



## Standard Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Gage<sup>1</sup>

This standard is issued under the fixed designation E 511; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

<sup>ε1</sup> NOTE—Section 10 was added editorially in December 1994.

### 1. Scope

1.1 This test method describes the measurement of heat flux absorbed by a thin circular foil of copper-constantan construction by either convection or radiation or a combination of both.

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

1.3 *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 The circular foil heat-flux gage provides a self-generated millivolt output in response to the thermal energy absorbed. The sensing foil (see Fig. 1) is connected at its perimeter to a heat sink having a thermoelectric potential different from that of the foil material, thus forming a thermocouple junction. Another thermocouple junction is made at the center of the foil using a fine wire. When the sensor is exposed to a heat source, the heat flux absorbed by the circular foil is transferred radially to the heat sink, and an equilibrium temperature difference is rapidly established between the center and edge of the foil. The equilibrium thermoelectric potential,  $E$ , between the center and edge of the foil will then vary in proportion to the heat flux,  $q$ , absorbed by the foil. The body is normally made of copper and the foil of thermocouple-type constantan. If these metals are used in the gage, the thermoelectric potential will be directly proportional to heat flux absorbed such that

$$q = KE \quad (1)$$

where  $K$  is a constant determined experimentally during calibration. All further discussion will assume the use of these two metals in the gage since this construction is by far the most common.

### 3. Significance and Use

3.1 The purpose of this test method is to measure the heat flux at a location from a radiant or convective source, or both. In the case of radiant energy, the absorptivity of the surface of the instrument should be known. In the case of convection energy, particularly at high velocities, the shape and size of the probe body in which the foil sensor is mounted should be the same as the test specimen.

3.2 The gage has certain limitations as follows:

3.2.1 The gage cannot measure conduction.

3.2.2 The body temperature must be in the range from 50 to 450°F (−45 to 235°C) in order for the calibration to be valid. At lower or higher temperatures, the gage is no longer linear due to changes in thermoelectric output not compensated for by changes in physical properties of the constantan foil.

3.2.3 Foil diameters and thickness are limited. Maximum optimum foil diameter to thickness ratio is 4 to 1 for sensors less than 2.54-mm (0.100-in.) diameter. Foil diameters range from 25.4 to 0.254 mm (1.0 to 0.010 in.) with most gages between 6.35 and 1.02 mm (0.250 and 0.040 in.).

3.2.4 Large-diameter foils in vacuum environment have significantly different sensitivities than in air and should not be so used unless calibrated in vacuum.

3.2.5 Response time is a function of the radius or diameter of the foil squared. Range is from 0.001 s (0.25 mm (0.010 in.) in diameter) to 6 s (25.4 mm (1 in.) in diameter). Response time is defined as the time to sense 63 % of a step function.

3.2.6 The response time,  $\tau$ , is approximated by the formula  $\tau = 6D^2$ , where  $D$  is in inches (**1**)<sup>2</sup> or  $\tau = 0.0094 D^2$  where  $D$  is in millimetres. The sensitivity of the gage may be expressed by the equation  $E/q = 0.03 D^2/S$  where  $D$  is the diameter of the foil in inches,  $S$  is the thickness of the foil in inches,  $E$  is the emf in millivolts and  $q$  is the heat flux in Btu/ft<sup>2</sup>·s. In SI, the equation is  $E/q = 0.0046 D^2/S$ , where  $D$  and  $S$  are in millimetres, and  $q$  is in cal/cm<sup>2</sup>·s or  $E/q = 19.3 D^2/S$  where  $D$  and  $S$  are in metres and  $q$  is in W/m<sup>2</sup>.

3.2.7 The field of uniform flux must exceed the area of the sensor.

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee E-21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.08 on Thermal Protection.

Current edition approved Nov. 27, 1973. Published January 1974.

<sup>2</sup> The boldface numbers in parentheses refer to the list of references at the end of this test method.

