Comparison of Techniques for In Situ, Non-Damaging Measurement of Infrared Emittances of Low-Slope Roof Membranes

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ABSTRACT

Techniques for measuring the infrared emittance of roof surfaces in situ are not well developed. Roof surfaces are often attached to or are part of a thick layer of asphaltic material with low-thermal conductivity. Standard steady-state techniques for use of portable infrared emissometers cannot be directly applied. This paper documents experience with a portable infrared emissometer using a special transient technique. With it, correction for the non-steady conditions is theoretically possible according to the manufacturer. Calibration of the technique was attempted with four roof coatings exhibiting a range in infrared emittance from 0.39 to 0.85. Values with the transient technique were, on average, 0.052 too high. The technique was applied to 24 coated and 4 uncoated surfaces on thick roof membranes. Results are also presented for infrared emittance of these 28 surfaces estimated from images recorded by an infrared camera. Independently measured surface temperatures were matched by adjusting the emittance of the surface in the camera's post-imaging analysis software. The infrared camera and the portable emissometer results agreed within the ±0.05 uncertainty of either technique if the latter's accuracy correction was ignored.

INTRODUCTION

An Energy Star Roof Products Program for reflective roofs has been implemented by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE). The program's approach is to require that initial and three-year weathered solar reflectances be above certain levels for products seeking the Energy Star label. The three-year requirement creates a challenging expectation—certification that large areas of roofs are meeting the prescribed performance criteria despite being subjected to weathering conditions in various locations. Such certification calls for in situ techniques to measure roof radiation properties. Cutting out samples for laboratory analysis of their properties would not be acceptable.

Our experience shows that both solar reflectance and infrared emittance are important for the thermal performance of low-slope roofs that are typical on commercial buildings in temperate climates (Wilkes et al. 2000). We have found that the heat flow through these assemblies into the conditioned space under them is especially sensitive to the reflectance of the roof in the solar part of the spectrum (wavelength from 0.2 to 2.5 micrometers) and the emittance of the roof in the far infrared (wavelength from 4 to 40 micrometers). In support of the U.S. EPA/DOE Energy Star Roof Products Program and with funding by the U.S. DOE Energy Efficiency and Renewable Energy Program, we have undertaken development and documentation of techniques for measuring the solar reflectance and infrared emittance of roof surfaces in situ. The work on solar reflectance measurement techniques has been presented elsewhere (Petrie et al. 2000).

This paper documents our experience with two techniques that are available for in situ measurement of the infrared emittance of roof samples. One technique uses a portable infrared emissometer with a heated detector. On thin samples, it is the instrument for the steady-state method discussed in ASTM Standard Method C1371-98 (ASTM 2000). We pursued a transient method presented by the manufacturer of the instrument for use on in-place surfaces and on materials

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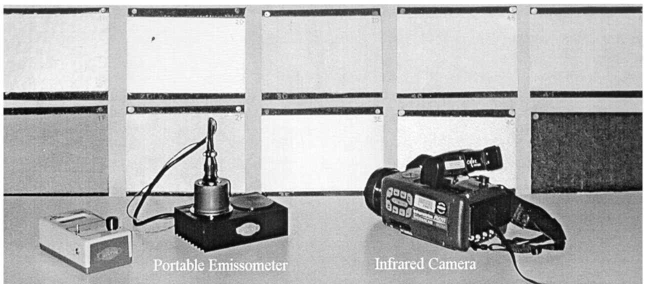

Figure 1 *Portable emissometer and infrared camera for measurement of the infrared emittance of low-slope roof surfaces.*

with low thermal conductivity, such as low-slope roof assemblies. The other technique uses post-imaging analyses of images of the low-slope roof surfaces taken by an infrared camera with inherent ability to account for effects of background radiation and effects of varying surface infrared emittance.

