Designation: E3057 − 19

Standard Test Method for Measuring Heat Flux Using Directional Flame Thermometers with Advanced Data Analysis Techniques[1]

This standard is issued under the fixed designation E3057; 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.

INTRODUCTION

This test method describes a technique for measuring the net heat flux to one or both surfaces of a sensor called a Directional Flame Thermometer. The sensor covered by this standard uses measurements of the temperature response of two metal plates along with a thermal model of the sensor to determine the net heat flux. These measurements can be used to estimate the total heat flux (also known as thermal exposure) and bi-directional heat fluxes for use in CFD thermal models.

The development of Directional Flame Thermometers (DFTs) as a device for measuring heat flux originated because commercially available, water-cooled heat flux gauges (for example, Gardon and Schmidt-Boelter gauges) did not work as desired in large fire tests. Because the Gardon and Schmidt-Boelter (S-B) gauges are water cooled, condensation and soot deposition can occur during fire testing or in furnaces. Both foul the sensing surface which in turn changes the sensitivity (calibration) of the gauge. This results in an error during data reduction. Therefore, a different type of sensor was needed; one such sensor is a DFT. DFTs are not cooled so condensation and soot deposition are minimized or eliminated.

Additionally, a body of work has shown that for both Gardon and Schmidt-Boelter gauges the sensitivity coefficients determined through the calibration process, which uses a radiative heat source, are not the same as the sensitivity coefficients determined if a purely convective source is used for calibration [Test Method E511-07; Keltner and Wildin, 1975 (**1, 2**); Borell, G. J., and Diller, T. E., 1987 (**3**); Gifford, A., et al., 2010 (**4**); Gritzo, L. A., et al., 1995 (**5**); Young, M. F., 1984 (**6**); Sobolik, et al., 1987 (**7**); Kuo and Kulkarni, 1991 (**8**); Keltner, 1995 (**9**); Gifford, et al., 2010 (**10**); Nakos, J. T., and Brown, A. L., 2011 (**11**)].[2] As a result, one can incur significant bias errors when reducing data in tests where there may be a non-negligible convective component because the only sensitivity coefficient available is for a radiation calibration. It was desired to reduce/eliminate these potential sources of error by designing a gauge that does not depend on a radiation only calibration. DFTs have this characteristic.

A sensor, also called a Directional Flame Thermometer, was developed to help estimate flame thickness in pool fire tests of hazardous material shipping containers [Burgess, M. H., 1986 (**12**); Fry, C. J., 1989 (**13**); Burgess, M. H., et al., 1990 (**14**); and Fry, C. J., 1992 (**15**)]. As originally designed, DFTs were quasi-equilibrium sensors that used a thin metal plate with a single thermocouple attached and backed by multiple radiation shields. To make a sensor suitable for continuous transient heat flux measurements, this basic design was modified to use two instrumented plates, with a layer of insulation in between.

For the Directional Flame Thermometers described in this standard, the net heat flux is calculated using transient temperature measurements of the two plates and temperature dependent material properties for the plates and the insulation. Three methods are described in this standard to calculate the net heat flux. The most accurate method for calculating the net heat flux is believed to be the 1-dimensional, nonlinear inverse heat conduction analysis, which uses the IHCP1D code. This is based on uncertainty analyses and comparisons with measurements made with Schmidt-Boelter and Gardon gauges, which have NIST traceable calibrations. The second method uses transient energy balances on the DFT. As will be shown below, the energy balance method compares very well with the inverse method, again based on uncertainty analyses. The third method uses sets of linearized, convolution digital filters based on IHCP1D. These allow a near real-time calculation of the net heat flux [Keltner, N. R., 2007 (**16**); Keltner, N. R., et al., 2010 (**17**)]. See Section 1 for more detailed information on each analysis technique. Additional information is given in the Annexes and Appendices.

Various DFT designs have been used in a variety of applications including very large pool fires, LNG spill fires, marine fire safety testing, automobile fires, to study rocket launch accident fires, and in research of forest and wild-land fires. Appendix X1 provides a comprehensive list of applications where DFTs have been successfully used.

Advantages of DFTs are their relatively low cost, ease of construction, they require no calibration (see later), and require no cooling. They are robust and can survive intense fire environments without failure. Disadvantages include most are large compared with Gardon and S-B heat flux gauges and because they are not calibrated, one cannot reference the measurements to a NIST standard. Because no calibration is required, one must quantify the uncertainties present in the temperature measurements and the data reduction methods used to calculate the heat flux. Also, DFTs measure net heat flux; for a direct comparison with Gardon and S-B gauges, which are calibrated to incident (or "cold wall") flux, one must use a thermal model to estimate the incident flux.

The best applications for DFTs are where Gardon and S-B gauges cannot be used (for example, due to high temperatures, lack of cooling, soot deposition, fouling, and so forth), or when long life and overall costs are a consideration. Gardon and Schmidt-Boelter gauges are recommended in non-sooty environments, when it is possible to mount the gauges and cooling lines, and in predominantly radiative environments with a small convective contribution.

1. Scope

1.1 This test method describes the continuous measurement of the hemispherical heat flux to one or both surfaces of an uncooled sensor called a "Directional Flame Thermometer" (DFT).

1.2 DFTs consist of two heavily oxidized, Inconel 600 plates with mineral insulated, metal-sheathed (MIMS) thermocouples (TCs, type K) attached to the unexposed faces and a layer of ceramic fiber insulation placed between the plates.

1.3 Post-test calculations of the net heat flux can be made using several methods. The most accurate method uses an inverse heat conduction code. Nonlinear inverse heat conduction analysis uses a thermal model of the DFT with temperature dependent thermal properties along with the two plate temperature measurement histories. The code provides transient heat flux on both exposed faces, temperature histories within the DFT as well as statistical information on the quality of the analysis.

1.4 A second method uses a transient energy balance on the DFT sensing surface and insulation, which uses the same temperature measurements as in the inverse calculations to estimate the net heat flux.

1.5 A third method uses Inverse Filter Functions (IFFs) to provide a near real time estimate of the net flux. The heat flux history for the "front face" (either surface exposed to the heat source) of a DFT can be calculated in real-time using a convolution type of digital filter algorithm.

