# Standard Test Method for Measuring Heat Transfer Rate Using a Thin-Skin Calorimeter[1]

This standard is issued under the fixed designation E459; 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 test method covers the design and use of a thin metallic calorimeter for measuring heat transfer rate (also called heat flux). Thermocouples are attached to the unexposed surface of the calorimeter. A one-dimensional heat flow analysis is used for calculating the heat transfer rate from the temperature measurements. Applications include aerodynamic heating, laser and radiation power measurements, and fire safety testing.

1.2 *Advantages:*

1.2.1 *Simplicity of Construction*—The calorimeter may be constructed from a number of materials. The size and shape can often be made to match the actual application. Thermocouples may be attached to the metal by spot, electron beam, or laser welding.

1.2.2 Heat transfer rate distributions may be obtained if metals with low thermal conductivity, such as some stainless steels, are used.

1.2.3 The calorimeters can be fabricated with smooth surfaces, without insulators or plugs and the attendant temperature discontinuities, to provide more realistic flow conditions for aerodynamic heating measurements.

1.2.4 The calorimeters described in this test method are relatively inexpensive. If necessary, they may be operated to burn-out to obtain heat transfer information.

1.3 *Limitations:*

1.3.1 At higher heat flux levels, short test times are necessary to ensure calorimeter survival.

1.3.2 For applications in wind tunnels or arc-jet facilities, the calorimeter must be operated at pressures and temperatures such that the thin-skin does not distort under pressure loads. Distortion of the surface will introduce measurement errors.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4.1 *Exception*—The values given in parentheses are for information only.

1.5 *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. Summary of Test Method

2.1 This test method for measuring the heat transfer rate to a metal calorimeter of finite thickness is based on the assumption of one-dimensional heat flow, known metal properties (density and specific heat), known metal thickness, and measurement of the rate of temperature rise of the back (or unexposed) surface of the calorimeter.

2.2 After an initial transient, the response of the calorimeter is approximated by a lumped parameter analysis:

$$q = \rho C_p \delta \frac{dT}{d\tau} \tag{1}$$

where:

$q$ = heat transfer rate, W/m$^2$,
$\rho$ = metal density, kg/m$^3$,
$\delta$ = metal thickness, m,
$C_p$ = metal specific heat, J/kg·K, and
$dT/d\tau$ = back surface temperature rise rate, K/s.

## 3. Significance and Use

3.1 This test method may be used to measure the heat transfer rate to a metallic or coated metallic surface for a variety of applications, including:

3.1.1 Measurements of aerodynamic heating when the calorimeter is placed into a flow environment, such as a wind tunnel or an arc jet; the calorimeters can be designed to have the same size and shape as the actual test specimens to minimize heat transfer corrections;

