Designation: C 1155 – 95

Standard Practice for
Determining Thermal Resistance of Building Envelope Components from the In-Situ Data[1]

This standard is issued under the fixed designation C 1155; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers how to obtain and use data from in-situ measurement of temperatures and heat fluxes on building envelopes to compute thermal resistance. Thermal resistance is defined in Terminology C 168 in terms of steady-state conditions only. This practice provides an estimate of that value for the range of temperatures encountered during the measurement of temperatures and heat flux.

1.2 This practice presents two specific techniques, the summation technique and the sum of least squares technique, and permits the use of other techniques that have been properly validated. This practice provides a means for estimating the mean temperature of the building component for estimating the dependence of measured R-value on temperature for the summation technique. The sum of least squares technique produces a calculation of thermal resistance which is a function of mean temperature.

1.3 Each thermal resistance calculation applies to a subsection of the building envelope component that was instrumented. Each calculation applies to temperature conditions similar to those of the measurement. The calculation of thermal resistance from in-situ data represents in-service conditions. However, field measurements of temperature and heat flux may not achieve the accuracy obtainable in laboratory apparatuses.

1.4 This practice permits calculation of thermal resistance on portions of a building envelope that have been properly instrumented with temperature and heat flux sensing instruments. The size of sensors and construction of the building component determine how many sensors shall be used and where they should be placed. Because of the variety of possible construction types, sensor placement and subsequent data analysis require the demonstrated good judgement of the user.

1.5 Each calculation pertains only to a defined subsection of the building envelope. Combining results from different subsections to characterize overall thermal resistance is beyond the scope of this practice.

1.6 This practice sets criteria for the data-collection techniques necessary for the calculation of thermal properties (see Note 1). Any valid technique may provide the data for this practice, but the results of this practice shall not be considered to be from an ASTM standard, unless the instrumentation technique itself is an ASTM standard.

NOTE 1—Currently only Practice C 1046 can provide the data for this practice. It also offers guidance on how to place sensors in a manner representative of more than just the instrumented portions of the building components.

1.7 This practice pertains to light-through medium-weight construction as defined by example in 5.8. The calculations apply to the range of indoor and outdoor temperatures observed.

1.8 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 168 Terminology Relating to Thermal Insulating Materials[2]

C 1046 Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelopes[2]

C 1060 Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings[2]

C 1130 Practice for Calibrating Thin Heat Flux Transducers[2]

C 1153 Practice for the Location of Wet Insulation in Roofing Systems Using Infrared Imaging[2]

3. Terminology

3.1 *Definitions*—For definitions of terms relating to thermal insulating materials, see Terminology C 168.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *building envelope component*—the portion of the building envelope, such as a wall, roof, floor, window, or door, that has consistent construction. — For example, an exterior stud wall would be a building envelope component, whereas a

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[1] This practice is under the jurisdiction of ASTM Committee C-16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

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[2] *Annual Book of ASTM Standards*, Vol 04.06.

layer thereof would not be.

3.2.2 *convergence factor for thermal resistance,* CR_n—the difference between R_e at time, *t*, and R_e at time, $t-n$, divided by R_e at time, *t*, where *n* is a time interval chosen by the user making the calculation of thermal resistance.

3.2.3 *corresponding mean temperature*—arithmetic average of the two boundary temperatures on a building envelope component, weighted to account for non-steady-state heat flux.

3.2.4 *estimate of thermal resistance,* R_e—the working calculation of thermal resistance from in-situ data at any one sensor site. This does not contribute to the thermal resistance calculated in this practice until criteria for sufficient data and for variance of R_e are met.

3.2.5 *heat flow sensor*—any device that produces a continuous output which is a function of heat flux or heat flow, for example, heat flux transducer (HFT) or portable calorimeter.

3.2.6 *temperature sensor*—any device that produces a continuous output which is a function of temperature, for example, thermocouple, thermistor, or resistance device.

