Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies[1]

This standard is issued under the fixed designation E1529; 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

The performance of structural members and assemblies exposed to fire conditions resulting from large, free-burning (that is, outdoors), fluid-hydrocarbon-fueled pool fires is of concern in the design of hydrocarbon processing industry (HPI) facilities and other facilities subject to these types of fires. In recognition of this unique fire protection problem, it is generally required that critical structural members and assemblies be of fire-resistant construction.

Historically, such requirements have been based upon tests conducted in accordance with Test Methods E119, the only available standardized test for fire resistant construction. However, the exposure specified in Test Methods E119 does not adequately characterize large hydrocarbon pool fires. Test Methods E119 is used for representation of building fires where the primary fuel is solid in nature, and in which there are significant constraints on the movement of air to the fire, and the combustion products away from the fire (that is, through doors, windows). In contrast, neither condition is typical of large hydrocarbon pool fires (see Appendix X1 on Commentary).

One of the most distinguishing features of the pool fire is the rapid development of high temperatures and heat fluxes that can subject exposed structural members and assemblies to a thermal shock much greater than that associated with Test Methods E119. As a result, it is important that fire resistance requirements for HPI assemblies of all types of materials be evaluated and specified in accordance with a standardized test that is more representative of the anticipated fire conditions. Such a standard is found in the test methods herein.

1. Scope*

1.1 The test methods described in this fire-test-response standard are used for determining the fire-test response of columns, girders, beams or similar structural members, and fire-containment walls, of either homogeneous or composite construction, that are employed in HPI or other facilities subject to large hydrocarbon pool fires.

1.2 It is the intent that tests conducted in accordance with these test methods will indicate whether structural members of assemblies, or fire-containment wall assemblies, will continue to perform their intended function during the period of fire exposure. These tests shall not be construed as having determined suitability for use after fire exposure.

1.3 These test methods prescribe a standard fire exposure for comparing the relative performance of different structural and fire-containment wall assemblies under controlled laboratory conditions. The application of these test results to predict the performance of actual assemblies when exposed to large pool fires requires a careful engineering evaluation.

1.4 These test methods provide for quantitative heat flux measurements during both the control calibration and the actual test. These heat flux measurements are being made to support the development of design fires and the use of fire safety engineering models to predict thermal exposure and material performance in a wide range of fire scenarios.

1.5 These test methods are useful for testing other items such as piping, electrical circuits in conduit, floors or decks, and cable trays. Testing of these types of items requires development of appropriate specimen details and end-point or failure criteria. Such failure criteria and test specimen descriptions are not provided in these test methods.

1.6 *Limitations*—These test methods do not provide the following:

1.6.1 Full information on the performance of assemblies constructed with components or of dimensions other than those tested.

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[1] These test methods are under the jurisdiction of ASTM Committee E05 on Fire Standards and are the direct responsibility of Subcommittee E05.11 on Fire Resistance.

Current edition approved Nov. 1, 2016. Published December 2016. Originally approved in 1993. Last previous edition approved in 2014 as E1529 – 14a. DOI: 10.1520/E1529-16.

***A Summary of Changes section appears at the end of this standard**

1.6.2 An evaluation of the degree to which the assembly contributes to the fire hazard through the generation of smoke, toxic gases, or other products of combustion.

1.6.3 Simulation of fire behavior of joints or connections between structural elements such as beam-to-column connections.

1.6.4 Measurement of flame spread over the surface of the test assembly.

1.6.5 Procedures for measuring the test performance of other structural shapes (such as vessel skirts), equipment (such as electrical cables, motor-operated valves, etc.), or items subject to large hydrocarbon pool fires, other than those described in 1.1.

1.6.6 The erosive effect that the velocities or turbulence, or both, generated in large pool fires has on some fire protection materials.

1.6.7 Full information on the performance of assemblies at times less than 5 min because the rise time called out in Section 5 is longer than that of a *real* fire.

1.7 These test methods do not preclude the use of a *real* fire or any other method of evaluating the performance of structural members and assemblies in simulated fire conditions. Any test method that is demonstrated to comply with Section 5 is acceptable.

1.8 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.9 *This standard is used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products, or assemblies under actual fire conditions.*

1.10 *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.*

1.11 The text of this standard references notes and footnotes which provide explanatory information. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

B117 Practice for Operating Salt Spray (Fog) Apparatus
D822 Practice for Filtered Open-Flame Carbon-Arc Exposures of Paint and Related Coatings
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
E814 Test Method for Fire Tests of Penetration Firestop Systems
E2683 Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages

2.2 *Code of Federal Regulations:*[3]

46 CFR 164.007 Structural Insulations

2.3 *IMO Documents:*[4]

IMO A754

2.4 *ISO Standard:*[5]

ISO 834-1 Fire Resistance Tests – Elements of Building Construction – Part 1: General Requirements

2.5 *ISO/IEC Standards:*[6]

17011 Conformity assessment—General Requirements for accreditation bodies accrediting conformity assessment bodies
17025 General requirements for the competence of testing and calibration laboratories

3. Terminology

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *total cold wall heat flux*—the heat flux that would be transferred to an object whose temperature is 70°F (21°C).

4. Summary of Test Methods

4.1 A standard fire exposure of controlled extent and severity is specified. The test setup will provide an average total cold wall heat flux on all exposed surfaces of the test specimen of 50 000 Btu/ft ^{2}·h ± 2500 Btu/ft^2·h (158 kW/m^2 ± 8 kW/m^2). The heat flux shall be attained within the first 5 min of test exposure and maintained for the duration of the test. The temperature of the environment that generates the heat flux of procedures in 6.2 shall be at least 1500°F (815°C) after the first 3 min of the test and shall be between 1850°F (1010°C) and 2150°F (1180°C) at all times after the first 5 min of the test. Performance is defined as the time period during which structural members or assemblies will continue to perform their intended function when subjected to fire exposure. The results are reported in terms of time increments such as ½ h, ¾ h, 1 h, 1½ h, etc.

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[2] 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.

[3] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

[4] Available from the International Maritime Organization (IMO), Environmental Standards Division (CG-5224), U.S. Coast Guard Headquarters, 2100 Second Street SW, Washington, DC 20593; http://www.uscg.mil/environmental_standards/

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

[6] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

4.1.1 These test methods require quantitative measurements of thermal exposure during both furnace calibration and actual testing.

4.1.2 These test methods are cited as the "Standard Large Hydrocarbon Pool Fire Tests."

5. Significance and Use

5.1 These test methods are intended to provide a basis for evaluating the time period during which a beam, girder, column, or similar structural assembly, or a nonbearing wall, will continue to perform its intended function when subjected to a controlled, standardized fire exposure.

5.1.1 In particular, the selected standard exposure condition simulates the condition of total continuous engulfment of a member or assembly in the luminous flame (fire plume) area of a large free-burning-fluid-hydrocarbon pool fire. The standard fire exposure is basically defined in terms of the total flux incident on the test specimen together with appropriate temperature conditions. Quantitative measurements of the thermal exposure (total heat flux) are required during both furnace calibration and actual testing.

5.1.2 It is recognized that the thermodynamic properties of free-burning, hydrocarbon fluid pool fires have not been completely characterized and are variable depending on the size of the fire, the fuel, environmental factors (such as wind conditions), the physical relationship of the structural member to the exposing fire, and other factors. As a result, the exposure specified in these test methods is not necessarily representative of all the conditions that exist in large hydrocarbon pool fires. The specified standard exposure is based upon the best available information and testing technology. It provides a basis for comparing the relative performance of different assemblies under controlled conditions.

5.1.3 Any variation to construction or conditions (that is, size, method of assembly, and materials) from that of the tested assembly is capable of substantially changing the performance characteristics of the assembly.

5.2 Separate procedures are specified for testing column specimens with and without an applied superimposed load.

5.2.1 The procedures for testing loaded columns stipulate that the load shall be applied axially. The applied load is to be the maximum load condition allowed under nationally recognized structural design criteria unless limited design criteria are specified and a corresponding reduced load applied.

5.2.2 The procedure for testing unloaded steel column specimens includes temperature limits. These limits are intended to define the temperature above which a steel column with an axially applied design allowable load would fail structurally.

5.2.3 The procedure for unloaded specimens also provides for the testing of other than steel columns provided that appropriate acceptance criteria have been established.

5.3 Separate procedures are also specified for testing beam assemblies with and without an applied superimposed load.

5.3.1 The procedure for testing loaded specimens stipulates that the beam shall be simply supported. Application of restraint against longitudinal thermal expansion depends on the intended use, as specified by the customer. The applied load is intended to be the allowable design load permitted for the beam as determined in accordance with accepted engineering practice.

5.3.2 The procedure for testing unloaded beams includes temperature limits for steel. These limits are to define the temperature above which a simply supported, unrestrained beam would fail structurally if subjected to the allowable design load. The procedure for unloaded specimens also provides for the testing of other than steel and reinforced concrete beams provided that appropriate acceptance criteria have been established.

5.3.3 It is recognized that beam assemblies that are tested without load will not deflect to the same extent as an identical assembly tested with load. As a result, tests conducted in accordance with the unloaded beam procedure are not intended to reflect the effects of crack formation, dislodgement of applied fire protection materials, and other factors that are influenced by the deflection of the assembly.

5.4 A separate procedure is specified for testing the fire-containment capability of a wall/bulkhead/partition, etc. Acceptance criteria include temperature rise of nonfire exposed surface, plus the ability of the wall to prohibit passage of flames or hot gases, or both.

5.5 In most cases, the structural assemblies that will be evaluated in accordance with these test methods will be located outdoors and subjected to varying weather conditions that are capable of adversely affecting the fire endurance of the assembly. A program of accelerated weathering followed by fire exposure is described to simulate such exposure.

5.6 These test methods provide for quantitative heat flux measurements to support the development of design fires and the use of fire safety engineering models to predict thermal exposure and material performance in a wide range of fire scenarios.

CONTROL OF FIRE TEST

6. Fire Test Exposure Conditions

6.1 Expose the test specimen to heat flux and temperature conditions representative of total continuous engulfment in the luminous flame regime of a large free-burning fluid-hydrocarbon-fueled pool fire. See Appendix X1, which describes measurements in intermediate to large scale pool fires with calorimeters of different sizes and shapes, for the rationale used in the selection of the temperatures and heat flux specifications. Essential conditions are specified in 6.2 and 6.3. Use calibration assemblies to demonstrate that the required heat flux and temperature levels are generated in the test facility.

6.2 After the first 5 min, the test setup will provide an average total cold wall heat flux (6.2.1) on all exposed surfaces of the test specimen of 50 000 Btu/ft^2·h ± 2500 Btu/ft^2·h (158 kW/m^2 ± 8 kW/m^2). Adjust the flow of fuel and air, or vary other parameters, or both, within the individual test facility as necessary to achieve the specified setup. Attain the cold wall heat flux of 50 000 Btu/ft^2·h within the first 5 min of test exposure; maintain it for the duration of the test. (See 7.1 through 7.3 for measurement and control details.)

6.2.1 In all cases in these test methods, the heat flux values cited are total cold wall heat fluxes, where the wall temperature is 50°C.

6.3 The temperature of the environment that generates the heat flux specified in 6.2 shall be at least 1500°F (815°C) after the first 3 min of the test and shall be between 1850°F (1010°C) and 2150°F (1180°C) at all times after the first 5 min of the test. (See 9.1 – 9.4 for measurement and control details.)

6.4 Continue the fire-endurance test until the specified conditions of acceptance are exceeded or until the specimen has withstood the fire exposure for a period equal to that for which classification is being sought. Continue the test beyond the time at which the specified conditions of acceptance are exceeded, when the purpose in doing so is to obtain additional performance data.

7. Heat Flux Measurements

7.1 Measure the total heat flux as specified in 6.2 using both calibration and fire-resistance (actual) tests.

7.2 The sensors to be used for this measurement during calibration tests are *(1)* water-cooled Schmidt-Boelter Gauges (thermopile design) or Gardon Gauges (aka Circular Foil Heat Flux Gauges - differential thermocouple design) or *(2)* Directional Flame Thermometers, which are uncooled (passive) sensors.

