ISSUES ASSOCIATED WITH THE USE OF INFRARED THERMOGRAPHY FOR EXPERIMENTAL TESTING OF INSULATED SYSTEMS

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ABSTRACT

Infrared scanning radiometers are used to generate temperature maps of building envelope components, including windows and insulation. These temperature maps may assist in evaluating the thermal performance of components. Although infrared imaging has long been used for field evaluations, controlled laboratory conditions allow improvements in quantitative measurements of surface temperature using reference emitter techniques.

This paper discusses issues associated with the accuracy of using infrared scanning radiometers to generate temperature maps of building envelope components under steady-state, controlled laboratory conditions. Preliminary experimental data are presented for the accuracy and uniformity of response of one commercial infrared scanner. The specified accuracy of this scanner for temperature measurements is 2°C or 2% of the total range of values (span) being measured. A technique is described for improving this accuracy using a temperature-controlled external reference emitter. Minimum temperature measurement accuracy with a reference emitter is estimated at ±0.5°C for ambient air and background radiation at 21.1°C and surface temperatures from 0°C to 21°C.

Infrared imaging, with a reference emitter technique, is being used to create a data base of temperature maps for a range of window systems, varying in physical complexity, material properties, and thermal performance. The data base is to be distributed to developers of fenestration heat transfer simulation programs to help validate their models. Representative data are included for two insulated glazing units with different spacer systems.

INTRODUCTION

The thermal performance of building components is being evaluated more and more through analysis of complete building *systems*, including two- and three-dimensional interactions between subcomponents. As building envelope components become more highly insulating, thermal bridging effects become increasingly significant. This trend, and industry's need to validate computational rating procedures, has given rise to new techniques for measuring the performance of components and subcomponents within building systems. For example, where a single heat-flux meter has been used to measure conductance of homogeneous insulation materials in a heat flowmeter apparatus, arrays of heat-flux meters are now being used to measure the spatial performance of more complex insulations. Similarly, the single conductance value resulting from guarded hot-box calorimetery may be augmented using infrared (IR) imaging radiometry to map surface temperatures of complex insulating systems, such as exterior windows and doors. IR imaging can help resolve small differences in the thermal performance of subcomponents of highly insulating systems.

A previous paper by the authors (Arasteh et al. 1992) discusses using infrared thermography (IR imaging with temperature data) for three purposes: validating finite-element and finite-difference computer modeling, aiding in the development of improved insulating products, and providing a means of testing window products in the laboratory for condensation resistance. This earlier paper describes ongoing research in the use of temperature-controlled extended-area reference emitters to improve the absolute accuracy of infrared surface temperature measurements. This paper evaluates the accuracy of infrared measurements using this referencing technique.

This paper addresses the use of state-of-the-art IR imaging radiometers for laboratory-based experimental testing of insulated building components that are undergoing steady-state heat transfer driven by constant, tem-

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perature-controlled airflows. Measurements of the warm-side surfaces of the glazing unit of a window under standard, cold-climate heating conditions are presented and the accuracy of temperature measurements are discussed. This paper also examines factors that influence the accuracy of results from commercial IR imagers and some procedures that may improve accuracy. The intent is to provide preliminary technical support for future efforts to develop standard IR testing procedures.

EXPERIMENTAL APPARATUS

The testing used the following equipment: an IR scanner, an IR computer, an external reference emitter, a calibrated transfer standard, and warm and cold environmental chambers.

IR Scanner

This section discusses the characteristics of the IR scanner used to conduct temperature measurements. The IR scanner used here is a long-wave, high-speed scanning, infrared imaging radiometer. Such imaging radiometers measure the energy of infrared, or thermal, radiation emanating from the surface of an object. Thermal radiation energy coming from a surface is a combination of reflected, transmitted, and emitted thermal radiation. (Because most building materials are opaque in the infrared, the transmitted component usually is neglected.) The scanner performs individual measurements of the radiated energy and combines them into a pixel-based image that is derived from varying levels of thermal contrast. *Infrared thermography* is the process of temperature measurement using infrared imaging radiometers. Infrared thermography is a noninvasive, nondestructive technique for measuring large contiguous sets of surface temperature data, producing surface temperature maps called *thermograms*. IR scanners typically use one photon detector and a system of mirrors and lenses to scan the field of view and gather the individual measurements of infrared radiation energy. Longwave IR scanners use detectors, such as mercury/cadmium/telluride, which are sensitive to thermal radiation in the range from 8 μm to 12 μm. This wavelength region corresponds to an atmospheric window of high transmission and provides good thermal contrast for ambient-temperature objects. Devices with high-speed scanning have simple focusing and pointing and minimum flicker, and also allow more rapid data averaging. Performance specifications for the commercial longwave IR scanner used here appear in Table 1 (II 1989).

