Designation: C1130 – 21

Standard Practice for Calibration of Thin Heat Flux Transducers[1]

This standard is issued under the fixed designation C1130; 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, in conjunction with either Test Method C177, C518, C1114, or C1363, establishes procedures for the calibration of heat flux transducers that are dimensionally thin in comparison to their planar dimensions.

1.1.1 The thickness of the heat flux transducer shall be less than 30 % of the narrowest planar dimension of the heat flux transducer.

1.2 This practice describes techniques for determining the sensitivity, *S*, of a heat flux transducer when subjected to one dimensional heat flow normal to the planar surface or when installed in a building application.

1.3 This practice shall be used in conjunction with Practice C1046 and Practice C1155 when performing in-situ measurements of heat flux on opaque building components. This practice is comparable, but not identical, to the calibration techniques described in ISO 9869-1.

1.4 This practice is not intended to determine the sensitivity of heat flux transducers used as components of heat flow meter apparatus, as in Test Method C518, or used for in-situ industrial applications, as covered in Practice C1041.

1.5 This practice does not preclude the laboratory calibration of heat flux transducers for large-scale insulation systems operated at temperatures lower or higher than that for building components. For these applications, the heat flux transducers shall be calibrated at the temperatures that the transducer will be used.

1.5.1 For cryogenic applications, the test apparatuses described in Guide C1774 are acceptable methods for calibration.

1.6 The text of this standard references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

1.7 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses are provided for information only and are not considered standard.

1.8 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C168 Terminology Relating to Thermal Insulation
C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
C1041 Practice for In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers (Withdrawn 2019)[3]
C1044 Practice for Using a Guarded-Hot-Plate Apparatus or Thin-Heater Apparatus in the Single-Sided Mode
C1046 Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components
C1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus
C1155 Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data
C1363 Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus
C1774 Guide for Thermal Performance Testing of Cryogenic Insulation Systems

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

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

2.2 *ISO Standards:*[4]

ISO 9869-1 Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance – Part 1: Heat flow meter method

3. Terminology

3.1 *Definitions*—For definitions of terms relating to thermal insulating materials, see Terminology C168.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *mask*—material (or materials) having the same, or nearly the same, thermal properties and thickness surrounding the heat flux transducer thereby promoting one-dimensional heat flow through the heat flux transducer.

3.2.2 *R-squared* (R^2)—coefficient of determination (also known as "goodness of fit") is a statistical measure of how close the data are to the fitted line.

3.2.3 *sensitivity*—the ratio of the electrical output of the heat flux transducer to the heat flux passing through the device when measured under steady-state heat flow.

3.2.4 *test stack*—a layer or a series of layers of material put together to comprise a test sample (for example, a roof system containing a membrane, an insulation, and a roof deck).

3.3 *Symbols:*

3.3.1 E—measured HFT output voltage, V.

3.3.2 q—steady-state heat flux, W/m^2 (Btu/h·ft^2).

3.3.3 S—sensitivity, V/(W/m^2) (V/(Btu/h·ft^2)).

3.3.4 u_c—combined standard uncertainty, V.

3.3.5 u_1—standard uncertainty of the regression coefficients, V.

3.3.6 u_2—standard uncertainty for replicate measurements, V.

3.3.7 u_3—standard uncertainty for the measurement, V.

4. Summary of Practice

4.1 This practice presents three techniques for the laboratory calibration of heat flux transducers **(1)**[5]: *(1)* ideally guarded; *(2)* embedded; and, *(3)* surface mounted. These techniques establish a hierarchy defined by the extent that the assumption of one-dimensional heat flow is satisfied **(1)**.

4.1.1 The ideally-guarded technique places the heat flux transducer (HFT) in a test stack consisting of homogeneous, thermally characterized materials that promotes one-dimensional heat flow normal to the planar dimensions of the HFT. The results of this technique provide a baseline calibration for the HFT.

4.1.2 The embedded technique places the HFT within a test stack consisting of material layers identical, or comparable to, the building construction to be studied under application.

4.1.3 The surface mounted calibration, which is the most complex, places the HFT on the external surface of a test stack and incorporates environmental effects that cause lateral heat flow in the locality of the HFT.

4.2 The calibration results are intended for use with Practice C1046 to measure in-situ the heat flux through opaque building components and with Practice C1155 for the subsequent analysis of the measurement data. The intended application of the HFT is used to determine the appropriate calibration technique **(2)**.