7.2.1 When using water-cooled heat flux sensors, the temperature of the cooling water shall be above the dew point in the furnace (50°C is usually sufficient). Otherwise, large uncertainties will result due to condensation. Gardon Gauges are more sensitive to this error than Schmidt-Boelter Gauges.

7.2.2 Because the radiative sensitivity of Gardon Gauges is up to 25 % greater than the convective sensitivity, they shall not be used in this test method unless the gauge rating is at least 8 times greater than the specified total heat flux.

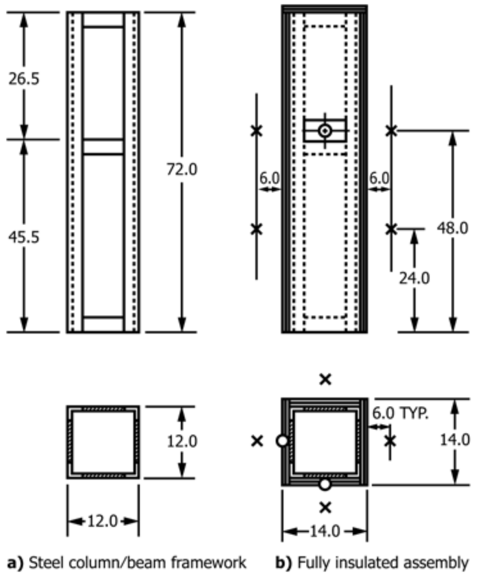
NOTE 1—Water-cooled heat flux gauges are discussed in Annex A1 for Gardon Gauges. See Test Method E511 (Subcommittee E21.08). E21.08 is developing a standard for Schmidt-Boelter Gauges.

7.2.3 When Directional Flame Thermometers (DFTs) are used, they shall be fabricated to meet the specifications contained in Annex A2. DFTs utilize two thermocouples. Methods for analyzing DFT data to obtain the heat flux history are given in Annex A2.

7.2.4 For columns or beams, the heat flux measurements will be made with a calibration assembly mounted in the appropriate orientation. The calibration assembly is to be fabricated from noncombustible materials. The dimensions and instrumentation are shown in Fig. 1.[7]

7.2.5 For fire-containment walls, the heat flux measurements will be made with a calibration assembly with a minimum of 5 points as shown in Fig. 2.

7.2.6 The sampling rate for all heat flux and DFT plate temperature measurements is required to be 1 Hz (1 s interval) to utilize certain data analysis tools; it is suggested that all measurements be made with a 1 s sampling rate.



a) Steel column/beam framework **b)** Fully insulated assembly

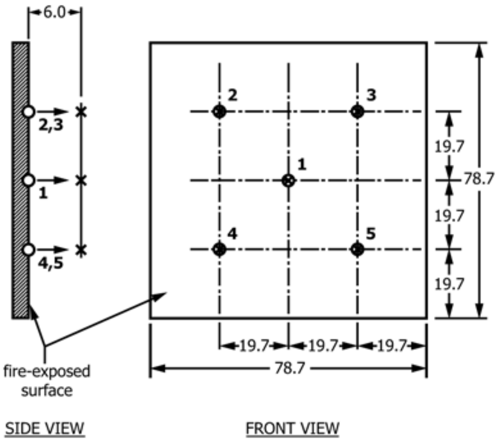
NOTE 1—**O** represents total heat flux sensor; **X** a gas temperature sensor.

NOTE 2—Heat flux measurements are required on two faces of the column.

NOTE 3—Temperature measurements are required on all faces.

NOTE 4—All dimensions are in inches.

FIG. 1 Calibration Assembly for Beams and Columns



NOTE 1—**O** denotes site of heat flux measurement, **X** a gas temperature sensor.

NOTE 2—Arrow denotes viewing direction of heat flux sensor.

NOTE 3—All dimensions are in inches.

FIG. 2 Calibration Assembly for Fire-Containment Walls

7.2.7 All measurements made within a 1 s interval (that is, recorded time ±0.5 s) shall be considered as having been made at the same time.

7.3 Directional Flame Thermometers (DFTs) shall be used during actual fire-resistance tests. They shall be fabricated to meet the specifications contained in Annex A2. DFTs utilize two thermocouples. Methods for analyzing DFT data to obtain the heat flux history are given in Annex A2.

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[7] The calibration assembly design shown in Fig. 1 is similar to one developed by Underwriters Laboratories for their test method UL 1709 and is used with permission. This test method does not require the use of an exact duplicate of the Underwriters calibration assembly.

7.4 At all times after the first 5 min of a calibration or fire endurance test, the total heat flux shall be:

7.4.1 At any one point, between 37 500 and 62 500 Btu/ft^2·h (118 to 197 kW/m^2). That is, 50 000 Btu/ft^2·h (158 kW/m^2) ± 25 %).

7.4.2 For the average of the total number of measurement sites, between 47 500 and 52 500 Btu/ft^2·h (50 000 Btu/ft^2·h (158 kW/m^2) ± 5 %.

8. Furnace Pressure Measurement

8.1 When testing any assembly that forms part of the wall of a test furnace (for example, walls, ceilings, floors, bulkheads, decks, doors, etc.), the furnace pressure shall be measured. The procedure is adapted from the differential pressure section of Test Method E814.

8.2 Measure the gauge pressure at three points 0.78 in. (20 mm) from the surface and located as follows:

8.2.1 *Vertical Surfaces,* at the center and quarter points on the vertical center line.

8.2.2 *Horizontal Surfaces,* at the center and quarter points on the longitudinal center line.

8.3 The pressure measuring probe tips shall be as shown in Fig. 3; this design is identical to the one shown in Fig. 4 of Test Method E814. The probe tips are to be manufactured from stainless steel or other suitable material.

8.4 Measure the pressure by means of a manometer or equivalent transducer. The manometer or transducer shall be capable of reading 0.01 in. H_2O (2.5 Pa) increments with a measurement precision of 0.005 in. H_2O (12.5 Pa).

9. Furnace Measurements – Furnace (Gas) Temperature and Thermal Exposure

9.1 *Furnace Temperature*—Measure the temperature of the gases adjacent to and impinging on the calibration or test specimens, as specified in 6.3. Mineral-Insulated, Metal-Sheathed (MIMS) thermocouples shall be used. Use Inconel-sheathed, 0.25-in. outside diameter (OD), Type K, (Chromel-Alumel) thermocouples. The time constant of the MIMS thermocouple assemblies shall be less than 60 s in air flowing at 65 ft/s (20 m/s). Use standard calibration thermocouples with an accuracy of ±0.75 %. A minimum length of 20 diameters (125 mm) of the sheathed junction end of the thermocouple shall be mounted parallel to the surface of the test specimen.

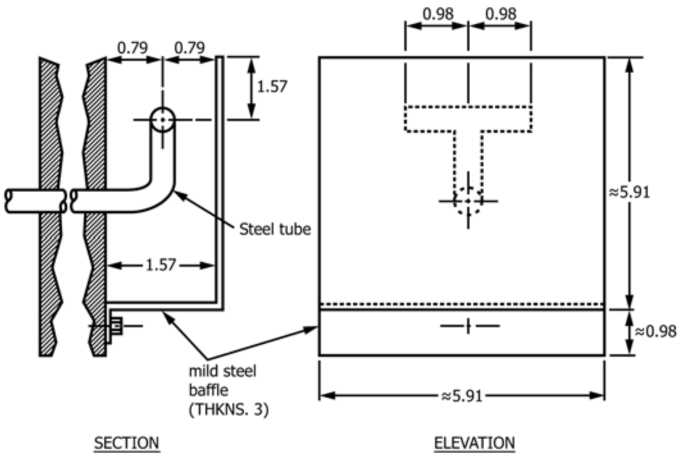

FIG. 3 Static Pressure-Measuring Device Dimensions in Millimetres

9.2 Obtain the gas temperature from the readings of not less than five thermocouples for a nonbearing wall specimen, and not less than eight thermocouples for a column or beam specimen. The thermocouples shall be symmetrically disposed and distributed to show the temperatures of the environment near all parts of the specimen.

9.2.1 For columns and beams, the thermocouple junction shall be placed 6 in. (152 mm) away from the exposed faces of the specimen at the beginning of the test, and during the test shall not touch the specimen as a result of specimen growth or deflection.

9.2.2 In the case of fire-containment walls, the thermocouple junctions shall be placed 6 in. (152 mm) away from the exposed face of the specimen at the beginning of the test, and shall not touch the specimen during the test as a result of specimen growth or deflection.

9.3 Measurements of the gas temperature will be made with a maximum sampling interval of 10 s at each required measurement site. Data recorded within ±10 s will satisfy the minimum requirements for calibration and control called out in Section 6.

9.4 At all times after the first 5 min of the test, the average gas temperature shall be between 1850°F (1010°C) and 2150°F (1180°C)

9.5 *Thermal Exposure*—To obtain total thermal exposure in these test methods, Directional Flame Thermometers (DFT) shall be used in both calibration and testing to provide quantitative heat flux measurements.

NOTE 2—Annex A2 provides specifications on the fabrication and use of DFTs. Appendix X2 explains the need for quantitative measurements and the rationale for selecting DFTs.

9.6 During a test run, one DFT will be mounted 6 in. (152 mm) from and parallel to the test unit wall of the furnace or 6 in. (152 mm) in front of one side of a column unit. A second DFT will be mounted 6 in. (152 mm) in front of the calibration unit during calibration runs.

9.7 Measurements of the DFT plate temperatures will be made with a sampling interval of 1 s. This is required for using the Inverse Filter Functions to calculate heat flux and thermal exposure.

10. Test Facility Design

10.1 These test methods specify the environment to which a specimen shall be exposed, but do not specify test facility design. This approach was taken for several reasons:

10.1.1 It is consistent with the approach of Test Methods E119,

10.1.2 It is important not to inhibit the creativity of experimenters in achieving the specified test environment, and

10.1.3 It is not desired to eliminate any existing facilities (or modification of them) or to eliminate the use of an actual fire *a priori.*

11. Calibration and Control of Furnace Type Test Facilities

11.1 If the test facility is of the furnace type, use the measurement and control procedures described in 11.2 – 11.6.

11.2 Calibration runs shall meet the following configurational and procedural criteria:

11.2.1 During all calibration runs, an instrumented calibration specimen shall be in place during the entire test. The calibration specimen shall be fabricated of noncombustible materials and shall be as follows:

11.2.1.1 For columns and beams, the box shape of Fig. 1, or its equivalent, oriented in the same position and inclination (for example, vertical or horizontal) as the subsequent materials test specimen would be.

11.2.1.2 For fire-containment wall specimens, the calibration specimen shall consist of 25 mm of ceramic insulating board[8] facing the fire. The board shall be suitably supported in a frame, and if necessary, its backface (that is, nonfire-exposed surface) shall be insulated with inorganic blanket insulation such that the temperature of the backface of the entire (composite) specimen does not exceed the criteria of 17.6.2.

11.2.2 Instrument the calibration specimen to make measurements that are specified as follows:

11.2.2.1 *Total Heat Flux*—See 7.1 through 7.4.

11.2.2.2 *Gas Temperature*—See 9.1 – 9.4 and *Thermal Exposure*, see 9.5 – 9.7.

11.2.3 The time duration of the calibration run shall be:

11.2.3.1 At least as long as the longest subsequent materials test for which it shall apply, or

11.2.3.2 Until the test facility has reached a steady condition such that the average cold wall heat flux and the average gas temperature are within ±5 % of the specified values over a continuous period of 15 min.

11.3 A successful calibration run shall meet the following criteria:

11.3.1 *For Total Heat Flux*—See 6.2 and Section 7.

11.3.2 *For Gas Temperature and Thermal Exposure*—See 6.3 and Section 9.

11.4 A furnace type facility shall be considered calibrated after an initial test that meets the requirements of 11.2 and 11.3.

11.5 After the initial calibration, recalibrate the test facility if any repair or modification is made to the heat generation, heat retention, flow or other characteristics of the furnace that is capable of affecting the initial calibration. Between calibrations, record any repairs, modifications, or maintenance made to the facility.

11.6 Once the test facility has been successfully calibrated, materials for testing shall be subjected to a fire environment simulated by reproducing the time-temperature curves recorded during the furnace calibration.