The purpose of this paper is to present the theoretical justification of the two techniques and to explain the procedures we followed to use the techniques on 24 different coated low-slope roofs and 4 uncoated roofs. Two sets of measurements were taken with each technique on fully weathered surfaces. The portable emissometer data are from May 1999 and May 2000, and the infrared camera data are from September 1999 and June 2000. The surfaces began continuous weathering in June 1997. Comments are offered about the effect of weathering on the infrared emittance of low-slope roof coatings. Differences between results from the two techniques are discussed in light of each one's accuracy and precision. Conclusions are made about the suitability of the techniques for in situ measurement of the infrared emittance of roofs.

TECHNIQUES FOR IN SITU MEASUREMENT OF INFRARED EMITTANCE

This section presents the theoretical background on the measurement of infrared emittance with a portable emissometer using a heated detector and from an image of the surface taken with an infrared camera. A photograph of the two instruments is shown in Figure 1. Samples of typical low-slope roof surfaces are in the background. Two U.S. national laboratories worked cooperatively to establish the accuracy of the techniques. Results of this effort are presented as part of the discussion for the portable emissometer.

Definition of Infrared Emittance

Any surface above absolute zero temperature emits thermal radiation in the whole spectrum of wavelengths. At each wavelength, the amount emitted is less than or equal to the maximum amount that a blackbody emits at that wavelength. This defines the wavelength-dependent hemispherical emittance:

$$\varepsilon_\lambda = e_\lambda / e_{b\lambda} \qquad (1)$$

where

ε_λ = wavelength-dependent hemispherical emittance,

e_λ = energy emitted from the surface at the wavelength λ over all directions, and

$e_{b\lambda}$ = blackbody radiation at the wavelength λ.

If the emittance is constant over the infrared wavelengths of interest for surfaces near room temperature, or an average value is adequate for characterizing the thermal performance of the surface, then

$$\varepsilon_{IR} = e_{IR} / e_{bIR} \qquad (2)$$

where

ε_{IR} = infrared emittance of the surface,

e_{IR} = total infrared energy emitted from the surface, and

e_{bIR} = blackbody radiation over infrared wavelengths (typically 4 to 40 micrometers).

The total blackbody radiation is temperature dependent as shown by the expression

$$e_b = \sigma T^4 \qquad (3)$$

where

e_b = total blackbody radiation over all wavelengths,

σ = Stefan-Boltzmann constant, and

T = absolute temperature of the surface.

At room temperature or below, most of the emitted radiation is in the infrared part of the spectrum. Only at elevated temperatures does a surface begin to glow—first dark red, then brighter as the wavelength at which most of the radiation is emitted moves toward the wavelengths at which the human eye is most sensitive, namely, wavelengths from 0.45 to 0.75 micrometers.

Portable Emissometer

The portable emissometer shown in the left half of Figure 1 and discussed in ASTM C1371-98 (ASTM 2000) uses an electrically heated sensing element. The 5 cm (2 in.) diameter sensing element is placed on the test section and the element is heated to about 65°C (150°F). Low and high emittance detectors in the sensing element produce an output proportional to the infrared emittance of the heated surface. The instrument is designed to reach a steady-state response, defined as a reading steady in the second decimal place of the readout, within a few minutes for thin samples placed on a heat sink exposed to the ambient temperature. Figure 1 shows a reference sample on a heat sink, both of which are supplied with the instrument. Thin samples with high thermal conductivity and the presence of the heat sink do not allow the sensing element to change the temperature of the sample except

TABLE 1
Infrared Emittances of Four Typical Roof Coatings

		Portable Emissometer		
	Spectral Average*	Steady-State† Measurement‡	Transient** Technique	Difference (Transient - SS)
Aluminized Asphalt Emulsion	0.86	0.79	0.86	+0.07
Fibrated Aluminum	0.40	0.39	0.45	+0.06
Aluminum Emulsion	0.61	0.60	0.63	+0.03
White Latex Coating	0.86	0.85	0.90	+0.05
			Average Difference	+0.052

* Assumed accurate to ±0.01 except for the aluminized asphalt emulsion
† Coatings on metal
‡ ASTM C1371-98 Procedure
** Coatings on 1.1 mm thick APP-modified bitumen

in the small area under the detectors. Temperatures and instrument response are steady.