4.2.1 If the HFT is to be embedded in the building envelope, the HFT shall be calibrated in a test stack of materials that simulate the surrounding construction materials.

4.2.2 If the HFT is to be surface mounted on the building envelope construction, the HFT shall be calibrated using a hot box that is oriented similarly (horizontal, vertical, or inclined) as the measurement site.

5. Significance and Use

5.1 The application of HFTs and temperature sensors to building envelopes provide in-situ data for evaluating the thermal performance of an opaque building component under actual environmental conditions, as described in Practices C1046 and C1155. These applications require calibration of the HFTs at levels of heat flux and temperature consistent with end-use conditions.

5.2 This practice provides calibration procedures for the determination of the heat flux transducer sensitivity, S, that relates the HFT voltage output, E, to a known input value of heat flux, q.

5.2.1 The applied heat flux, q, shall be obtained from steady-state tests conducted in accordance with either Test Method C177, C518, C1114, C1363, or, for cryogenic applications, Guide C1774.

5.2.2 The resulting voltage output, E, of the heat flux transducer is measured directly using (auxiliary) readout instrumentation connected to the electrical output leads of the sensor.

NOTE 1—A heat flux transducer (see also Terminology C168) is a thin stable substrate having a low mass in which a temperature difference across the thickness of the device is measured with thermocouples connected electrically in series (that is, a thermopile). Commercial HFTs typically have a central sensing region, a surrounding guard, and an integral temperature sensor that are contained in a thin durable enclosure. Practice C1046, Appendix X2 includes detailed descriptions of the internal constructions of two types of HFTs.

5.3 The HFT sensitivity depends on several factors including, but not limited to, size, thickness, construction, temperature, applied heat flux, and application conditions including adjacent material characteristics and environmental effects.

5.4 The subsequent conversion of the HFT voltage output to heat flux under application conditions requires *(1)* a standardized technique for determining the HFT sensitivity for the application of interest; and, *(2)* a comprehensive understanding of the factors affecting its output as described in Practice C1046.

5.5 The installation of a HFT potentially changes the local thermal resistance of the test artifact and the resulting heat flow

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[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

[5] The boldface numbers in parentheses refer to the references at the end of this standard.

differs from that for the undisturbed building component. The following techniques have been used to compensate for this effect.

5.5.1 Ensure that the installation is adequately guarded (**3**). In some cases, an assumption is made that the change in thermal resistance is negligible, particularly for very thin HFTs with a large surrounding guard, or is incalculable (**1**).

5.5.2 For the embedded configuration, analytical and numerical methods have been used to account for the disturbance of the heat flux due to the presence of the HFT. Such analyses are outside the scope of this practice but details are available in Refs (**4-8**).

5.5.3 For the surface-mounted configuration, measurement errors have been quantified by Trethowen (**9**). Empirical calibrations have also been determined by conducting a series of field calibrations or measurements. Such procedures are outside the scope of this practice but details are available in Orlandi et al. (**10**) and Desjarlais and Tye (**11**).

5.6 Cryogenic and high temperature calibrations shall consider the effect of parasitic heat transfer due to large environmental temperature differences in performing thermal balances. The calibration and testing of heat flux transducers at cryogenic temperatures using the flat plate boiloff absolute calorimeter described in Guide C1774 and an unguarded flat plate method are described by Johnson et al. (**12**).

6. Specimen Preparation

6.1 *Preparation of the HFT, Test Stack, and Surface-Mounted Installation:*

6.1.1 *HFT*—Verify the electrical continuity of the HFT and temperature sensor. Where auxiliary readout instrumentation, that is, voltmeter, recorder, or data acquisition system, is needed, the user shall provide appropriate provision for calibration. The instrumentation shall have a resolution capability of 2 μV.

6.1.2 *Test Stack*—Place the HFT and temperature sensor in the test stack located within the central metering area of the apparatus plates (Test Methods C177, C518, C1114, or Guide C1774).

6.1.3 *Surface-Mounted*—Place the HFT and temperature sensor in the central location of the metered area of the hot box (Test Method C1363).

6.1.4 *Sensor Leads*—The sensor output leads shall be placed in grooves or covered to minimize the presence of air gaps in the test stack or surface mounted installation. The HFT need not be physically adhered to the mask or embedding material. Thermally conductive gel or paste is applied, if necessary, to one or both faces of the heat flux transducer to improve the thermal contact.