Temperature values are obtained by comparing the intensity of IR radiation arriving from a test specimen to the level arriving from a known internal emitter, after system calibration. Surface temperature can be derived from measured IR radiosity with reasonable precision because of the fourth power temperature dependence of radiated energy. IR scanners have at least one internal reference emitter, which is continually viewed during scanning to provide a reference for the temperature analysis. The analysis involves calculating an equivalent black-body radiation from the measured energy of infrared radiation, a user-defined emissivity, and a separately measured background radiation effective temperature level. The equivalent black-body radiation calculation uses simple gray-body assumptions in correcting for emissivity and background. This equivalent radiation level is then referenced to temperature values by calibration. Factory calibration of the system involves measuring a number (17) of known, temperature-controlled surfaces (external reference emitters) and adjusting the system measurements to correspond to the known surface temperatures. The IR scanner used here was calibrated with a custom concentration of reference points at temperatures of 5°C, 10°C, 15°C, 20°C, and 25°C. A normal factory calibration routine may have only two reference points in this range because commercial applications typically measure wider temperature ranges.

TABLE 1 **IR Scanner Performance Specifications**

Detector Type	Hg/Cd/Te
Horizontal Field of View (HFOV)	20°
Vertical Field of View (VFOV)	15°
Instantaneous Field of View (IFOV)	2 mRad
Horizontal Scanning Frequency	7.8 kHz
Vertical Scanning Frequency	60 Hz
Horizontal Resolution at 50% Slit Contrast	2.4 mRad
IR Measurement Resolution	200 × 175
Digital Image Resolution	200 × 256
Measurement Accuracy	±2.0°C or 2% of span
Noise Equivalent Temperature Difference (NETD)	< 0.05°C
Dynamic Range of Temperature Values	256
Temperature Range, Normal	−20 to 400°C
Temperature Spans Available	5, 10, 20, 50, etc.

IR Computer

Computer hardware and software are connected to the IR scanner for image averaging, storage, and data postprocessing. A plug-in computer card samples the signal from the IR scanner, and specialized software allows data management and analysis. Image averaging combines data captured in separate frames, averaged over time, to generate a thermogram. Image averaging improves measurement resolution, accuracy, and repeatability, primarily because of the random nature of photon emission and detection. The thermal images, or thermograms, are stored as computer files. Postprocessing software enables a user to access temperature data from the large array in manageable groupings, such as spot/area temperatures, line profiles, histograms, and text data dumps from defined areas. Temperature values may be expressed in Celsius or Fahrenheit. In addition, measured values can be expressed, with better resolution, in *system level units,* which are the equivalent black-body radiation levels calculated from sensor readings and normally are used with calibration look-up tables to generate temperature values.

External Reference Emitter

An external reference emitter has a temperature-controlled surface of a known emissivity and temperature and is an independent reference that can be located near a test specimen to aid in removing bias when making absolute temperature measurements. External reference emitters, sometimes referred to as *extended-area black bodies,* are available commercially and typically are used in factory calibration of IR scanners. The use of external reference emitters in IR testing can provide additional data for verifying IR scanner performance or adjusting absolute temperature data values.

The emitter used for the measurements reported here consists of a rack-mounted electronic temperature controller and a separate emitter head and is traceable to the National Institute of Standards and Technology (NIST). The reference surface is an aluminum plate with a coating of emissivity 0.97 across the relevant IR spectrum. Thermoelectric elements provide heating and cooling using a fan-assisted heat sink. Temperature is measured with a platinum resistance thermometer. Performance specifications for the reference emitter are shown in Table 2 (CIS 1992), where the temperature differential in Table 2 refers to the difference between the emitter setpoint and its surrounding air temperature. A properly calibrated reference emitter can be expected to be a reference surface with temperatures accurate and uniform to within ±0.04°C for the conditions of these experiments.

TABLE 2 **External, Temperature-Controlled Reference Emitter Specifications**

Setpoint Temperature Range	5 to 100°C
Setpoint Resolution	0.01°C
Read-Out Resolution	0.01°C
Short-Term Temperature Stability	
Temperature Differential < 10°C	±0.003°C
Temperature Differential ≥ 10°C & < 50°C	±0.01°C
Long-Term Temperature Stability	
Per 1°C change in Ambient	0.002°C
Per Year	±0.04°C
Calibration Absolute Temperature Accuracy	
Temperature Differential < 5°C	±0.008°C
Temperature Differential ≥ 5°C & < 10°C	±0.02°C
Temperature Differential > 10°C	±0.03°C
Full Range	±0.04°C
Temperature Uniformity for 80% of Aperture	±0.01°C
Gray-Body Average Emissivity Over 8 μm to 12 μm	0.97

Calibrated Transfer Standard

A device known as a *calibrated transfer standard,* or CTS, is a form of heat-flux meter used to provide surface thermal resistance (film coefficient) data for standard fenestration testing (ASTM 1991). A description of the design and use of a CTS may be found in the previous reference. A CTS also provides surface temperature measurements useful for characterizing the response of an IR scanner. The CTS used here is a commercial product measuring 0.91 m by 0.91 m and consisting of expanded polystyrene foam insulation of 0.025-m thickness sandwiched between two sheets of 4.8-mm glass. It is instrumented with 18 pairs of type-T thermocouples situated directly across from each other between the foam and the glass on each side of the foam. The thermocouples are arranged in three vertical columns the same distance apart. The CTS is mounted in the test frame used for building component specimens and is situated between the cold and warm environmental chambers. Glass-to-air surface temperatures are generated by calculating an adjustment for the temperature difference across the glass based on the total heat-flow rate and the conductance of the glass. The special-limits thermocouple wire used in the CTS was calibrated using standard methods prior to assembly; deviations measured in calibration are applied to adjust readings.

