~~Designation:E511–01~~ Designation: E 511 – 07

Standard Test Method for
Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer[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.

1. Scope

1.1 This test method describes the measurement of radiative ~~or convective~~ heat ~~flux, or both,~~flux 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.~~ is a thin circular metal foil. These sensors are often called Gardon Gauges.

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

~~2.1The purpose of this test method is to facilitate measurement of heat flux from radiant or convective sources, or from a combination of the two.~~

~~2.2The circular foil heat flux transducer generates a millivolt output in response to the rate of thermal energy absorbed (see~~

2.1 The purpose of this test method is to facilitate measurement of a radiant heat flux. Although the sensor will measure heat fluxes from mixed radiative – convective or pure convective sources, the uncertainty will increase as the convective fraction of the total heat flux increases.

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 perimeter of the circular metal foil sensing element is mounted in a metal heat ~~sink around its perimeter,~~ sink, forming a reference thermocouple junction due to their different thermoelectric potentials. A differential thermocouple is created by 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, most of the heat energy ~~is~~ absorbed at the surface of the circular foil ~~and~~is conducted radially to the heat sink. ~~This establishes~~ If the heat flux is uniform and heat transfer down the center wire is neglected, a parabolic temperature ~~gradient~~ profile is established between the center and edge of the foil under steady-state conditions. The center – perimeter temperature ~~gradient~~difference produces a thermoelectric potential, *E*, ~~between the center wire and the heat sink~~ that will vary in proportion to the absorbed heat flux, q~~$''$.~~$'$. With prescribed foil diameter, thickness, and materials, the potential *E* is almost linearly proportional to the average heat flux q~~$''$~~$'$ absorbed by the foil. This relationship is described by the following equation:

~~$E=Kq''$~~

$$E = Kq' \qquad (1)$$

where:
K = a sensitivity constant determined experimentally.

2.3 For nearly linear response, the heat sink and the center wire of the transducer ~~normally is~~ are made of high purity copper and the foil of thermocouple grade ~~c~~Constantan. This combination of materials produces a nearly linear output over a gauge temperature range from ~~-45~~–45 to 232°C ~~(-50~~(–50 to 450°F). The linear range results from the basically offsetting effects of temperature-dependent changes in the thermal conductivity and the Seebeck coefficient of the ~~c~~Constantan **(3)** . All further discussion is based on the use of these two metals, since engineering practice has demonstrated they are commonly the most useful.

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[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 E511–73. Last previous edition E511–73 (1994)$^{\epsilon 1}$.~~

Current edition approved Nov. 1, 2007. Published December 2007. Originally approved in 1973. Last previous edition approved in 2001 as E 511 – 01.

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

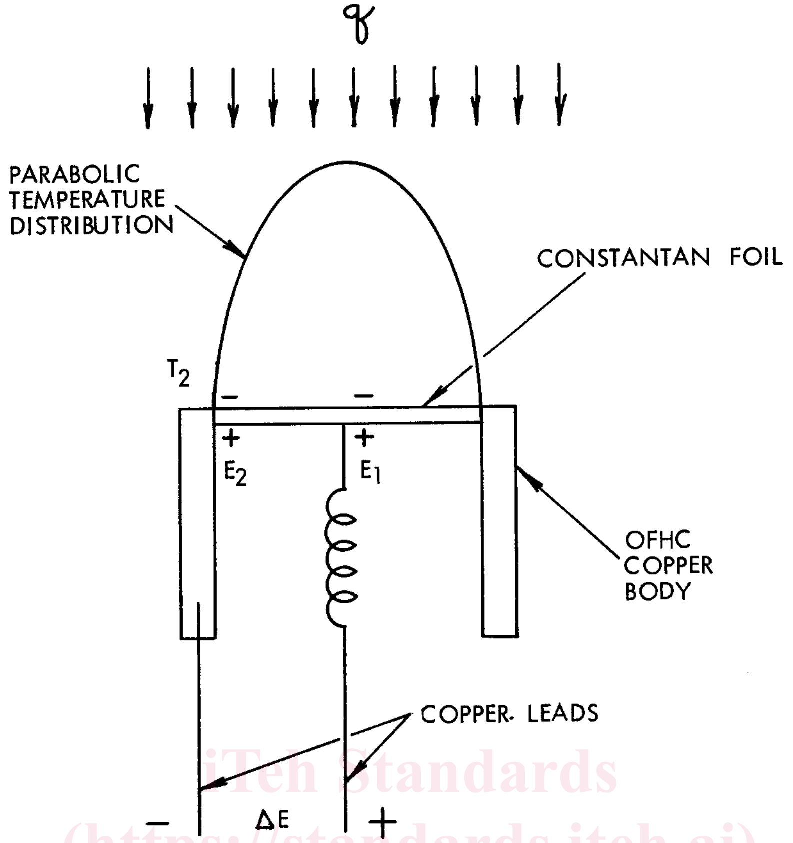

FIG. 1 Heat Drain—Either by Water Cooling the Body with a Surrounding Water Jacket or Conducting the Heat Away with Sufficient Thermal Mass