11.6.1 The accuracy of the furnace control shall be such that:

11.6.1.1 The area under the integrated heat-flux curve developed from Directional Flame Thermometer measurements of 9.1 – 9.3 is within 10 % of the corresponding curve developed in the furnace calibration for tests of ½ h or less duration, within 7.5 % for those over ½ h and not more than 1 h, and within 5 % for tests exceeding 1 h in duration.

11.6.1.2 The area under the time-temperature curve of the average of the gas temperature measurements of 9.1 – 9.3 is within 10 % of the corresponding curve developed in the furnace calibration for tests of ½ h or less duration, within 7.5 % for those over ½ h and not more than 1 h, and within 5 % for tests exceeding 1 h in duration.

TEST CONFIGURATIONS

12. Test Specimen

12.1 The test specimen shall be representative of the construction for which classification is desired as to materials, workmanship, and details such as the dimensions of various components. Build the test specimen under conditions representative of those encountered in actual construction to the extent possible. Determine the physical properties of the materials and components used in the construction of the test specimen where possible.

12.2 For fire-protected steel columns and beams, both the weight (*w*) and heated perimeter (*d*) of the steel member significantly influence fire endurance as determined in accordance with these test methods. Consideration of the *w/d* ratio is paramount when designing a test program in order to directly compare the performance of different fire protection materials applied to structural steel beams and columns. It is desirable to conduct tests on a common size member, such as a W10 by 49 (W250 by 73) column to accommodate ease of making relative comparisons of thermal performance.

12.3 For fire containment steel wall specimens, the thickness of the steel plate will influence fire endurance as determined by these test methods. When designing the test program, however, in order to directly compare the performance of different fire protection materials applied to steel wall specimens, tests shall be performed using a standard steel wall thickness of 0.18 ± 0.02-in. (4.5 ± 0.5-mm). The 0.18 ± 0.02-in. thick specimen is specified by IMO Resolution A.517(13) and as such, has had a large number of tests conducted on it.

13. Conditioning

13.1 Protect the test specimen during and after fabrication to ensure the quality of its condition at the time of test. The specimen shall not be tested until after its strength has at least attained its design strength.

13.2 If the test specimen contains moisture, solvents, plasticizers, curing compounds, or similar agents, condition the specimen prior to the test with the objective of providing a condition within the specimen which is representative of the intended end-use environment of the assembly. When accelerated drying techniques are used to achieve this objective, avoid

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[8] Marinite XL, a registered trademark of Johns-Manville Co., Manville Corp., Product Information Center, P.O. Box 5108, Denver, CO 80217, has been found suitable for this purpose. It has the following thermal properties: density of 46 lb/ft^3 (737 kg/m^3), thermal conductivity (at 350°F (177°C)) of 0.89 Btu.in./h·ft^2·°F (0.13 W/m·°K), and specific heat (at 200°F (93°C)) of 0.28 Btu/lb. °F (117 J/kg·K).

drying procedures that will alter the structural or fire endurance characteristics of the test specimen from those produced as a result of air drying under ambient atmospheric conditions. Record the temperature and humidity of the test specimen at the time of the fire test. (See 13.4.)

13.3 For some assemblies, it is difficult or impossible to achieve the objective of 13.2 even after an excessively lengthy period of time. In the event that specimens, air dried in a heated building, fail to meet this objective after a 12-month conditioning period or in the event that the nature of the assembly is such that it is evident that drying of the specimen interior is prevented due to hermetic sealing, the requirements of 13.2 are waived. In such cases, test the specimen after its strength has at least attained its design strength. Record the temperature and humidity of the test specimen at the time of the fire test. (See 13.4.)

13.4 If the specimen contains moisture or solvents, measure the actual content of such agents within 72 h prior to the test. Obtain this information by weight determinations, moisture meters, or any other appropriate techniques deemed suitable by the testing laboratory. If the condition of the tested specimen is capable of significantly changing within 72 h preceding the test, the actual content of moisture, solvents, and similar agents shall be made within 24 h prior to the test.

14. Accelerated Weathering and Aging Tests

14.1 Test procedures are specified in 14.2 – 14.9 that represent a recommended minimum test program for evaluating the weatherability for fire protection materials and assemblies using accelerated weathering and aging tests. These tests are applicable for fire protection materials for structural steel. Determination of the applicability of these test methods to other materials and assemblies is left to those interested parties involved. Further, because it is recognized that accelerated aging/weathering testing is an art and not a science, requirements for preconditioning tests prior to aging/weather exposure (for example, tensile stressing of brittle materials), and additional exposure environments for some fire protection materials for structural steel or other materials and assemblies, are left to the parties involved that have a particular concern about a particular material or an assembly in a particular environmental exposure.

NOTE 3—By defining a specific test program for protection materials for structural steel, it is not to be construed that the fire protection properties of these materials are especially vulnerable to weathering effects. Rather, it is a reflection of the state of the art that such a test program exists for these materials.

14.2 For evaluation of a protective material, apply the material to 2-ft long, 6 by 6 in. steel tubes with a $\frac{3}{16}$-in. wall thickness. Provide each end of each steel tube with steel caps covered with the protection material being investigated.

14.3 Locate four Type K thermocouples having a time constant not greater than 2 s on each steel tube. The thermocouples shall measure the temperature at the center of each face of the steel tube.

14.4 The protective material thickness shall be sufficient to provide an endurance time of approximately 70 ± 29 min in accordance with 16.2.5.

14.5 Prepare a minimum of seven samples. Expose at least six samples to the environments and use at least one sample as a control for comparison purposes. Expose a sample to only one environment before it is subjected to the fire endurance test.

14.6 The accelerated weathering or aging environments shall consist of:

14.6.1 *Accelerated Aging*—A circulating air oven maintained at 160 ± 5°F (71 ± 3°C) and the air circulated at a rate to change the air volume in the oven each 8 h. The exposure time shall be at least 6480 h (270 days).

14.6.2 *Accelerated Weathering Exposure*—A weatherometer in accordance with Practice D822. The exposure time shall be at least 720 h (30 days).

14.6.2.1 Samples are mounted on a rotating drum within the weatherometer. Operation of the weatherometer requires samples to be balanced and the sample weight not exceed the limits of the equipment.

14.6.3 *Wet/Freeze/Thaw Exposure*—Twelve cycles of simulated rainfall at 0.7 in. (17.8 mm) per hour for 72 h, followed by an immediate (while the specimen is still wet from the simulated rainfall) exposure to −40 ± 5°F (−40 ± 3°C) for 24 h, and then an immediate (while the specimen is still cold from the freeze exposure) exposure to +140 ± 5°F (+60 ± 3°C) for 72 h.

14.6.4 *High Humidity Exposure*—A chamber maintained at 100 % relative humidity (+0, −3 %) and 95 ± 5°F (35 ± 3°C). The exposure time shall be at least 4320 h (180 days).

14.6.5 *Heavy Industrial Atmospheric Exposure*—A chamber maintained at 95 ± 5°F (35 ± 3°C). There shall be a pan filled to a depth of 1 in. (25.4 mm) with water in the bottom of the test chamber. Maintain the gaseous mixture in the test chamber from 97 to 98 % air, 1 to 1.5 % sulphur dioxide, 1 to 1.5 % carbon dioxide (by volume). The exposure time shall be at least 720 h.

14.6.6 *Salt Spray or Salt Fog*—If this type of exposure is required, perform the test in accordance with Test Method B117.

14.7 Note any changes in the physical integrity, adhesion, or general appearance of fire protection materials or assemblies tested under the conditions of 14.6.

14.8 Subject seven samples to the fire exposure defined in Section 6. Determine the time to reach an average temperature of 1000°F (538°C) as measured by the thermocouples attached to a tube.

14.9 A fire protection material shall be judged to have not been affected by aging or weathering if the average endurance time to 1000°F for each sample exposed to the conditions of 14.6 is at least 75 % of the endurance time determined for the control sample.

TEST METHOD A—COLUMN TESTS

15. Procedure

15.1 *Loaded Specimens:*

15.1.1 Test the column assembly in a vertical orientation. The length of the assembly subjected to the fire exposure shall be not less than 9 ft (2.74 m). Apply the contemplated details of connections and their protection, if any, according to methods of field practice. Subject the assembly to the specified fire exposure simultaneously on all sides.

15.1.2 Throughout the fire endurance test, apply a superimposed load to the column to simulate the maximum load condition allowed under nationally recognized structural design criteria unless limited design criteria are specified with a corresponding reduced load. Calculate the applied load so as to be consistent with the degree of the end fixity inherent in the laboratory's system for transmitting the load to the column assembly. Make provisions for transmitting the load to the exposed portion of the column without increasing the effective column length.

15.1.3 The column assembly shall sustain the superimposed applied load during the fire endurance test for a period equal to that for which classification is desired.

15.2 *Unloaded Steel Specimens:*

15.2.1 The following test procedure does not require application of a superimposed load at any time. This procedure is used to evaluate the fire endurance of steel columns where the applied fire protection materials are not intended to carry any of the superimposed load acting on the column.

15.2.2 Use of this procedure for the testing of other than steel columns is allowed provided that appropriate endpoint or acceptance criteria have been established and substantiated. Base such acceptance criteria upon the temperature of the column assembly and other parameters that influence the load carrying capacity of the column (such as depth of char for timber columns). Unless otherwise specified, base the acceptance criteria upon an axially loaded specimen using the allowable design load for the specific column assembly as the applied load.

15.2.3 Test the column assembly in a vertical orientation. The length of the test specimen subjected to the fire exposure shall be not less than 8 ft (2.44 m). Apply the contemplated details of connections and their protection, if any, according to methods of field practice. Subject the column to the specified fire exposure simultaneously on all sides.

15.2.4 Restrain the applied protection against longitudinal temperature expansion greater than that of the steel column with rigid steel plates or reinforced concrete attached to the ends of the steel column before the protection is applied. The size of the plates or amount of concrete shall provide direct bearing for the entire transverse area of the protection. Provide the ends of the specimen, including the means for restraint of the applied protection, with thermal insulation to limit direct heat transfer from the furnace.

15.2.5 Measure the temperature of the column assembly at four levels throughout the fire endurance test. The upper and lower levels shall be located 2 ft (0.61 m) from the ends of the column and the intermediate levels shall be equally spaced. Position at least three thermocouples at each level so as to measure the temperature of significant elements of the steel column. Use metal or ceramic sheathed thermocouples if the nature of the protection material is such that other types of thermocouples will not function properly (for example, short-out in a charring type protection material or one that releases significant amounts of water).

15.2.6 The average temperature at each of the four levels shall not exceed 1000°F (538°C), and the maximum temperature recorded by any individual thermocouple shall not exceed 1200°F (649°C), for a period equal to that for which classification is desired.

TEST METHOD B—BEAM TESTS

16. Procedure

16.1 *Loaded Specimens:*

16.1.1 Test the beam assembly in a horizontal orientation. The length of the assembly subjected to the fire exposure shall be not less than 12 ft (3.7 m). Subject the assemblies to the specified fire exposure simultaneously on all sides (Note 4). The ends of the beam shall be simply supported and the beam shall not be restrained against longitudinal thermal expansion.

NOTE 4—Because this test method is aimed at fires generally occurring at HPI and similar facilities where flooring is not a great concern on structural beams, the fire test method for beam assemblies specifies that the beam be totally engulfed. This varies from Test Methods E119, in which the beam is an integral part of a ceiling assembly, and therefore is subjected to fire from only three sides.

16.1.2 Throughout the fire endurance test, apply a superimposed load to the beam to simulate maximum load condition. This load shall be the maximum load condition allowed under nationally recognized structural design criteria unless limited design criteria are specified and a corresponding reduced load applied.

16.1.3 The beam shall sustain the superimposed load during the fire endurance test for a period equal to that for which classification is desired.

16.1.4 The procedure for testing loaded specimens stipulates that the beam shall be simply supported and un-restrained. However, this procedure allows for testing of other than simply supported or un-restrained, or both, end conditions for experimentation of special approvals, provided that the support condition is documented in the test report, and if applicable, endpoint or acceptance criteria have been established and substantiated.

16.2 *Unloaded Steel Specimens:*

16.2.1 The following test procedure does not require the application of a superimposed load at any time. This procedure is used to evaluate the fire endurance of steel beams where the applied protection materials are not intended to carry any of the superimposed load acting on the beam.