Warm and Cold Environmental Chambers

The equipment described here is used with environmental chambers that generate steady-state heat flow

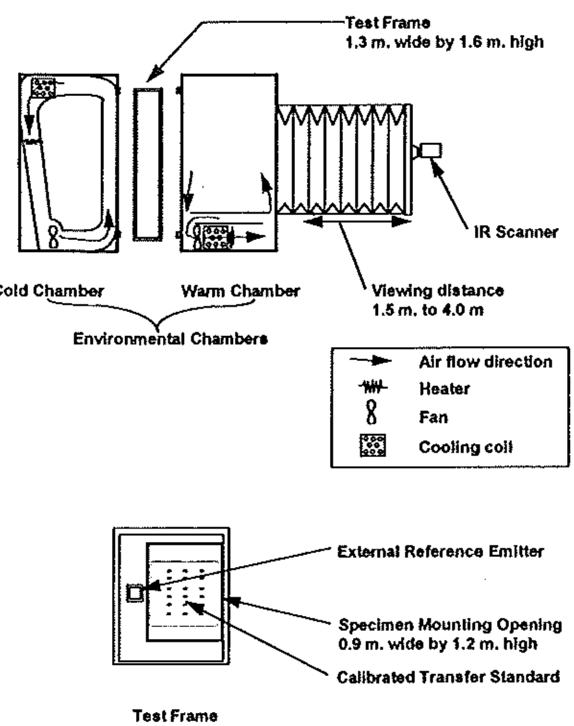

Figure 1 *Laboratory setup schematic.*

across a test specimen. Figure 1 diagrams the environmental chambers with the locations of the IR scanner, the external reference emitter, and the CTS or test specimen. A separate computer system measures and controls temperatures in the chambers. A plug-in computer card with internal processing provides real-time control of both warm and cold environmental chambers and measures air humidity, velocity, and temperature, as well as surface temperatures. Temperature sensors include both linear thermistor networks (15 total) and special-limits, type-T thermocouples (87 total). Air velocity is measured using two hot-wire anemometers. A separate platinum resistance thermometer system is used for calibration and continual verification of air temperature readings.

The cold chamber is a commercial food freezer modified for parallel upward plenum airflow. Temperature is controlled using pulse-switched heaters in three zones. Control setpoint accuracy is within ±0.5°C. Control stability over time and variations across the width of the airflow are both within ±0.1°C. Airflow plenum depth is adjusted to 100 mm, which provides a flow velocity of about 3.9 m/s. The surface film coefficient has been measured at 20 $W/m^2 \cdot °C$.

The warm chamber used in the testing is a special-purpose apparatus developed for use with an IR scanner. Typical environmental chambers for testing building envelope components use a plenum to direct warm air; however, this plenum would not allow viewing of the specimen with an IR scanner. Therefore, the chamber has an unobstructed volume of air between the specimen and the IR scanner, which can be located from 1.5 m to 4 m apart. Air temperature is controlled in a recirculation zone within the subfloor. Air enters the subfloor at the base of the test specimen plane and leaves at the rear of the subfloor. Air recirculates through a cooling coil and then across three zones of pulse-switched heaters. Variable fans allow airflow rates to change within the subfloor, so the air exchange rate to the main chamber can change for some control of warm-side convective surface resistance. Warm-side film coefficients have been measured at 8.7 $W/m^2 \cdot °C$.

IR THERMOGRAPHY PROCEDURE ISSUES

Using an IR scanner to obtain accurate, useful temperature measurements requires careful attention to several specific procedural details. Recommendations for correct overall operation of IR scanners appear in commercial product manuals and industry standard practice documentation (ASTM 1990a, 1990b).

IR Scanner Operation

This section focuses on the following settings of the thermography system: temperature span, center temperature, emissivity, background temperature, image averaging, and distance from specimen being measured.

IR scanners may be operated at various center temperatures and spans. Discrete span settings are available to select the width of the range of temperatures the measurement covers. The center temperature setting of the scanner determines the middle temperature of the span. Using the span and center temperature controls, an operator can adjust the range of temperatures measured. Data presented here are based on nominal spans of 5°C, 10°C, or 20°C with 8-bit resolution (256 levels) in each span. Other types of IR scanners have more resolution (12-bit) but use wider spans. Span selection becomes an issue when the object being measured has a temperature range that exceeds the minimum span available. Broader spans allow the operator to produce an image of the entire object but with reduced contrast. Alternatively, postprocessing allows an operator to compile data from separate measurements that use smaller spans and various center temperature settings. The advantage of this technique is improved thermal resolution, but the disadvantage is that data are taken at different times and the scanner performance or the object's true temperature may change over time. Results given here assess the performance of an IR scanner using different span and center temperature settings.