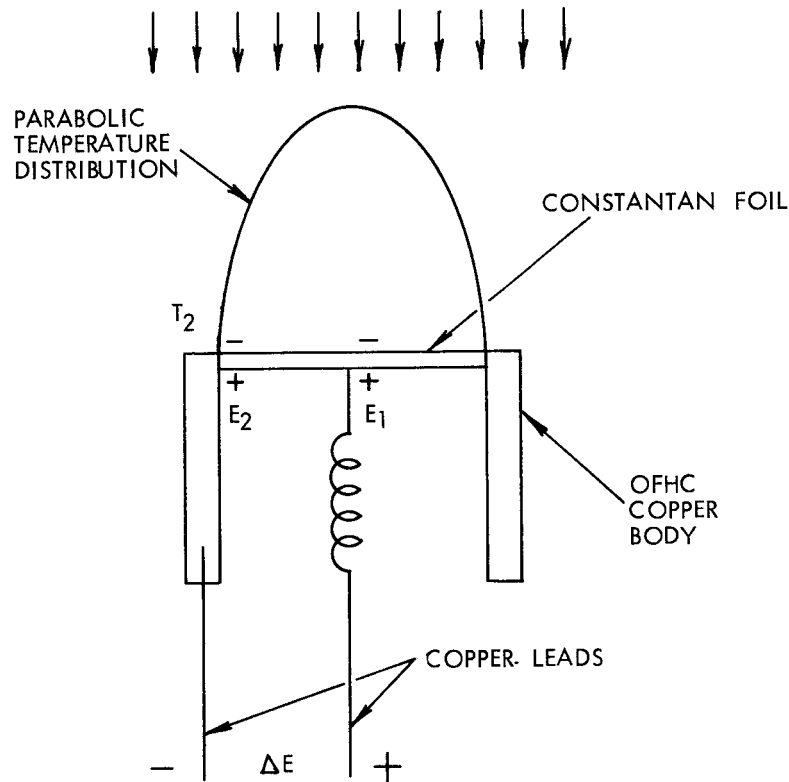


FIG. 1 Heat Drain—Either by Water Cooling the Body with a Surrounding Water Jacket or Conducting the Heat Away with Sufficient Thermal Mass

3.3 The temperature of the gage is normally low in comparison to the heat source. The resulting heat flux measured by the gage is known as a “cold-wall” heat flux.

#### 4. Apparatus

4.1 *Gage*—The gage shall consist of a circular foil sensor, as shown in Fig. 1, connected to a heat sink. The output leads from the calorimeter shall be connected to instrumentation capable of readout in millivolts. This instrumentation shall be potentiometric or have an impedance of 100 000  $\Omega$  or greater. (Sensor impedance is usually less than 1  $\Omega$ ).

4.2 *Sensor*—The sensor, constructed using a copper body, copper leads, and a constantan (thermocouple-type) foil, produces an emf output in millivolts which is a *linear function* of heat flux. Other metal combinations are used but most are nonlinear (2).

4.2.1 The wire leads used to convey the signal from the sensor to the readout device are usually made of stranded, tinned copper. The wires are usually TFE-fluorocarbon-coated and shielded with a braid overwrap which is also TFE-fluorocarbon-covered. The leads are color coded to distinguish the positive lead from the negative lead. It is common practice to use the color black on the negative lead.

4.3 *Circular Foil*—Figs. 2 and 3 may be used as a guide for the dimensions of the circular foil. As can be seen from Figs. 2 and 3, a variety of different thicknesses and diameters will result in the same sensitivity. Most units are designed for a maximum output of 10 mV. At this output, the center of the gage is about 400°F (205°C) higher than the edge temperature.

4.3.1 Certain conditions of very low heat-transfer rate exist under which convection will not be correctly measured using a circular foil heat-flux gage. This complex subject is discussed in the literature (3).

4.4 *Water-Cooled Sensors*—Water-cooled sensors should be used in any application in which the sensor body would otherwise rise above 450°F (235°C). Typical cooled assemblies are shown in Fig. 4.

4.4.1 *Amount of Coolant Flow*—Whatever coolant flow will prevent local boiling of the coolant at the face of the gage is adequate. This phenomenon can be detected by observing the outlet flow. If the outlet flow develops a pulsating output, boiling is occurring. The exact pressure required for a given design to achieve the desired flow varies according to the resistance to flow, which is dependent upon the design of the water-flow path. Rarely is a gage designed to require more than a few gallons of water per minute and most require only a fraction of a gallon per minute. Exposure time will have no effect upon gage performance as long as adequate cooling is provided.