6.2 *Ideally Guarded Configuration (One-dimensional Heat Flow):*

6.2.1 Refer to Fig. 1 for an illustration of the ideally-guarded stack configuration.

6.2.2 *Calibration of One HFT*—Place the HFT and temperature sensor in the center of a guard mask have the same thickness and thermal resistance as the HFT. The outer dimensions of the guard mask shall be the same size as the apparatus plates. Place the HFT/guard assembly between two layers of high-density fibrous glass insulation board or other homogenous semirigid insulating material. It is recommended that the test stack have the smallest acceptable thickness and thermal resistance to minimize edge effects during testing.

6.2.3 *Calibration of multiple HFTs*—To determine the sensitivity of multiple small heat flux transducers, replace the HFT/mask layer shown in Fig. 1 with a layer containing an arrangement of HFTs located within the metered area of the apparatus as illustrated in Fig. 2.

NOTE 2—The plate designs of some apparatus utilize a circular geometry.

6.3 *Embedded Configuration:*

6.3.1 Consult Practice C1046 for details on the installation of the HFT within the building envelope component of interest. Construct the test stack to have the same, or comparable, physical properties as the end-use application replicating the building construction under evaluation. Place the HFT and temperature sensor within the test stack in the same arrangement as intended in the end-use application.

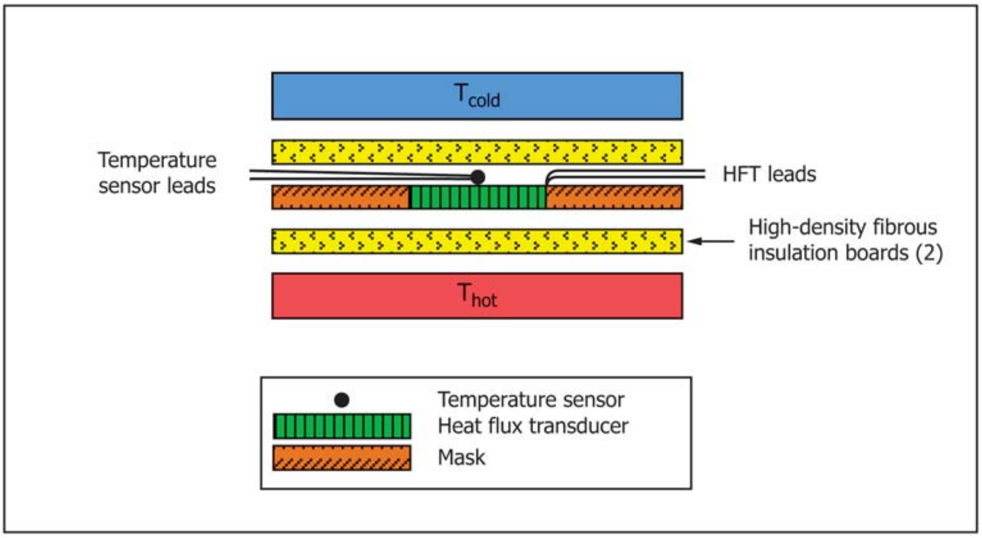

FIG. 1 Ideally Guarded Test Configuration for One HFT (Side View)

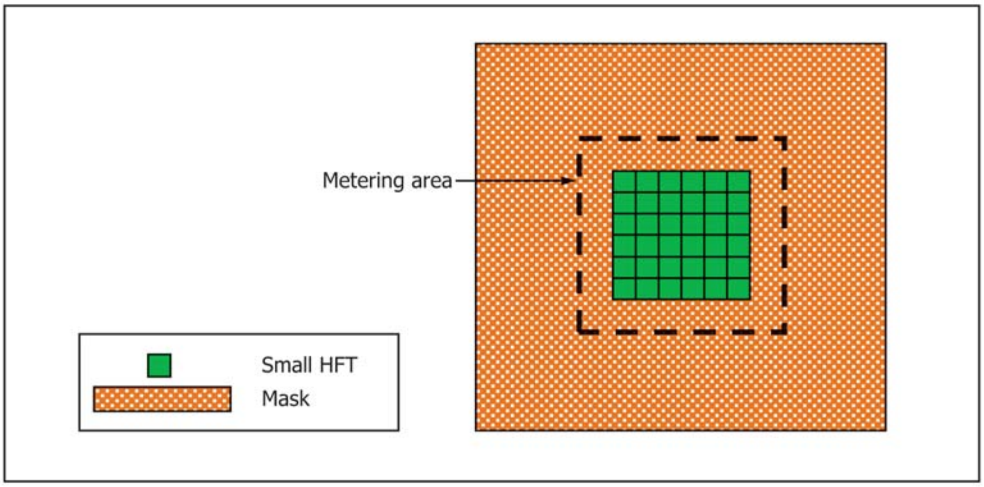

FIG. 2 Calibration of Multiple Small HFTs Evaluated Simultaneously (Top View)