3.1.2 Heat transfer measurements in fires and fire safety testing;

3.1.3 Laser power and laser absorption measurements; as well as,

3.1.4 X-ray and particle beam (electrons or ions) dosimetry measurements.

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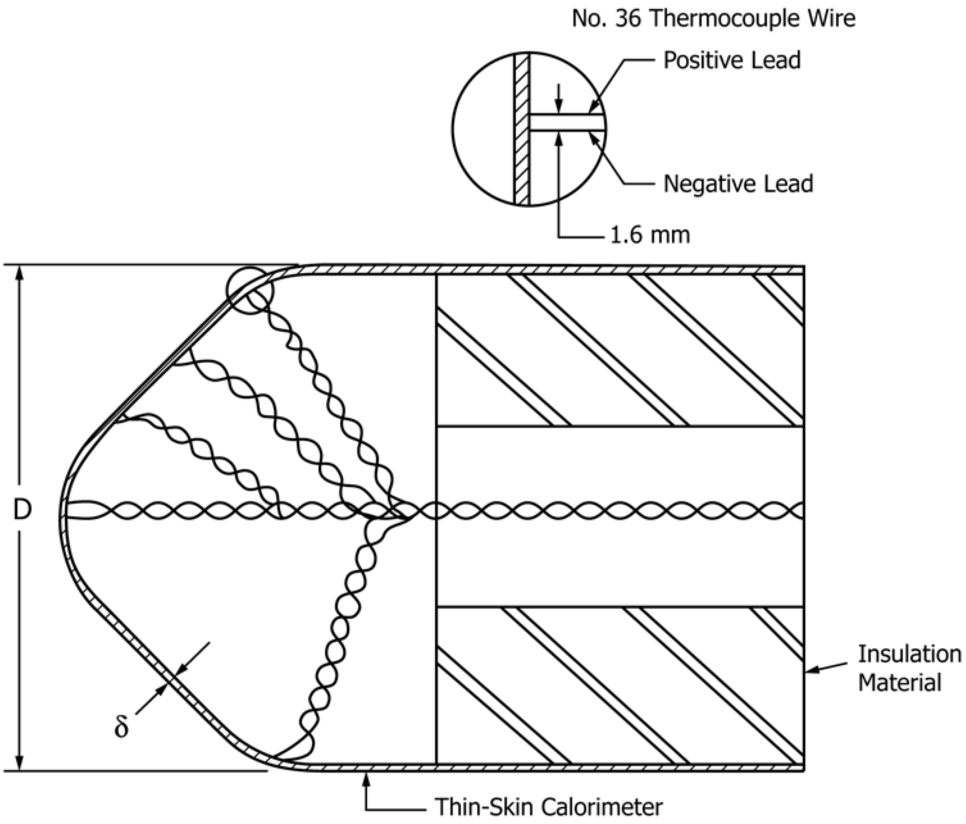

**FIG. 1 Typical Thin-Skin Calorimeter for Heat Transfer Measurement**

3.2 The thin-skin calorimeter is one of many concepts used to measure heat transfer rates. It may be used to measure convective, radiative, or combinations of convective and radiative (usually called mixed or total) heat transfer rates. However, when the calorimeter is used to measure radiative or mixed heat transfer rates, the absorptivity and reflectivity of the surface should be measured over the expected radiation wavelength region of the source.

3.3 In 4.6 and 4.7, it is demonstrated that lateral heat conduction effects on a local measurement can be minimized by using a calorimeter material with a low thermal conductivity. Alternatively, a distribution of the heat transfer rate may be obtained by placing a number of thermocouples along the back surface of the calorimeter.

3.4 In high temperature or high heat transfer rate applications, the principal drawback to the use of thin-skin calorimeters is the short exposure time necessary to ensure survival of the calorimeter such that repeat measurements can be made with the same sensor. When operation to burnout is necessary to obtain the desired heat flux measurements, thin-skin calorimeters are often a good choice because they are relatively inexpensive to fabricate.

## 4. Apparatus

4.1 *Calorimeter Design*—Typical details of a thin-skin calorimeter used for measuring aerodynamic heat transfer rates are shown in Fig. 1. The thermocouple wires (0.127 mm OD, 0.005 in., 36 gage) are individually welded to the back surface of the calorimeter using spot, electron beam, or laser techniques. This type of thermocouple joint (called an intrinsic thermocouple) has been found to provide superior transient response as compared to a peened joint or a beaded thermocouple that is soldered to the surface (**1, 2**).[2] The wires should be positioned approximately 1.6 mm apart along an expected isotherm. The use of a small thermocouple wire minimizes heat conduction into the wire but the calorimeter should still be rugged enough for repeated measurements. However, when the thickness of the calorimeter is on the order of the wire diameter to obtain the necessary response characteristics, the recommendations of Sobolik, et al. [1989], Burnett [1961], and Kidd [1985] (**2-4**) should be followed.

4.2 When heating starts, the response of the back (unheated) surface of the calorimeter lags behind that of the front (heated) surface. For a step change in the heat transfer rate, the initial response time of the calorimeter is the time required for the temperature rise rate of the unheated surface to approach the temperature rise rate of the front surface within 1 %. If conduction heat transfer into the thermocouple wire is ignored, the initial response time is generally defined as:

$$\tau_r = 0.5 \frac{\rho C_p \delta^2}{k} \tag{2}$$

where:

$\tau_r$ = initial response time, s, and

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

$k$ = thermal conductivity, W/m·K.

As an example, the 0.76 mm (0.030 in.) thick, 300 series stainless steel calorimeter analyzed in Ref **(4)** has an initial response time of 72 ms. Eq 2 can be rearranged to show that the initial response time also corresponds to a Fourier Number (a dimensionless time) of 0.5.