3.3 Symbols Applied to the Terms Used in This Standard:

3.3.1 *Variables for the Summation Technique*:

A = area associated with a single set of temperature and heat flux sensors,
C = thermal conductance, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot °R$),
CR = convergence factor (dimensionless),
e = error of measurement of heat flux, W/m^2 ($Btu/h \cdot ft^2$),
M = number of values of ΔT and q in the source data,
N = number of sensor sites,
n = test for convergence interval, h,
q = heat flux, W/m^2 ($Btu/h \cdot ft^2$),
R = thermal resistance, $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot °R/Btu$),
$s(x)$ = standard deviation of x, based on $N-1$ degrees of freedom,
T = temperature, K (°R, C, °F),
t = time, h,
$V(x)$ = coefficient of variation of x,
ΔT = difference in temperature between indoors and outdoors, K (°R, C, °F),
λ = apparent thermal conductivity, $W/m \cdot K$ ($Btu/h \cdot ft \cdot °R$), and
x = position coordinate (from 0 to distance L in increments of Δx),
ρ = material density, kg/m^3 (lb/ft^3).

3.3.2 *Subscripts for the Summation Technique*:

a = air,
e = estimate,
i = indoor,
j = counter for summation of sensor sites,
k = counter for summation of time-series data,
m = area coverage,
n = test for convergence value.
o = outdoor, and
s = surface,

3.3.3 *Variables for the Sum of Least Squares Technique*:

C_ρ = material specific heat, $J/kg \cdot K$ ($Btu/lb \cdot °F$),
Y_{mi} = measured temperature at indoor node m for time i K (°R, C, °F),
F_{ni} = measured heat flux at interior node n for time i W/m^2 ($Btu/h \cdot ft^2$),
λ = apparent thermal conductivity, $W/m \cdot K$ ($Btu/h \cdot ft \cdot °F$),
T_{mi} = calculated temperature at indoor node m for time i K (°R, C, °F),
q_{ni} = calculated heat flux at interior node n for time i W/m^2 ($Btu/h \cdot ft^2$),
W_{Tm} = weighting factor to normalize temperature contribution to Γ,
W_{qn} = weighting factor to normalize heat flux contribution to Γ, and
Γ = weighted sum of squares function.

3.3.4 *Subscripts for the Sum of Least Squares Technique*:

s = specific heat of value, "s," $J/kg \cdot K$ ($Btu/lb \cdot °F$)

4. Summary of Practice

4.1 This practice presents two mathematical procedures for calculating the thermal resistance of a building envelope subsection from measured in-situ temperature and heat flux data. The procedures are the summation technique **(1)**[3] and the sum of least squares technique **(2, 3)**. Proper validation of other techniques is required.

4.2 The results of each calculation pertain only to a particular subsection that was instrumented appropriately. Appropriate instrumentation implies that heat flow can be substantially accounted for by the placement of sensors within the defined subsection. Since data obtained from in-situ measurements are unlikely to represent steady-state conditions, a calculation of thermal resistance is possible only when certain criteria are met. The data also provide an estimate of whether the collection process has run long enough to satisfy an accuracy criterion for the calculation of thermal resistance. An estimate of error is also possible.

4.3 This practice provides a means for estimating the mean temperature of the building component (see 6.5.1.4) for estimating the dependence of measured *R*-value on temperature for the summation technique by weighting the recorded temperatures such that they correspond to the observed heat fluxes. The sum of least squares technique has its own means for estimating thermal resistance as a function of temperature.

5. Significance and Use

5.1 *Significance of Thermal Resistance Measurements*—Knowledge of the thermal resistance of new buildings is important to determine whether the quality of construction satisfies criteria set by the designer, by the owner, or by a regulatory agency. Differences in quality of materials or workmanship may cause building components not to achieve design performance.

5.1.1 *For Existing Buildings*—Knowledge of thermal resistance is important to the owners of older buildings to determine whether the buildings should receive insulation or other energy-conserving improvements. Inadequate knowledge of the thermal properties of materials or heat flow paths within the construction or degradation of materials may cause inaccurate assumptions in calculations that use published data.

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[3] The boldface numbers in parentheses refer to the list of references at the end of this practice.

5.2 *Advantage of In-Situ Data*—This practice provides information about thermal performance that is based on measured data. This may determine the quality of new construction for acceptance by the owner or occupant or it may provide justification for an energy conservation investment that could not be made based on calculations using published design data.

5.3 *Heat Flow Paths*—This practice assumes that net heat flow is perpendicular to the surface of the building envelope component within a given subsection. Knowledge of surface temperature in the area subject to measurement is required for placing sensors appropriately. Appropriate use of infrared thermography is often used to obtain such information. Thermography reveals nonuniform surface temperatures caused by structural members, convection currents, air leakage, and moisture in insulation. Practices C 1060 and C 1153 detail the appropriate use of infrared thermography. Note that thermography as a basis for extrapolating the results obtained at a measurement site to other similar parts of the same building is beyond the scope of this practice.

