Designation: ~~E2683 – 09~~ E2683 – 17

Standard Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages[1]

This standard is issued under the fixed designation E2683; 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 the net heat flux normal to a surface using gages inserted flush with the surface. The geometry is the same as heat-flux gages covered by Test Method E511, but the measurement principle is different. The gages covered by this standard all use a measurement of the temperature gradient normal to the surface to determine the heat that is exchanged to or from the surface. Although in a majority of cases the net heat flux is to the surface, the gages operate by the same principles for heat transfer in either direction.

1.2 This general test method is quite broad in its field of application, size and construction. Two different gage types that are commercially available are described in detail in later sections as examples. A summary of common heat-flux gages is given by Diller (**1**).[2] Applications include both radiation and convection heat transfer. The gages used for aerospace applications are generally small (0.155 to 1.27 cm diameter), have a fast time response (10 μs to 1 s), and are used to measure heat flux levels in the range 0.1 to 10 000 kW/m^2. Industrial applications are sometimes satisfied with physically larger gages.

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

1.4 *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.*

1.5 This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standard:*[3]

E511 Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *heat flux*—the heat transfer per unit area, q, with units of W/m^2(Btu/ft^2-s). Heat transfer (or alternatively heat transfer rate) is the rate of thermal energy movement across a system boundary with units of watts (Btu/s). This usage is consistent with most heat transfer books.

3.1.2 *heat transfer coefficient, (h)*—an important parameter in convective flows with units of W/m^2-K (Btu/ft^2-s-F). This is defined in terms of the heat flux q ~~as~~as:

$$h = \frac{q}{\Delta T} \tag{1}$$

where ΔT is a prescribed temperature difference between the surface and the fluid. The resulting value of h is intended to be only a function of the fluid flow and geometry, not the temperature difference. If the surface temperature is non-uniform or if

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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.

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

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

there is more than a single fluid free stream temperature, the proper definition of ΔT may be difficult to specify (**2**). It is always important to clearly define ΔT when calculating the heat transfer coefficient.

3.1.3 *surface emissivity, (ε)*—the ratio of the emitted thermal radiation from a surface to that of a blackbody at the same temperature. Surfaces are assumed to be gray bodies where the emissivity is equal to the absorptivity.

4. Summary of Test Method

4.1 A schematic of the sensing technique is illustrated in Fig. 1. Temperature difference is measured across a thermal-resistance layer of thickness, δ. This is the heat flux sensing mechanism of this method following Fourier's law. The measured heat flux is in the same direction as the temperature difference and is proportional to the temperature gradient through the thermal-resistance layer (TRL). The resistance layer is characterized by its thickness, δ, thermal conductivity, *k*, and thermal diffusivity, α. The properties are generally a weak function of temperature.

$$q = \frac{k}{\delta}\left(T_1 - T_2\right) \tag{2}$$

~~From this point the different gages may vary in how the temperature difference $T_1 - T_2$ is measured, the thickness of the thermal-resistance layer used, and how the sensing element is mounted in the gage. These three aspects of each different type of gage are discussed along with the implications for measurements. In all of the cases considered in this standard the gage housing is a circular cylinder that is inserted into a hole in the material of the test object flush with the surface.~~

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4.2 Gages using this test method generally use differential thermocouple pairs that give an output that is directly proportional to the required temperature difference. The differential thermocouple pairs are put in series to form a differential thermopile to increase the sensitivity to heat flux.

$$S = \frac{E}{q} = \frac{N\sigma_T\delta}{k} \tag{3}$$

~~Here N represents the number of thermocouple pairs forming the differential thermopile and σ_T is the effective temperature sensitivity (Seebeck coefficient) of the two thermocouple materials.~~

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5. Significance and Use

5.1 The purpose of this test method is to measure the net heat flux to or from a surface location. For measurement of the radiant energy component the emissivity or absorptivity of the surface coating of the gage is required. When measuring the convective energy component the potential physical and thermal disruptions of the surface must be minimized and characterized. Requisite is to consider how the presence of the gage alters the surface heat flux. The desired quantity is usually the heat flux at the surface location without the presence of the gage.