4.3 Conduction heat transfer into the thermocouple wire delays the time predicted by Eq 2 for which the measured back face temperature rise rate accurately follows (that is, within 1 %) the undisturbed back face temperature rise rate. For a 0.127 mm (0.005 in.) OD, Type K intrinsic thermocouple on a 0.76 mm (0.030 in.) thick, 300 series stainless steel calorimeter, the analysis in Ref **(4)** indicates the measured temperature rise rate is within 2 % of the undisturbed temperature rise rate in approximately 500 ms. An estimate of the measured temperature rise rate error (or slope error) can be obtained from Ref **(1)** for different material combinations:

$$\frac{dT_C}{dt} - \frac{dT_{TC}}{dt} = C_1 \exp\left( C_2^2 \frac{\alpha t}{R^2} \right) erfc\left( C_2 \sqrt{\frac{\alpha t}{R^2}} \right) \tag{3}$$

where:

$T_C$ = calorimeter temperature,
$T_{TC}$ = measured temperature (that is, thermocouple output),
$C_1$ = $\beta/(8/\pi^2 + \beta)$ and $C_2 = 4/(8/\pi + \beta\pi)$,
$\alpha$ = $k/\rho C_p$ (thermal diffusivity of the calorimeter material),
$\beta$ = $K/\sqrt{A}$ ,
$K$ = $k$ of thermocouple wire/k of calorimeter,
$A$ = $\alpha$ of thermocouple wire/$\alpha$ of calorimeter,
$R$ = radius of the thermocouple wire, and
$t$ = time.

Using thermal property values given in Ref **(4)** for the Alumel (negative) leg of the Type K thermocouple on 300 Series stainless steel ($K = 1.73$, $A = 1.56$, $\beta = 1.39$), Eq 3 can be used to show that the measured rate of temperature change (that is, the slope) is within 5 % of the actual rate of temperature change in approximately 150 ms. For this case, the time for a 1 % error in the measured temperature rise rate is roughly 50 times as long as the initial response time predicted by Eq 2; this ratio depends on the thermophysical properties of the calorimeter and thermocouple materials (see Table 1).

4.3.1 When the heat transfer rate varies with time, the thin-skin calorimeter should be designed so the response times defined using Eq 2 and 3 are smaller than the time for significant variations in the heat transfer rate. If this is not possible, methods for unfolding the dynamic measurement errors **(1,5)** should be used to compensate the temperature measurements before calculating the heat flux using Eq 1.

**TABLE 1 Time Required for Different Error Levels in the Unexposed Surface Temperature Rise Rate**

| Error Level Due to Heat Conduction into Thermocouple | 10 % | 5 % | 2 % | 1 % |
|---|---|---|---|---|
| Negative Leg (Alumel) of Type K on 304 Stainless | 35 ms | 150 ms | 945 ms | 3.8 s |
| Negative Leg (Constantan) of Type T on Copper | <1 ms | <1 ms | 1 ms | 4 ms |

4.4 Determine the maximum exposure time **(6)** by setting a maximum allowable temperature for the front surface as follows:

$$\tau_{\max} = \frac{\rho C_p \delta^2}{k} * \left[ \frac{k(T_{\max} - T_0)}{q\delta} - \frac{1}{3} \right] \tag{4}$$

where:

$\tau_{\max}$ = maximum exposure time, s,
$T_0$ = initial temperature, K, and
$T_{\max}$ = maximum allowable temperature, K.

4.4.1 In order to have time available for the heat transfer rate measurement, $\tau_{\max}$ must be greater than$\tau_R$, which requires that:

$$\frac{k(T_{\max} - T_0)}{q\delta} > \frac{5}{6} \tag{5}$$

4.4.2 Determine an optimum thickness that maximizes $(\tau_{\max} - \tau_R)$ **(7)** as follows:

$$\delta_{opt} = \frac{3}{5} \frac{k(T_{\max} - T_0)}{q} \tag{6}$$

4.4.3 Then calculate the maximum exposure time using the optimum thickness as follows:

$$\tau_{\max opt} = 0.48 \rho C_p k \left[ \frac{T_{\max} - T_0}{q} \right]^2 \tag{7}$$

4.4.4 When it is desirable for a calorimeter to cover a range of heat transfer rates without being operated to burn-out, design the calorimeter around the largest heat-transfer rate. This gives the thinnest calorimeter with the shortest initial response time (Eq 2); however, Refs **(2, 3, 8, 9)** all show the time to a given error level between the measured and undisturbed temperature rise rates (left hand side of Eq 3) increases as the thickness of the calorimeter decreases relative to the thermocouple wire diameter.