1.6 Although developed for use in fires and fire safety testing, this measurement method is quite broad in potential fields of application because of the size of the DFTs and their construction. It has been used to measure heat flux levels above 300 kW/m^2 in high temperature environments, up to about 1250 °C, which is the generally accepted upper limit of Type K or N thermocouples.

1.7 The transient response of the DFTs is limited by the response of the MIMS TCs. The larger the thermocouple the slower the transient response. Response times of approximately 1 to 2 s are typical for 1.6 mm diameter MIMS TCs attached to 1.6 mm thick plates. The response time can be improved by using a differential compensator.

1.8 The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

1.9 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *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 Standards:*[3]

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of

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[1] This test method was jointly developed by 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 standard.

[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.

the Guarded-Hot-Plate Apparatus

E119 Test Methods for Fire Tests of Building Construction and Materials

E176 Terminology of Fire Standards

E457 Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter

E459 Test Method for Measuring Heat Transfer Rate Using a Thin-Skin Calorimeter

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

E1529 Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies

E2683 Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages

2.2 *Other Standards:*

ISO 834-11:2014 Fire Resistance Tests—Elements of Building Construction—Part 11: Specific Requirements for the Assessment of Fire Protection to Structural Steel Elements[4]

IMO A754 Fire Resistance Tests: Fire Safety Onboard Ships[5]

2.3 *Other ASTM Document:*[6]

MNL12-4th Manual on the Use of Thermocouples in Temperature Measurement, Fourth Edition, 1993, Sponsored by ASTM Committee E20 on Temperature Measurement

3. Terminology

3.1 *Definitions*—Refer to Terminology E176 for definitions of some terms used in these test methods.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *incident radiative heat flux (irradiance; $q_{inc,r}$), n*—radiative heat flux impinging on the surface of the DFT or the unit under test.

3.2.2 *net heat flux, n*—storage in the DFT front plate + transmission (in other words, loss) to insulation layer. It is equal to the [absorbed radiative heat flux + convective heat flux] – [re-radiation from the exposed surface].

3.2.3 *total absorbed heat flux, n*—absorbed radiative heat flux + convective flux.

3.2.4 *total cold wall heat flux, n*—the heat flux that would be transferred by means of convection and radiation to an object whose temperature is 21 °C (70 °F).

3.2.5 *total heat flux (thermal exposure), n*—incident radiative heat flux + convective heat flux.

4. Summary of Test Method

4.1 This test method provides techniques for measurement of the net heat flux to a surface. Because Directional Flame Thermometers are un-cooled devices, they are minimally affected by soot deposition or condensation. Calibration factors or sensitivity coefficients are not required because alternate methods of data reduction are used. DFTs are simple to fabricate and use, but are more complicated when reducing the data. Gardon and Schmidt-Boelter gauges have relatively linear outputs with heat flux and only require a single sensitivity coefficient (for example, xx mv/unit of flux) to convert the output to an incident heat flux. DFTs have two thermocouple outputs as a function of time. Those outputs along with temperature dependent thermal properties and advanced analysis techniques are used with a thermal model to calculate the net heat flux. The net heat flux (with an energy balance) can be used to estimate the total cold wall heat flux, which is same as the measurement made by Gardon or S-B gauges [Janssens, 2007 (**18**)].

5. Significance and Use

5.1 *Need for Heat Flux Measurements:*

5.1.1 Independent measurements of temperature and heat flux support the development and validation of engineering models of fires and other high environments, such as furnaces. For tests of fire protection materials and structural assemblies, temperature and heat flux are necessary to fully specify the boundary conditions, also known as the thermal exposure. Temperature measurements alone cannot provide a complete set of boundary conditions.

5.1.2 Temperature is a scalar variable and a *primary variable*. Heat Flux is a vector quantity, and it is a *derived variable*. As a result, they should be measured separately just as current and voltage are in electrical systems. For steady-state or quasi-steady state conditions, analysis basically uses a thermal analog of Ohm's Law. The thermal circuit uses the temperature difference instead of voltage drop, the heat flux in place of the current and thermal resistance in place of electrical resistance. As with electrical systems, the thermal performance is not fully specified without knowing at least two of these three parameters (temperature drop, heat flux, or thermal resistance). For dynamic thermal experiments like fires or fire safety tests, the electrical capacitance is replaced by the volumetric heat capacity.

5.1.3 The net heat flux, which is measured by a DFT, is likely different than the heat flux into the test item of interest because of different surface temperatures. An alternative measurement is the total cold wall heat flux which is measured by water-cooled Gardon or S-B gauges. The incident radiative flux can be estimated from either measurement by use of an energy balance [Keltner, 2007 and 2008 (**16, 17**)]. The convective flux can be estimated from gas temperatures and the convective heat transfer coefficient, *h* [Janssens, 2007 (**18**)]. Assuming the sensor is physically close to the test item of interest; one can use the incident radiative and convective fluxes from the sensor as boundary conditions into the test item of interest.

5.1.4 In standardized fire resistance tests such as Test Methods E119 and E1529, or ISO 834 or IMO A754, the furnace temperature is controlled to a standard time-temperature curve. In all but Test Methods E1529, implicit assumptions have been made that the thermal exposure can be described solely by the measured furnace temperature history and that it will be repeatable from time to time and place to

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[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] Available from International Maritime Organization (IMO), 4, Albert Embankment, London SE1 7SR, United Kingdom, http://www.imo.org.

[6] Available from the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

place. However, these tests provide very different thermal exposures due to the use of temperature sensors with very different designs for furnace control. As a result, these different thermal exposure histories produce different fire ratings for the same item. Historical variations of up to 50 % or more in the qualitative fire protection ratings (for example, 1 h) between different furnaces or laboratories indicate that the assumptions for time-temperature control are not well founded. Also, due to different sensors, thermal exposure in a vertical furnace is generally higher than in a horizontal furnace, and thermal exposure on the floor of a horizontal furnace is generally higher than on the ceiling. These reasons provide support for why both temperature and heat flux measurements are needed to provide consistent test results.