5.1.1 Temperature limitations are determined by the gage material properties, the method of mounting the sensing element, and how the lead wires are attached. The range of heat flux that can be measured and the time response are limited by the gage design and construction details. Measurements of a fraction of 1 kW/m^2 to above 10 MW/m^2 are easily obtained with current gages. With thin film sensors a time response of less than 10 µs is possible, while thicker sensors may have response times on the order of 1 s. It is important to choose the gage style and characteristics to match the range and time response of the required application.

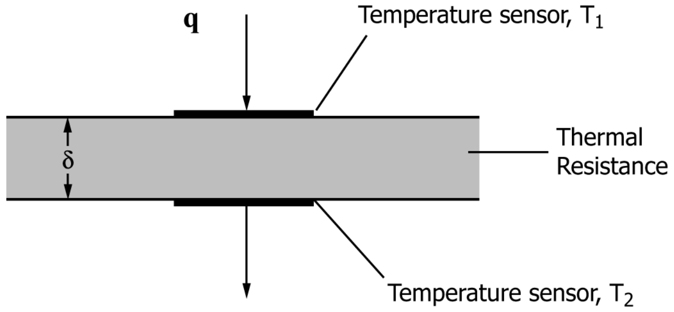

FIG. 1 Layered Heat-Flux Gage

5.1.2 When differential thermocouple sensors are operated as specified for one-dimensional heat flux and within the corresponding time response limitations, the voltage output is directly proportional to the heat flux. The sensitivity, however, may be a function of the gage temperature.

5.2 The measured heat flux is based on one-dimensional analysis with a uniform heat flux over the surface of the gage. Measurements of convective heat flux are particularly sensitive to disturbances of the temperature of the surface. Because the heat-transfer coefficient is also affected by any non-uniformities in the surface temperature, the effect of a small temperature change with location is further amplified as explained by Moffat et al. (**2**) and Diller (**3**). Moreover, the smaller the gage surface area, the larger is the effect on the heat transfer coefficient of any surface temperature non-uniformity. Therefore, surface temperature disruptions caused by the gage should be kept much smaller than the surface to environment temperature difference driving the heat flux. This necessitates a good thermal path between the sensor and the surface into which it is mounted. If the gage is not water cooled, a good thermal pathway to the system's heat sink is important. The gage should have an effective thermal conductivity as great or greater than the surrounding material. It should also have good physical contact insured by a tight fit in the hole and a method to tighten the gage into the surface. An example method used to tighten the gage to the surface material is illustrated in Fig. 2. The gage housing has a flange and a separate tightening nut tapped into the surface material.

5.2.1 If the gage is water cooled, the thermal pathway to the plate is less important. The heat transfer to the gage enters the water as the heat sink instead of the surrounding plate. Consequently, the thermal resistance between the gage and plate may even be increased to discourage heat transfer from the plate to the cooling water. Unfortunately, this may also increase the thermal mismatch between the gage and surrounding surface.

5.2.2 Fig. 2 shows a heat flux gage mounted into a plate with the surface temperature of the gage of T_s and the surface temperature of the surrounding plate of ~~Tp.~~T_p. As previously discussed, a difference in temperature between the gage and plate may also increase the local heat transfer coefficient over the gage. This amplifies the measurement error. Consequently, a well designed heat flux gage will keep the temperature difference between the gage surface and the plate to a minimum, particularly if any convection is being measured.

5.2.3 Under transient or unsteady heat transfer conditions a different thermal capacitance of the gage than the surrounding material may also cause a temperature difference that affects the measured heat flux. Independent measures of the substrate and the gage surface temperatures are advantageous for defining the heat transfer coefficient and ensuring that the gage thermal disruption is acceptably small.

5.3 The heat flux gages described here may also be water cooled to increase their survivability when introduced into high temperature environments. By limiting the rise in gage temperature, however, a large disruption of the measured heat flux may result, particularly if convection is present. For convection measurements to match the heat flux experienced by the surrounding surface, the gage temperature must match the temperature of that surface. This will usually require the surrounding surface to also be water cooled.