NOTE 5—This procedure is used for the testing of other than steel beams provided that appropriate endpoint or acceptance criteria have been established and substantiated. Such acceptance criteria shall be based upon the temperature of the beam assembly and other parameters that are capable of influencing the load carrying capacity of the beam (such as depth of char for timber beams).

16.2.2 Test the beam assembly in a horizontal orientation. The length of the test specimen subjected to the fire exposure shall be not less than 12 ft (3.67 m). Subject the beams to the specified fire exposure simultaneously on all sides (Note 4).

16.2.3 Restrain the applied protection against longitudinal temperature expansion greater than that of the steel beam or girder with rigid steel plates or reinforced concrete attached to the ends of the steel member before the protection is applied. The size of the plates or amount of concrete shall be adequate to provide direct bearing for the entire transverse area of the protection. Provide the ends of the member, including the means for restraint of the applied protection, with thermal insulation to limit direct heat transfer from the furnace.

16.2.4 Measure the temperature of the steel in the beam or girder with not less than four thermocouples at each of four sections equally spaced along the length of the beam and symmetrically disposed and not nearer than 2 ft (0.6 m) from the inside face of the test facility. Symmetrically place the thermocouples at each section so as to measure significant temperatures of the component elements of the steel section. Use metal- or ceramic-sheathed thermocouples if the nature of the protection material is such that other types of thermocouples will not function properly.

16.2.5 The average temperature at each of the four levels shall not exceed 1000°F (538°C), and the maximum temperature recorded by any individual thermocouple shall not exceed 1200°F (649°C), for a period equal to that for which classification is desired.

16.2.6 See 5.3.2.

16.2.7 *Piping*—Use of these procedures for the testing of items other than steel beams, such as piping is allowed. However, failure criteria are not provided in these test methods for these types of assemblies. As a result, these types of tests should not be conducted unless appropriate endpoint or acceptance criteria have been established and substantiated. Base such acceptance criteria upon the temperature of the assembly and any other parameters that may influence its performance.

TEST METHOD C—TESTS OF FIRE-CONTAINMENT CAPABILITY OF WALLS

17. Tests of Fire-Containment Capability of Walls

17.1 The purpose of this test method is to evaluate the fire-containment capability of members having structural, fire containment, or other functions, or combinations thereof, such as walls, partitions, or bulkheads in buildings, and marine structures and offshore petroleum chemical platforms. For brevity, the term *wall* is used in provisions that also apply to other barrier, or containment element configurations such as *partitions* or *bulkheads*.

17.2 *Size of Specimen*—The test specimen shall have a fire-exposed surface of not less than 50 ft^2 (4.65 m^2) and a height of not less than 8 ft (2.44 m). Restrain the test specimen on all four edges. See 12.3.

17.2.1 Adjust the specimen size when required to correspond with the size specified in a particular regulation. For example, 46 CFR 164.007, which concerns the performance of materials intended for use as structural insulation on merchant vessels, requires the samples to be 40 by 60 in. (1.02 by 1.52 m).

17.3 *Steel Wall*—The specimen shall have a structural core of flat steel plate, suitably stiffened, representative of the intended actual construction. In the absence of a specific construction design, the specimen shall have a structural core of stiffened flat steel plate designed and fabricated in accordance with the specifications shown in Fig. 4. When the actual construction will contain one or more joints, the specimen shall be tested with at least one joint.

NOTE 6—This procedure is used for the fire-containment listing of other than steel walls provided that an appropriate wall design has been defined and appropriate endpoint or acceptance criteria have been established and substantiated. Such acceptance criteria shall be based upon the temperature of the nonfire exposed face of the wall and other parameters that influence the intended fire-containment performance of the wall.

17.4 The surface of the wall assembly designated the exposed side shall be subjected to the specified fire exposure of 6.2 through 6.3.

17.5 *Temperature Measurements During Testing:*

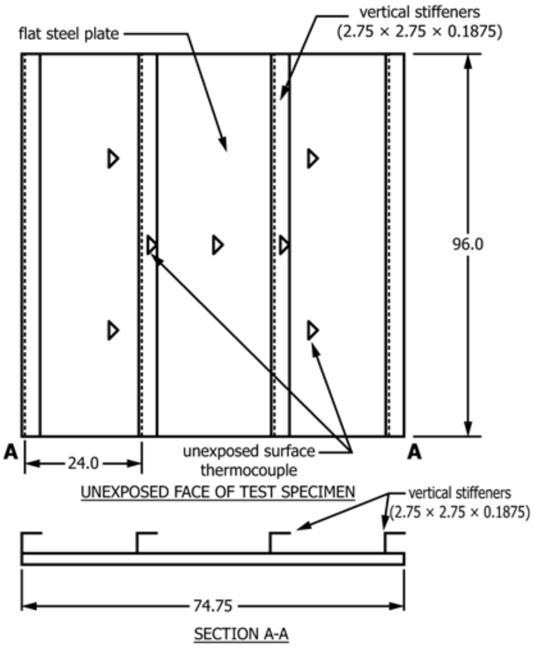
17.5.1 Measure the surface temperatures on the unexposed side of the test specimen throughout the fire test by thermocouples located as follows and indicated in Fig. 4:

17.5.1.1 Four thermocouples, each located approximately in the center of a quarter section of the test specimen.

17.5.1.2 One thermocouple located close to the center of the test specimen, but away from the joint, if any.

17.5.1.3 One thermocouple is placed within the partially enclosed area of each of the two central stiffeners, if such stiffeners are present. For a specific construction design, where the stiffeners form an enclosed channel, locate these thermocouples on areas of the unexposed wall surface adjacent to the two central stiffeners.

17.5.1.4 At least one thermocouple at a joint, if any is included in the specimen being tested.



NOTE 1—The overall dimensions shown are minimum. Increase as necessary to fit supporting frame into the wall of test furnace.

NOTE 2—Except for steel plate thickness and thermocouple instrumentation, this specimen is intended to be identical to the steel bulkhead specified in IMO Resolution A.517(13). If IMO acceptance is desired, a second set of thermocouples may be required.

FIG. 4 Design of Steel Fire-Containment Wall Test Specimen

17.5.2 Place the thermocouples used for temperature measurement on the unexposed surface in accordance with Test Methods E119. Also, see Fig. 4.

17.6 *Conditions of Acceptance*—The test method shall be regarded as successful if the following conditions are met:

17.6.1 The fire-containment wall assembly shall have withstood the fire endurance test without passage of flame or gases hot enough to ignite cotton waste, for a time period equal to that for which classification is desired.

17.6.2 Transmission of heat through the wall or partition during the fire endurance test period shall not have raised the average temperature on its unexposed surface more than 250°F (139°C) above its initial temperature, nor the temperature of any one point on the surface, including any joint, more than 325°F (181°C) above its initial temperature. The average temperature of the unexposed surface shall be the average of the readings of the thermocouples specified in 17.5.1 and 17.5.2.

18. Report

18.1 Report the following information:

18.1.1 General description of the test facility including the method of developing the specified fire environment and the results and date of the current calibration of the test facility. Report the type, location, and orientation of all instrumentation (such as heat flux meters and thermocouple assemblies) used to monitor or control, or both, the fire exposure.

18.1.2 For a calibration test, report the heat flux incident on the test specimen and the temperature of the fire environment with measurements at intervals of no more than 3 min. For an actual test, report the temperature of the fire environment with measurements at intervals of no more than 3 min.

18.1.3 Indicate whether the fire environment resulted in an exposure that satisfied the criteria set forth herein, in particular the agreement between the time-temperature curves from the calibration test and the actual test.

18.1.4 Indicate the test procedure that was followed and the resulting fire endurance period to the nearest minute. For loaded test specimens, include a description of the laboratory equipment for applying, measuring, and maintaining the load. Also include a discussion of the test method used to determine the applied load.

18.1.5 Specify the type and location of all thermocouples used to measure the temperature of the test specimen. All temperature measurements shall be given at no less than 3-min intervals. Describe and substantiate the test method used to determine the acceptance criteria (such as temperature limits) for unloaded specimens, if not in accordance with 15.2.6 or 16.2.5.

18.1.6 If the test specimen forms part of the wall of a test furnace, specify the location of the pressure measurements made during the test. All pressure measurements shall be given at no less than 3-min intervals.

18.1.7 Include a complete description of the test assembly including detailed drawings and photographs. The description shall include dimensions and physical properties of the various materials and components in sufficient detail to adequately define the test assembly. For columns and beams, report the w/d ratio. For plates and piping, report the wall thickness. Include a description of the construction and conditioning of the test specimen.

18.1.8 Contain visual observations recorded during the fire test at no less than 15-min intervals. The visual observations shall include any significant changes in the test specimens such as the development of cracks, buckling, flaming, spalling, and similar observable phenomena.

19. Precision and Bias

19.1 The precision and bias of these test methods have not yet been determined.

20. Keywords

20.1 fire test response; hydrocarbon pool fire; heat flux; temperature; thermal exposure; thermal shock

ANNEXES

(Mandatory Information)

A1. TOTAL HEAT FLUX SENSOR ("CALORIMETER")

A1.1 *General Description*—For measurement of total heat flux, a water-cooled, thermopile type "Schmidt-Boelter Gauge" or a circular foil "Gardon Gauge" heat flux sensor shall be used. To minimize the uncertainty, the Schmidt-Boelter Gauge is preferred.

A1.1.1 A general description of the Gardon Gauge is given in Test Method E511, which was developed by ASTM Subcommittee E21.08.

A1.1.2 A general description of the Schmidt-Boelter Gauge is given in Test Method E2683, which was developed by Subcommittee E21.08.

A1.1.3 While it is used to make total heat flux measurements, the Gardon Gauge is designed for making radiative heat flux measurements. Caution must be exercised when using it to make measurements with a large convective fraction as a result of calibration constant changes. Additional information is contained in the literature (**1-4**).[9] This rapid-response sensor derives its output from a differential thermocouple circuit that measures the temperature difference between the center and periphery of the active sensing area

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[9] The boldface numbers in parentheses refer to the list of references at the end of these test methods.

(which is the water-cooled circular foil). This millivolt output is self-generating and is directly proportional to the total heat flux.

A1.1.3.1 *Specifications:*

A1.1.3.2 *View Angle*—180°.

A1.1.3.3 *Manufacturer's Stated Accuracy*—±3 % of reading (during calibration with radiative fluxes).

A1.1.3.4 *Linearity*—±2 % of full range.

A1.1.3.5 *Repeatability*—±3 %.

A1.1.3.6 *Response Time*—0.5 s or less.

A1.1.3.7 *Surface Coating Absorptivity*—To be specified by the manufacturer for a 2500°R (1389 K) blackbody radiation spectrum.

A1.1.4 Similar specifications apply to the Schmidt-Boelter sensor designs. For additional information, see Refs (**5 and 6**).

A1.2 *Calibration:*

A1.2.1 Each instrument shall be calibrated by a calibration laboratory accredited to ISO/IEC Standard 17025 by an accreditation body complying with ISO/IEC Standard 17011. Calibration laboratories shall be accredited by an accreditation body recognized by the International Laboratory Accreditation Cooperation (ILAC).[10] The calibration under steady-state conditions shall cover the range of intended use. The instrument shall have a recalibration, for the range of intended use, whenever there is reason to suspect that recalibration is required (for example, if there is a change in the appearance of the sensor coating); or at least once per year, or after 25 testing hours, whichever comes first.

A1.2.2 Prior to each use, verify calibration of each instrument in accordance with procedures appropriate for the instrument as deemed acceptable by the accredited calibration facility (for example, use an accredited calibrated reference to verify the accuracy of an instrument prior to use).

NOTE A1.1—Accreditation is a formal, third party recognition of competence to perform specific tasks and provides a means to identify a proven, competent evaluator so that the selection of a laboratory, inspection, or certification body is an informed choice.

A1.3 *Operation*—Because condensation on the surface of the sensor can cause faulty readings, ensure the temperature of the sensor cooling water be kept above 120°F (49°C) or above the dew point of the local environment, whichever is greater. This can be accomplished by using a heat flux sensor with an attached thermocouple.

A1.4 *Mounting and Use*—Sensors shall be mounted in the calibration fixtures such that there is no direct flame or high velocity jet impingement. If a Gardon Gauge is used, the water cooling must be capable of maintaining foil edge temperature less than 300°F (149°C) to maintain linear sensor performance.