5.4 *User Knowledge Required*—This practice requires that the user have knowledge that the data employed represent an adequate sample of locations to describe the thermal performance of the construction. Sources for this knowledge include the referenced literature in Practice C 1046 and related works listed in Appendix X2. The accuracy of the calculation is strongly dependent on the history of the temperature differences across the envelope component. The sensing and data collection apparatuses shall have been used properly. Factors such as convection and moisture migration affect interpretation of the field data.

5.5 *Indoor-Outdoor Temperature Difference*—The speed of convergence of the summation technique described in this practice improves with the size of the average indoor-outdoor temperature difference across the building envelope. The sum of least squares technique is insensitive to indoor-outdoor temperature difference, to small and drifting temperature differences, and to small accumulated heat fluxes.

5.6 *Time-Varying Thermal Conditions*—The field data represent varying thermal conditions. Therefore, obtain time-series data at least five times more frequently than the most frequent cyclical heat input, such as a furnace cycle. Obtain the data for a long enough period such that two sets of data that end a user-chosen time period apart do not cause the calculation of thermal resistance to be different by more than 10 %, as discussed in 6.4.

5.6.1 Gather the data over an adequate range of thermal conditions to represent the thermal resistance under the conditions to be characterized.

NOTE 2—The construction of some building components includes materials whose thermal performance is dependent on the direction of heat flow, for example, switching modes between convection and stable stratification in horizontal air spaces.

5.7 *Lateral Heat Flow*—Avoid areas with significant lateral heat flow. Report the location of each source of temperature and heat flux data. Identify possible sources of lateral heat flow, including a highly conductive surface, thermal bridges beneath the surface, convection cells, etc., that may violate the assumption of heat flow perpendicular to the building envelope component.

NOTE 3—Appropriate choice of heat flow sensors and placement of those sensors can sometimes provide meaningful results in the presence of lateral heat flow in building components. Metal surfaces and certain concrete or masonry components may create severe difficulties for measurement due to lateral heat flow.

5.8 *Light- to Medium-Weight Construction*—This practice is limited to light- to medium-weight construction that has an indoor temperature that varies by less than 3 K (5°F). The heaviest construction to which this practice applies would weigh 440 kg/m^2 (90 lb/ft^2), assuming that the massive elements in building construction all have a specific heat of about 0.9 kJ/kg K (0.2 Btu/lb·°F). Examples of the heaviest construction include: (*1*) a 390-kg/m^2 (80-lb/ft^2) wall with a brick veneer, a layer of insulation, and concrete blocks on the inside layer or (*2*) a 76-mm (3-in.) concrete slab with insulated built-up roofing of 240 kg/m^2 (50 lb/ft^2). Insufficient knowledge and experience exists to extend the practice to heavier construction.

5.9 *Heat Flow Modes*—The mode of heat flow is a significant factor determining *R*-value in construction that contains air spaces. In horizontal construction, air stratifies or convects, depending on whether heat flow is downwards or upwards. In vertical construction, such as walls with cavities, convection cells affect determination of *R*-value significantly. In these configurations, apparent *R*-value is a function of mean temperature, temperature difference, and location along the height of the convection cell. Measurements on a construction whose performance is changing with conditions is beyond the scope of this practice.

6. Procedure

6.1 *Selection of Subsections for Measurement*—This practice determines thermal resistance within defined regions or subsections where perpendicular heat flow has been measured by placement of heat flux sensors. Choose subsections that represent uniform, non-varying thermal resistance and install the instrumentation to represent that subsection as a whole. The defined subsection shall have no significant heat flow that bypasses the instrumentation in a manner that is uncharacteristic of where the instrumentation was placed. Use thermography to identify appropriate subsections. Each subsection is the subject of a separate calculation from in-situ heat flux and temperature data from instrumentation that represents that subsection. Demonstration that sensor sites appropriately represent each subsection is required in the report (7.3).

NOTE 4—A uniformly insulated region between studs may have an essentially uniform thermal resistance. Similarly, a framing member may define a consistent region of interest.

6.1.1 *Perpendicular Heat Flow*—Determine whether the subregions chosen best represent perpendicular or non-perpendicular heat flow by considering evidence of thermal bridges and convection. Assume perpendicular flow in regions where no temperature gradient is detectable at the most sensitive setting of the thermal imager or other instrumentation.