Because low-slope roofing samples are thick and have a low thermal conductivity, local heating of the area under the detectors cannot be avoided. If steady-state response of the instrument is not achieved within 90 seconds, the manufacturer has developed a transient technique (D&S 1979). The infrared emittance of a thin piece of high-emittance material, such as ordinary masking tape, is measured on the heat sink. The instrument's response in terms of apparent infrared emittance is then recorded from two to four minutes after the sensor head is placed over the tape affixed to the sample. In this time interval, the apparent emittance is decreasing linearly due to heating of the surface under and near the detectors. Before two minutes, nonlinear response is typical. The apparent emittance of the tape from two to four minutes is extrapolated back to zero time. Extrapolation to zero time is also done for the apparent emittance from two to four minutes of the surface itself under the detectors. The ratio of the tape's emittance at steady state on the heat sink and the tape's apparent emittance at zero time on the surface of interest is formed. This ratio is the correction for heating of the surface under and near the detectors. The product of the correction and the apparent emittance at zero time of the surface itself yields the estimate of the actual emittance of the surface by the transient technique.

The manufacturer does not present data to evaluate the accuracy of the transient technique. For this purpose we prepared samples, each about 7.5 cm (3 in.) square, of four different roof coatings on thin metal substrates and on 1.1 mm (0.045 in.) thick pieces of atactic polypropylene (APP) modified bitumen roof membrane material. We measured the infrared emittance of the coated metals before sending the samples to another U.S. national laboratory for evaluation of their infrared emittances with a scanning emissometer. Table 1 presents the results for the four coatings. Our steady-state measurements agreed with the averages of emittance over the infrared spectrum obtained with the scanning emissometer with the exception of the aluminized asphalt emulsion sample. The scanning emissometer heated the surfaces to 85°C (185°F), which adversely affected this emulsion. Otherwise, we assume that the spectral data from the scanning emissometer are accurate to ±0.01, which was the resolution of the spectral plots from the instrument.

Details of the transient measurements for the samples on APP-modified bitumen substrates, including the extrapolations to zero time for the non-steady data, are shown in Figure 2. The formula in the heading yields the emittance by the transient technique. In this formula, $\varepsilon\bullet$ denotes the emittance of the tape on the heat sink, and ε_{0+} and ε_{0x} denote the extrapolations to zero time of the data from two to four minutes for the coating alone and for the tape on the coating, respectively.

The infrared emittances from the transient technique, given for each surface in the upper right-hand corner of its graph, are repeated in Table 1. The respective differences between the transient measurements on coated APP-modified bitumen material and steady-state measurements on the four coated metal samples are uniformly positive with an average difference of +0.052. This is interpreted as evidence that the transient technique is inaccurate by +0.052 with these roof samples.

Infrared Camera

An infrared (IR) camera stores an image of emissions from an object in the camera's view in the wavelength range of its detector. Our camera, shown in the right half of Figure 1, is sensitive to the range from 8 to 12 micrometers. IR cameras of comparable quality with sensitivity bands anywhere in the range of 3 to 12 micrometers should work equally well to determine the infrared emittance of opaque surfaces.

The radiation seen by the camera can be emitted by the object itself and, if the object is a blackbody, this is the total source of emissions. The surfaces we studied were not, in general, blackbodies. If the object is partially transparent to infrared radiation, some of the radiation is emitted by objects behind the object of interest. This complicates use of the