3. ~~Characteristics and Limitations~~

~~3.1The 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 (~~**Description of the Instrument**

3.1 Fig. 1 is a sectional view of an example circular foil heat-flux transducer. It consists of a circular Constantan 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 heat-sink body. The transducer impedance is usually less than 1 V. To minimize current flow, the data acquisition system (DAS) should be a potentiometric system or have an input impedance of at least 100 000 Ω.

3.2 As noted in 2.3, an approximately 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 **(4)** are nonlinear.

3.3 Because the thermocouple junction 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.

3.4 Transducers with a heat-sink thermocouple can be used to indicate the foil center temperature. Once the edge temperature is known, 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.

3.5 *Water-Cooled Transducer*:

3.5.1 A water-cooled transducer should be used in any application where the copper heat-sink would rise above 235°C (450°F) without cooling. Examples of cooled transducers are shown in Fig. 2. The coolant flow must be sufficient to prevent local boiling of the coolant inside the transducer body, with its characteristic pulsations (“chugging”) of the exit flow indicating that boiling is occurring. Water-cooled transducers can use brass water tubes and sides for better machinability and mechanical strength.

3.5.2 The water pressure required for a given transducer design and heat-flux level depends on the flow resistance and the shape

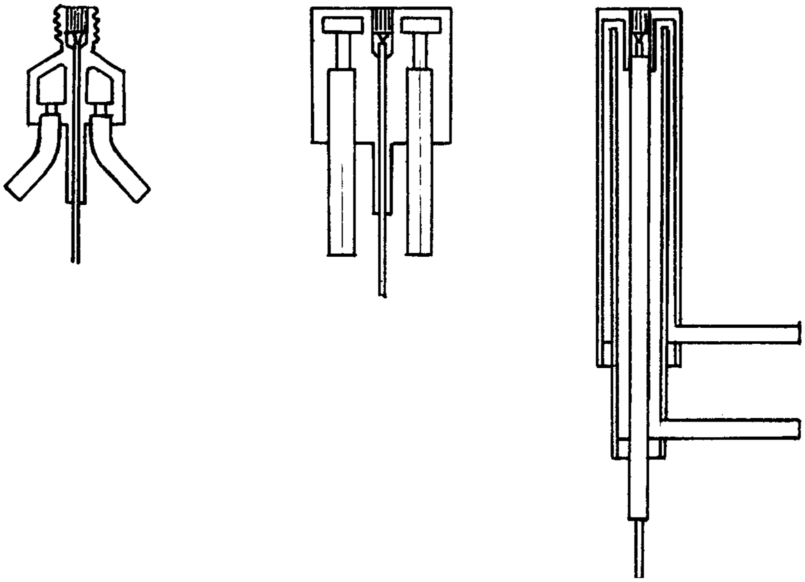

FIG. 2 Cross-Sectional View of Water-Cooled Heat-Flux Gages

of the internal passages. Rarely will a transducer require more than a few litres of water per minute. Most require only a fraction of litres per minute.

3.5.3 Heat fluxes in excess of 3400 W/cm^2 (3000 Btu/ft^2/s) may require transducers with thin internal shells for efficient transfer of heat from the foil/heat sink into a high-velocity water channel. Velocities of 15 to 30 m/s (49 to 98 ft/s) are produced by water at 3.4 to 6.9 MPa (500 to 1000 psi). For such thin shells, zirconium-copper may be used for its combination of strength and high thermal conductivity.

NOTE 1—Changing the heat sink from pure copper to zirconium copper may change the sensitivity and the linearity of the response.

3.6 *Foil Coating*:

3.6.1 High-absorptance coatings are used when radiant energy is to be measured. Ideally, the high-absorptance coating should provide a nearly diffuse absorbing surface, where absorption is independent of the angle of incidence of radiation on the coating. Such a coating is said to be Lambertian and the sensor output is proportional to the cosine of the angle of incidence with respect to normal. An ideal coating also would have no dependency of absorption with wavelength, approximating a gray-body. Only a few coatings approach these ideal characteristics.