6.3.2 Refer to Fig. 3 for an illustration of an embedded stack configuration placed between the hot and cold apparatus plates. The example in Fig. 3 depicts a case where an HFT is embedded in gypsum wallboard and faces an insulated wall cavity. It is recommended that, when compressible materials are present, rigid spacer stops or other means be utilized to maintain a fixed plate separation during testing.

6.4 *Surface-Mounted Configuration:*

6.4.1 Consult Practice C1046 for details on the installation of the HFT to the surface of the building envelope component of interest. Attach the HFT and temperature sensor to the surface of a test panel having the same, or comparable, physical properties as the building construction under evaluation replicating the end-use conditions. The test panel shall have the same orientation (horizontal, vertical, or inclined) as the building construction under evaluation.

NOTE 3—Trethowen (**13**) recommends mounting of the HFT on interior building surfaces. Exterior mounting of the HFT need only be considered if inside mounting is impossible.

6.4.2 It is recommended that a guard mask be placed around the HFT to compensate for local heat flux perturbations caused by the presence of the HFT. The guard mask shall have the same emittance as the HFT. Guidance on the determination of the size of the guard mask is available in Burch et al. (**3**), van der Graaf (**8**), and Trethowen (**9**).

6.4.3 Refer to Fig. 4 for an illustration of a surface-mounted configuration calibrated in a hot box (one chamber not shown). The example in Fig. 4 depicts a case where an HFT (guard mask not shown) is affixed to a homogeneous test specimen of known thermal resistance.

7. Procedure

7.1 Use a guarded-hot-plate, thin-heater, heat-flow-meter, or hot box apparatus to calibrate the HFT/stack assembly and follow the test procedure of either Test Method C177, C518, C1114, or C1363, respectively.

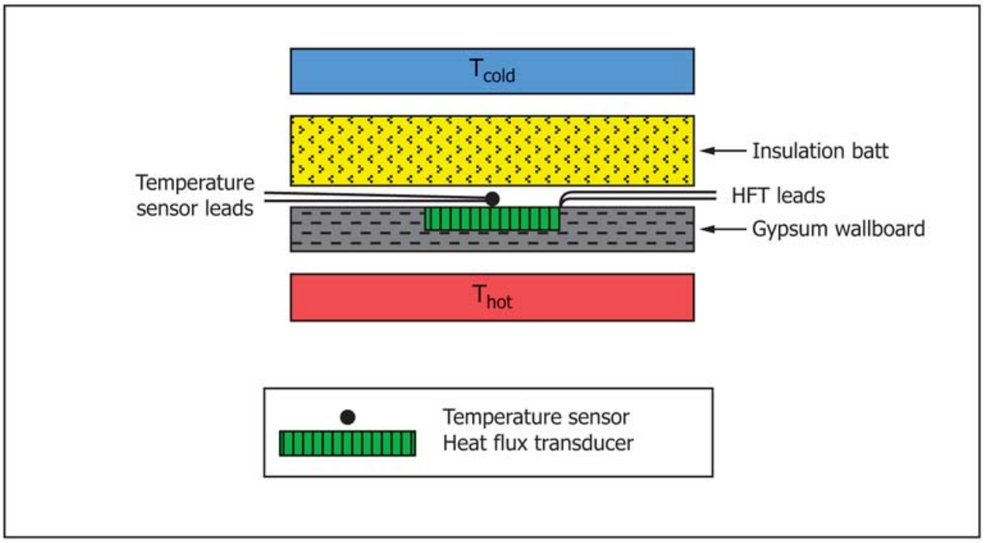

FIG. 3 Test Stack for an HFT Embedded Within an Insulated Wall Cavity (Side View)