6.1.2 *Non-Perpendicular Heat Flow*—Assume non-perpendicular heat flow for those regions where a temperature gradient is detectable at the most sensitive setting of the thermal imager or other instrumentation. Choose the subsection (6.1) in such a manner that heat flowing between the indoor and outdoor surfaces is fully accounted for. Averaging temperatures across a subsection satisfies this requirement.

6.1.3 *Estimate Thermal Time Constant*—Estimate the thermal time constant of the building envelope component. Use Practice C 1046, Appendix X1 (Estimating Thermal Time Constants), or other recognized method. Estimate the thicknesses and thermal diffusivities of the constituent layers of the building component, as required.

6.2 *Sensor Placement*—Choose locations for sensors to represent each subsection subject to the measurement. Temperature and heat flux sensors are used at various locations to determine the inside and outside surface temperatures of the subsection and heat flow through the subsection. Refer to the appropriate ASTM standards for use of the sensors chosen. If heat flux transducers (HFTs) are employed, then refer to Practice C 1046, Section 8 (Selection of Sensor Sites), to select sites for HFTs and temperature sensors on building envelope components to obtain in-situ data. Refer to Practice C 1046, Section 9 (Test Procedures), for applying heat flux transducers and temperature sensors to the building. Instrumentation shall be properly calibrated. Refer to Practice C 1130 for calibration of HFTs. The following sections cover the important aspects of instrumentation.

NOTE 5—Most planar heat flow sensors may be surface-mounted; HFTs may also be embedded. Infrared thermography is useful in assessing whether the absorptivity of the HFT surface matches that of its surroundings.

6.2.1 *Heat Flux Transducers*—Do not expose surface-mounted HFTs to strong thermal radiation sources, especially the sun. Indoors, close blinds to avoid direct sunlight from radiating to the sensors.

6.2.2 *Temperature Sensors*—At a minimum, place temperature sensors to obtain surface temperature measurements at points that are at opposite ends of the heat flow path on the inside and outside surfaces of the building envelope component.

6.3 *Data Time Intervals*—Sample each sensor at least every 5 min. Average the output, compute the averaged value for temperature and heat flux, and record each value at intervals of 60 min or less.

6.4 *Calculate Temperature Difference*—Calculate the temperature difference between the inside and outside surfaces of the building envelope component, as follows, depending on whether heat flow is perpendicular, or not.

6.4.1 *Perpendicular Heat Flow*—In cases where the assumption of heat flow perpendicular to the surface of the building envelope component is valid, subtract, for each time interval, the outside surface temperature from the indoor surface temperature to obtain the temperature difference (ΔT_s) for that surface.

$$\Delta T_s = T_{is} - T_{os} \tag{1}$$

ΔT_s may be obtained directly from the instrumentation, for example, by connecting indoor and outdoor thermocouples in series, if other calculations do not require values for surface temperatures.

6.4.2 *Non-Perpendicular Heat Flow*—In cases with probable lateral heat flow, for each time interval, average the temperatures on each surface and subtract the average outside surface temperature from the average indoor surface temperature to obtain the temperature difference (ΔT_s) for that surface.

NOTE 6—Eq 1 represents a common case where the sum of heat flux paths from a region on one side of the construction connect to a corresponding region on the opposite side of the construction. In other cases, corresponding regions on opposite surfaces may not account for the total heat flow through that segment of the construction, because of lateral heat flow. In the general case for Eq 1, surface regions shall be so defined to represent opposite ends of the heat flow paths of interest.

6.5 *Calculation of Thermal Resistance*—This practice presents two mathematical procedures for calculating the thermal resistance of a building envelope subsection from measured in-situ temperature and heat flux data. The procedures are the summation technique and the sum of least squares technique. Any other technique used shall be shown to calculate thermal resistance for the pertinent construction, based on a mathematical derivation (see Note 7). The precision and bias for any other technique shall also be determined.

NOTE 7—References **(1, 2, and 3)** contain examples of such a derivation applied to the summation and least squares techniques, respectively. Other methods **(4, 5, 6, 7)** that have been used or suggested are multiple regression analysis, Fourier analysis, and digital filtering.