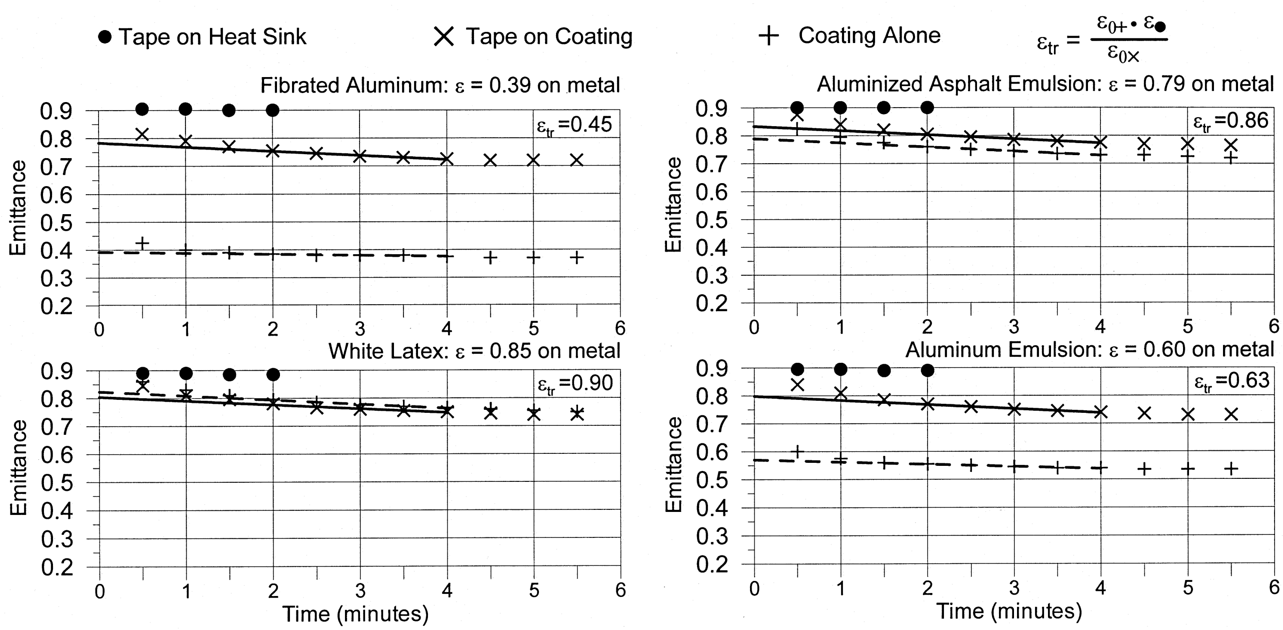

Figure 2 *Transient measurements of apparent infrared emittance for four roof coatings on atactic polypropylene-modified bitumen.*

camera for any quantitative analysis of temperatures or infrared emittances. Coated and uncoated low-slope roof surfaces and the samples of coatings on the metal and APP-modified bitumen substrates in this study are opaque to infrared radiation.

For opaque surfaces with infrared emittances less than one, the camera captures some reflected background radiation and the rest is directly emitted by the surfaces. A special foil-covered, portable square frame on short legs was constructed for this study. It was placed around and slightly above each specimen during the imaging in order to frame each specimen with a low emittance surface to allow determination of background temperature. Background temperature was an input parameter for the camera's post-imaging software. The foil had an infrared emittance of 0.05 as determined by a steady-state measurement with the portable emissometer and it was thick enough to be opaque. The foil's emittance of 0.05 means that 95% of the radiation seen from the foil surface is reflected from the background.

All images were taken on cloudless days with the sun behind the camera so no sunlight directly entered the images. The cloudless days were necessary for two reasons. First, they did not allow background conditions to change. Since the sun was behind the camera, the background was the relatively cold sky. Second, the cloudless conditions allowed the sun to heat the specimens well above sky temperature and enhanced the infrared radiation that was emitted by the surfaces. Thus, even with a relatively low-emittance surface like one covered by the fibrated aluminum coating in Table 1, the camera image was sensitive to emitted radiation from the surfaces of interest.

Our infrared camera allowed separate settings of ambient temperature and background temperature. Ambient temperature affects the automatic calibration of the camera. Background temperature affects the reflected radiation correction when emittance is not unity. To obtain a correct surface temperature when emittance is not unity, emittance must be known. Conversely, in the technique used herein, emittance can be varied until the temperature indicated by the camera is the same as that indicated by an independent measurement of each surface's temperature. Here, the surface temperatures of the specimens were determined from thermocouples installed directly under the membrane surfaces of the individual specimens.

Our infrared camera allows an average emittance of a specimen to be determined inside a box superimposed on the specimen's image. The height and width of the box can be adjusted to enclose areas on the specimen of uniform appearance. Figure 3 shows images of specimens labeled as 3A through 3H along with the emittances required to obtain the known temperatures of the specimens. The range of temperatures, shown in degrees Fahrenheit at the center bottom of each image, was varied during the analysis in order to have the known temperature lie in the middle of the approximately 60°F to 100°F span. Dark to light shades of gray indicate different temperatures in each range.