5.1.5 In the mid-90's, the U. S. Coast Guard authorized a study of the problems in marine fire resistance tests, such as large variations in the ratings obtained in different furnaces. One important conclusion was that the thermal exposure in furnaces could not be predicted solely from furnace temperature measurements without large static and dynamic uncertainties [Wittasek, N. A., 1996 (**19**)].

5.1.6 One of the recommendations that resulted from NIST's investigation of the World Trade Center disaster was the need to move towards performance based codes and standards. A report developed for The Fire Protection Research Foundation expanded on this recommendation [Beyler, C., et al., 2008 (**20**)]. Part of this effort involves making a more comprehensive set of measurements in fire resistance tests including quantitative heat flux measurements. It also involves the development and use of "design fires" and defining their relationship with standardized test methods.

5.1.7 Work at Sandia National Laboratories on transportation accidents involving hazardous materials compares the Prescriptive and Performance based approaches [Tieszen, et al., 2010 (**21**)].

5.1.8 Work by the National Research Council of Canada used four (4) different temperature sensors to control a horizontal furnace. Differences in the thermal exposure (see definition in 3.2.5) were as high as 100 % during the first 10 min [Sultan, M., 2006 and 2008 (**22, 23**)]. Assuming the temperature measurements from the different sensors or different installations of the same sensor are actually the furnace temperature, one can predict very different thermal exposures depending on which temperature measurement method is used.

5.1.9 In another series of horizontal furnace tests, the National Research Council of Canada (NRCC) studied the effect of six (6) different temperature sensor designs on fire resistance tests in a large, horizontal furnace [Sultan, 2008 (**23**)]. NRCC used six different temperature sensors for furnace control: Test Methods E119 Shielded Thermocouple, ISO 834 Plate Thermometer, 6 mm MIMS TC from Test Methods E1529, Directional Flame Thermometers, and 1.6 mm MIMS TCs with grounded and ungrounded junctions. Total heat flux at the ceiling was measured using a Gardon gauge. Results showed that very different thermal exposures are possible depending on the measurement method used. During the first 10 min of a fire resistance test, the integrated heat flux varies by a factor of two.

5.1.10 Reports by Sultan, M., (2006 and 2008) (**22, 23**) and Janssens, M., (2008) (**18**) have shown it is difficult to measure one parameter in a fire resistance test (such as the furnace temperature) and calculate the other (heat flux or thermal exposure).

5.1.11 From the discussions in 5.1, it is highly recommended that both temperature and heat flux be measured independently in fire tests.

5.2 *Use for DFTs:*

5.2.1 Although both cooled and non-cooled sensors can be used to measure heat flux, the results are generally quite different. Water-cooled sensors are the direct reading Schmidt-Boelter or Gardon gauge designs that are used in some Committee E5 Methods (Test Methods E2683 and E511, respectively, have been developed for these sensors by Subcommittee E21.08).

5.2.2 There are three types of passive or un-cooled sensors that can be used to measure net heat flux. One is the hybrid sensor (so-called High Temperature Heat Flux Sensor, HTHFS) developed by Diller, et al., at Virginia Tech. It is designed to measure heat transfer to a surface without water cooling [Gifford, A., Hubble, D., Pullins, C., and Diller, T., 2010 (**4**)]. The HTHFS requires a calibration factor that is a function of sensor temperature [Pullins and Diller, 2010 (**24**)]. Another is the so-called "direct write heat flux sensor" which can be used at temperatures from 25 to 860 °C [Trelewicz, Longtin, Hubble, and Greenlaw, 2015 (**25**)]; this gauge requires a calibration coefficient. The third is the Directional Flame Thermometer (DFT), which was developed at Sandia National Laboratories (based on work in the UK) and elsewhere for measuring heat transfer in large sooty pool fires. DFTs do not require a calibration factor, which may be viewed as a mixed benefit. The passive sensors typically have higher temperature capability, based mainly on the Type K or N TC limit of about 1250 °C. Even though they are water cooled, quite often Gardon and Schmidt-Boelter gauges do not survive in temperatures due to fouling of the sensing surface, and other effects. DFTs usually survive up to about 1100 °C. They are very rugged, require no cooling, and are not susceptible to fouling of the sensing surface. These characteristics simplify installation in a wide range of fire and other applications. This standard will only address DFTs. See 10.2.2 for a more thorough discussion of heat flux gauge calibrations.

5.2.3 Early work on DFTs (and the data analysis techniques for them) focused on acquiring quantitative heat flux data to help define the thermal conditions in large, liquid hydrocarbon pool or spill fires. Large pool fires can reach quasi-steady conditions in times as short as a minute. As a result, Pool Fire DFTs were designed with 1.6 mm thick plates to provide rapid equilibration with the fire (the maximum heating rate in these fires was approximately 30 °C/s).

6. Apparatus

6.1 *DFT Construction:*

6.1.1 DFT apparatus consists of the DFT, mounting hardware, and a data acquisition system.

6.1.2 The DFT consists of two heavily oxidized Inconel plates with a ceramic fiber insulation layer sandwiched between the plates. Alternately, to obtain a high emissivity surface one can apply high emissivity paint to the exposed surface. If paint is used, one must be careful as at high temperatures some paints do not remain in place. A 1.6 mm OD, mineral-insulated, metal-sheathed (MIMS) thermocouple (TC) is attached to each unexposed face. Typically the sheath material is Inconel. To optimize the response in a variety of fire scenarios, there are three basic DFT designs. The original furnace DFT uses two 3 mm (nominal) thick plates; the original pool fire DFT uses two 1.6 mm (nominal) thick plates. Both Inconel and SS have been used; Inconel 600 is recommended because 304SS can sometimes form a scale that falls off the surface. The modified furnace DFT uses a 3 mm plate facing into the furnace with a 1.6 mm back plate. Different plate thicknesses are used for different applications. Some special designs have used a third plate and thermocouple. Some used in automotive fires were small and used intrinsic thermocouples[7] to provide very fast response. Fig. 1 shows the construction of a typical DFT, and Fig. 2 shows a photo of a typical DFT.

