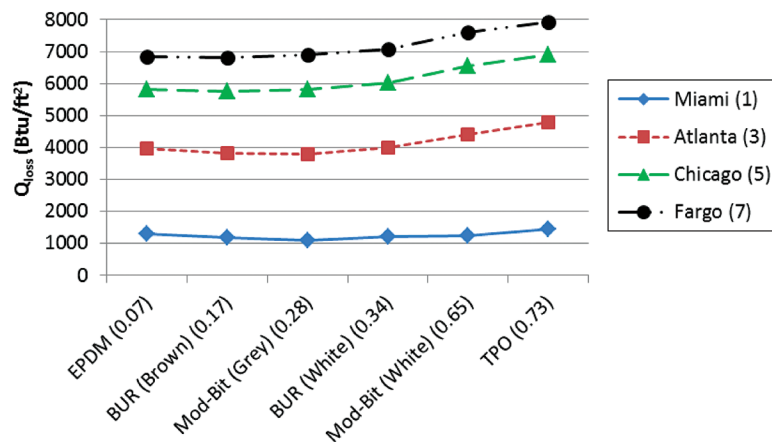



Figure 16 – Comparison of calculated annual heat losses in climate zones 1, 3, 5 and 7.

Finally, Figures 15 and 16 show the trend in the calculated annual heat gains and losses for the cities in climate zones 1 (Miami), 3 (Atlanta), 5 (Chicago), and 7 (Fargo), for illustration purposes. The solar reflectance values of the roofs are also listed along the x-axis labels.

SUMMARY

Several different low-slope roof technologies were experimentally and numerically investigated. These included built-up roofing (BUR), modified-bitumen (mod-bit) roofs, as well as single-ply roofs with EPDM and TPO membranes. Simulations were performed using a one-dimensional, finite-difference conduction heat transfer model called Simplified Transient Analysis of Roofs (STAR). The experimental data were used to validate the STAR models. Next, the validated models were used for annual simulations under weather conditions of multiple cities representing the different climate zones. The calculated annual heat gains and heat losses were primarily functions of the surface solar reflectance. Thermal mass due to the added aggregate layer on selected BUR and mod-bit roofs also had an impact in reducing the heat losses compared to the EPDM roof.

Roofing professionals should not dismiss the use of these roofing systems from an energy efficiency perspective because they can be created to compete with today's cool roofing alternatives, use thermal inertia to slightly enhance their energy performance, and have a history of long life. Thermal mass seems to have a greater effect on the heat losses; the addition of thermal inertia is clearly evident under these conditions. The color of the aggregate selected can create asphaltic roofing systems that reduce cooling load by almost as much as a traditional cool roof. 

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