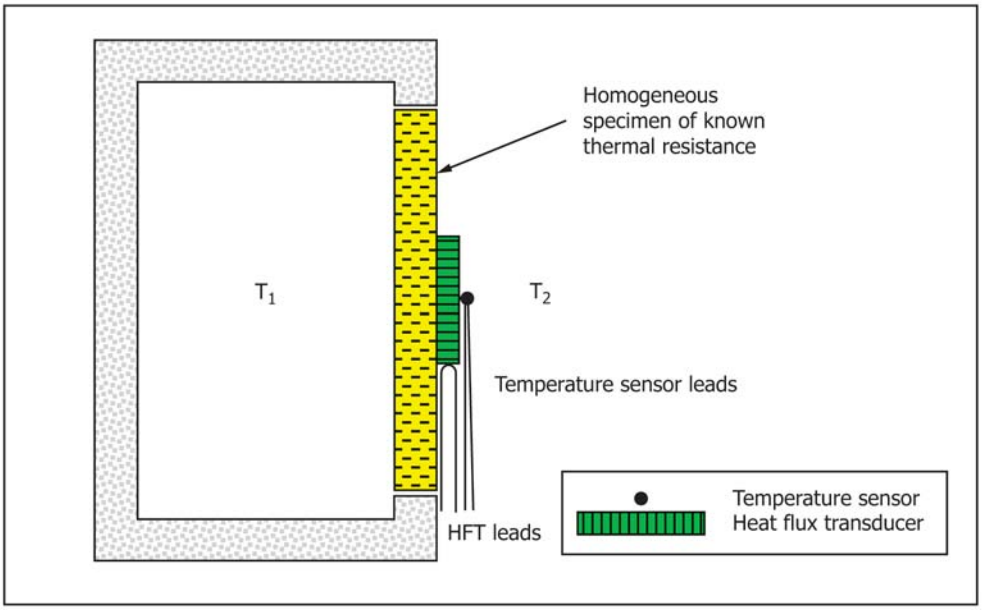

FIG. 4 Surface Mounted HFT Configuration (Side View)

7.1.1 For apparatuses that typically require two specimens follow Practice C1044 for operation of the apparatus in the single-sided mode.

7.1.2 For calibration under cryogenic conditions, utilize the appropriate apparatus and test procedure described in Guide C1774.

7.2 Install the HFT/test stack assembly in the apparatus and connect the voltage output leads from the HFT(s) and temperature sensor(s) to the appropriate readout instrumentation. The presence of air gaps between the apparatus and test stack shall be minimized by sealing or covering with adhesive tape.

7.3 Consult Annex A1 to select hot and cold test temperatures to cover the appropriate ranges of heat fluxes and temperatures for the calibration. The heat fluxes shall be sufficiently large to limit errors due to the readout instrumentation and shall be similar to anticipated levels of the end-use application.

NOTE 4—For most building applications, a heat flux range from 3 W/m^2 to 20 W/m^2 is adequate for calibration of the HFT (ISO 9869-1). A minimum of three levels of heat flux are required to check the linearity response of the HFT. During calibration, it is recommended that bidirectional heat flows through the HFT be investigated.

7.4 *Surface-Mounted Configuration*—For Test Method C1363, replicate the application conditions by also controlling environmental conditions such as convection and radiation effects.

7.5 The calibration of the HFT shall be conducted under steady-state conditions as specified in the appropriate ASTM test method. During steady-state conditions, the output voltages of the HFT and corresponding temperature sensor shall be sampled and recorded using the readout instrumentation.

8. Calculation

8.1 For a specific set of temperature conditions, that is, a single-point calibration, calculate the sensitivity, S, of the HFT using Eq 1.

$$S = \frac{E}{q} \tag{1}$$

NOTE 5—Practice C1046 uses the terms "calibration factor" or "conversion factor" to denote the conversion of the HFT voltage output to heat flux. These terms, which are defined as the multiplicative inverse of the HFT sensitivity defined in Eq 1, have the units are (W/m^2) per V.

8.2 For conditions covering a range of temperatures, fit the output voltage data, E, as a function of heat flux q to determine the sensitivity, S, following the guidelines described in Appendix X1. Examples of least-squares fits for heat flux and temperature are illustrated in Fig. 5 (top and bottom, respectively).

