



Designation: E 511 – 01

Standard Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer¹

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.

1. Scope

1.1 This test method describes the measurement of radiative or convective heat flux, or both, using a transducer whose sensing element **(1, 2)**² is a thin circular metal foil. While benchmark calibration standards exist for radiative environments, no uniform agreement among practitioners or government entities exists for convective environments.

1.2 The values stated in SI units are to be regarded as the standard. The values stated in parentheses are provided 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 purpose of this test method is to facilitate measurement of heat flux from radiant or convective sources, or from a combination of the two.

2.2 The circular foil heat flux transducer generates a millivolt output in response to the rate of thermal energy absorbed (see Fig. 1). The circular metal foil sensing element is mounted in a metal heat sink around its perimeter, forming a reference thermocouple junction due to their different thermoelectric potentials. A second thermocouple junction is formed at the center of the foil using a fine wire of the same metal as the heat sink. When the sensing element is exposed to a heat source, heat energy is absorbed at the surface of the circular foil and conducted radially to the heat sink. This establishes a parabolic temperature gradient between the center and edge of the foil. The temperature gradient produces a thermoelectric potential, E , between the center wire and the heat sink that will vary in proportion to the heat flux, q'' . With prescribed foil diameter, thickness, and materials, the potential E is linearly proportional

to the heat flux q'' absorbed by the foil. This relationship is described by the following equation:

$$E = Kq''$$

where:

K = a sensitivity constant determined experimentally.

2.3 For linear response, the heat sink of the transducer normally is made of copper and the foil of thermocouple grade constantan. This combination of materials produces a linear output over a temperature range from -45 to 232°C (-50 to 450°F). The linear range results from offsetting effects of temperature-dependent changes in the thermal conductivity and Seebeck coefficient of the constantan. All further discussion is based on the use of these two metals, since engineering practice has demonstrated they are commonly the most useful.

3. Characteristics and Limitations

3.1 The principal response characteristics of a circular foil heat flux transducer are sensitivity, full-scale range, and the time constant, which are established by the foil diameter and thickness. For a given heat flux, the transducer sensitivity is proportional to the temperature difference between the center and edge of the circular foil. To increase sensitivity, the foil is made thinner or its diameter is increased. The full-scale range of a transducer is limited by the maximum allowed temperature at the center of the foil. The range may be increased by making the foil smaller in diameter, or thicker. The transducer time constant approximately is proportional to the square of the foil diameter, and is characterized by **(3)**:

$$\tau = \rho c d^2 / 16k$$

where the foil properties are:

ρ = density,
 c = specific heat,
 d = foil diameter, and
 k = foil conductivity.

3.2 Foil diameters and thicknesses are limited by typical manufacturing constraints. Maximum optimum foil diameter to thickness ratio is 4 to 1 for sensors less than 2.54 mm diameter. Foil diameters range from 25.4 mm to 0.254 mm, with most gauges between 1.02 and 6.35 mm. The time constants, τ , for a

¹ This test method is under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.08 on Thermal Protection.

Current edition approved Oct. 10, 2001. Published January 2002. Originally published as E 511 – 73. Last previous edition E 511 – 73 (1994)^{\epsilon 1}.