4.5 *Mount Materials of Construction*—Mount bodies are normally made of oxygen-free high-conductivity (OFHC) copper. The sides of the body may be made of brass, but copper is frequently used throughout except for water inlet stems, which for support purposes, are usually brass or stainless steel.

4.5.1 *Special Case: Heat fluxes in excess of 34 050 kW/m<sup>2</sup> (3000 Btu/ft<sup>2</sup>·s)*—Such high fluxes require thin external shells for quick transfer of heat into high velocity (15 to 30 m/s

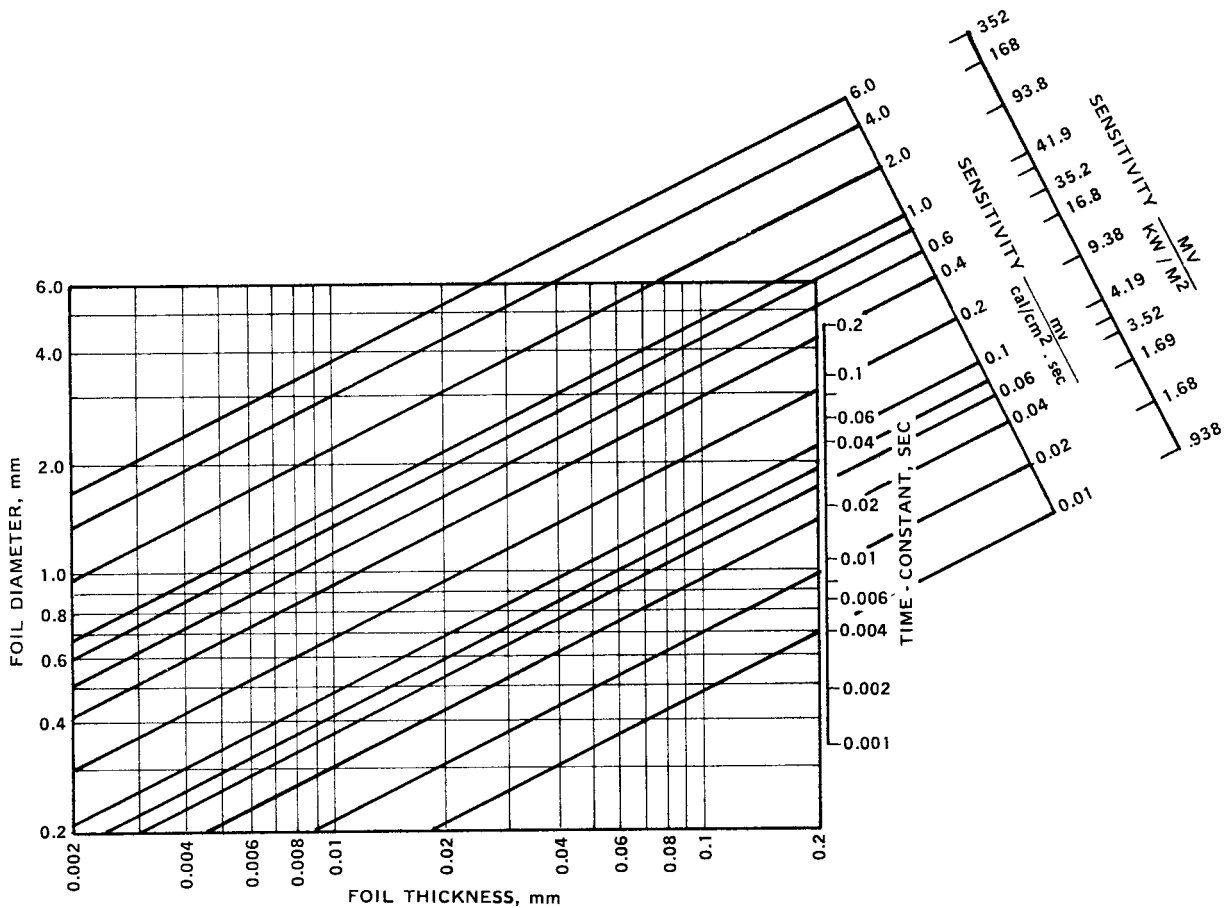


FIG. 2 Chart for Design of Copper-Constantan Circular Foil Heat-Flow Meters (SI Units)

(50 to 100 ft/s)) water channels. The high velocity is produced by high-pressure water 3.4 to 6.9 MPa (500 to 1000 psi). For such high pressure shells, zirconium-copper is used since its yield strength is much larger than OFHC copper.