The value for emissivity is input by the user. A thorough discussion of emissivity measuring and its effect on the accuracy of IR temperature measurements is beyond the scope of this paper. However, the emissivity value used should be for the wavelengths measured by the IR scanner and the relevant temperatures. Different emissivities can be used for analyzing different parts of the object if necessary. Emissivity should be input as accurately as possible and not adjusted for the purpose of changing IR scanner results to match ancillary direct contact measurements. Such adjustments are recommended in the infrared industry, but they result in temperature "corrections" that are inappropriate when an object has a range of temperatures. These emissivity adjustments yield misleading data because the magnitude of correction for emissivity varies with the temperature difference between the surface and the background. It is best to quantify emissivity by conducting special reference emittance tests on sample material mounted to a temperature-controlled plate using the same IR scanner that will be used to measure the building system. Only specimens with relatively high emissivity (perhaps > 0.5) can be measured reasonably accurately. Although the importance of emissivity cannot be overlooked, the errors associated with it generally are repeatable. The correct emissivity value should not affect precision or accuracy of the IR measurements. In the analysis here it is assumed that the emissivity is correct and that errors associated with the gray-body assumptions are small.

Correcting for the level of background radiation is associated closely with corrections for emissivity and is performed by the IR scanner and computer. The level of background radiation is quantified by its temperature and can be measured with the IR scanner by viewing a surface with low emissivity located in front of the specimen. This background temperature is input by the user. It is critical that the background radiation be as uniform as possible. The IR scanner itself, however, always produces a cold nonuniformity in the background because the detector electronics inside are cooled to cryogenic temperatures and the lens is IR transparent. For specular surfaces, the scanner reflection may be easily located in the measured image, and data from this region then can be discarded. Nonspecular surfaces require special adjustments to minimize this problem because the effects of the cold scanner lens are not as easily identified in the measured image; this problem can be alleviated with off-angle viewing.

Image averaging is important for obtaining accurate IR data. The IR scanner signal is a real-time stream of data, encoded like a standard video signal. IR data are obtained by averaging many frozen frames over a period of time. Image averaging helps to improve measurement resolution, accuracy, and repeatability. Collecting a large number of samples and averaging them creates the most accurate thermogram because of randomness in photon emission and detector performance. Data presented here are averaged in either of two ways: 50 frames at the fastest rate possible (during a period of 16 seconds) or 60 frames of data taken at 10-second intervals (during a period of 10 minutes).

The distance between the scanner and the object has a direct effect on the accuracy of the IR scanner surface temperature measurement, especially when relatively small features of the object have high thermal contrast. The view area must be large enough to include the test specimen, or feature of interest, and a reference emitter when a referencing technique is used. The spatial resolution of a thermogram is a function of both the IR scanner resolution and the viewing distance. The individual field of view, or IFOV, describes the angular size of each actual IR measurement. The IR temperature measurement is averaged over the area within the IFOV. For high thermal contrast areas of a test specimen, the resolution of the IR scanner and the viewing distance must be such that enough measurements are performed on the high-contrast area to provide useful spatial temperature data. The viewing distance also affects the image's perspective. Closer distances cause more geometric distortion and increase views of perpendicular surfaces compared to longer distance measurements. Testing presented here is conducted at distances that include the entire specimen and reference emitter, to the nearest 0.5-m increment.

IR Data Postprocessing

Temperature data from an IR scanner are a large array of values that are assigned to pixels, which make up an image. A thermogram assigns a color or tone scale to the pixels to correlate with the array of temperature values. Individual pixel values, however, are not reliable for accurate temperature data because of shading and averaging that occurs during digitizing and because of other signal noise and operational variances. Using averaged frames for IR data reduces the variation or noise but does not eliminate it. For example, data taken from an isothermal surface (±0.01°C) show individual pixels deviating by as much as 0.2°C for 50 frames of data compared to individual deviations of 0.3°C for 20 frames of data and 2.0°C for a single frame of data. To obtain useful engineering data, statistical analysis is performed on a defined area of the image. Data presented here are obtained by two methods. The first is referred to as spot temperatures; data are analyzed over an entire orthogonal area and average, maximum, and minimum values are obtained. The second method is a line scan; data are averaged in only one dimension of a defined area, and a distribution of temperatures is gathered in the other dimension. Spot temperatures are useful for areas with minimal actual temperature gradients; line scans are most useful for regions with gradients in only one direction.

Reference Emitter Technique

A reference emitter located near the test specimen and included in each IR image provides a means of checking and scaling IR-measured data. A temperature-controlled external reference emitter is used as an independent reference to correlate IR radiosity with absolute temperature. The reference emitter is located near the specimen but is isolated far enough away so that heat flow at the specimen is not disrupted. IR scanner measurement performance fluctuates over time. The bias, or error, in temperature measurement arising from this fluctuation may be partially removed by including a reference emitter in each image. IR-measured temperatures of the test specimen are adjusted by a correction factor obtained from the difference between the IR measurement of the reference emitter and the emitter setpoint. The setpoint for the reference emitter should be selected so that the emitter's temperature is near the specimen temperatures of interest. Multiple setpoints and IR measurements may be useful when a large range of temperatures is present. Referenced IR measurements presented here refer to IR data that have been offset (linearly) by the deviation from the reference emitter.