In the processed images of Figure 3, the foil-covered frame is black. This means its temperature is below the range of sensitivity indicated in the range bar at the bottom of each image. Background temperature for each image was determined separately by minimizing the box area and moving it to sample four to six different locations on the frame. The range

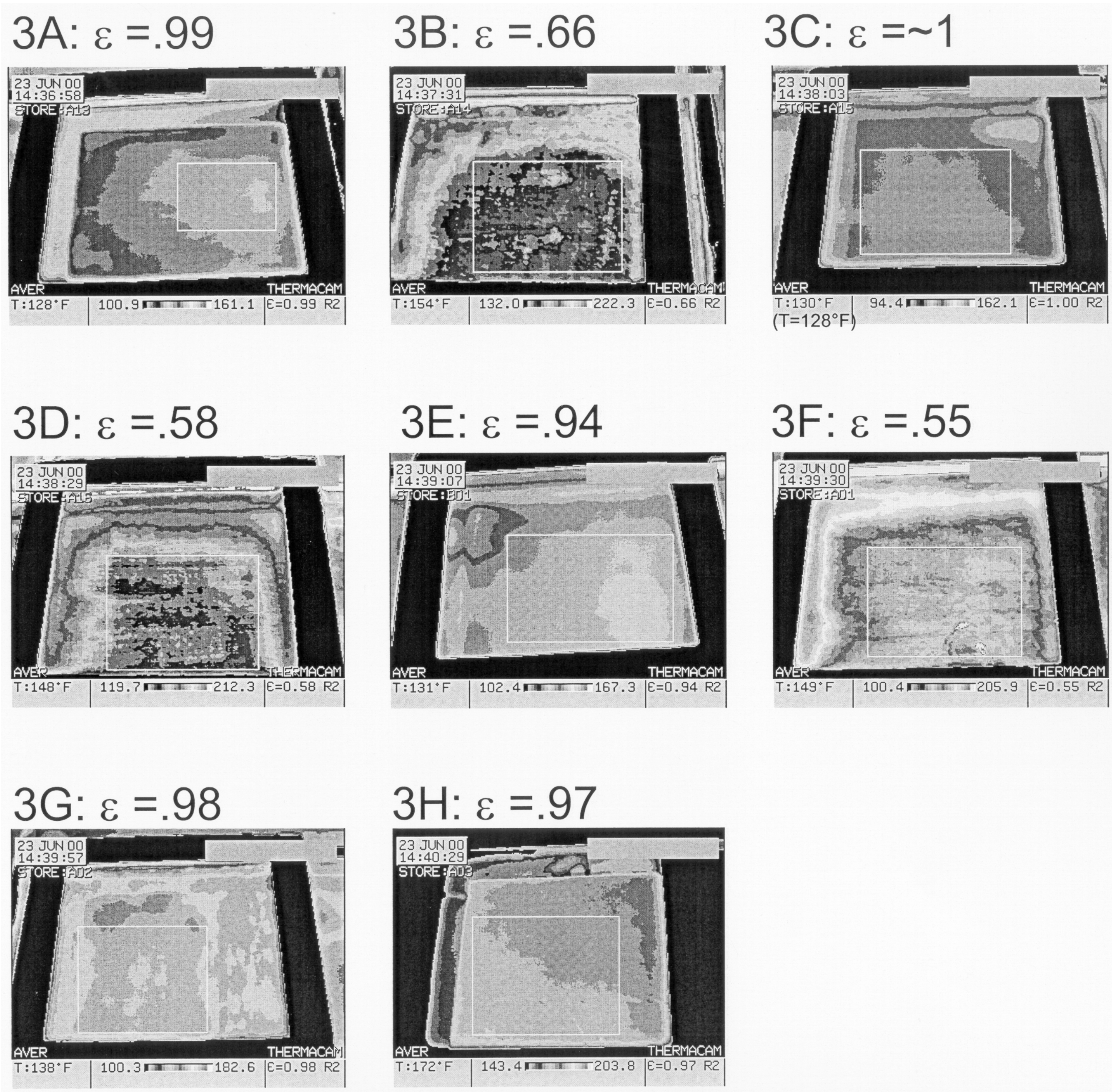

Figure 3 *Average infrared emittance in the boxes shown on infrared images of aluminum-coated (3B, 3D, and 3F), white latex-coated (3A, 3C, 3E, and 3G), and uncoated (3H) low-slope roofs.*