4.6 *Sensor Surface*—Gage performance is highly sensitive to surface condition. Gages are coated with thin layers of metallic and nonmetallic materials for special applications. Coatings are used to affect the radiant or convective heat absorbing qualities of the gage, or both. Basic surface conditions are:

- (a) No coating;
- (b) High emissivity coatings, high absorption;
- (c) Low emissivity coatings, reflection; and
- (d) Coatings that catalyze recombination reactions in non-equilibrium flow.

4.6.1 A gage with no coating is recommended for use in most convective applications.

4.6.2 *High Absorption*—High-emissivity coatings are used when radiant energy is to be measured. Ideally the coating should provide a nearly diffuse absorbing surface. A diffuse coating is defined as one that has no change in absorption with change in angle of incidence of radiation on the coating. An ideal coating would also have no change in absorption with change in wavelength, which by definition is a graybody. Some coatings approach these ideal conditions, but most coatings have marked deviations from these ideal conditions of being diffuse, graybody absorbers. Typical carbon soots are acetylene

soot (total normal emittance,  $\epsilon_{TN} = 0.99$ ) (4), and camphor soot ( $\epsilon_{TN} = 0.98$ ) (4). The soots all have the disadvantage of low oxidation resistance and poor adhesion to the gage surface. Colloidal graphite coatings ( $\epsilon_{TN} = 0.83$ ) (5) are commonly used since they are readily dried from acetone or alcohol solutions and tenaciously adhere to the gage surface. However, the coatings can be quickly removed from solvents. Spray black lacquer paints ( $\epsilon_{TN} =$  up to 0.98), some of which may require baking, are also used and are intermediate between the colloidal graphites and soots in oxidation resistance and adherence.

4.6.2.1 The emissivity or absorbance of the coating should be determined to the required accuracy if a coating of unknown emittance is used. If the emittance of the coating is altered during the test, it should be redetermined at the end of the test.

4.6.3 *Reflection*—Low emissivity metallic coatings such as highly polished gold and nickel are also used in special cases where the reflection of radiant heat is desired. The coatings are usually only a fraction of a mil thick. Such coatings decrease the sensitivity of the gage. The gold coating also causes the gage output to be nonlinear whereas the nickel coating does not. This is due to large changes in the thermal conductivity of gold with temperature.

4.6.4 *Catalytic Effects*—Coatings of any kind will affect the convective heat input to the gage from nonequilibrium regime sources (usually high enthalpy, low pressure). Under these circumstances the boundary layer contains highly ionized