6.1.3 Plate thicknesses vary depending on the application. If faster response is desired a thinner plate is used (for example, 1.6 mm), or if slower response is acceptable, a thicker plate can be used (for example, 3 mm). It is advisable to never have the plate thickness less than the TC sheath diameter, so the effect of the TC on the plate temperature measurement is minimized [see Figueroa, 2005 (**26-28**) for a detailed analysis]. Due to

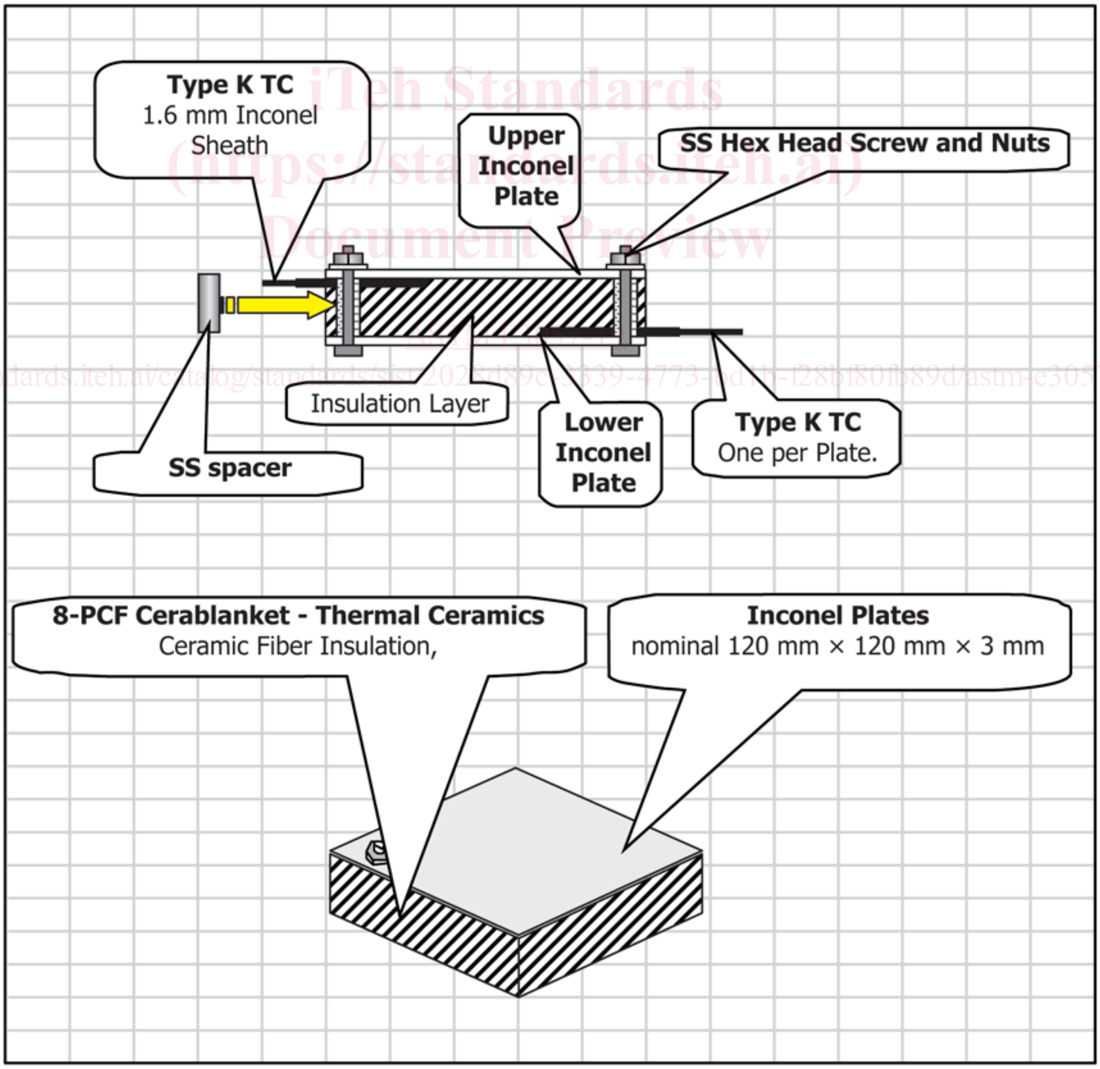

FIG. 1 Basic Design of a Directional Flame Thermometer (Using 3 mm Thick Plates)

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[7] Intrinsic thermocouples use bare wires welded to the metal surface of the DFT. This forms an "intrinsic" junction using the metal of the DFT. Intrinsic TCs have small dynamic errors compared with ungrounded junction (sheathed) TCs but are not very robust and fail more often. MIMS TCs are fully sheathed and encase the TC junction, and can be grounded or ungrounded.