3.6.2 Most high absorptivity coatings have different absorptivities when exposed to hemispherically-incident or narrower-angle, incident radiation. For five coatings, measurements by Alpert, et al, showed the near-normal absorptivity was 3 to 5 % higher than the hemispherical absorptivity (**5**). This work also showed that commercial heat flux gauge coatings generally maintain Lambertian (Cosine Law) behavior out to incidence angles 60° to 70° off-normal.

3.6.3 Acetylene soot (total absorptance $\alpha_T = 0.99$) and camphor soot ($\alpha_T = 0.98$) have the disadvantages (**4**) of low oxidation resistance and poor adhesion to the transducer surface. Colloidal graphite coatings dried from acetone or alcohol solutions ($\alpha_T = 0.83$) are commonly used because they adhere well to the transducer surface over a wide temperature range. Spray black lacquer paints ($\alpha_T = 0.94$ to 0.98), some of which may require baking, also are used. They are intermediate in oxidation resistance and adhesion between the colloidal graphites and soots. Colloidal graphite is commonly used as a primer for other, higher-absorptance coatings.

3.6.4 Low-absorptance metallic coatings, such as highly polished gold or nickel, may be used to reduce a transducer's response to radiant heat. Because these coatings effectively increase the foil thickness, they reduce the transducer sensitivity. Gold coating also makes the transducer response nonlinear because the thermal conductivity of this metal changes more rapidly with temperature than that of constantan or nickel; the coating must be thin to avoid changing the Seebeck Coefficient.

3.6.5 Exothermic reactions occurring at the foil surface will cause additional heating of the transducer. This effect may be highly dependent on the catalytic properties of the foil surface. Catalysis can be controlled by surface coatings (**3**).

4. Characteristics and Limitations

4.1 The principal response characteristics of a circular foil heat flux transducer are sensitivity, full-scale range, and the nominal time constant, which are established by the foil material, 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. An approximate transducer time constant is proportional to the square of the foil radius, and is characterized by (**1, 3, 6**): ~~$\tau = \rho c d$~~

$\tau \approx \rho c R^2$~~$/16k$~~ /4k (2)

where the foil properties and dimensions are:

τ = radial coordinate,
ρ = density,
c = specific heat,
~~*d*~~*R* = ~~foil diameter, and~~ radius, and
k = ~~foil conductivity.~~conductivity.

~~3.2Foil~~4.2 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 gages between 1.02 and 6.35 mm. The time constants, τ, for a 25.4-mm and 0.254-mm diameter foil are 6 s and ~~0.001~~0.0006 s, respectively. For constantan, the time constant is approximated by ~~τ=0.0094~~ $\tau = 0.0094\ d^2$~~, where *d* is in mm.~~

~~3.3The sensitivity of commercially available transducers is limited to about 2 mV/W/cm~~, where *d* is in mm. The effects of foil dimensions on the nominal time constant are shown in Fig. 3. Keltner and Wildin provide a detailed analysis of the sensitivity and dynamic response that includes the effect of heat transfer down the center wire **(7)**.

4.3 The radiative sensitivity of commercially available transducers is limited to about 2 mV/W/cm^2 (1.76 BTU/ft ^{2}/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/cm^2~~(8811 BTU/ft~~ (~8800 BTU/ ft^2~~/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~~