4.5 In most applications, the value of $T_{\max}$ should be well below the melting temperature to obtain a satisfactory design. Limiting the maximum temperature to 700 K will keep radiation losses below 15 kW/m$^2$. For a maximum temperature rise ($T_{\max} - T_0$) of 400 K, Fig. 2 shows the optimum thickness of copper and stainless steel calorimeters as a function of the heat-transfer rate. The maximum exposure time of an optimum thickness calorimeter for a 400 K temperature rise is shown as a function of the heat-transfer rate in Fig. 3.

4.6 The one-dimensional heat flow assumption used in 2.2 and 4.3–4.4 is valid for a uniform heat-transfer rate; however, in practice the calorimeter will generally have a heat-transfer rate distribution over the surface. Refs **(9, 10)** both consider the effects of lateral heat conduction in a hemispherical calorimeter on heat transfer measurements in a supersonic stream. For a cosine shaped heat flux distribution at the stagnation-point of the hemisphere, Starner gives the lateral conduction error relative to the surface heating as

$$E_{C_L} = \frac{2\alpha t}{R^2} = \frac{8kt}{\rho C_p D^2} \tag{8}$$

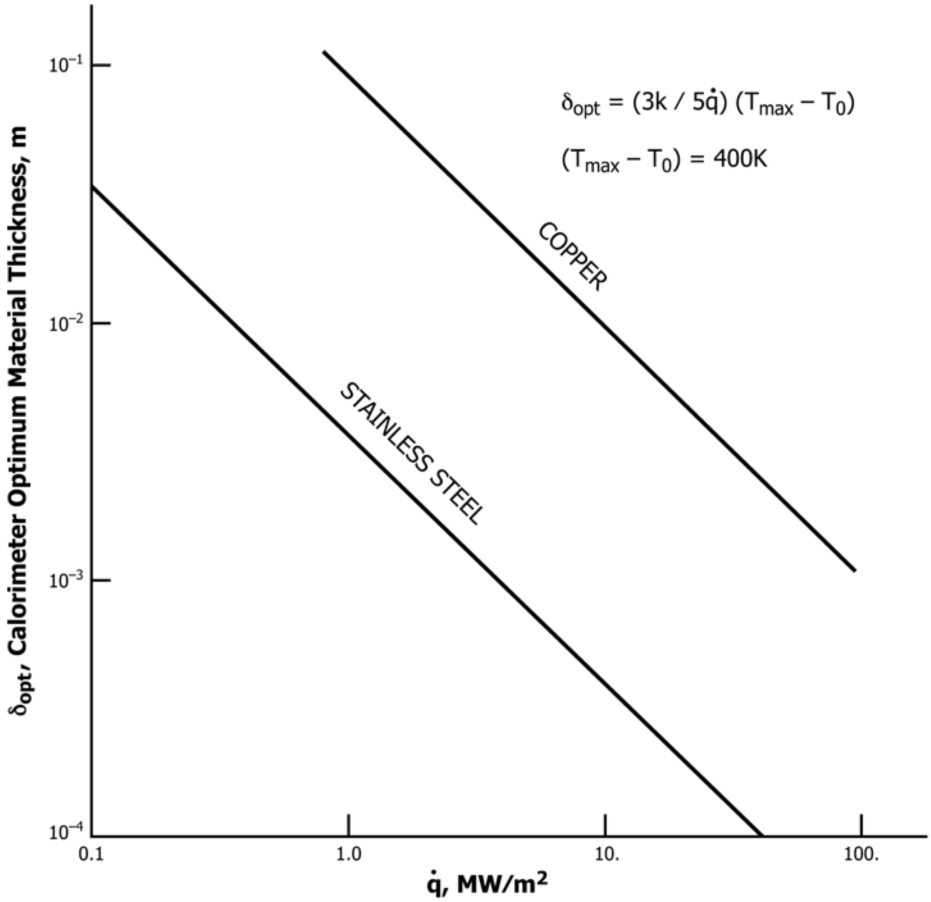

FIG. 2 Calorimeter Optimum Material Thickness as a Function of Heat Transfer Rate and Material

where:

$E$ = relative heat-transfer rate ratio,
$R$ = radius of curvature of the body (D/2), and
$t$ = exposure time.