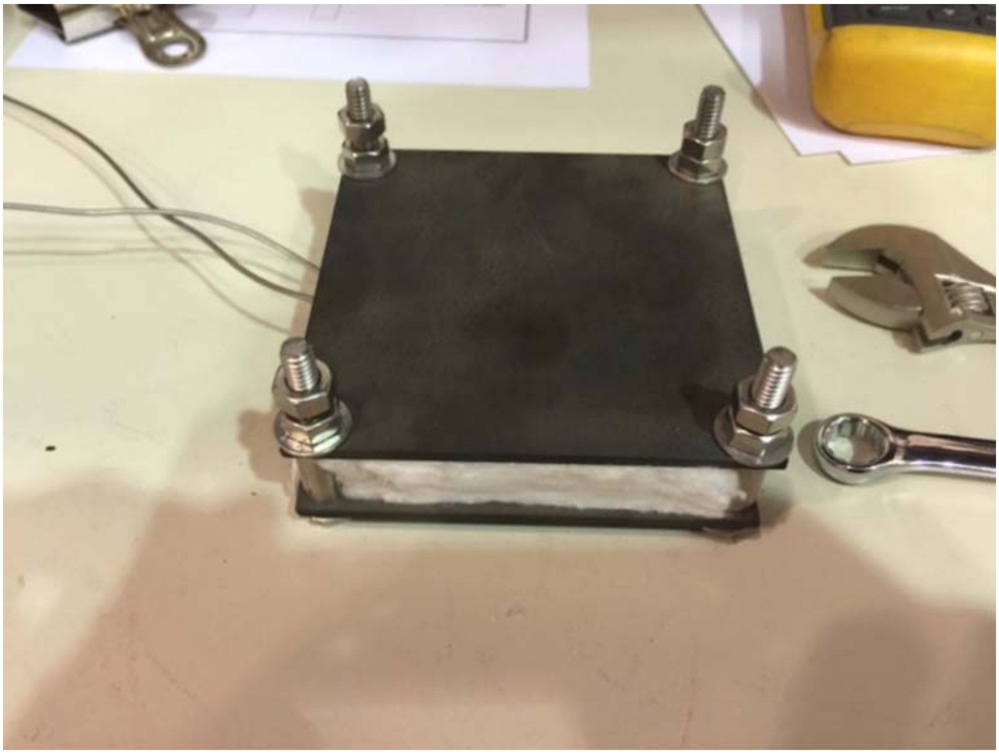

FIG. 2 Photo of Typical DFT

manufacturers recommended limits on MIMS thermocouples, TC sheath diameters less than 1.6 mm are not recommended.

6.1.4 The Inconel plates are mounted parallel with a layer of ceramic fiber insulation material lightly compressed in between the plates. The plates are held together with four bolts. One thermocouple is mounted on the inside surface of each of the Inconel plates. A 12 mm wide by 25 mm long strip of nickel or Nichrome foil (for example, 0.08 mm thick) is formed over the tip of the thermocouple and spot welded to the unexposed surface of each plate (see Fig. 3). This technique provides a good thermo-mechanical attachment of the thermocouples, which is critical for good dynamic response In general the

FIG. 3 Photo of Typical TC Installation

nichrome strip should be as small as possible while still ensuring good mechanical contact with the surface (see MNL12, page 183). Fig. 3 shows a typical TC installation.

6.1.5 Apparatus to mount the DFT near the test unit should be as small as possible to disturb the environment as little as possible. The DFT should be mounted so that one of the Inconel plates is facing the environment one wants to measure. The DFT has a 180° field of view, so the DFT should be oriented so that the entire environment is captured within that field of view.

6.1.6 The data acquisition system needs to be able to accurately record Type K or Type N thermocouples. Many such systems exist and we will not discuss them further here.

7. Preparation of Apparatus

7.1 *Fabrication of Directional Flame Thermometers:*

7.1.1 See Fig. 1 for a sketch of a DFT.

7.1.2 See Fig. 2 for a photograph of a DFT.

7.1.3 Cut or shear two 1.6 or 3 mm (1⁄16 or 0.12 in.) thick Inconel plates, 120 mm^2 (4.75 in.^{2}).

7.1.4 Drill 6.75 mm (letter drill H, 17⁄64 in.) holes in four corners, leaving approximately one hole diameter from each edge.

7.1.5 Heat the plates in a furnace at approximately 1000 °C for 24 h to develop a stable, high absorptivity oxide layer.[8] If this is not possible, one can substitute a high emissivity paint that adheres to the plate at high temperatures.

7.1.6 Use 1.6 mm (1⁄16 in.) OD Inconel sheathed Type K (Chromel/Alumel) or Type N thermocouples (TCs) with an ungrounded junction. Sand the oxide off the plate over a 3 by 1.5–3.9 cm (1.2 by 0.6–1.3 in.) area in the center of each plate.

7.1.7 Using 0.08 mm (0.003 in.) thick by 6.4 mm (0.25 in.) wide Nickel or Nichrome foil, form the foil strips tightly over last 25 mm (1 in.) of the TC and completely cover the TC tip. Then, spot weld the foil to the sanded area of the plate (do not spot weld to the TC sheath). Provide a loop for stress relief. Do not weld the TC because the welding process might penetrate through the sheath. See Fig. 3 (in the photo the strap is shorter than recommended).

7.1.8 Cut a 120 by 120 by 25 mm (4.75 by 4.75 by 1 in.) piece of 128 kg/m^3 (8 lb/ft^3) ceramic fiber insulation and place between the plates. Temperature dependent thermal properties of a Thermal Ceramics insulation called "Cerablanket" have been measured, and those properties are provided in Annex A1. If a different insulation is used, it is important to measure the properties of that material. There are other brands (for example, Kaowool by Morgan Thermal Ceramics, http://www.morganthermalceramics.com/products/refractory-ceramic-fibre-rcf/blanket) that can be used, but the temperature dependent, thermal properties would need to be measured.

7.1.9 Assemble the DFT using four 9.53 mm (~3⁄8 in. diameter) Inconel 600 or silver plated SS bolts and tubular spacers (for example, made of 304 stainless steel) to compress the insulation layer to a thickness of 19 mm (0.75 in.). This compression is important because the insulation thermal properties depend on thickness. See Annex A1.

7.1.10 Route the two TCs together out of the heated region. It is recommended that the TC sheaths be insulated until they reach a room temperature location.

7.2 *Fabrication of Mounting Hardware*—Mounting hardware is not unique. Any mounting design that holds the DFT in place but does not affect the environment is suitable. Any material that can withstand the temperatures in the environment of interest can be used. Mild steel can be used if the melt temperature is not exceeded. But recall that the strength of mild steel at high temperatures is reduced to approximately that of aluminum, so strength is much reduced. Stainless steel is the better, but more expensive option.

8. Hazards

8.1 This standard does not purport to address all of the safety concerns, if any, associated with the use of DFTs. 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.

8.2 **Warning—**The only known potential hazard is related to the insulation in the DFT. Long durations in unventilated areas with used insulation may be cause for concern because some of the ceramic fibers may become airborne. The user should contact the insulation manufacturer for information about proper safety procedures related to the insulation.