was adjusted downward from what is seen in the range bar and emittance was set to unity. The average was taken of the four to six temperatures, yielding an average background temperature from –9°C to –6°C (15°F to 20°F) for these images. There was small variation from image to image due to reflections from utility poles and other features of the surroundings.

The variation in temperatures indicated in Figure 3 by different shades of gray within a box is actually due to emittance variations. Moving a small box to different colored areas showed, at worst, ±0.05 variation in emittance from that indicated in the right bottom of each image and repeated in the heading. This is taken to be an estimate of the uncertainty in the indicated emittances. For location 3C, emittance is indicated as ~1. No more precise estimation was possible because, to decrease the temperature indicated by the camera in the left bottom of each image, the emittance needs to be increased. Emittance for 3C has been set at the maximum value of 1.00 and indicated specimen temperature is 130°F—still a few degrees above the target temperature of 128°F shown in parentheses.

In general, as Figure 3 shows for all locations except 3C, the target temperature was achieved by adjusting the infrared emittance to suit the particular specimen. Locations 3A, 3C, 3E, and 3G are coated with white latex roof coatings. Locations 3B, 3D, and 3F are coated with aluminum roof coatings. Location 3H is uncoated. The images and average infrared emittances to achieve the target temperatures are typical for these different surfaces. The white latex-coated and uncoated surfaces have more uniform emittances (uniform shades of gray) while the aluminum-coated surfaces show more irregular emittances (mottled shades of gray).

MEASURED INFRARED EMITTANCES FOR LOW-SLOPE ROOF SPECIMENS

In June 1997, four outdoor low-slope roof test panels were configured and a three-year test was begun with them. The objective of the testing was to document the effect on thermal performance of exposure of the variety of low-slope roof surfaces to East Tennessee climatic conditions. The surfaces were 22 different roof coatings brushed onto typical low-slope roof membranes, two capsheets (thin metal films factory-adhered to membrane material, which was torch-applied to the low-slope roof membranes), and four uncoated roof membrane specimens. Each of the resulting 28 roof specimens was fully instrumented to monitor thermal performance. Instrumentation included thermocouples to measure the surface temperature under the membrane in the center of each 0.6 m (2 ft) square test section.

To support a companion modeling effort that sought to predict the measured thermal performance and generalize it (Wilkes et al. 2000), thermal radiation properties were measured periodically. To determine the effect of weathering, infrared emittance was measured for the unweathered specimens and at about one-year intervals during the study. This paper deals with the infrared emittance measured for that purpose on weathered test sections in May 1999 and May 2000 with the portable emissometer. The test panels on which the surfaces existed were taken inside the laboratory to ensure constant ambient conditions for the measurements. Measurements were attempted in May 1998 outside on a cool, but sunny, day. More scatter was evident in those results due to variations in the ambient conditions and the surface temperatures.

Measuring infrared emittance with the transient technique is tedious. A measurement at one location on a sample takes about 30 minutes. Not only is time needed to obtain the three different responses graphed in Figure 2, but settling time is also needed to ensure that the instrument continues to give the correct response for the reference specimen on the heat sink shown in Figure 1.

To produce results comparable to those with the portable emissometer, additional measurements of infrared emittance were done with the infrared camera from images of the test sections taken in September 1999 and June 2000. The images were captured at about 30-second intervals but required cloudless conditions with totally dry specimens. Post-imaging analyses were done in the laboratory.