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

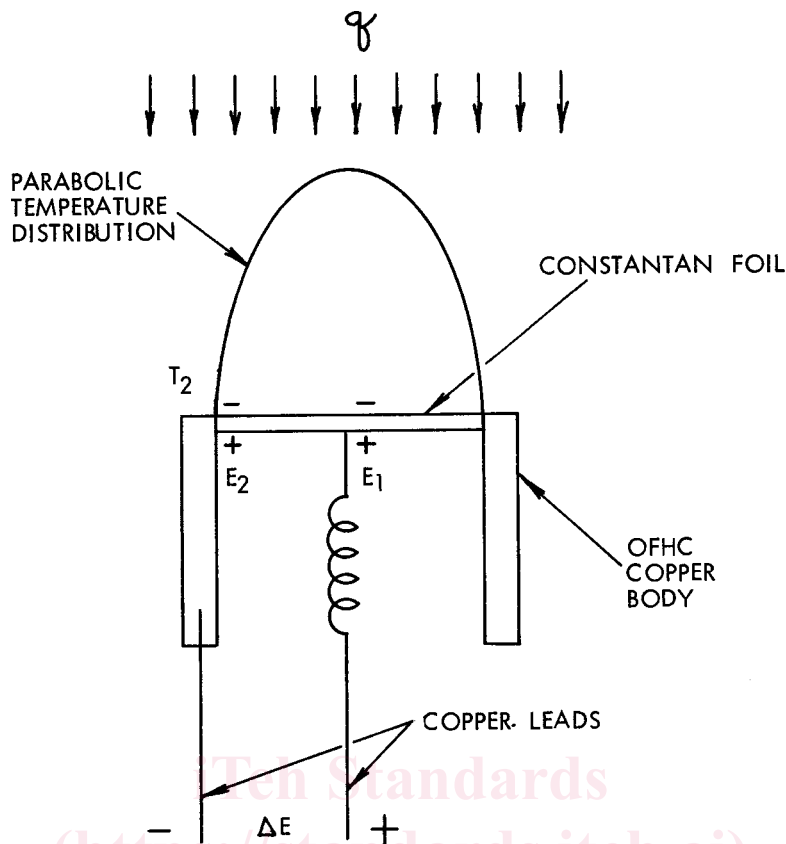


FIG. 1 Heat Drain—Either by Water Cooling the Body with a Surrounding Water Jacket or Conducting the Heat Away with Sufficient Thermal Mass

25.4-mm and 0.254-mm diameter foil are 6 s and 0.001 s, respectively. For constantan, the time constant is approximated by $\tau = 0.0094 d^2$, where d is in mm.

3.3 The sensitivity of commercially available transducers is limited to about 2 mV/W/cm² (1.76 BTU/ft²/s). Higher sensitivities can be achieved, but the foils of more sensitive transducers are extremely fragile. The range of commercial transducers may be up to 10 000 W/cm² (8811 BTU/ft²/s), and typically is limited by the capacity of the heat sink for heat removal. The full-scale range is normally specified as that which produces 10 mV of output. This is the potential produced by a copper-constantan transducer with a temperature difference between the foil center and edge of 190°C (374°F). These transducers may be used to measure heat fluxes exceeding the full-scale (10 mV output) rating; however, more than 50 % over-ranging will shorten the life and possibly change the transducer characteristics. If a transducer is used beyond 200 % of its full-scale rating, it should be returned to the manufacturer for inspection and recalibration before further use. Care should be taken not to exceed recommended temperature limits to ensure linear response. This is designed for in two ways: active cooling and by providing a heatsink with the copper body. Water-cooled sensors should be used in any application in which the sensor body would otherwise rise above 235°C (450°F). Typical cooled assemblies are shown in Fig. 2. When applying a liquid-cooled transducer in a hot environment, it may be important to insulate the body of the transducer from

the surrounding structure if it is also hot. This will improve the effectiveness of cooling and reduce the required liquid flow rate.

3.4 The temperature of the gage normally is low in comparison to the heat source. The resulting heat flux measured by the gage is known as a “cold wall” heat flux. For measurement of purely radiant heat flux, the circular foil is coated with a black paint or carbon soot of high absorptivity (0.98). Since the transducer signal is a direct response of the energy *absorbed* by the foil, the absorptivity of the surface of the coating must be known to correctly calculate the *incident* radiation flux.

3.5 Error Sources

3.5.1 Physical or chemical processes other than heat transfer may affect the accuracy of measurements made with a circular foil heat-flux transducer. If the dew point of the atmosphere at the face of the transducer is above the temperature of the circular foil, condensation may occur. This will release heat energy sensed as heat flux resulting in errors; thus, it is advisable to use a cooling water supply whose temperature is above the dew point of the atmosphere surrounding the transducer. Measurements of heat flux produced by flames in closed chambers are particularly subject to this error if the fuel being burned contains hydrogen. Catalytic processes at the face of the transducer (4) can cause similar errors.