IR SCANNER TEST RESULTS

There are many sources of error in IR temperature measurement. The errors can be categorized by dependence on time, dependence on operation, or independence of either time or operation. Operational sources include errors in scanner settings for emissivity, background, and the distance at which the measurement was made. Errors that depend on time arise from the fluctuation of scanner response over time resulting from the complex electromechanical nature of the instrument and are caused by such things as electronic drift, scanner temperature changes, scanner internal radiation, optical drift, and atmospheric changes. Operation error is generally repeatable; this analysis assumes that correct procedures will reduce operation errors, except for errors from measurement distance arising from tradeoffs in resolution and utility. The errors from the scanner's measurement performance variation over time are reduced by expanding the measurement system to include an external reference emitter that provides a reference for calibrating each measurement. This referencing is intended to remove measurement performance fluctuations over time. Sources of error that remain for referenced measurements include thermal radiation noise, calibration errors, referencing inaccuracy, and nonuniform performance across the field of view and ranges in temperature. Remaining sources of error are assessed by experimenting with the base IR scanner response and evaluating the accuracy of measurements conducted with this referencing technique.

The surface temperature measurement capabilities of one commercial IR scanner are assessed. The IR scanner's absolute measurement accuracy for different operational settings (span and center temperature) are evaluated by imaging a temperature-controlled reference emitter. The reference emitter technique was then used to adjust data from IR scanner measurements of a CTS. This technique also was used in measurements of an insulated glazing unit (IG) at distances from 1.5 m to 4 m.

Measurements were conducted viewing through ambient air controlled at 21.1°C. Building heating conditions (cold-side air at –17.8°C and 3.7 m/s, warm-side air at 21.1°C and < 0.3 m/s) are applied to CTS and IG. The scanner was located in the laboratory outside the ambient control chamber. Scanner temperature, ambient air relative humidity, and all relevant temperatures were recorded.

IR Measurements of External Reference Emitter

The basic temperature measurement accuracy of the scanner was evaluated by conducting a series of measurements on a temperature-controlled reference emitter. Temperature setpoint for the reference emitter, location of the reference emitter in the image, and scanner settings for span and center temperature were all varied in the testing. This testing was essentially a detailed check of the factory calibration and absolute temperature accuracy of the scanner under controlled conditions and for the temperature range of interest. These measurements were conducted at a distance of

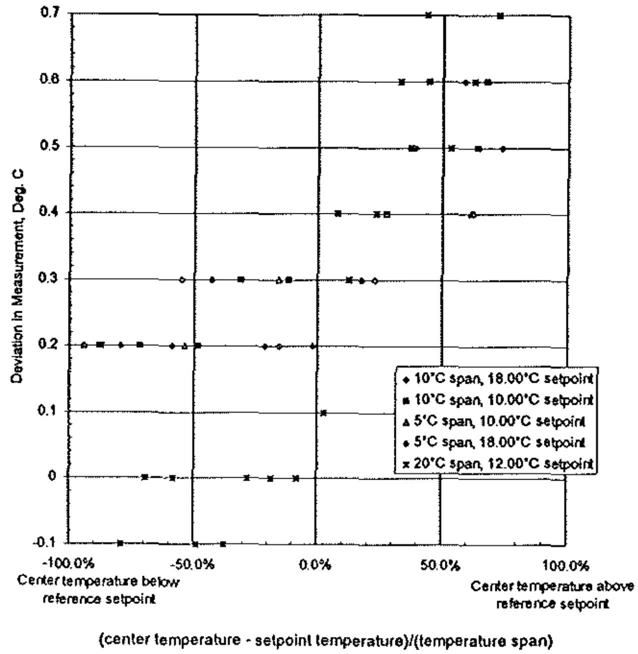

Figure 2 *Typical deviations in IR temperature measurements for varied center temperature setting.*

2.0 m. IR data averaging was 50 frames of data collected during 16 seconds. The testing was necessarily conducted over time, so the variations as a result of time are present in the data.

Table 3 shows an example of the deviations between the IR-measured surface temperature and the setpoint temperature of the reference emitter during one day of operation. Each set of data in Table 3 is for one setting of scanner center temperature and span. To cover temperatures from 5°C to 21°C, four center temperature settings were used for the 5°C span, and two settings were used for 10°C span. The variation of deviations within one set of data shows the uncertainty arising from nonuniformity of measurement over the span of temperatures being measured. The deviations within a particular set of data vary 0.2°C for the 5°C span, 0.3°C for the 10°C span, and 0.5°C for the 20°C span. These deviations also include variations over time (data sets are obtained over a 15-minute period).

Figure 2 shows deviations between IR-measured surface temperatures and the setpoint temperature of the reference emitter for various center temperature settings. The horizontal axis quantifies the relation of the reference emitter setpoint (which is fixed) to the center temperature setting of the IR scanner (which is varied). These values are normalized to the span setting of the IR scanner.