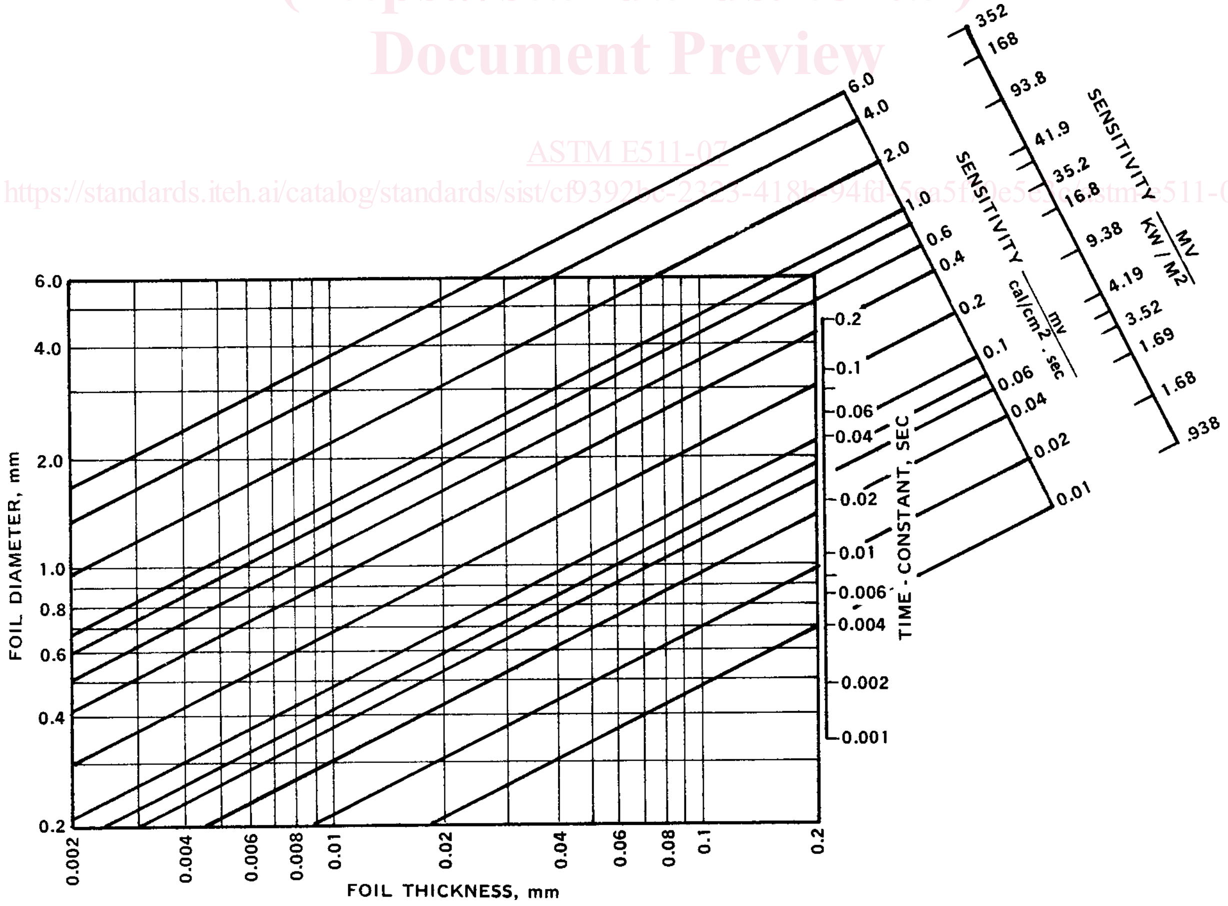

FIG. 3 Chart for Design of Copper-Constantan Circular Foil Heat-Flow Meters (SI Units)

~~improve the effectiveness of cooling and reduce the required liquid flow rate.~~

~~3.4The 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**~~

~~3.5.1Physical 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/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 heat sink with the copper body. The effects of foil dimensions on the transducer sensitivity are shown in Fig. 4. Refs (7-9)** ~~**can cause similar errors.**~~

~~3.5.2A 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 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.~~

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

~~3.5.4Commercial transducers are calibrated with heat flux sources that are essentially uniform over the foil area, producing a~~