9. Procedure

9.1 Fabricate DFT in accordance with 7.1 and the mounting hardware in accordance with 7.2.

9.2 Mount the DFT so that the field of view of the DFT encompasses the entire heat source.

9.3 Route the two thermocouple leads to a room temperature location. The TC sheaths should be protected from the heat source by wrapping them with the same type of insulation used in the DFT. This protection can reduce the chance of "shunting" occurring. See Appendix X3.2.

9.4 Calibrate the DAS by using a NIST traceable source to place a known input into each channel at a select number of temperatures to ensure each DAS channel is reading properly.

9.5 Connect the TCs to a data acquisition system (DAS).

9.6 Do not calibrate the TCs used in the DFT, because for Type K TCs the calibration process can change the output of the TC and therefore change the calibration (**30**, **31**).

9.7 Set up DAS to scan at a rate of about 1 Hz. Because the time constant of the TCs can be several seconds, there is no reason to sample at a faster rate.

9.8 Measure pre- and post-test emissivity of the exposed DFT plate surfaces. These measurements can be used to estimate the incident heat flux.

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[8] Work at Sandia National Laboratories has shown the Inconel emissivity can vary considerably depending on the extent of the oxide layer. Values of about 0.85 have been measured [for example, Figueroa, 2006 (**26-28**)], but others [Brundage, A., et al (**29**)] measured emissivity between 0.67 and 0.90. For highest accuracy the user should either measure the emissivity measurements or apply high emissivity black paint with known emissivity.

9.9 Carefully review thermocouple results to ensure anomalies are not present (for example, a spike in temperature that has no basis for occurring).

9.10 Reduce data by means of one of the methods described below.

10. Calibration and Standardization

10.1 *Apparatus Calibration*—Two items should be calibrated when using DFTs, the data acquisition system and the thermocouples. However, the thermocouples should be "calibrated" in a manner different than is typically done.

10.1.1 *Thermocouple "Calibration"*—The ASTM standards for accuracy are sufficiently good for use in DFTs. It has been shown that Type K thermocouples are actually affected by the calibration process. As a result, the chemistry of the Chromel and Alumel wires change when calibrated above about 320 °C (**30**, **31**). TCs used in DFTs should be calibrated up to the maximum temperature expected (for example, 1100 °C). Therefore, one should not use the TC after calibration. This apparent conundrum is resolved in the following manner. One can obtain additional TCs fabricated from the same spool of wire from the manufacturer (preferably wire before and after the TCs used on the DFTs). Those additional TCs are sent through the calibration process. If those calibrated TCs meet or exceed the ASTM standard for Type K TCs (in other words, ±2.2 °C or ±0.75 % of reading in °C, see MNL12, 1993), then one assumes the remaining TCs from the same spool also meet the same ASTM standard. Experience has shown that in all cases the calibrated TCs were more accurate than the ASTM standard. But the more accurate values are not used; one uses the accuracy specifications from the MNL12, so as not to assume accuracy better than the standard.

10.1.2 *Data Acquisition System Calibration*—The recommended method to assure that the data acquisition system uncertainty is known is to calibrate each channel over the range of temperatures expected. For example, if one expects temperatures ranging from 20 to 1100 °C, one can calibrate at several set points over the range (for example, 20, 200, 400, 600, 800, 1100 °C). The calibration is performed using a NIST traceable thermocouple simulator (for example, Fluke and Ectron make such calibrators). A statistically significant sample (for example, 10s of samples) is taken at each set point, then the mean and standard deviation of each set point on each channel can be estimated. Because this can be a very large data set, one can average the data for all channels at all set points to provide a single estimate of the accuracy of all DAS channels. Typically this source of uncertainty is small, but on occasion one finds a bad channel so the exercise is worthwhile.

10.1.3 *Detailed Measurements of DFT*—Detailed measurements of the DFT materials should be made before assembly, because those measurements will be used in the data reduction process.

10.1.3.1 Measure and record the thickness of both Inconel plates as close to the center as possible. Estimate the accuracy of those measurements.

10.1.3.2 Measure and record the spacer thicknesses to confirm they are 1.91 cm (0.75 in.).

10.1.3.3 Verify insulation (8 lb/ft^3) is compressed to 1.91 cm thickness and is not forced out the sides of the plates. If the insulation is different from Cerablanket, measure the temperature dependent thermal properties. See Annex A1.

10.1.3.4 Verify the TCs are mounted according to the procedure in 7.1.

10.1.3.5 Verify the plate surfaces have a stable oxidation layer or stable paint layer (if one cannot oxidize the plates at 1000 °C, an alternate is to use a high absorptivity paint).

10.1.3.6 Measure and record the hemispherical total surface emissivity of exposed surfaces of each plate. This is used if one desires to convert the net heat flux to incident heat flux. Estimate the emissivity uncertainty by making multiple measurements and using the manufacturer's reported accuracy.

10.2 *Reference Standards and Calibration Curves and Tables:*

10.2.1 Refer to MNL12 for Thermocouple accuracies.

10.2.1.1 For type K thermocouples, MNL12 specifies the range to be from 0 to 1250 °C (32 to 2300 °F). The "standard tolerance" is ±2.2 °C or 0.75 % of the reading in °C, whichever is greater. The "special tolerance" is ±1.1 °C or 0.4 % of the reading in °C, whichever is greater.

10.2.2 *Discussion on Calibration of DFTs:*

10.2.2.1 Most heat flux gauges (for example, thin film, Gardon, Schmidt-Boelter) are designed to have a linear output with heat flux. Data reduction is easy because the gauge comes with a calibration in the form of a sensitivity coefficient (in other words, xx mV/unit of heat flux), and these sensitivity coefficients are made with reference to a NIST standard.

10.2.2.2 Traditional heat flux gauge calibrations use a radiative only heat source and seek to minimize convection effects (for example, NIST, Medtherm, and so forth). Details of those calibration procedures will not be discussed in detail here. Typical accuracies reported are ±3 %. An effort was initiated at NIST to develop a convective heat transfer calibration capability, but the effort was not completed and no such facility exists at NIST. A convective calibration capability does exist at Virginia Tech University under the guidance of Prof. Tom Diller.