Figure 4 is a bar chart with the two sets of results with the portable emissometer and the two sets of results with the infrared camera. The locations are labeled with numbers denoting panels 1 through 4. Panels 1 and 2 had an APP-modified bitumen base and locations A through D and F were coated while location E was left uncoated. Panels 3 and 4 had a built-up roof (BUR) membrane and locations A through G on panel 3 and A through F and H on panel 4 were coated. Locations 3H and 4G were left uncoated. The infrared images in Figure 3 were from panel 3.

Location 1A had a factory-applied white coating on an aluminum capsheet. Location 1B had a shiny bare aluminum capsheet. Location 1F had an aluminized asphalt emulsion. These are labeled special coatings. Results for the 13 aluminum-coated and eight white latex-coated specimens follow the special coatings in Figure 4. Results for the two uncoated APP locations, 1E and 2E, are averaged and labeled APP. Results for the two uncoated BUR specimens, 3H and 4G, are averaged and labeled BUR.

The infrared emittances for location 1A, location 1F, all the white latex-coated locations, and the uncoated locations show similar high values. All results with the portable emissometer are corrected by –0.052 except those for locations 1A and 1B. The metal film that comprised the capsheets allowed steady-state responses to be achieved after a few minutes and, therefore, the transient technique was not necessary. The infrared emittances for the aluminum-coated locations show mid-range values. Location 1B, with the shiny bare aluminum surface, exhibits a behavior typical of slightly oxidized aluminum. The bright aluminum foil covering the frame placed around the test sections during infrared image acquisition yielded an infrared emittance of 0.05, which is 0.04 to 0.06 lower than that of location 1B. The emittance of location 1B

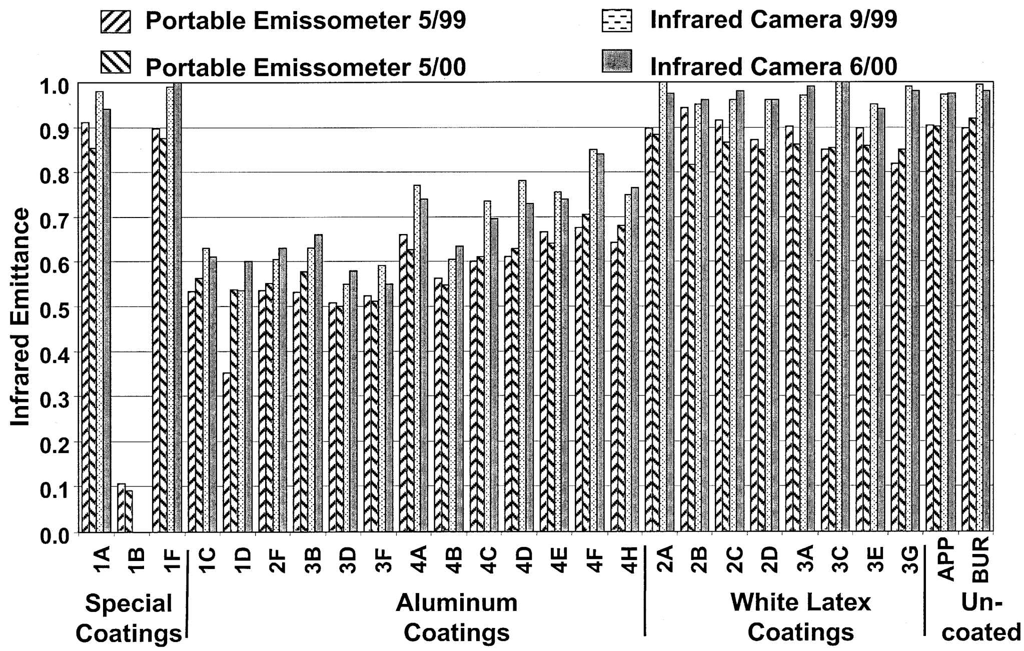

Figure 4 *Results of surveys of the infrared emittance of 28 low-slope roof test sections with a portable emissometer and with an infrared camera.*

was too low to produce an estimate of its value with the infrared camera. Too much background radiation from the relatively cold sky reflected off this capsheet to achieve the target temperature measured under it. Even with infrared emittance set to 0.1, the lowest value allowed by the camera's post-imaging software, the camera reported a surface temperature nearly 50°F too low.