Note the lateral conduction error described in Eq 8 is not a function of the calorimeter skin thickness or the heat-transfer rate; the magnitude of the error is shown in Fig. 4 for copper and stainless steel. The errors for most other base metal calorimeters will fall in between these two lines. While the lateral conduction errors can be minimized by using materials with low thermal diffusivity and short exposure times, these may aggravate some of the other constraints, as described in Eq 2 and 3. Ref (**9**) also describes the lateral conduction errors for cones and cylinders.

4.7 An approximation of the lateral conduction error can be obtained experimentally by continuing to record the unexposed surface temperature after the heating is removed and calculating the ratio of the rates of temperature change.

$$E \sim \left. \frac{\left.\frac{dT}{dt}\right|_{cool\ down}}{\frac{dT}{dt}} \right|_{test} \tag{9}$$

4.8 When the average heat transfer rate over the exposed area is desired, Wedekind and Beck [1989] (**11**) give another approach for evaluation of the measured rate of temperature change. The analysis was developed for laser experiments where only part of the calorimeter surface was exposed to heating and the exposure time was long compared to the thermal penetration time to the edges of the unexposed area (penetration time calculation is similar to Eq 2 with L, the distance to the edge, substituted for δ, the thickness).

4.9 A device for recording the thermocouple signals with time is required. The response time of an analog recording system should be an order of magnitude smaller than the calorimeter response time (see Eq 2). The sampling time of a digital recording system should be no more than 40 % of the calorimeter response time; the 3 db frequency of any low-pass filters in the data acquisition system should be greater than

$$f_{3db} > \frac{1}{2\pi\tau} = \frac{h}{2\pi\rho C_p\delta} \tag{10}$$

where:

$h$ = estimated heat transfer coefficient for the experiment.

## 5. Procedure

5.1 Expose the thin-skin calorimeter to the thermal environment as rapidly as practical. Operate the recording system for several seconds before the exposure to provide data for evaluating any noise in the calorimeter and data acquisition