5.4 The time response of the heat flux sensor can be estimated analytically if the thermal properties of the thermal resistance layer are well known. The time required for 98 % response to a step input (**4**) based on a one-dimensional analysis is:

$$t = \frac{1.5\delta^2}{\alpha} \tag{4}$$

~~where α is the thermal diffusivity of the TRL. Covering or encapsulation layers must also be included in the analysis. The calibrated gage sensitivity in Eq 3 applies only under steady-state conditions.~~

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5.4.1 For thin-film sensors the TRL material properties may be much different from those of bulk materials. Therefore, a direct experimental verification of the time response is desirable. If the gage is designed to absorb radiation, a pulsed laser or optically switched Bragg cell can be used to give rise times of less than 1 µs (**5**,**6**). A rise time on the order of 5 µs can be provided in a convective flow with a shock tunnel (**7**).

5.4.2 Because the response of these gages is close to an exponential rise, a measure of the first-order time constant, τ, for the gage can be obtained by matching the experimental response to step changes in heat flux with exponential curves.

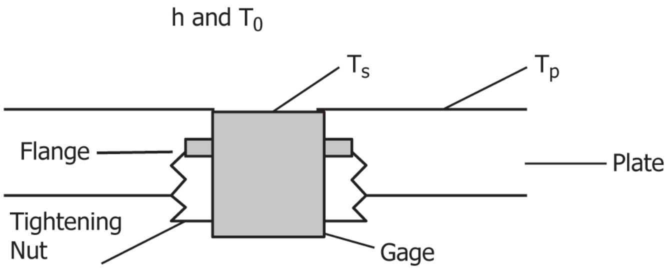

FIG. 2 Diagram of an Installed Insert Heat-Flux Gage

$$q = q_{ss}\left(1 - e^{-t/\tau}\right) \tag{5}$$

The value of the step change in imposed heat flux is represented by q_{ss}. The resulting time constant characterizes the first-order sensor response.

5.4.3 The time response of the gage can be improved by up to a factor of 28 by using a simple data processing routine (**8**). It uses a combination of the temporal and spatial temperature measurements of the sensor. This is another reason for measuring and recording temperature signals along with the heat flux.

6. Apparatus-Sensor Constructions

6.1 While the principle of operation is similar, the method of construction and details of operation varies for each different type of gage. ~~The two popular commercially~~ Commercially available types are described in detail below.

6.2 *Thin-film Sensors*—The thermal resistance and thermocouple layers can all be deposited directly onto a substrate to give more design and manufacturing flexibility. Such a thin-film device has been described in detail by Diller and Onishi (**~~8~~9**) and was first produced by Hager et al. (**5**) using sputtering techniques. It is currently made by Vatell.[4] The thermal resistance layer of 1 µm silicon monoxide is deposited directly onto the surface. Microfabrication methods are used to deposit hundreds of thermocouple pairs around the silicon monoxide layer to create the desired differential thermopile as specified for Eq 3. Because of the thin-films used, it has been named the Heat Flux Microsensor (HFM). Either photolithography or stencil masks can be used to define the patterns. Precise registration of the elements in each of the five layers allows a fine pattern to be created in a small surface area. A cross-section of the gage, which does not need an adhesive layer, is illustrated in Fig. 3. The resulting physical and thermal disruption of the surface due to the presence of the sensor is extremely small because of the low sensor mass.