6.5.1 *Summation Technique*—This calculation procedure employs an accumulation of data on heat flux and differences in surface temperatures over time. It requires a significant difference in temperatures and a constant temperature on one side for rapid convergence. Temperature reversals prolong this calculation technique because negative values of ΔT and q offset the accumulated positive values of these variables. Since the procedure does not account for thermal storage, the technique is also sensitive to having a gradual increase or decrease in temperature differences (for example, low-frequency variations), especially with more massive construction. For each time interval, starting from the beginning of the measurement, calculate the estimate of thermal resistance:

$$R_e = \frac{\sum_{k=1}^{M} \Delta T_{sk}}{\sum_{k=1}^{M} q_k} \tag{2}$$

NOTE 8—Eq 2 represents the common simple case where heat flux paths between opposite surfaces pass between corresponding opposite regions. In cases with significant lateral heat flux, a more general version of Eq 2 shall account for heat flux paths between corresponding regions that are not opposite each other.

6.5.1.1 *Duration of Test*—The test should last one or more multiples of 24 h, because 24 h is a dominant temperature cycle. Calculate whether enough data have been obtained before dismantling the instrumentation (6.5.1.2). For the summation technique, choose at least one characteristic test-for-convergence interval, n, for testing for a difference between the current R_e and the value of R_e a period of n time units earlier. Reference **(7)** explains a required choice of $n = 12$ h. As an option, also choose other values of *n*, between 6 and 48 h, and use the most severe choice as the test, as follows. After the time period that commences *n* h after the first set of data, start computing the convergence factor:

$$CR_n = \frac{R_e(t) - R_e(t-n)}{R_e(t)} \tag{3}$$

NOTE 9—Eq 3 applies specifically to the summation technique. Other techniques may require a different test to determine whether enough data have been obtained. Such a test shall be demonstrated as appropriate.

6.5.1.2 *Test for Convergence*—Determine at which time CR_n remains below a chosen value for at least 3 periods of length *n* ($CR_n < 0.10$ is required). Then use the R_e for this time to determine the thermal resistance of the building component, according to the steps outlined in 6.7. Plot R_e as a function of time to confirm that the curve is converging to a constant value.

6.5.1.3 *Variance of R-values*—To estimate the variance of R_e, collect enough data to repeat the steps in 6.5.1.2 at least two more times, each time starting where the convergence or goodness of fit criterion was met for the previous set of data, to obtain at least three independent values for R_e. Calculate the coefficient of variation ($V(R_e)$) according to the following:

$$V(R_e) = [s(R_e)/\text{mean}\,(R_e)] \times (100\,\%) \tag{4}$$

where:

$s(R_e)$ = calculated with $N-1$ degrees of freedom, and

N = number of values of $R_e (N \geq 3)$.

If $V(R_e)$ is less than 10 %, then use the mean of R_e to calculate the thermal resistance of the building component. If $V(R_e) > 10\,\%$, then the calculation method has not provided an acceptable R_e value for the set of data that was analyzed.

NOTE 10—A value of less than 10 % has been found to be readily obtainable for wood frame construction **(8, 9, 10)**.

6.5.1.4 *Corresponding Mean Temperature*—When using the summation technique, calculate an estimated mean temperature for the low- to medium-weight construction covered in this practice, using a weighted average **(11)**:

$$T_e = \frac{\sum_{k=1}^{M} \Delta T_k [T_{isk} - (1/2)(\Delta T_k)]}{\sum_{k=1}^{M} [\Delta T_k]} \tag{5}$$

Average calculated temperature at the midpoint between surfaces is not appropriate.

6.5.2 *Sum of Least Squares Technique*—For sensors installed at the boundaries of a homogeneous layer within an insulated component in which one-dimensional, transient conduction is the heat transfer mechanism, the governing equation, allowing for variable temperature thermal properties is as follows:

$$\frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T}{\partial x}\right) = (\rho C_p)_s \frac{\partial T}{\partial t} \quad \text{with} \quad q = -\lambda_s \frac{\partial T}{\partial x} \tag{6}$$

NOTE 11—This technique solves Eq 6 numerically using the Crank-Nicholson method to obtain a finite difference approximation. The boundary conditions are the measured temperature or heat flux histories, or both, on each side of the building component. The thermal properties estimated are typically apparent thermal conductivity as a function of temperature and a constant value of the product ρ and C_p.