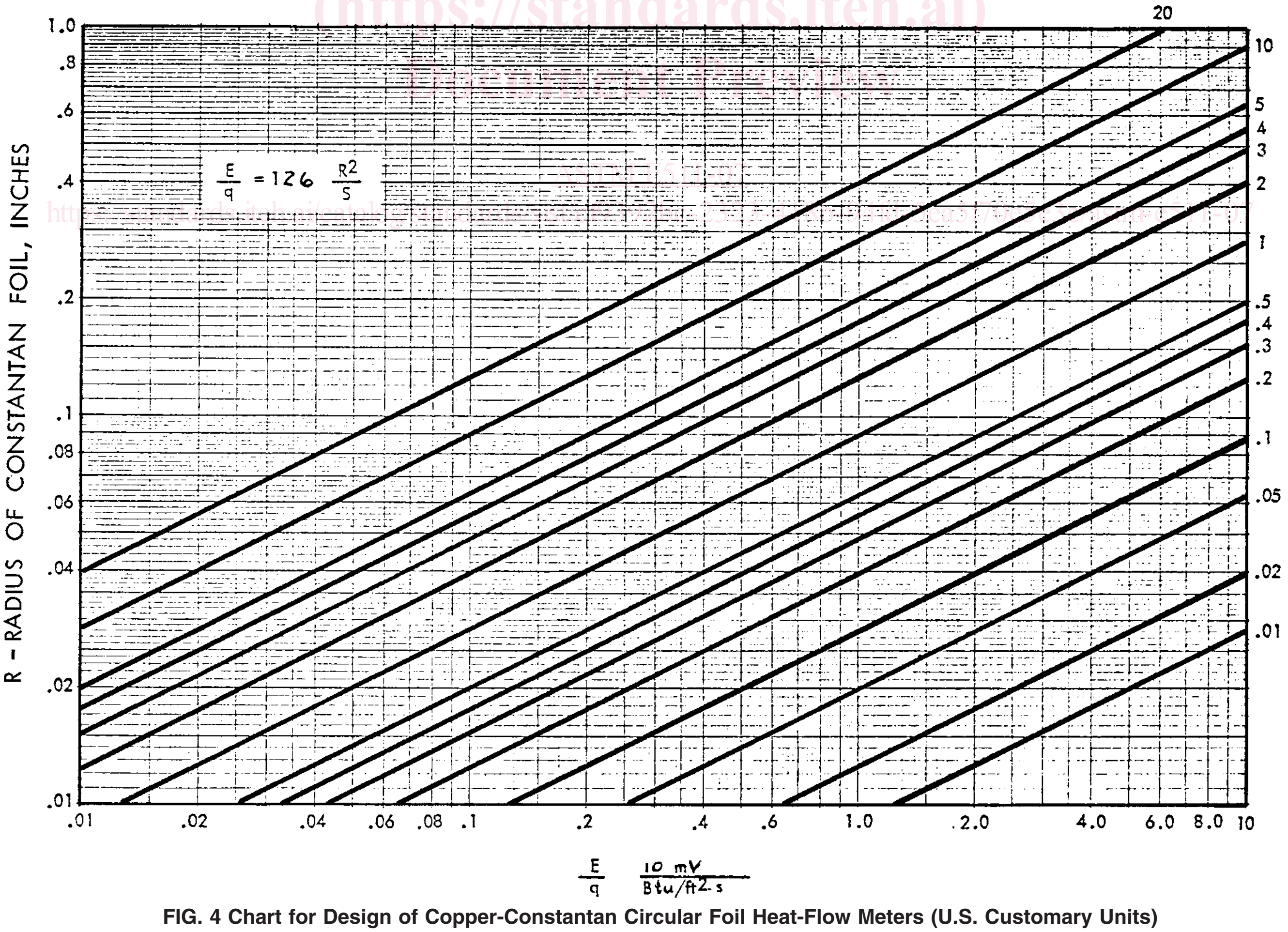

FIG. 4 Chart for Design of Copper-Constantan Circular Foil Heat-Flow Meters (U.S. Customary Units)

~~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.~~

~~3.5.5The field of view of a circular foil transducer used for radiative heat flux measurements is a half plane, or 180º. 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 180º field of view.~~

~~3.6**Convection**~~

~~3.6.1Circular foil transducers may be used to measure convective heat transfer, but certain cautions (~~**provide more detailed analysis of the sensitivity that includes the effects of heat transfer down the center wire.**

4.4 Water-cooled sensors are recommended for any application in which the sensor body would otherwise rise above 235°C (450°F). 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.

4.5 The temperature of the gage body 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.

4.6 For measurements of purely radiant heat flux, the transducer output signal is a direct response to the energy *absorbed* by the foil; the absorptivity of the surface of the coating must be known to correctly calculate the *incident* radiation flux **(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.**

4.7 The circular foil transducer cannot be used for conduction heat-flux measurements.

4.8 The circular foil transducer should be used with great care for convective heat-flux measurements because *(a)* there are no standardized calibration methods; *(b)* the uncertainty increases rapidly for free-stream temperatures below 1000ºC, although proper range selection can minimize the increase; and, *(c)* the uncertainty varies with the free-stream velocity vector **(10,11)**. ~~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~~

~~4.1Fig. 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.~~

~~4.2A 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~~ **. In shear flows, the sensors can display nonlinear response and high uncertainty (~~10~~12,13)~~are nonlinear.~~**

~~4.3Because 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.~~

~~4.4Transducers 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.~~

~~4.5**Water-Cooled Transducer**~~

~~4.5.1A water-cooled transducer should be used in any application where the copper heatsink would rise above 235°C (450°F) without cooling. Examples of cooled transducers are shown in Fig. 2. The coolant flow must be sufficient to prevent local boiling of the coolant inside the transducer body, with its characteristic pulsations ("chugging") of the exit flow indicating that boiling is occurring. Water-cooled transducers can use brass water tubes and sides for better machinability and mechanical strength.~~

~~4.5.2The water pressure required for a given transducer design and heat-flux level depends on the flow resistance and the shape of the internal passages. Rarely will a transducer require more than a few litres of water per min. Most require only a fraction of L/min.~~

~~4.5.3Heat fluxes in excess of 3405 W/cm~~

4.9 *Error Sources*:

4.9.1 *Radiative Heat Transfer*—If there is a uniform incident heat flux over the foil, convective and radiative heat losses from