9. Report

9.1 Report the following information:

9.1.1 Name of the measuring institution.

9.1.2 A unique identification number for traceability to the individual measurements taken during the test.

9.1.3 The HFT manufacturer, model, and physical characteristics including size, thickness, and geometry.

9.1.4 The type of temperature sensor applied to the HFT (or near the HFT) or whether integrated with the HFT.

9.1.5 The calibration technique: either ideally guarded; embedded; or, surface mounted and the ASTM test method used.

9.1.6 The test stack materials including a drawing with the location(s) of the HFT(s) and temperature sensor(s).

9.1.7 Tables or plots or both of test temperatures and heat fluxes.

9.1.8 Plots of HFT output as a function of heat flux or mean temperature, or both.

9.1.9 HFT sensitivity and calculation approach (that is, single-point or regression analysis).

10. Precision and Bias

10.1 Precision data from one laboratory using Test Method C177 are given in Table 1 for two sizes of heat flux transducers

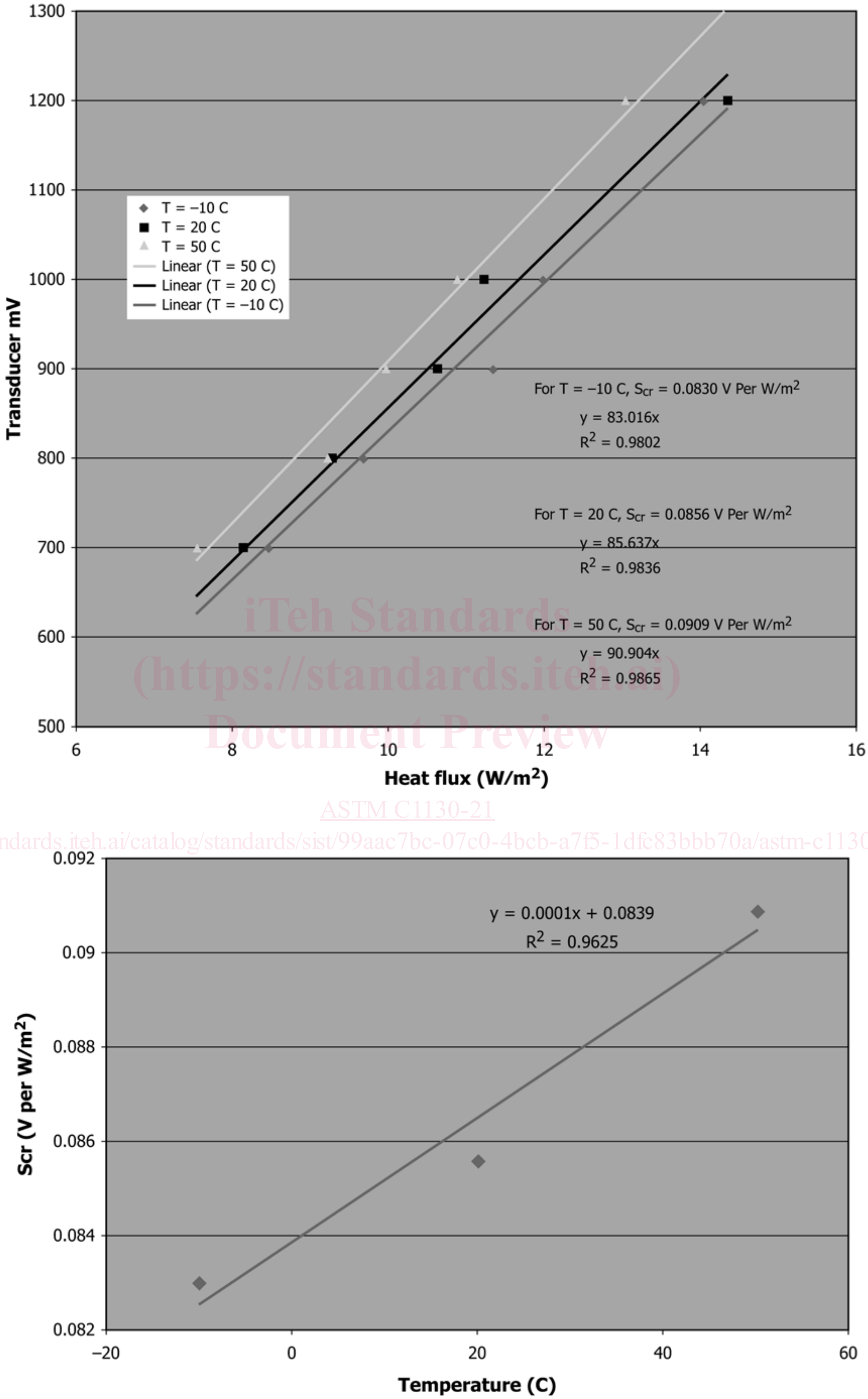

FIG. 5 HFT Output as Function of Heat Flux (top) and HFT Sensitivities as a Linear Function of Temperature (bottom)