10.2.2.3 A detailed analysis of heat flux gauges has led to a better understanding of under what conditions one can assume the linear sensitivity coefficients are an accurate representation of the behavior of the heat flux gauges. A body of evidence has shown that in fact the sensitivity coefficients developed for radiation only calibrations are not accurate for mixed heat transfer applications where convection is non-negligible. (See references in the Introduction.)

10.2.2.4 For both Gardon and Schmidt-Boelter gauges what has been discovered is that the gauge sensitivity for an equivalent level of radiant heat flux is different than for the same level of convective heat flux. One might reasonably ask: "So what?" How much does this affect readings? These are good questions that will be discussed below. First, a simple example will be discussed to show possible effects of the problem.

10.2.2.5 For a radiation only heat flux measurement, one records the voltage output and multiplies the output by the sensitivity coefficient provided by the manufacturer to get an estimate of heat flux. This is expressed in Eq 1:

$$q = v \cdot S \tag{1}$$

where:

q = the heat flux,
v = the voltage output, and
S = the sensitivity coefficient (unit of heat flux/volt).

10.2.2.6 What is normally done is the user assumes the sensitivity coefficient is the same for all modes of heat transfer, therefore one estimates the heat flux using Eq 1. But it has been shown that one should not assume the sensitivity coefficients are the same, therefore, a different data reduction method is appropriate. How then does the user reduce his data?

10.2.2.7 One method to reduce the data is to use a linear combination of the fluxes as shown in Eq 2:

$$q = v \cdot (F_{rad} \cdot S_{rad} + F_{conv} \cdot S_{conv}) \tag{2}$$

where:

F_{rad} and F_{conv} = the fractions of the total heat flux attributed to radiation and convection, and
S_{rad} and S_{conv} = the radiative and convective sensitivity coefficients.

10.2.2.8 What makes Eq 2 difficult to use is that most of the terms are not known to high accuracy. Only S_{rad} is known to good accuracy (from the manufacturer); none of the others are known except the output voltage.

10.2.2.9 Eq 2 assumes that both the radiative and convective sensitivity coefficients are linear with heat flux. This is true for radiative flux but it has not been shown the case for convection. But Eq 2 serves to make the point, as follows.

10.2.2.10 In Eq 2, assuming the radiative and convective sensitivity coefficients are equal, and the sum of the radiative and convective fractions equals 1.0, then Eq 2 is reduced to Eq 1. This is in fact what every user of heat flux gauges assumes, whether known or not, when using a calibration performed in radiation only.

10.2.2.11 For Gardon and S-B gauges the convective sensitivity coefficients can be quite different from radiative sensitivity coefficients. For example, Gifford, et al., 2010 (**4, 10**), showed that for S-B gauges the convection sensitivity coefficients can be up to about 20 % different than the radiation sensitivity coefficients. Further complicating matters is that the convective sensitivity coefficients are different for shear and stagnation flows. Similar results have been shown for Gardon gauges by Kuo and Kulkarni, 1991 (**8**).

10.2.2.12 Why would Gardon and S-B gauges have different sensitivity coefficients in radiative and convective environments? A qualitative understanding is possible by understanding how the gauges are constructed. Gardon gauges have a very thin sensing element that has a parabolic temperature profile from the center of the element to the edge when exposed to a uniform radiative heat flux. But during a convective shear flow, the temperature profile can "tilt" to the downstream side of the sensing element. There is good reason to expect that the sensitivity coefficient for a Gardon gauge in shear flow might be different than for the same magnitude of radiative heat flux.

10.2.2.13 Similarly, for S-B gauges, one assumes a uniform exposure of radiative flux over the sensing element. In shear flow this is not the case so again one might expect different sensitivities for radiative and convective fluxes.

10.2.2.14 Therefore, because sensitivity coefficients in radiative and convective heat transfer environments are different when using Gardon and S-B gauges, and there is no NIST traceable convective heat flux calibration capability, and because making an estimate (for example, using Eq 2) of the heat flux in mixed heat transfer environments has a number of uncertain parameters, it is difficult to fully understand the uncertainty of these types of gauges when used in a mixed mode heat transfer environment. Therefore, a different method to estimate heat flux was developed.

10.2.2.15 Characteristics of this "different" method were as follows:

(1) The gauge had to be rugged and survive temperatures up to about 1100 °C.

(2) The gauge should not be actively cooled.

(3) The gauge does not use a single sensitivity coefficient, so one does not suffer from the issues discussed above (different radiative and convective sensitivity coefficients).

(4) The gauge is simple so can be analyzed by means of a thermal model.

(5) The gauge responds to both radiation and convection so one measures the total heat flux to a surface.

10.2.2.16 DFTs satisfy all of the desired characteristics listed above. But the downside is the complication of data reduction and a more complicated uncertainty analysis. The uncertainty analysis for DFTs is more complicated, and depends on the data reduction method used (in other words, energy storage method, inverse heat conduction, inverse filter function).

10.2.2.17 With DFTs, one trades the convenience of having a linear sensitivity coefficient with known and traceable accuracy and a relatively complicated gauge design (S-B and Gardon) for a much simpler design (in other words, DFTs) with a more complicated data reduction and uncertainty analysis.

10.2.2.18 The discussion above sheds light on the advantages of using a gauge that does not require a calibration, assuming one has the tools to reduce the data and analyze the uncertainties when using DFTs.

11. Calculation or Interpretation of Results

11.1 *General:*

11.1.1 The data analysis techniques in this section use the DFT plate temperature histories and material properties to provide quantitative estimates of net heat flux data over the entire test duration. The inverse heat conduction analysis and energy storage methods both calculate the net heat flux post-test. The inverse filter function method provides near real-time estimates of net heat flux during a test.

11.1.2 Implicit in the energy storage method analyses is that the temperature measurements, made on the unexposed side of the plate, are sufficiently close to the exposed side temperature. This is due to the relatively high conductivity of the Inconel plate. The TCs are mounted on the unexposed side because the bias errors are lower and survivability is higher. This assumption can be confirmed with an inverse heat conduction analysis which provides an estimate of the exposed side plate temperature. The measurements are typically very close to that estimated from inverse heat conduction calculations (see Appendix X5 for an example). This approximation is more accurate for the 1.6 mm plate. The inverse heat conduction method does not suffer from this assumption.