A1.5 *Radiometers and Calibrations*—Radiant heat flux measurements are not required in the test method. If radiant heat flux measurements are desired, radiometers based on the designs of the total heat flux sensors are available.[11] If the radiometer uses a window, calibration of the sensors shall be performed with the window in place using a thermal source with a radiation spectrum similar to that present in a furnace at 2500°R.

A1.6 *Acceptable Sensors*—Several sensors[11] have been verified by their manufacturers to meet the requirements of A1.1, A1.1.3, and A1.5.

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[10] Listed at www.ilac.org.

[11] In the U.S., suitable Schmidt-Boelter and/or Gardon Gauge heat flux sensors are manufactured by Medtherm Corp., P.O. Box 312, Huntsville, AL 35804; Rdf Corp., 23 Elm Ave., P.O. Box 490, Hudson, NH 03051-0490; and Vatell Corp., P.O. Box 66, Christiansburg, VA 24068.

A2. DIRECTIONAL FLAME THERMOMETERS (DFTs)

A2.1 Introduction

A2.1.1 Directional Flame Thermometers or DFTs are being added to E1529 to provide quantitative heat flux measurements. These sensors have been developed to help define the effective thermal exposure conditions during fire resistance tests in furnaces.

A2.2 Directional Flame Thermometers

A2.2.1 For fire resistance tests, the Furnace DFT consists of two Inconel plates (3 mm thick) with a 1.6 mm OD, mineral-insulated, metal-sheathed (MIMS) thermocouple (TC) attached to each unexposed face; an insulation layer is sandwiched in between the plates. See Fig. A2.1.

A2.2.2 The DFT plate temperature measurements and the data analysis techniques in A2.4 will be used to provide quantitative heat flux measurements in conjunction with the traditional furnace control thermocouples and measurements.

A2.2.3 The measured temperature histories from the two thermocouples in a DFT enable a calculation of heat flux over the entire test duration. The heat flux calculations use two simple techniques for early (< T5 min) and later times (>15 min); numerical inverse heat conduction techniques are used to cover either the middle period (5 < time <15 min) or the entire duration (Refs (**7-12**)). The inverse heat conduction analysis uses a one dimensional, nonlinear, transient thermal model of the DFT.

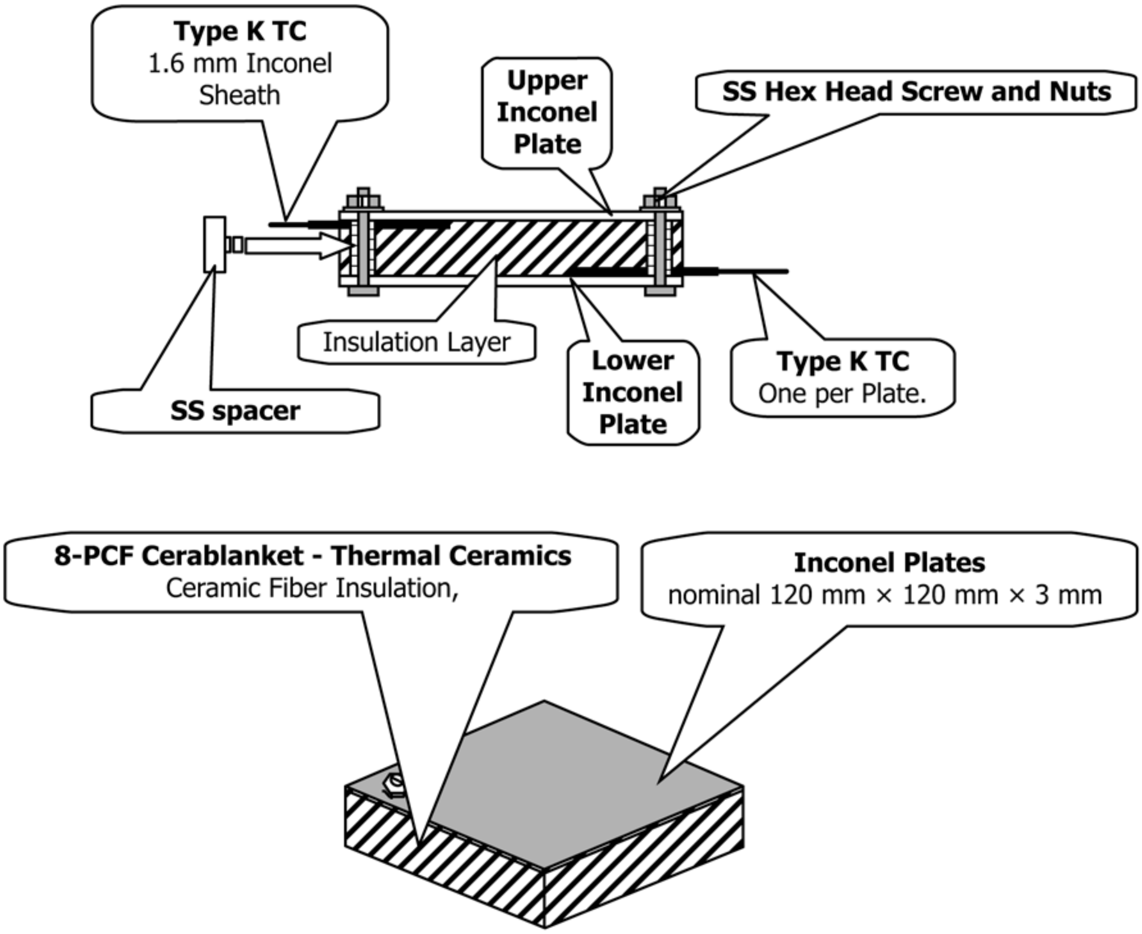

FIG. A2.1 Basic Design of a Furnace Directional Thermometer

NOTE A2.1—IHCP1D, which is a nonlinear inverse heat conduction analysis code, was used to develop sets of linear, digital, inverse filter functions to provide real-time readout of heat flux during a fire resistance test (**7**,**8**). These filter functions can be programmed into modern data acquisition systems to cover the operational furnace temperature range.

A2.2.4 For DFTs, heat flux during the early part of the test (time <5 min) can be calculated from the Furnace DFT front plate (furnace side) temperature measurements using Test Method E457 or Test Method E459(**9**,**10**). See A2.4.2.

NOTE A2.2—In tests sponsored by the US Coast Guard using marine fire resistance test methods (IMO A754), these slug and thin-skin calorimeter approaches were used for DFTs with 1.6 mm or 3.2 mm thick, Inconel face plates. The analysis was effective and showed peak heat flux exposures of 30-40 kW/m^2 in vertical furnaces and 25-30 kW/m^2 in horizontal furnaces during the rapid heating portion of these fire resistance tests, approximately the first 5 min (**11**,**12**).

A2.2.5 After the first 15 min (that is, later times), heat transfer through the DFT is in a quasi-steady state condition; that is, the temperatures of the front and back plates are rising at essentially the same rate. As a result, the late time analysis calculates the heat transfer through the DFT using the temperature dependent, thermal conductivity of the ceramic fiber insulation layer that separates the two Inconel plates. This heat transfer is used as part of a front plate energy balance analysis. An alternative calculation uses the Reradiation Differential between the Front and Back Plates; while not quite as accurate, it is much easier to calculate (**11**).

A2.2.6 Using the Conduction Heat Transfer or the Reradiation Differential in an energy balance for the DFT Front Plate, an "Effective Furnace Radiation Temperature" can be calculated (**12**); this is the blackbody temperature that would produce the same total heat flux exposure. The "effective furnace radiation temperature" calculation accounts for energy storage in the plates, transmission through the insulation layer and heat loss (reradiation) off both the front and back faces of the DFT to the test assembly. As a result, it provides a more accurate measure of late time thermal exposure than estimates made from temperature measurements made with either the E119 Furnace Thermocouple or the ISO 834-1 Plate Thermometer (**13**).

A2.3 Fabricating Directional Flame Thermometers for Fire Resistance Tests

A2.3.1 Cut or shear two, 3.0 mm thick Inconel plates, 4.75 by 4.75 in. (120 mm square).

A2.3.2 Drill 0.266 in. (letter drill H, 17/64 in.) holes in 4 corners.

A2.3.3 Oxidize the plates in a furnace at approximately 1000°C for 24 h to develop a stable, high absorptivity oxide layer. Work at Sandia National Laboratories has shown the absorptivity is approximately 0.85 (**11**).

A2.3.4 Use 1/16 in. (1.6 mm) OD Inconel sheathed, Chromel – Alumel (Type K) Thermocouples (TCs), with an ungrounded junction. Sand the oxide off the plate over a 1.25 by 0.5 in. area; using 0.003 in. (0.08 mm) Nickel or Nichrome foil, form the foil tightly over the last inch (25 mm) of TC and completely covering the TC tip, then spot weld the foil to the sanded area of the plate.

NOTE A2.3—To obtain the proper dynamic response, the diameter of sheathed TC must be less than or equal to plate thickness. When using a 1.6 mm sheathed TC installation on a 1.6 mm thick 304 stainless steel plate, experiments showed an empirically derived time constant for this thermocouple installation of 1.9 ± 0.05 s.(**9**) The specified thermocouple installation on a 3 mm plate will be close to this value.

A2.3.5 Cut a 5 by 5 by 1 in. (125 by 125 by 25 mm) piece of 8 pound per cubic foot (8 PCf or 128 kg/m^3) Cerablanket (Thermal Ceramics) ceramic fiber insulation between the plates. Using stainless steel tubular spacers with 304 stainless steel, Inconel or Silver Plated SS bolts, compress the insulation layer to a thickness of 0.75 in. (19 mm).

NOTE A2.4—8 PCF (128 kg/m^3) Cerablanket ceramic fiber insulation from Thermal Ceramics has been used in the development of the inverse filter functions that provide a real-time heat flux readout capability for DFTs. The data in Table A2.1 applies only to the 1 in. thick Cerablanket when it is compressed to 75 % of its original thickness. 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). Any changes in materials, material thicknesses, thermocouple design and attachment method or data sampling rate will invalidate the use of the filter functions.

NOTE A2.5—The thermal conductivity shown in Table A2.2 is the local conductivity; it is not the effective conductivity typically shown in the insulation manufacturer's literature. If other ceramic fiber insulations are used in place of Cerablanket, the Inverse Filter Function developed for a DFT fabricated with the Cerablanket will be in error. If other insulation materials are used, the initial density of the insulation layer, the actual thermal conductivity and the specific heat as functions of temperature, and the change in thermal conductivity for any compression are required for accurate analysis of heat flux exposures using an inverse heat conduction code.

A2.4 Data Analysis

A2.4.1 *Heat Flux Definitions:*

A2.4.1.1 Total Heat Flux = Absorbed Radiation Heat Transfer + Convective Heat Transfer

A2.4.1.2 Net Heat Transfer = Storage in the DFT Front Plate + Transmission (Loss) to Insulation Layer. It is equal to the [Absorbed Radiation Heat transfer + Convective Heat Transfer] – [Reradiation from the Exposed Surface]. This is the heat flux calculated in an inverse heat conduction analysis (IHCP1D).

TABLE A2.1 Temperature Dependent Thermal Properties of Iconel 600

Thermal conductivity table			
Temperatures for thermal conductivity (°C)			
25	127	527	727
Components of thermal conductivity (W/m-°C)			
14.9	16.6	22.6	25.4
Volumetric heat capacity table			
Temperatures for volumetric heat capacity (°C)			
25	127	527	727
Components of volumetric heat capacity (J/m^3 – °C)			
3768000	4068500	4598000	482000

TABLE A2.2 Temperature Dependent Thermal Properties of Cerablanket

Thermal Ceramics – 8 lbs per cubic foot Cerablanket – compressed 25 %				
Thermal conductivity table				
Temperatures for thermal conductivity (°C)				
35	238	516	765	855
Components of thermal conductivity (W/m-°C)				
0.047	0.072	0.125	0.205	0.244
Volumetric heat capacity table				
Temperatures for volumetric heat capacity (°C)				
23	250	500	750	1000
Components of volumetric heat capacity (J/m^3 – °C)				
145900	169400	185700	200200	210900

A2.4.1.3 Thermal Exposure = Absorbed + Reflected Radiation + Convective Heat Transfer

NOTE A2.6—A CFD model, like FDS (NIST-BFRL) or VULCAN (Sandia National Laboratories), is needed to calculate total thermal exposure at early times.