TABLE 1 Repeatability Standard Deviations for a Heat Flux Transducer (14) Determined Using Test Method C177

Size	500 mm × 500 mm	610 mm × 610 mm
Meter Area	250 mm × 250 mm	305 mm × 305 mm
Nominal Thickness	0.8 mm	0.8 mm
S	94.0 μV/(W/m^2)	136.4 μV/(W/m^2)
Standard deviation	0.53 μV/(W/m^2)	0.40 μV/(W/m^2)
Number of Specimens	9	3

having coplanar copper-constantan thermoelectric junctions in a glass-fiber reinforced epoxy substrate. The repeatability standard deviations were determined by pooling replicate data and weighting with their respective degrees of freedoms (**14**).

10.2 *Bias*—No information can be presented on the bias of the procedure in Practice C1130 for calibrating thin heat flux transducers because no transducer having an accepted reference value is available.

10.3 After the heat flux transducers are calibrated, they are used to measure heat flux in a building assembly. The heat flux measured by two different types of independently calibrated HFTs installed at the same time in the same roof assembly measured a difference in heat flux of approximately 8 % (**15**).

11. Measurement Uncertainty

11.1 Evaluate the uncertainty for the calibration results using current international guidelines (**16**). Determine the combined standard uncertainty using Eq 2.

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2} \tag{2}$$

11.2 The measurement uncertainty includes the standard uncertainty of the test method used for calibration and the standard uncertainty of any auxiliary measurement equipment, for example, the voltmeter used to measure the DC output signal of the heat flux transducer(s).

11.3 The uncertainty of the heat flux and the HFT output must be determined along with the departure from unidirectional heat flow when the masking technique is employed. The magnitude of this effect can be determined by performing a series of experiments with masks of varying thermal resistances.

12. Keywords

12.1 calibration; heat flux transducer; in situ testing; sensitivity

ANNEX

(Mandatory Information)

A1. GUIDANCE FOR DETERMINATION OF TEST TEMPERATURES

A1.1 For guidance, A1.3 and A1.4 provide equations for the determination of test temperatures for calibration of the heat flux transducers.

A1.2 *Symbols*—The following symbols refer to equations in Annex A1 and Appendix X1:

a_i = regression coefficient
b_i = regression coefficient
ε = random error term, V
q_{app} = application heat flux, W/m^2 (Btu/h·ft^2)
i = index
n = total number of material layers
$R_{i,\,TS}$ = thermal resistance of a layer located in the test stack, m^2·K/W (h·ft^2·F/Btu)
$R_{i,\,AC}$ = thermal resistance of a layer located in the application construction, m^2·K/W (h·ft^2·F/Btu)
T_c = test cold-side temperature, K (°F)
$T_{c,\,app}$ = application boundary cold-side temperature, K (°F)
T_h = test hot-side temperature, K (°F)
$T_{h,\,app}$ = application boundary hot-side temperature, K (°F)
T_{HFT} = heat flux transducer temperature, K (°F)
ΔT = temperature difference, K (°F)

A1.3 *Case 1: Heat Flux and HFT Temperature Are Known:*

A1.3.1 Using nominal values for the thermal resistance of each material in the test stack, calculate the required temperature difference to determine the desired heat flux using Eq A1.1.

$$\Delta T = q_{app} \times \sum_{i}^{n} R_{i,TS} \tag{A1.1}$$

A1.3.2 Calculate the hot- and cold-side temperatures using Eq A1.2 and Eq A1.3, respectively.

$$T_c = T_{HFT} - \left(q_{app} \times \sum_{coldplate}^{HFT} R_{i,TS} \right) \tag{A1.2}$$

$$T_h = T_c + \Delta T \tag{A1.3}$$

A1.4 *Case 2: Application Boundary Temperatures Are Known:*

A1.4.1 Using nominal values for the thermal resistance of each material in the test stack and each material in the full application construction, calculate application heat flux using Eq A1.4. The overall thermal resistance in Eq A1.4 shall include the thermal resistance due to the film coefficient.

$$q_{app} = \frac{(T_{h,app} - T_{c,app})}{\sum_{i}^{n} R_{i,AC}} \tag{A1.4}$$