11.1.3 Before the heat flux estimation techniques are described, an energy balance on the sensing surface will be developed, and how one should use the measurement will be discussed.

11.2 *Energy Balance on DFT:*

11.2.1 An energy balance on the surface of a DFT is important to understand how heat flux is estimated. All measurement devices (for example, DFTs, S-B and Gardon gauges) generate a voltage output based on the net energy absorbed into the sensing surface. But in gauges that are calibrated to a known standard (for example, Schmidt-Boelter and Gardon types), the gauge output is calibrated to the source, which is known to high accuracy and is traceable to NIST. Typically Gardon and Schmidt-Boelter gauges are calibrated to an incident heat flux.

11.2.2 The energy balance on any surface (DFT, test item, and so forth) is formulated as follows:

$$q_{net} = q_{inc,r} - q_{refl} - q_{emit} + q_{conv} \tag{3}$$

where:

q_{net} = net heat flux into the surface, which includes both radiative and convective contributions,
$q_{inc,r}$ = incident radiative heat flux, also called irradiance,
q_{refl} = reflected radiative heat flux, fraction of incident radiative heat flux reflected from the surface,
q_{emit} = emitted heat flux from surface, and
q_{conv} = convective heat flux, assumed positive into the surface; q_{conv} is expressed as Newton's Law of Cooling.

11.2.3 The net heat flux (q_{net}) is the absorbed heat flux minus the re-radiated flux. When using DFTs, the net heat flux is what is estimated from an inverse heat conduction analysis or energy storage method. For Gardon and S-B gauges, which are water cooled, the emitted flux is negligible and the convective flux is minimized by a careful design of the calibration apparatus. For Gardon or S-B gauges one normally calibrates the gauge output to the incident flux (any gauge generates an output proportional to the energy absorbed, which is the net flux, but Gardon and S-B gauges are calibrated to the incident flux).

11.2.4 Implicit in Eq 3 is there are no other sources of heat transfer present (for example, condensation).

11.2.5 The first two terms on the RHS of Eq 3 can be combined:

$$q_{inc,r} - q_{refl} = \alpha_{DFT} q_{inc,r} \tag{4}$$

11.2.6 The emitted heat flux can be expressed as follows:

$$q_{emit} = \varepsilon_{DFT} \cdot \sigma \cdot T^4_{DFT} \tag{5}$$

where:

α_{DFT} = the plate absorptivity, and
ε_{DFT} = the plate emissivity.

11.2.7 Rearranging Eq 3 and assuming $\varepsilon_{DFT} = \alpha_{DFT}$:

$$q_{inc,r} = (q_{net} / \varepsilon_{DFT}) + (\sigma \cdot T^4_{DFT}) + \left[\left(\frac{h}{\varepsilon_{DFT}} \right) \cdot (T_{DFT} - T_{gas}) \right] \tag{6}$$

11.2.8 In Eq 6, one can measure or estimate ε_{DFT} and h. T_{DFT} is measured. T_{gas} can be assumed equal to the fire or flame temperature. If CFD simulations are available, the temperature of the fluid near the DFT can be used for T_{gas}. Because 'h' and T_{gas} are assumed constant, one should consider this a quasi-steady energy balance. q_{net} can be estimated in three ways as discussed next.

11.3 *Inverse Heat Conduction Analysis Method:*

11.3.1 The inverse heat conduction analysis uses a one dimensional, nonlinear, transient thermal model of the DFT [in other words, Beck, J. V., 1985, 1999 (**32, 33**); Blackwell, B., 1987 (**34**)]. Temperature dependent thermal properties are used in this analysis. The inverse heat conduction analysis is used to obtain the net heat flux over the entire test duration. The inverse calculations use a dynamic thermal model of the sensor with the two DFT plate temperature measurements to calculate the net heat flux to the exposed surface. Inverse calculations are performed post-test. Note that the net flux estimated from an inverse heat conduction analysis is not unique. For example the results will change depending on the number of "future times" used during the calculation (the number of future times is an input to the program).

11.3.2 One example of an inverse heat conduction code is "IHCP1D" [Beck, J. V., 1999 (**33**)]. IHCP1D is a nonlinear inverse heat conduction analysis code from Beck Engineering Consultants, Okemos, MI. Another code is called "SODDIT" for Sandia One Dimensional Direct and Inverse Thermal code [Blackwell, B. F., 1980 (**34**)]. Other inverse heat conduction codes can also be used.

11.4 *Inverse Filter Functions (IFF) Analysis Method:*

11.4.1 For a near real time estimate of heat flux one can use Inverse Filter Functions (IFF) [Beck, J. V., 2008 (**35**); Keltner, N. R., 2008 (**17**)]. The IFFs can be programmed into data acquisition systems to cover a furnace temperature range of ambient to 950 °C. The IFFs are copyrighted: they will be provided under license to ASTM for use in ASTM Test Methods. They are specific to a DFT design and construction, require a 1 Hz data acquisition rate, 3 mm thick plates, and provide one second resolution of the heat flux. They have only been developed using IHCP1D. IFFs have not yet been developed for SODDIT. Using data from a Test Methods E119 furnace test, Fig. 4 shows a comparison of the heat flux histories calculated with IHCP1D and the Inverse Filter Functions. As can be seen the agreement is good. In this example, the oscillations in heat flux in the first 700 to 800 s are due to the very slow response of the furnace control thermocouple.

NOTE 1—8 PCF (128 kg/m^3) Cerablanket ceramic fiber insulation from Thermal Ceramics has been used in the development of the inverse filter functions for DFTs. The inverse filter functions are specific to the specified DFT design, the specified plate and insulation materials, and a data sampling rate of 1 Hz (1 s). The data in Annex A1 applies only to the 1 in. thick Cerablanket when it is compressed to 75 % of its original thickness (1.91 cm; 0.75 in.). Any changes in materials, material thicknesses, thermocouple design and attachment method or data sampling rate will invalidate the use of the filter functions.

11.5 *Energy Storage Method:*