3.5.2 A circular foil transducer can be used in a vacuum for radiant heat flux measurements, but if maximum accuracy is desired, the transducer should be calibrated in a similar

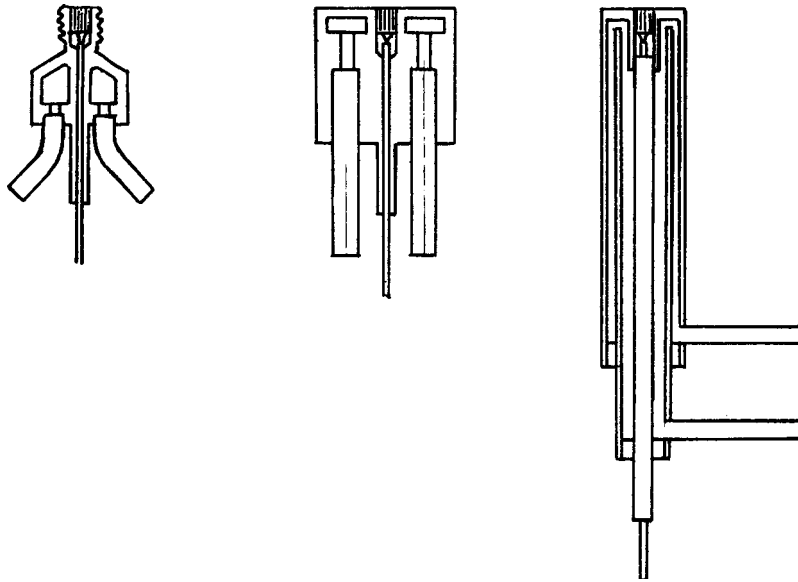


FIG. 2 Cross-Sectional View of Water-Cooled Heat-Flux Gages

vacuum. The output of the transducer will be slightly higher in a vacuum because of a small convective heat flow between the back of the foil and the body of the transducer when it is used at atmospheric pressure, to a degree that depends on the foil dimensions.

3.5.3 The circular foil transducer cannot be used for conducted heat-flux measurements.

3.5.4 Commercial transducers are calibrated with heat flux sources that are essentially uniform over the foil area, producing a parabolic temperature difference across the foil. If a transducer is used to measure a sharply focused light source, such as a laser beam or imaging optical system, its calibration may not be valid.

3.5.5 The field of view of a circular foil transducer used for radiative heat flux measurements is a half plane, or 180° . Transducer sensitivity to a point source of heat flux is greatest at normal incidence, and follows an approximate cosine law for other angles. Off-normal radiative sensitivity may be a function of the incident wavelength and the condition of the circular foil surface. Measurements made with a circular foil transducer and any other transducer (for example, radiometer) with a more limited field of view are not directly comparable unless the radiant source for both transducers has uniform intensity over the 180° field of view.

3.6 Convection

3.6.1 Circular foil transducers may be used to measure convective heat transfer, but certain cautions (5, 6, 7) should be observed. Because the heat transfer due to convection is proportional to the difference in temperature in the normal direction between the fluid and the surface, the gradient in temperature along the foil in the parallel direction creates a nonuniform heat flux. This nonuniformity is maximized when the bulk flow is parallel to the surface (8). The nonuniformity is lessened when the full-scale range of the transducer is much greater than the expected maximum convective heat flux, so the temperature rise at the center of the foil is closer to that of its edge. A method for selecting the transducer full-scale rating

(9) has been developed, but its utility is limited by the requirement that the convective heat transfer coefficient must be known. Generally, the transducer should produce no more than 0.5 mV output at the maximum convective heat flux, or a 10°C (18°F) temperature difference from foil center to edge. Under these circumstances, electrical noise may limit the signal resolution.

4. Description of the Instrument

4.1 Fig. 1 is a sectional view of an example circular foil heat-flux transducer. It consists of a circular foil attached by a metallic bonding process to a heat sink of oxygen-free high conductivity copper (OFHC), with copper leads attached at the center of the circular foil and at any point on the body. This data acquisition system (DAS) should be potentiometric, or have an input impedance of at least 100 000 ohms. The transducer impedance is usually less than 1 ohm.

4.2 A linear output (versus heat flux) is produced when the body and center wire of the transducer are constructed of copper and the circular foil is constantan. Other metal combinations may be employed for use at higher temperatures, but most (10) are nonlinear.

4.3 Because the thermocouple at the edge of the foil is the reference for the center thermocouple, no cold junction compensation is required with this instrument. The wire leads used to convey the signal from the transducer to the readout device are normally made of stranded, tinned copper, insulated with TFE-fluorocarbon and shielded with a braid over-wrap that is also TFE-fluorocarbon-covered.

4.4 Transducers with a heatsink thermocouple can be used to indicate the foil center temperature. The temperature difference from the foil edge to its center may be directly read from the copper-constantan (Type T) thermocouple table. This temperature difference then is added to the body temperature, indicating the foil center temperature. The effects of foil dimensions on transducer characteristics are shown in Figs. 3 and 4.