Uniformity of response over the temperature span is evaluated by varying the reference setpoint in Table 3 and the center temperature in Figure 2. The deviations within a particular set of data vary 0.2°C for the 5°C

TABLE 3 Typical Deviations in IR Temperatures for Three Spans with Fixed Center Temperatures

Reference Emitter Setpoint, °C	Deviations in IR Measurement from Reference Setpoint, °C						
	20°C Span	10°C Span		5°C Span			
5.00	0.7	0.8		0.9			
6.00	0.6	0.8		0.8			
7.00	0.4	0.7		0.8			
8.00	0.3	0.6		0.9			
9.00	0.2	0.6		0.8			
10.00	0.3	0.5			0.6		
11.00	0.3	0.6			0.4		
12.00	0.2	0.6			0.5		
13.00	0.3	0.8	0.3		0.6		
14.00	0.3	0.7	0.2		0.6		
15.00	0.4		0.2			0.3	
16.00	0.4		0.2			0.3	
17.00	0.4		0.4			0.4	
18.00	0.5		0.2			0.4	0.3
19.00	0.5		0.4			0.4	0.2
20.00	0.4		0.4				0.3
21.00	0.3		0.3				0.3

span, 0.4°C for the 10°C span, and 0.8°C for the 20°C span. These deviations also include variations over time (data sets are obtained over a 20-minute period).

Another series of tests was conducted by fixing the location of the reference emitter and varying how the IR scanner was pointed so that its position in the field of view changed. This testing was conducted with fixed scanner settings and a constant reference emitter setpoint. The IR image was divided into a geometric matrix of seven columns and five rows, and for each test the scanner was pointed so that the reference emitter was located in one of the positions. The deviations between IR-measured data and the reference emitter setpoint ranged from 0.3°C to 0.9°C, with an average deviation of 0.48°C for 50 separate measurements. This testing was intended to investigate the uniformity of IR measurement across the field of view; however, the data did not correlate well because of variation in scanner performance with time.

Referenced IR Measurements of Calibrated Transfer Standard

The reference emitter technique for IR surface temperature measurements was evaluated by imaging the glass surface of a CTS under steady-state heat transfer. The thermocouple instrumentation of the CTS is an independent method of determining the surface temperatures. Table 4 summarizes the deviation between measurements from the referenced IR measurements and the corrected values from the CTS thermocouples. There is a vertically oriented gradient in the CTS surface temperature because of natural convection on the warm side. The combined convection and radiation surface thermal resistance coefficient has been measured at 8.7 $W/m^2 \cdot °C$. All data for Table 4 are derived from temperatures in the range of 15.3°C to 18.1°C. Each data set is based on an IR measurement for a single time frame and includes comparisons of surface temperatures for 18 spatially distributed locations. IR measurements are conducted at a distance of 3.5 m through air at 21.1°C and a relative humidity of 44%. Data series 1 through 6 use an IR averaging scheme of 60 frames during 10 minutes. Data series 7 through 10 use an IR averaging scheme of 50 frames during 16 seconds.

Referenced IR Measurements of an Insulated Glazing Unit at Various Distances

The reference emitter technique for IR surface temperature measurements was used to test the insulated glazing unit (IG) of a window at various distances. The IG used for this testing has a triple-layer, air-filled design with a conventional steel spacer; the same IG is used for the sample data presented here. The IG is mounted in 2 in. of extruded polystyrene foam and has 0.5-in.-thick foam trim strips covering the spacer region of the IG to the sightlines. Midheight, horizontal temperature distributions at the edge of the glazing were obtained for distances from 1.5 m to 4.0 m, in 0.5-m increments. This region offers interesting temperature contrast because discontinuities in material and in surface geometry create relatively low temperatures and a

TABLE 4 Deviations in Referenced IR Temperatures from CTS Thermocouples

Data Series	Scanner Span, °C	Reference Set-point, °C	IR Data Adjustment, °C	Average Deviation, °C	Maximum Deviation, °C	Range of Deviation, °C
1	5	17.00	−0.8	0.01	0.17	0.30
2	10	17.00	−0.7	−0.07	−0.23	0.30
3	20	17.00	−0.8	−0.24	−0.33	0.20
4	5	17.00	−0.7	−0.05	−0.13	0.20
5	5	17.00	−0.8	0.02	0.17	0.20
6	5	17.00	−0.9	−0.08	−0.14	0.21
7	20	18.00	−0.7	−0.23	−0.44	0.31
8	20	10.00	−1.3	−0.83	−1.04	0.41
9	20	10.00	−1.1	−0.04	−0.23	0.30
10	20	18.00	−1.0	0.01	0.17	0.31

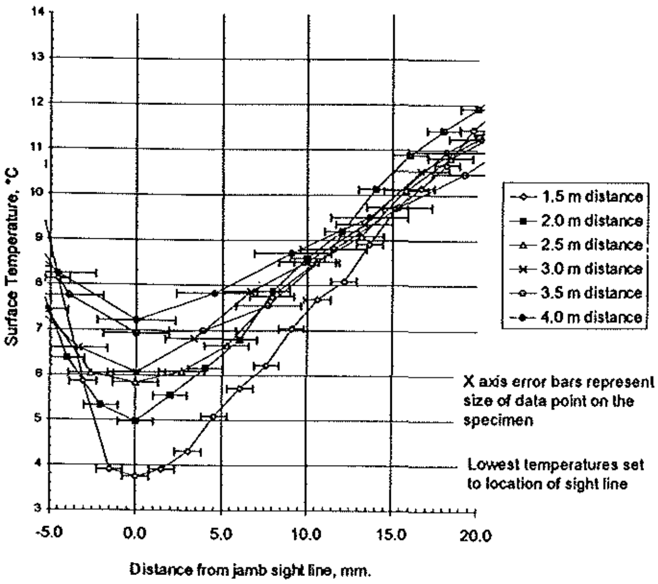

Figure 3 *Horizontal temperature distribution of triple-layer glazing unit from various measurement distances.*