Table 2 presents averages for the aluminum coatings, the white latex coatings, and the uncoated specimens arranged by technique and time of measurement. It allows a direct comparison of the two techniques and provides insight into the effect of weathering on the infrared emittance of low-slope roof surfaces. Both the portable emissometer and infrared camera show that exposure to the East Tennessee climate, between the two sets of measurements with each technique, did not affect infrared emittance. In fact, the averages of results with the infrared camera for each type of surface are exactly the same from its two sets of measurements. This is a remarkable occurrence given the changes that are apparent in the individual results in Figure 4.

The uncertainty in the values with the infrared camera was established as ±0.05 by measuring variations over the areas used to report the box averages. The boxes are shown, for example, in Figure 3. The uncertainty is about ±0.05 in any value with the portable emissometer, too. To establish this uncertainty, the transient technique was repeated on several test sections during the two sets of measurements with the portable emissometer. For the year between surveys, the portable emissometer shows an apparent increase of 0.02 for the aluminum coatings and an apparent decrease of 0.03 for the white latex coatings. Neither change is significant in light of the observed ±0.05 uncertainty.

TABLE 2
Average Infrared Emittances of Aluminum-Coated, White Latex-Coated, and Uncoated Roof Surfaces Measured with a Portable Emissometer and an Infrared Camera

	Portable Emissometer*		Infrared Camera†	
	May 1999	May 2000	Sept. 1999	June 2000
Aluminum-Coated	0.57	0.59	0.68	0.68
White Latex-Coated	0.89	0.86	0.97	0.97
Uncoated	0.90	0.91	0.98	0.98

* Transient technique corrected by subtracting 0.052 from each result at spot in center of test section.
† Post-image analysis for average over significant fraction of each 0.6 m (2 ft) square test section.

The most significant observation from the data in Table 2 is that the average values with the portable emissometer are 0.08 to 0.10 lower than the respective averages with the infrared camera. A major part of this difference is the –0.052 correction for the apparent inaccuracy of the transient technique documented in Table 1. The portable emissometer, even when it yields a steady-state result, as it did for locations 1A and 1B, is not a standard laboratory technique to measure hemispherical infrared emittance. Table 2 argues for the conclusion that the correction was not warranted. To establish the accuracy of the infrared camera, we relied on its internal self-calibration routine, which it executed each time we turned the camera on. This is no substitute for a standard laboratory technique. This matter is under consideration by the American Society of Testing and Materials in the subcommittee that produced the standard test method 1371-98 (ASTM 2000).

CONCLUSIONS

We have investigated two techniques for measuring in situ the infrared emittance of thick, low thermal conductivity roof surfaces. Both techniques produce estimates of infrared emittance with an uncertainty level of about ±0.05. Regarding the transient technique with a portable emissometer using a heated detector:

- The method requires about 30 minutes to do a single measurement at one spot under the detector on a surface over a thick substrate with low thermal conductivity.
- When results from the transient technique are compared to steady-state results for the same surfaces on thin metal substrates, the results with the transient technique appear too high by +0.052 on average for four different surfaces exhibiting a range of infrared emittances from 0.39 to 0.85.

Regarding the post-imaging analysis of images taken with an infrared camera:

- Each image can be obtained within about 30 seconds once conditions are suitable. For outdoor measurements, cloudless conditions with dry, hot test surfaces are needed. An independent measurement of surface temperature is also needed. Post-imaging analysis can be done in the laboratory and permits infrared emittance to be determined for any spot on the surface. Alternately, with the camera we used, an average emittance was determined for an area of the surface enclosed in a box whose size was varied to suit.
- The infrared camera yields estimates of infrared emittance for 28 specimens of low-slope roofs that are 0.08 to 0.10 higher than the corrected results with the transient technique for the portable emissometer.

If the correction for the transient technique with the portable emissometer is ignored for 28 specimens of low-slope roofs, the results with the portable emissometer and the infrared camera are identical within the ±0.05 uncertainty.

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