Designation: E 511 – 73 (Reapproved 1994)$^{\epsilon 1}$

Standard Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Gage[1]

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 (ε) indicates an editorial change since the last revision or reapproval.

ϵ^1 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, τ, is approximated by the formula $\tau = 6D^2$, where D is in inches **(1)**[2] 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^2·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^2·s or $E/q = 19.3\ D^2/S$ where D and S are in metres and q is in W/m^2.

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

[1] 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.

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

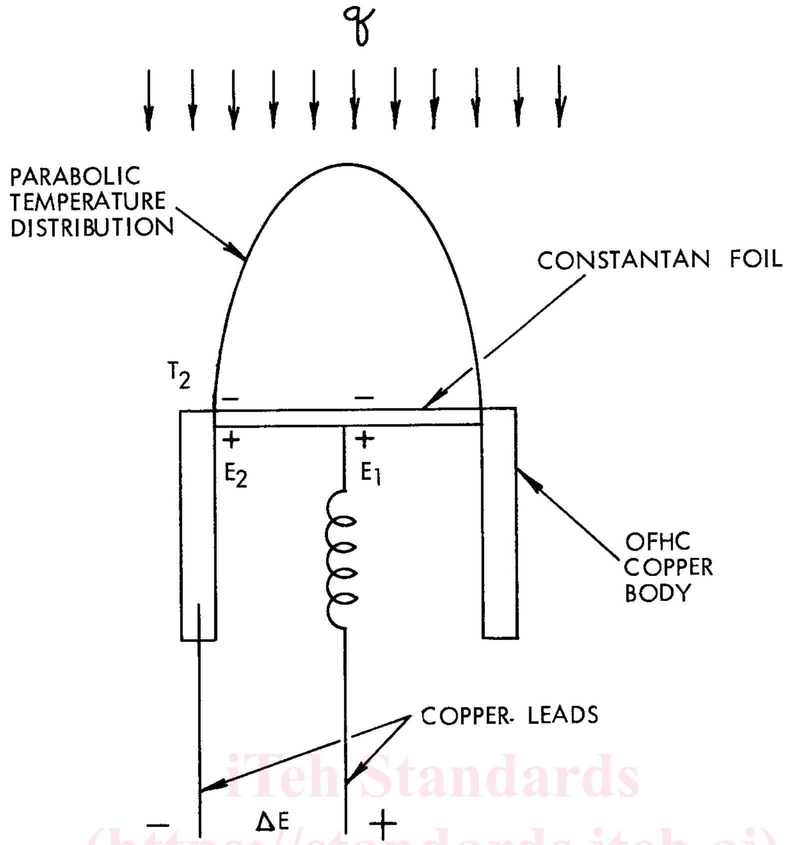

FIG. 1 Heat Drain—Either by Water Cooling the Body with a Surrounding Water Jacket or Conducting the Heat Away with Sufficient Thermal Mass

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 Ω or greater. (Sensor impedance is usually less than 1 Ω).

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^2(3000 Btu/ft^2·s)—Such high fluxes require thin external shells for quick transfer of heat into high velocity (15 to 30 m/s

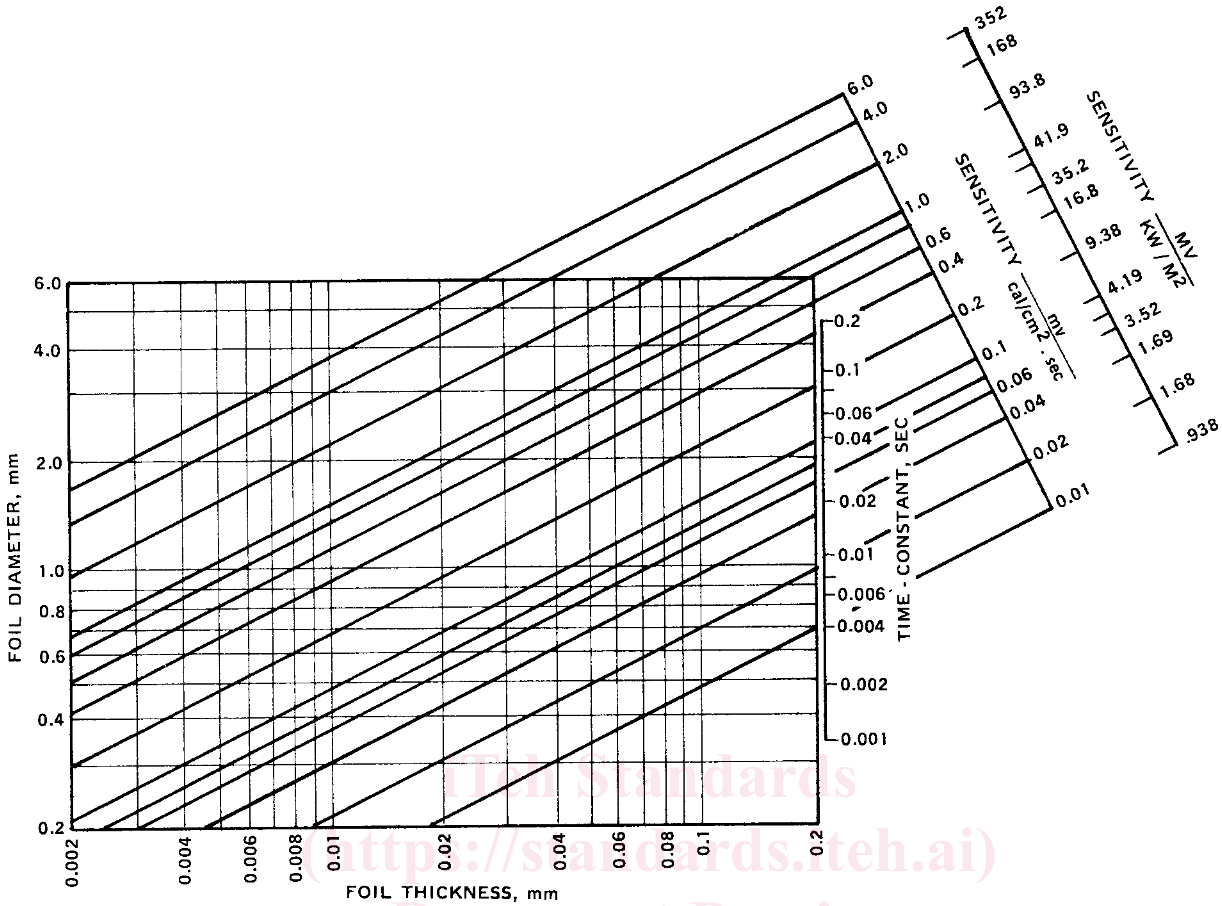

FIG. 2 Chart for Design of Copper-Constantan Circular Foil Heat-Flow Meters (SI Units)

(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 nonequilibrium 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 (ϵ_{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