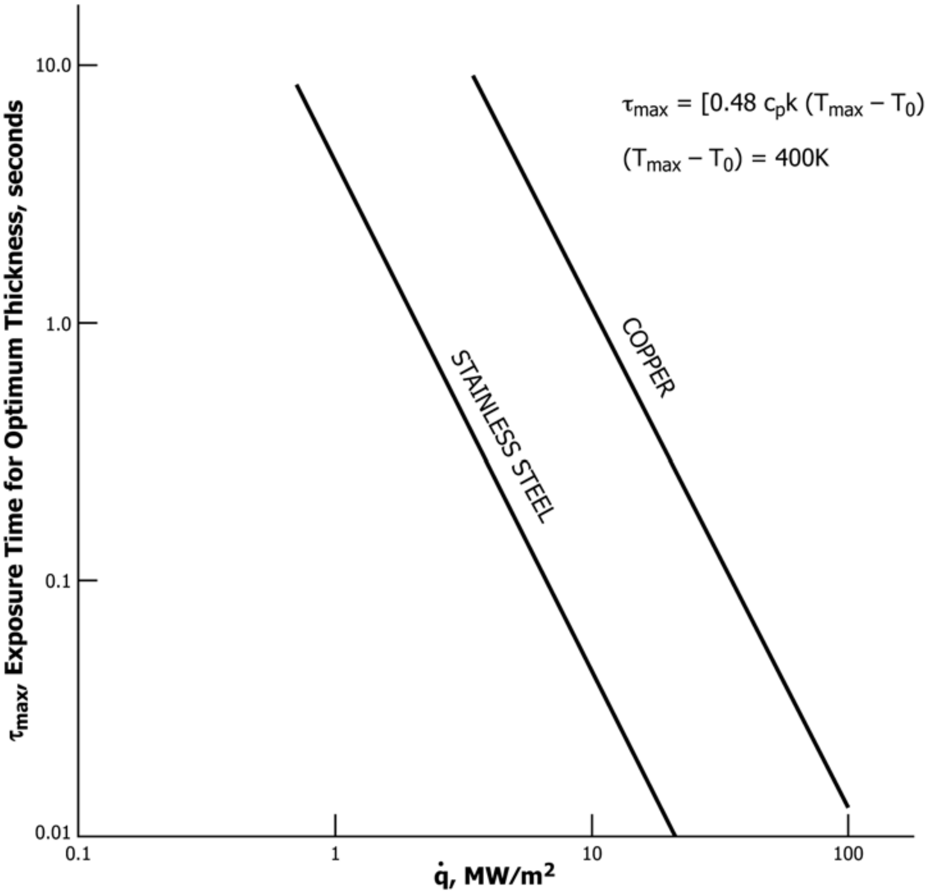

**FIG. 3 Maximum Exposure Time for an Optimum Thickness Calorimeter as a Function of Heat-Transfer Rate and Material**

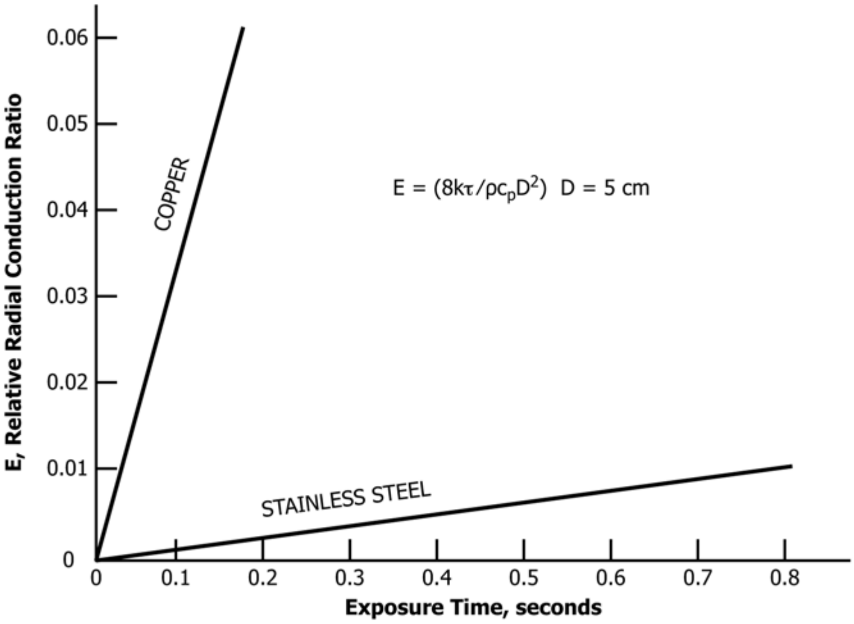

**FIG. 4 Radial Conduction as a Function of Time and Material**

system. Operate it for enough time after the exposure to obtain an estimate of the lateral heat conduction effects as indicated in 4.7.

5.2 Cool the calorimeter to the initial temperature before repeating the measurements.

5.3 Take enough measurements with the same calorimeter at a particular test condition to obtain an estimate of the reproducibility of the technique. The density and thickness of the calorimeter material may be determined with good accuracy. If the calorimeter is used over temperature ranges where the specific heat of the calorimeter material is well established; the measurement of the heat-transfer rate on the exposed surface may be made with the same accuracy as the measurement of the rate of temperature rise of the unexposed surface.

5.4 Uncertainties in relating these measurements to the thermal environment can occur for a number of reasons. In high temperature gas flows such as flames or arc-heated jets, ionization and catalytic effects can introduce uncertainties. For radiation heat transfer, uncertainties in the surface properties can introduce uncertainties.

## 6. Calculation

6.1 Calculate the heat-transfer rate using Eq 1 with the necessary physical measurements and evaluate the density and specific heat at the mean temperature for which the slope of the temperature-time curve is taken.