temperature gradient primarily in one direction. Figure 3 shows line scans of temperature data where the data for five distances (between scanner and specimen) have been plotted vs. horizontal distance across the face of the specimen. The locations in the x-direction with the lowest temperature are aligned at zero, which should correspond to the IG sightline. The areas represented by each pixel are plotted as error bars to show the spatial resolution of the data. Measurements of the thermally stable IG, taken from a distance of 1.5 m, found the coldest temperature to be 3.5°C lower than the coldest reading from measurements made 4.0 m away.

TEMPERATURE MEASUREMENT ACCURACY DISCUSSION

To evaluate the usefulness of the surface temperature data, an understanding of the accuracy of IR scanner temperature measurements is needed. Product specifications for absolute accuracy typically are within 2°C or 2% of span, whichever is greater. Because more accurate data would be useful, the actual accuracy displayed by the base IR scanner is evaluated for the controlled conditions of measuring building components in a laboratory. Product specifications also show a thermal sensitivity, or noise equivalent temperature difference (NETD), of 0.05°C (with averaging), which indicates that the instrument is precise enough that improvements on the 2°C accuracy figure may be attainable with additional calibration and referencing. Considering that the reference emitter is imaged at only one location and temperature in the data set, it is interesting to assess the uniformity of the scanner's performance across the field of view and temperature span.

IR Scanner Absolute Accuracy

IR scanner temperature measurement accuracy cannot be expected to surpass equipment specifications that indicate that the scanner tested here is accurate to within 2.0°C. The data in Table 3 and Figure 2 show example deviations, or errors, of as much as 0.8°C. Experience shows that these errors vary by as much as 1.0°C from day to day. Even during a single period of operation, scanner deviation can vary by as much as 0.4°C over an hour. This drift in measurement performance over time is inherent in the complex electro-mechanical instrument.

Referenced IR Measurement Accuracy

The problems arising from the variation in scanner accuracy over time may be mitigated by referencing each measurement image. The data sets from a single time frame in Table 4 show that deviations, or errors, for referenced IR measurements compared to CTS thermocouple measurements can be as low as ±0.2°C for the 5°C span, ±0.3°C for 10°C span, and ±0.4°C for 20°C span. Because the special-limits type-T thermocouple wire's specified accuracy is 0.5°C, the IR measurements can be considered in agreement. Referencing procedures are important, as shown by data series 8 in Table 4, where the reference emitter setpoint was too low and error increased to 1.0°C.

IR Measurement Distance

A number of important considerations go into determining the distance from which a specimen should be measured with an IR scanner. The scanner optics, IR data resolution, specimen size, temperature contrast on the specimen, subcomponents of particular interest, and inclusion of an external reference emitter must all be considered in determining the distance from which the IR scanner takes measurements. Distance also can affect the temperature measurement, as shown in Figure 3. When the temperature of the coldest part of the test specimen is the goal, distance issues can cause measurement deviations of as much as 3.5°C. There is a tradeoff between measuring close to the specimen to obtain better resolution of small features and measuring farther away to obtain data for the whole system and/or to include a temperature-controlled reference emitter.

To understand the effects of the distance between scanner and specimen, it is useful to analyze the basic geometric resolution of the measurement and compare this to the size of the test specimen, thermal feature, or subcomponent of interest. Table 5 shows calculated values for the horizontal physical size of spatial measurement parameters at the plane of the specimen for various distances, based on equipment specifications of Instantaneous Field of View (IFOV) of 2 milliradians, Horizontal Field of View (HFOV) of 20°, and Vertical Field of View (VFOV) of 15°.

TABLE 5 **Distance Effect on Size of Field of View and Data Resolution at Test Specimen Plane**

Measurement Distance m	Horizontal View m	Vertical View m	Individual IR Temperature Measurement m	Digital Image Pixel m
0.5	0.18	0.13	0.001	0.0007
1.0	0.35	0.26	0.002	0.0014
1.5	0.53	0.39	0.003	0.0021
2.0	0.71	0.52	0.004	0.0028
2.5	0.88	0.66	0.005	0.0034
3.0	1.06	0.79	0.006	0.0041
3.5	1.23	0.92	0.007	0.0048
4.0	1.41	1.05	0.008	0.0055

TABLE 6 **Minimum Uncertainty in Referenced IR Measurements for 5°C Span**

Thermal Radiation Noise	± 0.05°C
Reference Emitter	± 0.04°C
Spatial FOV Variation	± 0.20°C
Variations Across Span	± 0.20°C
Total	± 0.5°C