A2.4.2 *Simplified Early Time Heat Flux Calculations (time <5 min)*—For DFTs used in fire resistance tests, a modified version of procedures described in Test Methods E457 and E459 can be used to provide a more accurate estimate. The modification involves using an estimate of the heat transfer (loss) into the insulation layer to calculate the Net Heat Transfer. Heat loss from the front plate into the Cerablanket insulation layer was approximated using a model for a high thermal conductivity plate laid on a very thick layer of insulation ((**Ref 14**) - Ch. 12.4. Eq 12). Using an Inconel plate thickness of 3 mm with the thermal conductivity and volumetric heat capacity (density * specific heat) of both the Inconel and Cerablanket evaluated at roughly the midpoint temperature (250-275ºC), the analysis showed the slope of the plate temperature versus time was approximately 90 % of the slope when the unexposed surface of the plate was assumed to be adiabatic. The heat capacity of the plate (volumetric heat capacity * thickness) = 4333000 *.003 = 13000. The emissivity or absorptivity is 0.85. Then for the DFT front plate,

$$\text{Total Absorbed Heat Flux}(t) = 13000*(\Delta T/\Delta t)/0.9+0.85*\sigma*T^4 \qquad \text{(A2.1)}$$

where:

T = measured front plate temperature,
t = time, and
σ = Stefan-Boltzmann Constant.

A2.4.3 *Simplified Later Time Heat Flux Calculations (time >15 min)*—At later times, the thermal exposure is assumed to be almost totally radiative. Then the net heat flux is what crosses the exposed surface of the sensor; it is the absorbed heat flux minus the re-radiated flux. The total (absorbed) heat flux is calculated by adding the net flux and reradiation calculated from the hot-face temperature measurement history. (**11**) Using the net heat flux to the DFT and the DFT hot-face temperature, an Effective Furnace Radiation Temperature (EFRT) can be calculated. The EFRT, an equivalent blackbody temperature, is an estimate of the fire exposure or incident heat flux. The Adiabatic Surface Temperature (AST) is a similar estimate obtained from the temperature measurement history of Plate Thermometer temperature measurement history (**15**).

Because it accounts for heat transfer to the sensor, the EFRT provides a more accurate estimate of the thermal exposure than the AST.

A2.4.3.1 The late-time furnace conditions are in a quasi-steady state, the DFT emissivitiy and absorptivity are equal. $\alpha_{DFT} = \varepsilon_{DFT} = 0.85$; T_{DFT} = absolute front face temperature; T_{back}= DFT absolute back plate temperature; and σ = Stefan Boltzmann Constant. As a result: absorbed heat flux = net heat flux + reradiation. One simple equation for calculating the net heat flux is:

$$\text{net heat flux} = \rho C_p(T_{DFT})\, L \times \frac{dT_{DFT}}{dt} + k(T_{DFT}) \times (T_{DFT} - T_{Back}) \tag{A2.2}$$

$$\alpha_{DFT} \times (\sigma \times T^4_{Effective}) = (\text{net heat flux} + \epsilon_{DFT} \times (\sigma \times T^4_{DFT}))$$

$$T_{Effective} = (\text{net heat flux}/\alpha_{DFT} + \sigma \times T^4_{DFT})^{\frac{1}{4}}$$

For times greater than 10-15 min, the thermal exposure (incident heat flux) can be calculated from the Effective Furnace (or Blackbody) Radiation Temperature ($T_{Effective}$):

$$\text{Thermal Exposure} = \sigma \times T^4_{Effective} \tag{A2.3}$$

A2.4.4 *Inverse Heat Conduction Analysis*—A nonlinear (that is, temperature-dependent thermal properties) Inverse Heat Conduction Analysis is required to obtain the net heat fluxes 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 DFT hot-face.

A2.4.4.1 The full inverse analysis uses a nonlinear inverse heat conduction code (**8**) or sets of Inverse Filter Functions (IFF) (**7,16**)

A2.4.4.2 A set of Inverse Filter Functions (IFF) have been developed specifically for the Furnace DFTs with 3-mm plates (**17**). Convolution of these digital filters with the DFT temperatures provides a real time readout and closely approximates the full inverse analysis. Tables of the filter coefficients will be made available to ASTM for use with this test method (**17**).

A2.4.4.3 After adjusting for the difference in surface temperatures, work at the Southwest Research Institute has shown good agreement between thermal exposures measured with DFTs and Schmidt-Boelter heat flux sensors (**18**).

APPENDIXES

(Nonmandatory Information)

X1. COMMENTARY

X1.1 *Introduction*—This commentary has been prepared to provide the user of these test methods with background information and rationale on the development of these test methods and the selected standard test condition. These test methods are primarily intended for evaluation of materials used for fire protection of structures in the hydrocarbon processing industry (HPI) (such as oil refineries, petrochemical plants, offshore oil production platforms, etc.), and other structures that can be exposed to large, free-burning, fluid-hydrocarbon-fueled, *pool* fires. No attempt has been made to incorporate all the available information on pool fires in this commentary.

X1.2 *Basic Differences in Large Pool Fire Test versus Test Methods E119*—Prior to the development of these test methods, Test Methods E119 was the only standardized test available for evaluation of the thermal response of structural members and assemblies to fires. These test methods differ from Test Methods E119 in two major ways:

X1.2.1 When a furnace is used to produce the thermal exposure, the primary control for these test methods is based on a calibration procedure that develops a time-temperature curve to produce a specified heat flux incident upon the test specimen.

X1.2.2 These test methods "get hotter faster" than in Test Methods E119, which consequently subjects the test specimens to a strong thermal shock. Specifically, these test methods specify a cold wall heat flux of 50 000 Btu/ft^2·h (158 kW/m^2) upon the test specimen within 5 min of test initiation. This compares to values measured in a major Test Methods E119 furnace of 11 100 Btu/ft^2·h (35 kW/m^2) at 5 min and 37 400 Btu/ft^2·h (118 kW/m^2) at 60 min (**19,20**).

X1.3 *The Need to Control Heat Flux*—The heat flux incident upon an object is defined as energy per unit area per unit time (for example, Btu/ft^2·h (kW/m^2)). During the initial stages of the fire, the thermal response of an object to the fire is a direct function of the heat flux to which the object is exposed (**19-25**). While temperature is an important driving force for heat flux, temperature alone does not sufficiently define a fire environment. For example, both a match and a large pool fire (for example, 50 ft in diameter) burn in a roughly similar temperature regime (from 1600 to 2000°F (871 to 1093°C)), but clearly a person can *safely* get within a few inches of a match. The reason is that the size of the pool fire results in a much higher incident heat flux. Therefore it is temperature as well as other factors, such as fire size, flame thickness, etc., that cause heat flux. One study of the Test Methods E119 test concluded:

> Exposure severity is given indirectly and incompletely by specification of the furnace temperature. The true measure of severity is given by the heat flux... . Our overriding conclusion is to recommend that future improvements of Test Methods E119 focus more on the control, measurement, and specification of the heat flux condition rather than the ambient gas temperature history (**10**).

Therefore specifying a combination of the heat flux and the temperature for the control of these test methods represents an advance in fire technology, not a unique requirement for large pool fires per se.

X1.4 *The Need for a Large Hydrocarbon Pool Fire Test:*

X1.4.1 A large pool fire is loosely defined as that resulting from hundreds (or thousands) of gallons of liquid hydrocarbon fuel burning over a large area (several hundred to several thousand square feet) with relatively unrestricted air flow to it and combustion products from it (for example, outdoors). A number of large pool fire experimentalists (**26-33**) have shown that high heat flux and temperature conditions are rapidly achieved in this fire (typically in less than 1 min). This is in sharp contrast to the slow rate of buildup of thermal conditions in the Test Methods E119 fire, which simulates a fire where the fuel is solid and restrictions exist on air flow to (and combustion products from) the fire.

X1.4.2 HPI facilities, which largely are located outdoors, handle large quantities of hydrocarbon fluids. Personnel responsible for safety and loss prevention in these facilities are concerned that when they have a fire of consequence, it is a large pool fire, not a Test Methods E119 type fire, and that structures, assemblies, and fire protection materials should be designed based on ratings in a large pool fire, not the Test Methods E119 fire (**34-37**). Indeed, Norway now specifies firewalls on offshore platforms rated per a hydrocarbon fire (**38**).

X1.4.3 The concern for materials and structural performance in large pool fires has led to the development of several different types of large pool fire simulation tests (**20**, **21**, **35**, **39-42**) that have shown that materials can perform quite differently in Test Methods E119 versus pool fire tests. For example, one experimenter showed that 2 in. of a standard fireproofing material gave only 1 h in a pool fire simulation test versus a nominal 3 h Test Methods E119 rating (**35**).

X1.4.4 However, the existence of various simulation tests has sometimes led to confusing and conflicting results, and the lack of a standardized test has inhibited acceptance of ratings in accordance with this test method (**36**). Therefore, the need was established for this standardized test method that simulates the effects of large pool fires on the types of structures and assemblies that are used in HPI facilities.

X1.5 *Rationale for the Specific Test Conditions:*

X1.5.1 *The Need for a Single Set of Test Conditions*—To establish a standardized large pool fire simulation test, the issue becomes one of selection of the condition(s) to simulate. As demonstrated by the various large pool fire experimenters, a range of temperatures, velocities, heat fluxes, and chemical conditions exist, and they vary dramatically with time and spatial location (**27**, **29**). From a pragmatic viewpoint, selection of multiple test conditions would probably result in prohibitively high testing costs. Therefore, it becomes a case of whether engineering judgment can be exercised in selecting a single set of test conditions that represent a *reasonable worst case* for HPI facility design purposes.

NOTE X1.1—*Reasonable worst case* is a fairly standard engineering term that means, in essence, designing to withstand the most severe set of conditions that could be expected, within reason, to occur. Note that the design solution for a structure exposed to the reasonable worst case set of fire conditions selected does not necessarily have to be limited exclusively to fire protection but can (and generally does) include a combination of fire protection plus active systems (fixed and mobile).

X1.5.2 *Radiant Heat Flux and the Continuous Total Flame Engulfment Criterion*—There is a consensus that radiation is the dominant heat transfer mechanism to an object immersed in a large pool fire (**21**, **24**, **26**, **27**, **29**, **32**). Radiant heat transfer to an object is defined by the Stefan-Boltzmann equation as follows:

$$q = \sigma \varepsilon_f F_{sf} T_f^4 \qquad \text{(X1.1)}$$

where:

q = radiant heat flux incident on the exposed time, Btu/ft^2·h (kW/m)^2,
σ = Stefan-Boltzmann constant, 0.1714*10^{-8} Btu/ft^2·h °R ^{4} (0.567*10^{-14} kW/m^2 K^4),
ε = emissivity of the fire as viewed from the exposed item (by definition $0 \leq \varepsilon \leq 1$), the case where $\varepsilon = 1$ is given the name *blackbody radiation*,
F = view factor of the exposed item to the fire (by definition $0 \leq F \leq 1$), and
T = absolute temperature of the fire, °R or K.

Therefore, to determine a *reasonable worst case* radiation condition, consideration must be given to the view factor to the fire, fire emissivity, and time-continuity, as well as fire temperature.

X1.5.2.1 *View Factor*—Only those surfaces of an object that are in a direct visual line to a fire can receive heat flux. Because an object located outside of, or on the periphery of, a fire has a view factor (to the fire) of 0.5 or less, it is clear that maximum radiation occurs when the object is fully engulfed in the fire and hence has a view factor of 1.0 (which is the theoretical maximum) and that this is a *reasonable* maximum.

X1.5.2.2 *Emissivity of a Fire*—By definition, emissivity ranges from zero (for example, no flames at all) to 1.0 (for example, flames so thick that they cannot be optically seen through). Experimenters are tending to believe that in a fire that has a large quantity of luminous soot particles (such as a liquid hydrocarbon fueled pool fire), flames only have to be 3 to 6 ft thick to be optically opaque (**15**). Clearly, then, it is a reasonable maximum to have an emissivity of 1.0.