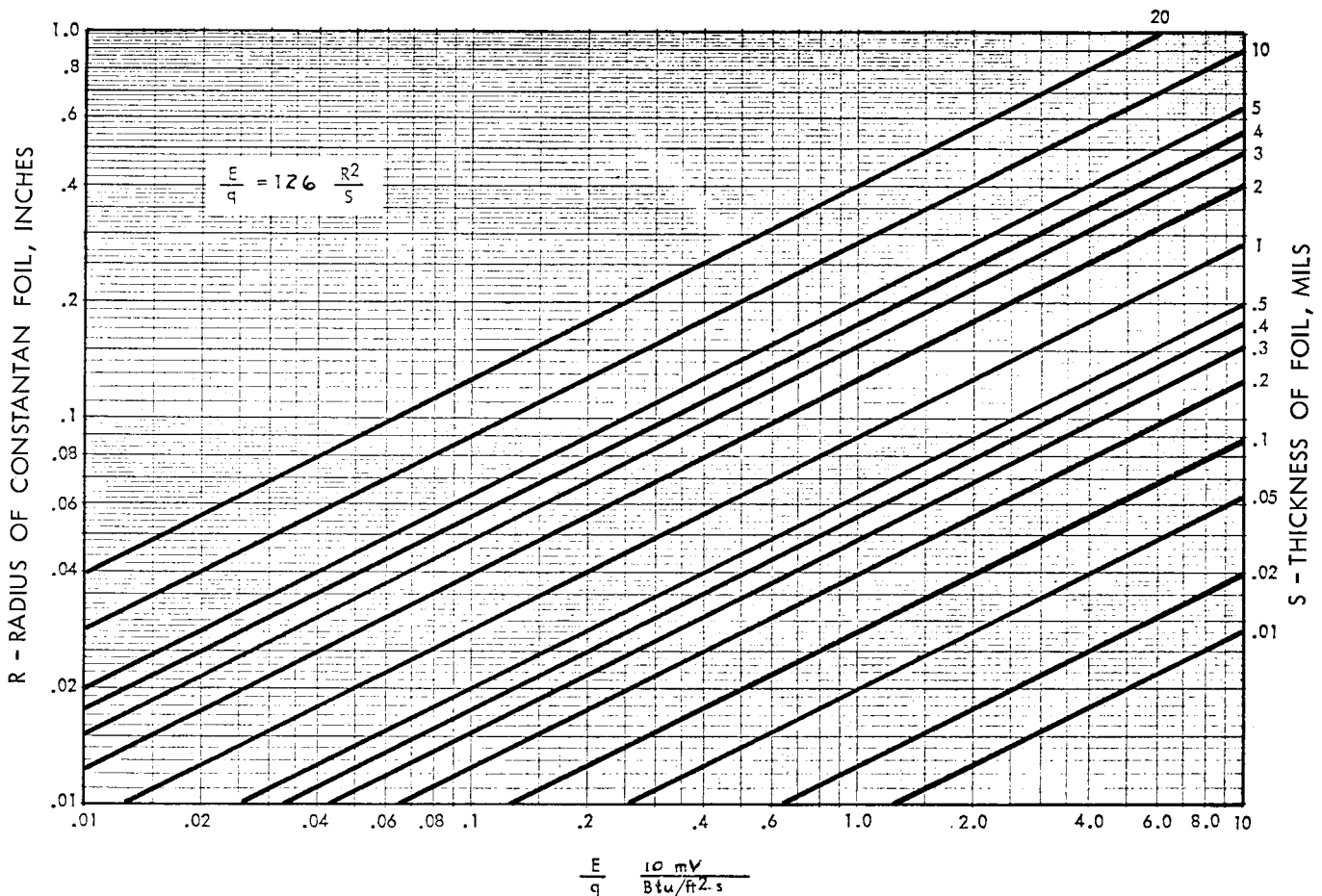


FIG. 3 Chart for Design of Copper-Constantan Circular Foil Heat-Flow Meters (U.S. Customary Units)