Uncertainty Analysis for Referenced Temperature Measurements

If it is assumed that the system is adjusted appropriately for background radiation and emissivity, and that temperature errors from these issues are repeatable and can be reduced through detailed procedures, then the remaining types of error are noise in the photon emission and detection, accuracy and uniformity of the reference emitter, uniformity of scanner response across the field of view and temperature span, and spatial resolution problems arising from the chosen viewing distance. For parts of the specimen with low thermal contrast, errors arising from viewing distance and limited spatial resolution are small. Table 6 summarizes the uncertainty from the remaining sources of error for a 5°C span measurement of a low thermal contrast area. Thermal radiation noise uncertainty is quantified by the minimum thermal resolution of the IR system or noise equivalent temperature difference (see Table 1). Uncertainty from the reference emitter is obtained from equipment specifications (see Table 2). Uncertainty arising from variations across the image field of view are quantified from results of the referenced IR measurements of the CTS. The CTS provides 18 spatially distributed points of reference for one time period. The data in Table 4 show that the maximum deviation is less than ±0.2°C for a 5°C span. Uncertainty arising from variations across the temperature span are estimated from the data in Table 3 and Figure 2. Individual sets of data for fixed center temperatures in Table 3 show data for a 5°C span varying by 0.2°C. The variation in 5°C span data for a fixed reference temperature and varied center temperature (Figure 2) also is within 0.2°C. The overall uncertainty in the IR measurement can be estimated by summing the individual sources of error arriving at an uncertainty of 0.5°C for 5°C span measurements of a low thermal contrast region.

EXAMPLE IR DATA

Samples of referenced IR data are presented for two insulated glazing units mounted in foam. Data for an expanded set of fenestration specimens is planned and may be made available separately. Additional IR measurements on a vacuum window system will be included in separate paper in these proceedings (Collins et al. 1995). The two IGs measure 0.6 m by 0.4 m The specially built IGs are air-filled, triple-layer units with suspended polyester films having low emissivity coatings. They have two different spacer systems; one has dual conventional steel spacers and the other has a thermally broken system with high-density foam separating dual steel spacers. Cavity gap widths are the same for both IGs and are 7.9 mm and 11.1 mm. The IGs are mounted in 50-mm extruded polystyrene foam and have 12-mm-thick foam trim strips covering the spacer region of the IG to the sightline. IR measurements are taken at a distance of 2.5 m and are averaged from 50 frames of data during 16 seconds. Figure 4 shows the distribution of temperatures in the vertical direction of the glazing where data are averaged in the horizontal direction over the middle 15% of the glazing system. The uncertainty in temperature values is ±0.5°C for the center-of-glass region; values for the edge of glass probably are less accurate, with uncertainty estimated at ±1.0°C.

The data are interesting in that the temperatures for the center region of the glazing differ by about 0.9°C for separate units with the same glazing design. Surface temperatures near the sightline of the IG are colder for

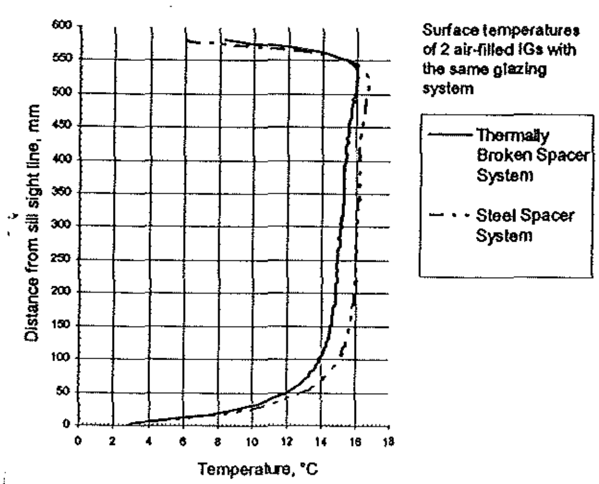

Figure 4 *Vertical temperature distribution of triple-layer glazing units.*

the conventional steel spacer system than for the thermally broken spacer system, but the difference at the sill is only 0.5°C.

SUMMARY

IR scanners can be used for noninvasive measurements of surface temperature for building envelope components such as windows. The accuracy of an IR scanner for laboratory-based surface temperature measurements was evaluated, and procedural details important for achieving maximum accuracy were identified. An external reference emitter is useful for improving the accuracy of IR measurements. For a defined set of conditions, the minimum uncertainty in IR temperature measurement was found to be ±0.5°C.

CONCLUSIONS

- Using an external reference emitter to scale the absolute value of IR scanner temperature measurements can improve the scanner's accuracy from 2°C to as low as 0.5°C for a 5°C span. This accuracy is comparable to the accuracy of type-T thermocouples widely used in the testing of building components.
- Operational procedures particularly are important in IR scanner measurements and easily can increase errors to greater than 0.5°C. The actual accuracy of an IR measurement will vary with the test specimen geometry, magnitude of temperature gradients, and scanner settings such as emissivity.
- Future efforts to develop standard IR thermographic test procedures should address the standardization of
  - location and mounting of external reference emitter,
  - guidelines for IR measurement distance and spatial resolution,
  - warm-side environmental chamber designs for unobstructed IR imaging and temperature-controlled air with natural convection conditions,
  - emissivity values for common materials that depend on temperatures and IR scanner types,
  - procedures for setting scanner center temperature and span and reference emitter setpoint,
  - postprocessing procedures for combining referenced data and data from separate images, and
  - uniform methods of presenting final data.

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