## 7. Report

7.1 Report the following information:

7.1.1 Calorimeter material, size, and shape,

7.1.2 Calorimeter thickness,

7.1.3 Calorimeter density,

7.1.4 Calorimeter nominal specific heat,

7.1.5 Calorimeter temperature history,

7.1.6 Calculated heat-transfer rate,

7.1.7 Relative conduction ratio,

7.1.8 Reproducibility, and

7.1.9 Surface condition.

## 8. Thermocouple Temperature Uncertainty

8.1 There are a number of methods that can be used for the determination of measurement uncertainty. A recent summary of the various uncertainty analysis methods is provided in Ref **(12)**. The American Society of Mechanical Engineers' (ASME's) earlier performance test code PTC 19.1-1985 **(13)** has been revised and was replaced by Ref **(14)** in 1998. In Refs **(13)** and **(14)**, uncertainties were separated into two types: "bias" or "systematic" uncertainties (B) and "random" or "precision" uncertainties (S). Systematic uncertainties (Type B) are often (but not always) constant for the duration of the experiment. Random uncertainties are not constant and are characterized via the standard deviation of the random measurements, thus the abbreviation 'S.'

8.2 ASME's new standard **(14)** proposes use of the following model:

$$U_{95} = \pm t_{95}\left[(B_T/2)^2 + (S_T)^2\right]^{\frac{1}{2}} \tag{11}$$

where $t_{95}$ is determined from the number of degrees of freedom (DOF) in the data provided. For large DOF (that is, 30 or larger) $t_{95}$ is almost 2. $B_T$ is the total bias or systematic uncertainty of the result, $S_T$ is the total random uncertainty or precision of the result, and $t_{95}$ is "Student's t" at 95 % for the appropriate degrees of freedom (DOF).

8.3 In the case of a temperature measurement with a thermocouple, types of systematic uncertainties are mounting errors, non-linearity, and gain. Less commonly discussed systematic uncertainties are those that result from the sensor design (that is, TC junction type) and coupling with the environment. Types of random uncertainty are common mode and normal mode noise.

8.4 To quantify the total uncertainty of a measurement, the entire measurement system must be examined. For a thermocouple measurement the following uncertainty sources must be considered:

8.4.1 Thermocouple wire accuracy.

8.4.2 Thermocouple connectors.

8.4.3 Thermocouple extension cable.

8.4.4 Thermocouple mounting error (transient and steady).

8.4.5 Data acquisition system (DAS).

8.4.6 Conversion equation (mV to temperature).

8.4.7 Positioning errors.

8.4.8 Angular errors.

8.5 Additional uncertainty can be attributed to the engineering application of the thermocouple transducer to the environment, or material, of interest. Specific examples include:

8.5.1 Contact between a thermocouple and its environment, or thermal contact conductance between the bead and material. The contact conductance must be characterized to analyze the bead transient response versus the environment.

8.5.2 Radiation versus convective heat transfer of the environment versus heat transferred to the bead. The bead emissivity must be known or estimated for incident radiative environment calculations.

8.5.3 Time response of the thermocouple bead (or probe) versus the estimated transient thermal environment to be measured to ensure the TC is not too slow to measure gradients of interest.

8.5.4 Position location uncertainty of the TC junction must be known to perform material response analysis. The uncertainty of temperature measurement location will propagate error into material response calculations.

8.5.5 When using mineral-insulated, metal-sheathed thermocouples, the TC wires are surrounded with the metal sheath to keep the TC wires from shorting, melting, and so forth. But in doing so, the TC measuring junction is insulated from the environment being measured, and the measurement will have some thermal lag. The TC thermal lag is increasingly worse as the transient environment becomes faster.

8.6 It is important to realize that any transducer has finite mass and heat transfer characteristics. Therefore, the thermocouple (for example) will read a temperature different from the surface you are measuring. In a well-designed experimental system the difference between the "true" temperature and the TC reading can be reduced to acceptable values. Errors are not zero or negligible, but acceptable from an uncertainty budget perspective. The main point is uncertainty exists, and, it must be quantified to produce meaningful data.

## 9. Keywords

9.1 calorimeter; convective; heat flux; heat transfer distribution; heat transfer rate; radiative; thin-skin

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