6.2.1 While the original version of these sensors placed the temperature sensors almost directly over top of each other across a single TRL, it is not a requirement. The bottom temperature sensors simply need to be at a uniform temperature and the top temperature sensors need to be at a temperature dictated by the heat flux perpendicular to the surface. This can be accomplished on a high conductivity substrate by separate thermal resistance pads for the top temperature measurements. The pattern is illustrated in Fig. 4 (**7**). The bottom temperature sensors can be placed directly on the substrate with or without thermal resistance pads on top. If the thermal resistance of the pads is large relative to the lateral thermal resistance in the substrate between individual temperature sensors, the pads on the lower thermocouple junctions are redundant and not necessary. For the Heat Flux Microsensor this is accomplished using aluminum nitride as the substrate material. With a thermal conductivity of approximately 170 W/m-*K*, which is several orders of magnitude higher than the conductivity of the silicon monoxide, and excellent electrical insulation properties, it forms an ideal substrate material. Leads are taken down the side and attached to wires on the side or behind the sensor substrate, which is then press fit into a high conductivity metal housing. A thin-film RTD or thermocouple is also deposited on the surface for independent temperature measurement of the sensor surface. Consequently, these gages cause little if any thermal disruption if properly mounted in any material with thermal conductivity equal to or less than common aluminum, which includes most materials except high-conductivity silver or copper.

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[4] The sole source of supply of the apparatus known to the committee at this time is Vatell. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

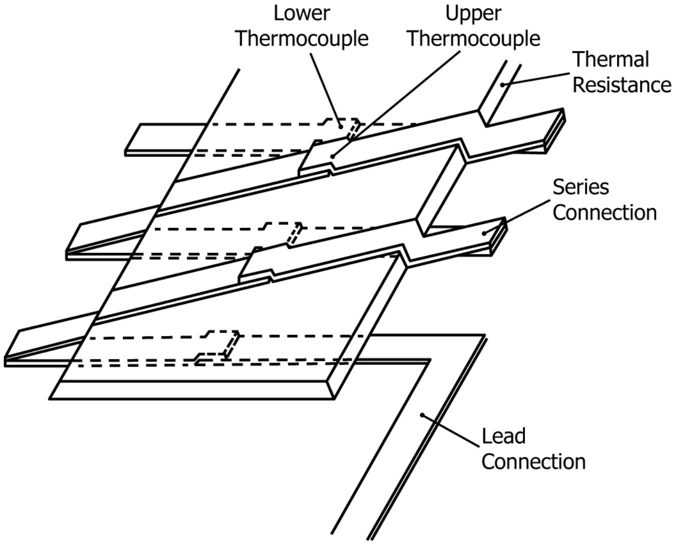

FIG. 3 Isometric View of Thin-Film Gage Pattern

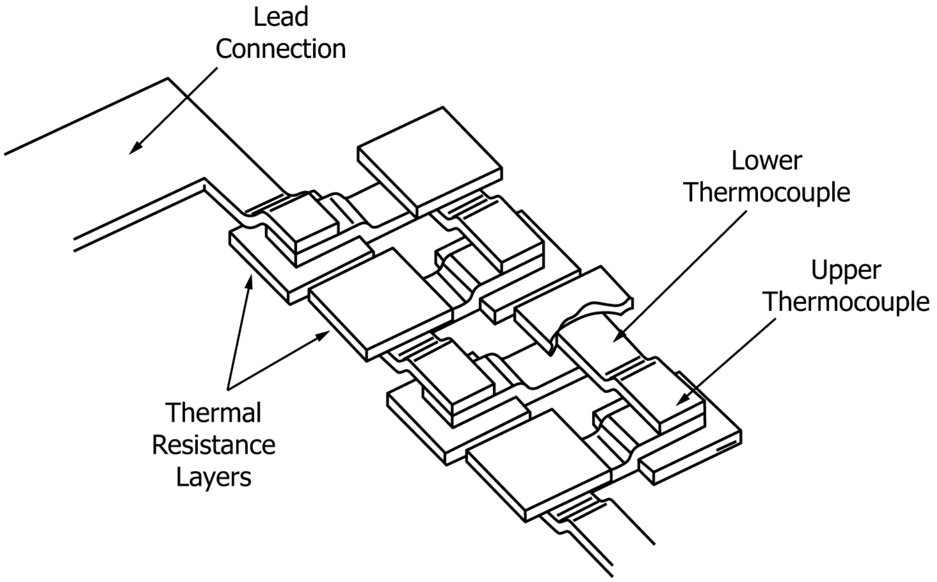

FIG. 4 Side-by-Side Thermopile Construction

6.2.2 Use of high-temperature thermocouple materials (**~~9~~10**) allows sensor operating temperatures to exceed ~~800°C~~800 °C for the high-temperature models. They are best suited for heat flux values above 1 kW/m^2, with no practical upper limit. Because the sensor is so thin, the thermal response time is less than ~~10 μs~~ 10 μs (**7**), giving a good frequency response well above 10 kHz when no radiation coating is applied. The gage can also be water or air cooled for high-flux radiation measurements. Because cooling would disrupt convection processes, the cooled versions should not be used if convection is a significant portion of the heat flux.