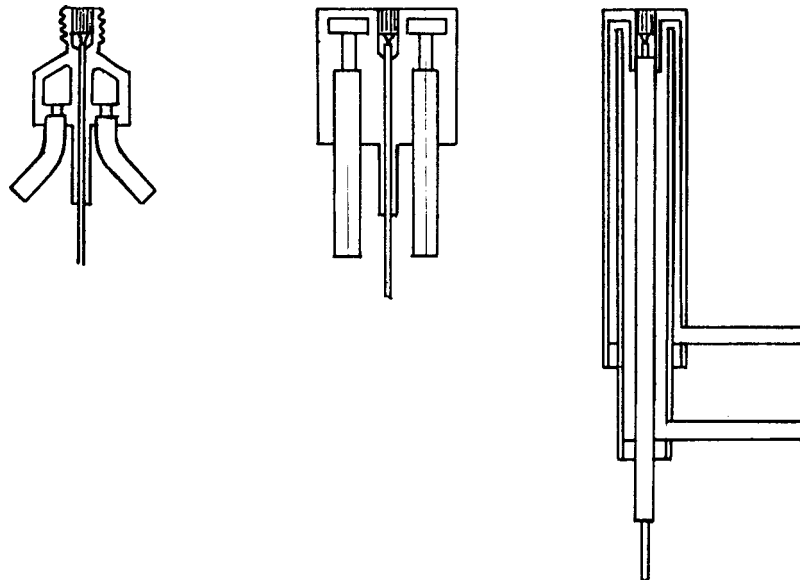


FIG. 4 Cross-Sectional View of Water-Cooled Heat-Flux Gages

atomic particles or molecular species, or both, which may recombine at the surface of the gage. These reactions are exothermic causing additional heating of the gage. The degree to which surface recombination occurs is highly dependent upon catalytic effects of the surface of the gage. This catalytic

effect can be varied by surface coatings (6). The ideal condition would be to have the same catalytic effect on the gage surface as on the surface of the material to be tested. Since this is largely unknown, usually no attempt is made to match surface catalytic effects. The recommended practice is to use an

uncoated gage carefully cleaned with chemical copper cleaners such as commonly found in household stores. All cleaner should be removed with water. Care should be taken not to allow any body contact with this surface after cleaning by the installer. If coatings are used, this information should be noted in test records with explanation of the reasons for the use of the coating.

4.7 For range of heat flux measurement from 0.1135 to  $5.67 \times 10^4$  kW/m<sup>2</sup>(0.01 to 5000 Btu/ft<sup>2</sup>·s):

4.7.1 In the  $2.27 \times 10^4$  to  $5.67 \times 10^4$  kW/m<sup>2</sup>(2000 to 5000 Btu/ft<sup>2</sup>·s) range specially designed water cooling designs using high-pressure (up to 6.9 MPa (1000 psi)) water are required in order to prevent melting of the calorimeter face. Water passages are designed to be thin enough that water velocities are in the 12 to 30-m/s (40 to 100-ft/s) region. Sensors are small in diameter ranging from 1.27 to 0.51 mm (0.050 to 0.020 in.).

4.7.2 In the 1135 to  $2.27 \times 10^4$  kW/m<sup>2</sup>(100 to 2000-Btu/ft<sup>2</sup>·s) range, water cooling is not as critical and 0.17 to 1.7 MPa (25 to 250 psi) water with larger water passages permit adequate cooling.

4.7.3 In the 113.5 to 1135 kW/m<sup>2</sup>(10 to 100 Btu/ft<sup>2</sup>·s) range, units can be operated without water cooling if adequate thermally protected mass is attached to the calorimeter as to permit good heat sinking. For long-term application, water cooling may be necessary.

4.7.4 When the source temperature approaches the sensor temperature, it is desirable to use a high-gain (100 to 500) voltage amplifier with relatively insensitive foils designed to produce only a few microvolts of signal. Thus, the temperature difference between the center and edge of the foil is at the most a few degrees apart and the gage does not reradiate heat flux which may be a significant percentage of the absorbed flux. The gage also may be at or near the temperature of the body in which it is installed. This is particularly true if the body has a relatively high thermal conductivity such as many metallic bodies. Under these circumstances, “hot” wall heat rates can be measured assuming  $T_w < 235^\circ\text{C}$  (450°F). A “hot” wall heat rate is defined as the heat rate associated with the actual test material. In order for a gage to measure this heat rate, it must assume the thermal properties of the test material so that it will be at the same temperature at any time as the test material. The circular foil heat flux gage has been used under these specialized conditions (7).

## 5. Calibration

5.1 Secondary standard gages are calibrated against a known heat flux source such as a blackbody radiator (5). The heat flux is varied and the emf output from the gage versus the calculated absorbed heat flux is plotted in graphical form.

5.2 Production gages are normally calibrated by comparison to a secondary standard gage using a uniform radiant target with a common view factor to both gages. Normally the carbonaceous high-emissivity coating used on the secondary standard is also used on the gage being calibrated, and is less than a total absorber. Under these circumstances, the gage is calibrated for absorbed heat flux. Subsequent removal or changing of the coating does not change the calibration of the gage. The amount of incident radiation actually transferred into the gage will vary with the surface reflectance but the calibra-

tion of a gage calibrated for absorbed heat flux is independent of the gage surface coating. Therefore, the coating can be removed without affecting the calibration.