X1.5.2.3 *Time-Continuity*—This is perhaps the most important factor. Consider an example of fire exposure of an individual structural member, such as a beam or column, centered in a pool fire on the order of 30 or 40 ft in diameter. It is clear that, at least at some times during the fire, an optically opaque fire can totally engulf the beam or column. Hence it is reasonable for the view factor and fire emissivity to be 1.0 at some times, with respect to the beam or column. The question then must be answered: For what percentage of the time duration of the fire (for example, if it is a 1-h fire) do these conditions prevail? Since these pool fires predominantly occur outdoors, and since even small winds can cause the fires to fluctuate greatly in a given space (Note X1.2) (**27**, **30-33**), this is a very difficult question to answer. Therefore,an assumption has to be made, and the reasonable worst case assumption made is that the total engulfment conditions prevail 100 % of the duration of the fire exposure. In other words, total continuous engulfment means that at no time during the fire does any part of the structural member ever *see out* (nor would an imaginary observer anywhere outside of the fire ever *see in* to the member). Another way of looking at it: Because the performance of any individual member (for example, a column) can be critical, this total continuous engulfment criterion designs the member as if it were in the central portion of a large stationary fuel spill on a relatively windless day for the duration of the protection time desired (for example, 1.0 h).

NOTE X1.2—Indeed, virtually all large pool fire experimenters specifically wait for windless (or special prevailing wind) conditions to conduct their fires so they have a measure of control on their experiment.

X1.5.3 *Total Heat Flux:*

X1.5.3.1 The specified total heat flux is 50 000 Btu/ft^2·h (158 kW/m^2) within 5 min of fire initiation, and is a summation of the radiative plus convective components, with the radiative component being very dominant:

$$q_T = q_R + q_C \tag{X1.2}$$

where:

q_T = total heat flux, Btu/ft^2·h or kW/m^2,
q_R = radiant heat flux = $\sigma \varepsilon_f F_{sf}(T_f^4 - T_s^4)$, see (Eq X1.1), and
q_C = convective heat flux = $h(T_f - T_s)$, see (Eq X1.3).

Therefore, total heat flux is a strong function of fire temperature(s), and the convective component is a function of the temperature and velocity of the gases in the fire. Paragraphs X1.5.4 and X1.5.5 discuss fire temperature and gas velocity.

X1.5.3.2 Measurement of heat flux in a fire is a difficult experimental task. However, it is surprising how much agreement there is between experimenters, given this experimental difficulty plus the fluctuation of conditions within a given fire, as well as the differences in types and sizes of fires and where and how the heat flux measurements are made, and other variables (for example, wind).

(1) Bader of Sandia (**26**) measured heat fluxes in large pool fires by several methods, and developed a simplified computer model to predict the response of an object immersed in the fire. Using slug (that is, solid metal) calorimeters, the maximum time-integrated measured heat flux in 18 by 18-ft (5.5 by 5.5-m) fires was 47 500 Btu/ft^2·h (150 kW/m^2). For modelling of an object's response, he states:

> It was realized that both radiant and convective heat transfer played significant parts as energy transfer modes within a fire, but it was reasoned that at high temperature the radiant mode would be dominant. Therefore, effort was expended towards the selection of an effective black body source temperature which would combine the effects of radiation and convection. A study of experimental temperature measurements was undertaken.

After analyses, "It was decided that a good numerical representation of a large free burning fire was possible using an 1850° (1010°C) black body temperature as the input."

NOTE X1.3—This *input* began at ~1 min after fire initiation. Black body radiation at 1850°F gives a heat flux of 48 800 Btu/ft^2·h (154 kW/m^2).

(2) Canfield and Russell of the U.S. Navy (**27**) mapped the temperature and radiant heat flux (using Gardon gauges) at up to 32 points in the flame plume of a 16 by 8-ft (4.9 by 2.4-m) pool fire. The maximum mean value of radiant heat flux was 51 000 Btu/ft^2·h (161 kW/m^2), this being in the (spatially) small hot core of the flames (measured from 1945 to 1974°F (1063 to 1079°C)).

(3) NASA and Avco (**28**) measured total heat flux in a 48 by 54-ft (14.6 by 16.5-m) pool fire using a Gardon Guage. The maximum total heat flux measured was 50 600 Btu/ft^2·h (160 kW/m^2).

(4) Brown of the FAA (**31**) also used Gardon Gauges to measure total heat flux at one point in a series of 20 by 20-ft (6.1 by 6.1-m) pool fires under various wind conditions. The result: "The heat flux to the ... calorimeters averaged about 50 400 Btu/ft^2·h (159 kW/m^2) for calm wind or steady perpendicular wind (blowing fire toward calorimeter) tests." (The heat flux was about 18 000 Btu/ft^2·h (56.7 kW/m^2) for wind blowing away.) The heat flux reached quasi-steady state values in less than 20 s.

(5) Mansfield of NASA (**29**) also used Gardon Gauges. His fires were 25 by 25 ft (7.6 by 7.6 m) and 30 by 80 ft (9.1 by 9.1 m). The average total heat flux of three points was 50 800 Btu/ft^2·h.

(6) In a series of tests at Sandia National Laboratories (**32, 33, 43**), a variety of flat plate and cylindrical calorimeters have been used in 30 by 60 ft (9 by 18 m) pool fires to obtain hot wall heat fluxes to objects of different sizes and shapes. The maximum average value of the cold wall heat flux in these tests was slightly less than 50 000 Btu/ft^2·h (158 kW/m^2).

X1.5.3.3 Therefore, the selected value of 50 000 Btu/ft^2·h (158 kW/m^2) is a reasonable average of the experimental values. This is assumed to be a *reasonable worst case* exposure.

X1.5.4 *Convective Heat Flux and Gas Velocity:*

X1.5.4.1 While the convective heat flux is not called out separately in these test methods, on a vertical column it is expected to be approximately 10 % of the total heat flux or about 5000 Btu/ft^2·h (16 kW/m^2) (see X1.5.4.4).

X1.5.4.2 Convective heat flux to an object occurs as the result of the flow over the object of gases of higher temperature than the object. For an object of a given shape (for example, a 9-ft tall column), and gases of a given temperature and composition, the convective heat flux is then a function of the velocity of the gases and their orientation to the object. In the continuous engulfment portion (see X1.5.2) of a large pool fire, the prevalent (time-wise at any one spatial point) velocity of the combustion gases is vertical due to the buoyant forces of the flame plume (for example, in comparison to any wind conditions that could exist which would add horizontal component to the gas velocity, and to very sporadic cyclone-type whirling vortices). For the example of a 9-ft (2.7-mm) tall column, the flow is parallel to the 9-ft height and is turbulent and the convective heat flux can be quantified by:

$$q_c = h_{avg}(T_g - T_s) \tag{X1.3}$$

with

$$h = 0.0037*(k/L)*(VL/\nu)^{0.8}*Pr^{0.33} \tag{X1.4}$$

where:

qc = cold wall convective heat flux, Btu/ft^2·h; wall at 70°F,
h_{avg} = average heat transfer coefficient, Btu/ft^2·h °F,
T = average gas temperature, °F,
L = height of the column, ft,

k = thermal conductivity of the gases, Btu/ft^2·h °F,
ν = kinematic viscosity of the gases, ft^2/h,
Pr = Prandtl Number, and
V = average velocity of the gases, ft/h.

X1.5.4.3 Unfortunately, state-of-the-art heat transfer theory for buoyant plume velocities in large pool fires is extremely complex and there is very little experimental corroboration. Theory (**14, 44-48**) states that maximum (vertical) velocity occurs at the centerline of a fire (under windless conditions), and increases with height (until a height is reached where lateral air entrainment/dilution effects cause the flame plume to become dissipated) (Note X1.3). Vertical velocity in general decreases with lateral distance from the fire centerline. Published data on velocity measurements is scarce. One published value of measured vertical plume velocity in a large pool fire is 38 ft/s (11.6 m/s) at a 20-ft (6.1-m) elevation at the exact centerline of a 50-ft (15.2-m) diameter fire (**32**). Ref (**34**) provides average velocities at the centerline of a 9 by 18 m fire of 4.8 m/s at 2.2 m, 8.2 m/s at 3.4 m, 8.9 m/s at 4.8 m, and 9.5 m/s at 6.1 m; velocities measured during periods of low winds are up to 30 % higher. Refs (**33, 44-48**) provide theoretical analysis.

X1.5.4.4 Using Eq X1.3 and Eq X1.4, and using $T = 2000°F$ (1093°C) and estimated properties (that is k, ν, Pr) for the combustion gases, q computes to slightly over 5000 Btu/ft^2·h (15.8 kW/m ^{2}) for a 9-ft (2.7-m) tall column. Referring to the total specified heat flux of 50 000 Btu/ft^2·h (158 kW/m^2), this agrees well with Mansfield's observation (**29**): "This division of radiant and convective energy transfer is similar to a frequently accepted average or standard radiant/convective ratio of 9:1 for large pool fires."

X1.5.4.5 Although theory predicts higher velocities at higher elevations, common HPI design practice limits the major areas of fire protection concern to a maximum of 30 to 40 ft (9.1 to 12.2 m) above the fire source (**38**). The 20-ft (6.1-m) height at which the 38 ft/s (11.6 m/s) value was reported (**32**) or the 41 ft/s (12.6 m/s) value reported in (**33**) during low winds are therefore at the approximate average height of HPI concern. It should be noted that the data reported (**33**) show that the temperatures at this elevation are lower than at some elevations closer to the pool surface.

X1.5.4.6 As a counterpoint to the discussion of X1.5.4.4, the possibility exists that some fireproofing materials might be susceptible to erosive damage due to exposure to high temperature gases with velocities representative of those measured in large pool fires. However, preliminary analysis, of measurements made in large pool fires at Sandia National Laboratories, gives a shear stress estimate of less than 1 psf (50 Pa). As technology advances, this entire subject of gas velocity and its effects is one that could use further attention.

X1.5.4.7 As a pragmatic point, it is extremely difficult and expensive experimentally to generate high velocities of large quantities of hot gases and direct them in a highly controlled manner on a large test specimen. In fact, it is not clear if any existing test facility, other than an actual fire, has the capability of generating the representative velocities.

X1.5.5 *Fire Temperature:*

X1.5.5.1 The specified *fire* temperature (that is, the temperature of the environment that generates the heat fluxes of X1.5.3 and X1.5.4) is from 1850 to 2150°F (1010 to 1180°C). While this range is narrower than that seen in large pool fires (**30, 32, 33**), it was selected for two reasons:

(1) As the discussion in X1.5.5 presents, fires do not burn at any one temperature, but rather consist of gases with a wide range of temperatures, depending on spatial and time position in the fire. The range from 1700 to 2300°F (927 to 1260°C) is typical of the luminous plume engulfment region of large pool fires (**27, 30, 32, 33**). The selected range is in the middle of the broader range.

(2) The selected temperature range provides the experimenter/test facility with some flexibility and latitude in the means used to achieve the specified heat fluxes.

X1.5.5.2 As a reference point, using Eq X1.1 (the Stefan-Boltzmann equation for radiant energy transfer), if one is disposed to think of the fire at a single idealized temperature, then for the black body radiation case of emissivity = 1 and view factor of $F = 1$, $Tf = 2000°F$ (1093°C) gives an incident radiant heat flux of 62 770 Btu/ft^2·h (198 kW/m^2). Indeed this concept of a single fire temperature is quite useful if an enclosed furnace is used as the test simulation facility. The heat flux of 50 000 Btu/ft^2·h called out in this test method would require a surface absorptivity of ~0.8

X1.5.5.3 Temperature can be thought of as the driving potential for the heat flux. In actuality, the temperature in a luminous mass of combusting gases from a pool fire is not a constant but varies over a wide range, from about 1000 to 1200°F (649 to 1038°C) at the air-entraining edge of the plume to a broad internal zone from 1200 to 1900°F to a small central hot core from about 1900 to 2200°F (1038 to 1204°C) (**27, 30**). One set of data for a spatially fixed grid of up to 50 thermocouples in the vertical cylindrical space over a 50-ft (15.2-m) diameter pool fire on a windless day gave the following time-averaged volumetric distribution (**46**):

Less than 1200°F (649°C)—66 %
1200 to 1900°F (649 to 1038°C)—23 %
1900 to 2200°F (1038 to 1204°C)—11 %

Given the fluctuating nature of a pool fire (and therefore the probability that at some times the member will *see out* through the fire, thus counterbalancing exposures to higher temperatures), the specified range appears to meet the criterion of a *reasonable worst case.*

X1.5.6 *Gas Chemistry and Oxygen Content:*

X1.5.6.1 While the chemistry of the gases adjacent to the test specimen are not specified in these test methods, some discussion of these topics was considered appropriate for commentary.

