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·K (Btu/h·ft^2·°R),
CR = convergence factor (dimensionless),
e = error of measurement of heat flux, W/m^2 (Btu/h·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·ft^2),
R = thermal resistance, m^2·K/W (h·ft^2·°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·K (Btu/h·ft·°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·K (Btu/lb·°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·ft^2),
λ = apparent thermal conductivity, W/m·K (Btu/h·ft·°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·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·K (Btu/lb·°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