6.2.3 As a warning, if both temperature sensors are placed on the substrate with a thermal pad over one to create the temperature difference, the resulting heat flux sensor operates based on a lateral temperature gradient in the substrate and is not covered by this method. The dynamic and steady response of such a gage is substantially different from the gages with normal temperature gradients that are described in this section.

6.3 *Thick-Film Gage*—A gage with a similar design as shown in Fig. 3 made by MesoScribe[5] with thermal spray technology is an order-of-magnitude thicker (**11**). The thermopile consists of N-type thermocouple junctions and the thermal resistance layer is a dielectric material such as yttria-stabilized zirconia or aluminum-doped magnesium aluminate spinel. The typical thickness of the resistance layer is 75 μm. It operates up to 860 °C sensor temperature. One time constant is 27 msec.

6.4 *Welded Heat Flux Gage*—A particularly durable sensor for operating temperatures up to 1000 °C was developed by Gifford et al. (**12**) by welding K-type thermocouples in a "z" pattern. The thermal resistance layer is actually composed of the thermocouples themselves. Small pieces of ceramic are used to separate the metal elements. The element is mounted in an Inconel housing. The 3.2 mm thick sensor has a time constant less than one second when using the method of Hubble and Diller (**8**). These HTHFS sensors are currently made by FluxTeq.[6]

6.5 *The Wire-Wound Gage (generally known as the Schmidt-Boelter Gage)*—The Schmidt-Boelter gage, the earliest practical heat flux gage, consisted of a plated wire wrapped around the TRL in place of the thermocouples. It is commonly associated with the early discovery by Schmidt (**~~10~~13**) in 1924. A modification to this technique by L.M.K. Boelter in the 1940s simplified and miniaturized the construction of the gage. However, this type of gage has been marketed by commercial suppliers since the 1950s under several different names. As illustrated in Fig. 5, it provides a self-generated voltage output in response to the thermal energy absorbed at the sensing surface. This device measures the temperature difference between the top and bottom surface planes of a parallel wall slab. The top surface of the slab is located near the sensing surface of the transducer and the bottom surface is in good thermal contact with a heat sink. This temperature difference is established as the thermal energy absorbed at the sensing surface is rapidly transferred laterally through the parallel wall slab and into the heat sink.

6.5.1 The temperature-sensing device is a number of differential thermocouple circuits connected in electrical series to form a thermopile (Fig. 4). Although any thermocouple materials can in theory be used, the practical common arrangement uses a fine constantan wire wrapped around the thermal resistance material *N* number of turns. One-half of the wire is then electroplated with copper. The result is a set of thermocouple junctions where the electroplating stops on the top and bottom of the thermal resistance.

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[5] The sole source of supply of the apparatus known to the committee at this time is MesoScribe. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

[6] The sole source of supply of the apparatus known to the committee at this time is FluxTeq. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