To obtain the best estimates for as many parameters as required, compute temperatures and heat fluxes with trial initial values of the parameters. Compare them to measurements at the interior nodes where independent measurements are available. Compute a weighted sum of squares function Γ from the differences between calculated and measured heat fluxes and temperatures.

$$\Gamma = \sum_{i=1}^{K} \sum_{m=1}^{M} (Y_{mi} - T_{mi})^2 \cdot W_{Tm} + \sum_{i=1}^{K} \sum_{n=1}^{N} (F_{ni} - q_{ni})^2 \cdot W_{qn} \tag{7}$$

Use the Gauss linearization method **(2)** to minimize Γ as the analysis iterates with better and better estimates of the desired properties until the desired convergence is obtained.

6.5.2.1 *Duration of Test*—Calculate whether enough data have been obtained before dismantling the instrumentation (6.5.2.2). The least squares method uses goodness of fit as a test for how well the model matches the data obtained.

6.5.2.2 *Test for Convergence*—Obtain enough data to ensure that the uncertainty of the value for thermal resistance or conductivity remains within 10 % at a 95 % confidence level.

6.5.2.3 *Statistical Tests for R-value*—The sum of least squares technique offers many statistical tests, including confidence intervals, sensitivity coefficients, and residual analysis. Refer to **(11)** to perform these tests.

6.6 *Calculation of Thermal Resistance and Mean Temperature*—The final R_e obtained at any one sensor location does not adequately represent the building envelope component chosen, even where thermal anomalies are not present. Therefore, calculate thermal resistance from the area-weighted averages of the final values of R_e, using appropriate groupings of sensors in representative subsections. There are two cases: where associated heat flux and temperature sensors are placed to cover equal areas of the building component and where they cover unequal areas.

6.6.1 *Sensors Associated with Equal Areas*—Calculate the thermal resistance of a building component subsection which has been instrumented with a line or matrix of sensors covering equal areas as follows, using values of R_e from Eq 2 or some other appropriate source for each sensor site, *j*:

$$R_m = \frac{N}{\sum_{j=1}^{N} (1/R_j)} \tag{8}$$

Similarly, calculate the overall estimated mean temperature, using values of T_e from Eq 5 for each sensor site, *j*:

$$T_m = \frac{[\sum_{j=1}^{N} T_{ej}]}{N} \tag{9}$$

6.6.2 *Sensors Associated with Unequal Areas*—If the sensor groupings are on unequal areas within a building component subsection, then the calculation of *R* shall be area-weighted, using summations of ΔT and *q* for each sensor site, *j*, as follows:

$$R_m = \frac{[\sum_{j=1}^{N} A_j]}{[\sum_{j=1}^{N} A_j/R_{ej}]} \tag{10}$$

where A_k = area around sensor *j*.

Similarly, the overall estimated mean temperature may be calculated, using values of T_e from Eq 5 for each sensor site, j:

$$T_m = \frac{[\sum_{j=1}^{N} (A_j)(T_{ej})]}{[\sum_{j=1}^{N} A_j]} \tag{11}$$

NOTE 12—Area-weighting the values of R_e, according to Eq 10 or Eq 11, should give a reasonable thermal resistance for the segment of building envelope that was instrumented.

NOTE 13—A plot of the values R_e obtained at each location along a vertical line on a wall, as a function of height can reveal the presence or absence of internal convection.

7. Report

7.1 Incorporate the reports of all ASTM practices that were used to obtain the temperature and heat flux data.

7.2 Report the calculation technique used. If a technique other than the summation or sum of least squares technique was used, include documentation of its mathematical validity and the precision and bias of the calculation with the data used.

7.3 Describe and explain the choice of subsections of the building envelope that were measured and the choice of sensor sites. For example, what subsections were being measured for thermal resistance, how did sensor placement relate to thermal variation of the subsection, what types of thermal variation were anticipated, how were they dealt with by sensor placement, and was their presence confirmed by the data or by infrared thermography.

7.4 Report R_e (Eq 2 or other) and CR_n (Eq 3) (see Note 9) for each sensor site. Report $V(R_e)$ (Eq 4) for each site that an estimate of variance was made. Average the final values of R_e for each grouping of sensors and for each grouping report thermal resistance (Eq 8 or Eq 10).

NOTE 14—If the convergence criterion is inapplicable to the technique used, then show that sufficient data were obtained, both that the data were frequent enough and that they were obtained over a sufficiently long duration.

7.5 Report the mean temperature obtained for each sensor site (Eq 5). Average the mean temperatures for the same groupings of sensors for which the thermal resistance was calculated (Eq 9 or Eq 11). Report the average ΔT for these groupings of sensors or the average surface temperatures, indoors and outdoors, so that it is clear which direction the heat flow occurred primarily during the course of the measurement.