5.3 If a gage is calibrated for incident radiant energy, as are most circular foil gages used as radiometers, then the coating directly affects the calibration and the gage should only be used with the coating that is on the gage during calibration.

5.4 Gages should be calibrated at periodic intervals depending upon usage and severity of application.

## 6. Procedure

6.1 Select the gage depending on the heat-flux limits expected. Mount the gage in whatever mechanical holder is deemed appropriate for the particular test. Provide a means of properly cooling the mount, if the mechanical mount will also be exposed to the flux. Consideration of a lead-out path for the wires of the gage may also require that this area be thermally insulated or cooled to prevent damage to the leads. Connect the wiring to the potentiometric- or high-impedance readout device. If water cooling is required, turn on the flow and check the pressure of the water system to ensure stable operation at the required pressure. Start the test and record the output of the gage. Check the outlet water, if any, early in the test to see if “chugging” (which is a sign of local boiling in the gage) is occurring. If this condition occurs, discontinue the test immediately. At the end of the test, allow the cooling water, if any, to remain flowing until all parts surrounding the gage are cool.

## 7. Calculation

7.1 The circular foil gage is a linear instrument and, therefore, has a constant sensitivity expressed in units of heat flux per millivolt output. Multiply this sensitivity factor by the output in millivolts to determine the heat flux.

## 8. Report

8.1 Test results should include a record of the millivolt output versus the time trace, if a recorder is used. Data that can be calculated from this trace are maximum heat flux, average heat flux, variations in heat flux as a function of time, and total run time. The sensitivity of the gage should be recorded on the record along with the values for the calibration steps of the recorder, if any, in inches per millivolt. If a hand-operated device is used to record the output of the gage, a list of millivolt readings along with the times at which the readings occurred should be tabulated. The size of the sensing area should be recorded. In the case of high velocity flow, the contour of the gage body around the sensor should also be recorded. If radiant energy is measured, then the total normal emittance of the coating should be recorded.

## 9. Precision and Bias

9.1 *Precision:* Designs such as screws and elongated stems are to be avoided as these designs cannot usually be properly heat sunk. If such designs are used, a thermocouple should be attached to the body to indicate when the body temperature exceeds the 450°F (235°C) limit.

9.1.1 Properly made gages with all welded construction are capable of ½ % repeatability. Therefore, repeat runs showing greater percentage deviation than this figure are the result of

variation in the test condition or inadequate construction. Improperly heat-sinked gages will cause substantial output degradation.

9.2 *Bias*: Typical stated bias of commercial units is  $\pm 3\%$  of full scale.

## 10. Keywords

10.1 calorimeter; cold-wall heat flux; constantan foil; convection; heat flux; heat flux gage; radiation

## REFERENCES

- (1) Gardon, R., "An Instrument for the Direct Measurement of Intense Thermal Radiation," *The Review of Scientific Instruments*, Vol 24, No. 5, May 1953.
- (2) Malone, E. W., et al, "Heat Flux Measurement," The Boeing Company, Report D2-35057, December 1962.
- (3) Ulrich, R. D., and Coffin, G. R., "An Analysis and Discussion of Heat Flux Meters," Brigham Young University, Utah, 1960.
- (4) Hsu, S. T., *Engineering Heat Transfer*, D. Van Nostrand, Inc., 1963.
- (5) Brookley, C. E., *A Method for the Rapid Calibration of Circular Foil Calorimeters to 500 Btu/ft<sup>2</sup>*, Thermogage Inc., March 1969.
- (6) Baughn, J. W., and Arnold, J. E., "Surface Catalycity Effects on Heat Flux Measurements," *Atomics International*, presented at the 20th Annual ISA Conference and Exhibit, October 1965.
- (7) Gardon, R., "A Transducer for the Measurement of Heat Flow Rate," *Journal of Heat Transfer*, Am. Soc. Mechanical Engrs., November 1960.

*The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.*

*This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 100 Barr Harbor Drive, West Conshohocken, PA 19428.*

*This standard is copyrighted by ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (<http://www.astm.org>).*