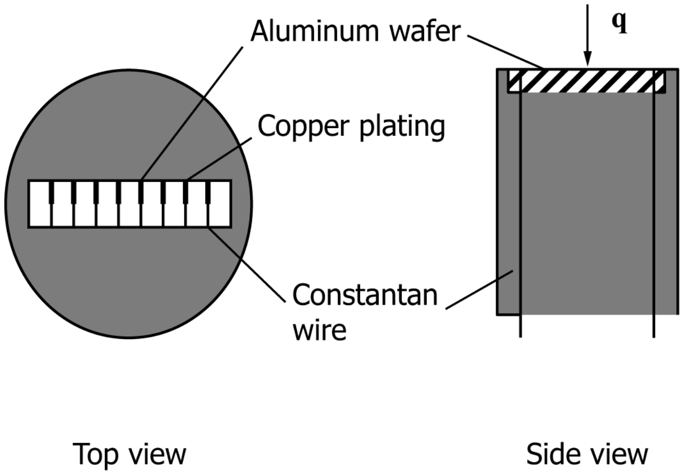

FIG. 5 Schematic of a Wire-Wound Heat-Flux Gage

The equilibrium thermoelectric potential, E, between the two parallel plane surfaces is proportional to the heat flux, q, absorbed by the device according to the simple expression:

$$E = qS \tag{6}$$

where S is a constant determined experimentally during calibration. The voltage output is lower than that specified by Eq 3 for an equivalent copper/constantan thermopile because of the electrical shunting through the constantan wire (~~11~~14). Because of the much lower electrical resistivity of copper, the output is still dominated by the thermocouple effect, however.

6.5.2 The TRL by necessity must be an electrical insulator in the wire-wound device and it largely determines the sensitivity and time response of the gage. This gage provides a direct measurement of heat flux by virtue of the fact that the heat flux incident upon the surface is directly proportional to the temperature difference developed between parallel planes on the top and bottom of the TRL in an axial direction in the gage configuration. An anodized aluminum wafer (~ 0.5 mm thickness) has been used as the TRL in gages developed by several different manufacturers. The material, thickness and overall size of this wafer can be changed depending on the intended application and heat flux range of the device. Particularly for convection measurements it is important to minimize the temperature difference across the wafer and associated potting material to minimize the surface temperature disruption caused by the gage. Diller (3) discusses how the mismatch in temperature between the gage and surrounding surface can easily lead to large errors in the measured convection heat transfer. Unfortunately, this also minimizes the voltage output of the sensor and requires a careful matching of the gage characteristics with the intended test conditions.

6.5.3 Thermal analyses using finite element heat conduction codes have been utilized to accurately predict the actual heat conduction paths within the gage for a variety of input boundary conditions (~~11~~14,~~12~~15). These analyses show that the gage sensitivity and non-uniformity of surface temperature are more dependent upon the thickness and properties of the potting materials than the anodized aluminum wafer itself. For instance, the actual time response of the gage is not predicted very well by just considering the aluminum wafer as the TRL. This gives an unusually fast time response and does not represent the actual behavior of the gage. On the other hand, when the thermal properties of the potting material above and below the aluminum wafer are accounted for, the analytical time response closely approximates the actual measured gage response.

6.5.4 The transient response generally does not follow a single exponential time constant as depicted in Eq 5. A procedure for recovering some of the transient response has been detailed by Kidd and Adams (~~13~~16) for the usual Schmidt-Boelter gages. Modifications of the design have been developed (~~13~~16,~~14~~17) that give close to an exponential response as shown in Eq 5. In both cases the design of the gage is altered to encourage the heat flux from the wafer to the heat sink on the sides while the heat sink on the back of the wafer is isolated. The time constants can be as small as ~~10-15~~ 10 to 15 ms.

6.5.5 Another advantage of the Schmidt-Boelter gage is that the surface of the gage can be rounded slightly to fit a curved surface.

6.5.6 The Schmidt-Boelter gage has the following limitations:

6.5.6.1 The gage responds differently to radiative and convective heating. Measurement of radiant heating is straightforward and requires no adjustments for temperature of the heat source within certain manufacturer-defined constraints. Conversely, the measurement of convective or mixed mode heating is more complex and requires that the gage surface temperature disruption be minimized with regard to the total temperature of the heat source. This usually requires the use of a high quality dc amplifier to provide a large enough output signal for adequate resolution of the measured heat flux.

6.5.6.2 Care must be exercised in using the gage to measure convective heating in a shear flow environment. The asymmetric heating that occurs in shear makes it difficult to properly interpret the output signal from the gage.

6.5.6.3 The field of uniform heat flux must exceed the surface area of the gage.