8. Precision and Bias

8.1 The precision and bias of the calculation procedure in this practice depend on the precision and bias of the instrumentation employed, on the construction measured, on the choice of sensor sites, on the calculation technique used, and on the nature of the data obtained. In most instances of field thermal measurements using this practice, there is sufficient experimental error to expect a coefficient of variation on the order of 10 % for the summation technique and 6 % for the sum of least squares technique **(5, 6, 7)**.

8.1.1 Refer to Practice C 1046 for a discussion of the precision and bias of heat flux transducers.

8.1.2 Constructions with significant lateral heat flow may cause a bias in the calculation of thermal resistance from in-situ data. Techniques that account for heat flow paths from one surface to the other improve the accuracy of the calculation of thermal resistance.

8.1.3 Knowledgeable placement of sensors can improve the accuracy of the calculation of thermal resistance. Sufficient numbers of sensor sites can provide enough data to average out the effects of lateral heat flow.

8.1.4 Temperature swings, the average ΔT, and duration of data collection affect precision and bias.

8.2 *Precision of Calculation*—The precision of the summation technique calculation can be tested by taking independent values of fully converged R_e and determining their coefficient of variation, according to Eq 4. In general, if the convergence criterion 6.5.1.2 is satisfied, ΔT shall be large compared to the random errors for temperature sensors. In such cases, the variance of $C = 1/R$ by the summation technique is as follows **(10)**:

$$\text{Variance } (C) = \frac{M \cdot s^2(q)}{[\sum_{k=1}^{M} \Delta T_k]^2} \tag{12}$$

where $s^2(q)$ = variance of q. The variance of ΔT is negligible.

This also offers an independent check of precision of the sum of least squares technique which has built-in tests for precision.

NOTE 15—A comparison between the two techniques, used with separately calibrated instrumentation side by side on the same construction, determined that they agreed within 4 % for heat fluxes greater than 0.15 W/m^2 (0.048 Btu/ft^2·h) **(11)**.

8.2.1 A discussion of the derivation of Eq 12 appears in Appendix X1. If a calculation technique uses temperature values where the variance of temperatures are not negligible, then a more complete expression would be required. The variance of any other calculation procedure used in this practice shall be derived and documented.

8.3 *Bias of Calculation*—Neither the summation technique nor the sum of least squares calculation procedures in this practice have a significant source of bias, insofar as the data used in the calculations are unbiased, the lateral heat flux is not significant, and providing that the convergence criterion has been met. The accuracy of any other calculation procedure used in this practice shall be derived and documented.

NOTE 16—In some cases the measurement of thermal resistance for light- to medium-weight construction may satisfy the convergence criterion, yet it may be too short in duration because of a long time constant, that is, construction with an extremely high thermal resistance. In any case, the duration of measurement shall be much longer than the time constant of the construction. Refer to Practice C 1046, Appendix X1 to estimate thermal time constants.

9. Keywords

9.1 calculation; heat flow; heat flux transducers; HFT; in-situ; mean temperature; measurement; thermal resistance

APPENDIXES

(Nonmandatory Information)

X1. DERIVATION OF THE VARIANCE OF *C*-VALUE, CALCULATED BY SUMMATION

X1.1 This derivation comes from Ref **(6)**. Refer to Eq 2 and define $C = 1/R_e$. Assume that the variance of the ΔT readings is negligible, compared with that of the data for q. If we define $q_k = C_k + e_k$, where C_k is the true heat flux for each k, and e_k is the error of measurement for each k and is a random variable. Therefore,

$$\text{Variance}\ (q) = \text{Variance}\ (C) + \text{Variance}\ (e) = 0 + s^2(e) \tag{X1.1}$$

From Eq 2, and our definition of C:

$$\text{Variance}\ (C) = \text{Variance}\left[\frac{1}{R_e}\right] \tag{X1.2}$$

$$= \text{Variance}\frac{\sum_{k=1}^{M} q_k}{[\sum_{k=1}^{M} \Delta T_k]} \tag{X1.3}$$

$$= \frac{M \cdot s^2(q)}{[\sum_{k=1}^{M} \Delta T_k]^2} \tag{X1.4}$$

since $(\sum_{k=1}^{M} \Delta T_k)$ is a constant because we assumed its variance to be negligible.

X2. ADDITIONAL MATERIAL

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