X1.5.6.2 The chemistry in the fire plume of a pool fire is, like temperature, not a constant, but dynamic with time and spatial position. On the one hand, the chemistry is complex with a number of species present in varying mole fractions such as CO, CO, HO, O, N, H, Cn Hm (for example, various hydrocarbons), soot particles, etc. On the other hand, the chemistry is relatively straightforward—that of a fluid hydrocarbon reacting with air. Therefore, the range of chemical species present are relatively well known.

X1.5.6.3 The most extensive measurement of chemistry in a pool fire is given by Ref (**30**), where up to 23 spatial points were sampled periodically in the cylindrical area over a 50-ft (15.2-m) diameter pool fire. One analysis of this data led to the statement: "The overall conclusion from the data presented is that in the JP-4 fuel fire there is very little oxygen at the center of the fire up to a height of 1.5 fire radius. That is, combustion is still taking place" (**45**). For the 50-ft diameter fire cited, a height of 1.5 fire radius is about 38 ft (11.6 m), approximately the normal maximum height of primary interest for fire protection (per the HPI; see X1.5.4.4).

X2. USE OF FURNACE TYPE FACILITIES

X2.1 While these test methods do not restrict the technique used to achieve the test conditions specified in Section 6 for the purposes stated in Section 1, there is strong interest in the use of traditional fire test facilities. The use of enclosed furnaces to simulate the thermal effects of a hydrocarbon fire is discussed.

X2.2 Traditionally, enclosed furnace type facilities have been used for testing of structural response of materials (for example, for Test Methods E119 testing). These furnaces normally are fueled by a clean burning gas such as natural gas or propane. Experimental experience to date indicates that gas-fired enclosed furnaces are in concept also usable to simulate the pool fire conditions specified in Section 6 for the purposes specified in Section 1. The reason that an enclosed furnace type facility appears applicable to simulating the pool fire can be understood by referring to the discussion in X1.5.2, which explained that the 50 000 Btu/ft^2·h heat flux condition simulates total engulfment in the luminous portion of the flame plume. That is, the view factor F and emissivity are at the maximum value of 1.0. In addition, the fire is conceptualized as being at a uniform temperature of 1865°F, as explained in X1.5.5.2. Consider a 9-ft (2.7-m) column in an enclosed furnace with optically opaque walls at 1865°F (1018°C), and with optically transparent gases in the furnace also at 1865°F. The view factor of the column to the walls of the furnace is 1.0. If the walls of the furnace and the surface of the column are at a uniform temperature, the effective emissivity of the walls is 1.0 (Note X2.1). The radiant heat flux to the specimen in accordance with Eq X1.1 is the specified 50 000 Btu/ft^2·h. As long as the temperatures are uniform throughout the furnace, the same discussion for radiant heat fluxes holds true even if the gases in the furnace aren't transparent.

NOTE X2.1—For the case of a fully enclosed furnace with optically opaque walls and at a uniform temperature, the radiosity (that is, the sum of the emitted and reflected radiation) of the walls is constant and equal to that of a blackbody at the same temperature, regardless of the materials of construction of the furnace (**49**). The walls have an effective emissivity of 1.0, regardless of the actual emissivity of the wall material. If the test specimen is at a temperature lower that that of the furnace walls, the heat flux to the specimen will drop below the blackbody flux based on the wall temperature. The size of the effect depends on the size of the test specimen relative to the furnace volume, the temperature difference, and the radiative properties of the test specimen and the furnace materials (**50**).

X3. QUANTITATIVE HEAT FLUX MEASUREMENTS

X3.1 *Introduction*—In standardized fire resistance tests such as E119 and E1529 or ISO 834 or IMO A754, the furnace temperature is controlled to a standard time-temperature curve. Implicit assumptions are 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 place. 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 these assumptions are not well founded.

X3.1.1 Although the standardized fire resistance tests for enclosures, E119, ISO 834-IMO, and IMO A754 all use basically the same temperature versus time curve for controlling test furnaces, the tests provide very different thermal exposures due to the use of different furnace control thermocouples. These different thermal exposure histories produce different fire ratings for the same item.

X3.1.2 One of the recommendations that came 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 (**51**). 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.

X3.2 *Thermal Exposure*—In the mid-90s, 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 (heat transfer) in furnaces could not be predicted solely from furnace temperature measurements without large static and dynamic uncertainties (**52**).

X3.2.1 The source of these problems is that thermocouples can only measure their own temperature. This difficulty has been recognized for a long time. In Volume II of Jakob's classic heat transfer text, the title of Section 33.1 is "Heat Transfer, a Prerequisite of Thermometry"(**53**). Numerous papers have used heat transfer models to study temperature measurement errors. Blevins and Pitts evaluated gas temperature measurement errors for bare wire and aspirated thermocouples in compartment fires(**54**). Nakos, et al, evaluated temperature measurement errors in pool fires (**55**). Young evaluated dynamic gas temperature measurement errors and methods of compensating for these errors (**56**).

X3.2.1.1 In reality, there is no such thing as "A Furnace Temperature" because the temperatures of the walls, ceiling, floor and gas are all generally different. In addition, the test unit affects the measured temperatures and heat transfer in the furnace (**52**,**54**,**55**,**57**,**58**).

X3.2.1.2 In fire resistance tests, the "measured furnace temperature" is the result of a continuous, analog energy balance involving many different heat transfer paths – radiation exchange with all of the bounding surfaces, radiative and convective heat transfer with the gases in the furnace volume, energy storage due to the continually increasing temperature plus any conduction in the thermocouple stem. The measured furnace temperature history in fire resistance tests thus depends on the sensor design (thermal mass, size, shape, internal thermocouple installation, etc.), the sensor installation (location, orientation, etc.), the furnace design and the properties of the test unit (**57**).

X3.2.2 IMO A754 (and older versions of ISO 834) uses bare wire thermocouples for furnace control. Bare wire thermocouples respond the fastest due to their low thermal mass. However, the small diameter increases the sensitivity to convective (more local) heat transfer.

X3.2.3 Plate Thermometers (PTs) were developed by SP in Sweden. PTs have been incorporated into and used to control ISO 834-1 Fire Resistance Tests to help harmonize the furnace tests. Plate Thermometers use a 1 mm OD, metal sheathed thermocouple attached to the unexposed surface of the 0.7 mm metal plate, which faces into the furnace (**13**). An insulation board is mounted on the unexposed surface of the plate. Plate Thermometers provide a different but more consistent measure of the furnace temperature than bare-wire furnace thermocouples. The larger size and flat plate configuration reduces the sensitivity to convective heat transfer. The thermal mass is larger and it responds slower than a bare wire thermocouple. As a result, it increases the thermal exposure during the initial part of the test (**59**).

X3.2.3.1 The design allows better interpretation of the temperature measurements due to the directionality of the sensor. For times after the first 7 min, SP has developed a technique called the Adiabatic Surface Temperature for approximating the heat flux exposure from the measured Plate Thermometer temperatures in fire safety test furnaces (**15**).

X3.2.4 The E119 Shielded Thermocouple often uses a ½ in. – Schedule 40 pipe (13.7 mm OD with a 2.8 mm thick wall) as the outer shield. The thermal mass is larger due to a thicker wall and it responds slower than a Plate Thermometer.

X3.2.5 For the E1529 high-rise or hydrocarbon-curve fire resistance tests, the furnace temperature is controlled with 6.4 mm OD (1 mm wall), Inconel sheathed (mineral-insulated, metal-sheathed or MIMS) thermocouples (TCs). The dynamic response of the MIMS TC is between that of the Plate Thermometer and the E119 Shielded Thermocouple

X3.2.5.1 Thermal exposure is measured with a Directional Flame Thermometer (DFT). The Furnace DFT design consists of two Inconel plates (3mm thick). A layer of ceramic fiber insulation is compressed between the plates. A 1.6 mm OD, Inconel sheathed (mineral-insulated, metal-sheathed or MIMS) thermocouple (TC) attached to the unexposed faces. The dynamic temperature response of front plate of this DFT is similar to the E119 Shielded Thermocouple response (**18**).

X3.2.6 Due to the continuous energy balances involved in making thermocouple measurements, there are situations both early and later in the test where there are significant systematic errors in the furnace temperature measurements. These occur with all of the temperature sensors; bare wire thermocouples, the E119 Shielded Thermocouples, the MIMS TCs, the Plate Thermometers or the front plates of Furnace Directional Flame Thermometers.

X3.2.6.1 In the time-temperature curve used for fire resistance tests, the rate of change at the start of the test is over 100 times greater than it is after an hour (2.5ºC/min). After 6 min, it is still 10 times higher than at 60 min. As a result of the sensor dependent dynamic response, placing different temperature sensors in any one furnace provides different temperature measurements. Changing the location or orientation of the individual sensors also changes the measurements (**12**).

X3.2.6.2 During the initial rapid temperature ramp, the dynamic temperature response of the furnace control sensors is more important; it depends in great part on the thermal mass of the sensor. For all but the bare wire thermocouples, energy storage in the exposed surface element and significant heat transfer from the unexposed surface of the element slow the measured temperature rise.

X3.2.6.3 "Dynamic Differences" of 200-300ºC or more have been reported between different sensor designs or different installations of a single design (**50**,**60**,**61**). Assuming the temperature measurements from the different sensors or different installations of the same sensor are actually the furnace temperature, leads to heat flux estimates that can vary by a factor of 2 or more during the first 5-10 min (the fast, initial ramp) (**12**,**62**).

X3.2.6.4 After the first 15 min (that is, later times), heat transfer through a PT or DFT is in a quasi-steady state condition. For the DFTs, the temperatures of the front and back plates are rising at essentially the same rate. Near the end of an hour, the temperature is rising very slowly and radiation heat transfer is dominant. During this period, there can be significant heat losses off the backward facing portion of the sensors when the test units have high thermal inertia or are a special design, such as glazed or uninsulated fire barriers. Due to the lower temperature of the test unit, the measured "furnace temperature" is depressed by the heat loss off the backward facing surface.

X3.2.6.5 At these later times, "Static Differences" of 20 to 100ºC between different sensor design have been observed (**11**). Depression of the measured furnace temperature increases the furnace firing rate to bring the measured temperature up to the control curve and thus increases the thermal exposure above the expected level during the latter part of these fire resistance tests.

X3.2.7 From a horizontal furnace test with an uninsulated steel ceiling, a total heat flux exposure of 102 kW/m^2 was calculated from measurements made with the Directional Flame Thermometers measurements at 25 min (quasi-steady later time); the effective furnace radiation temperature was

885°C (**12**,**17**,**60**). The estimated thermal exposure (heat flux) based on other temperature measurements were all lower, the DFT Front Face 840°C (18 % low), ISO 834 Plate Thermometer 824°C (25 % low), and ASTM E119 Shielded Thermocouple 787°C (44 % low).

X3.2.7.1 In the same furnace with an insulated ceiling, the total heat flux exposure based on measurements made with the Directional Flame Thermometers was 79 kW/m^2 (effective furnace radiation temperature of 805 °C); this is 22 % lower than the uninsulated case. The estimates of thermal exposure (heat flux) based on other temperature measurements were all close: DFT Front Face 794°C (4 % low); ISO 834 Plate Thermometer 812°C (3 % high); and, ASTM E119 Shielded Thermocouple 796 °C (3 % low).

X3.2.8 When trying to compare the results of fire resistance tests run under different standards (for example, ASTM, ISO, IMO) or in different furnaces, differences in the designs of the temperature sensors used for furnace control produce differences in the dynamic and steady-state response of the sensors. As shown above, these produce significant changes in the actual thermal exposures (heat fluxes) as do the different furnace designs. Work by the National Research Council of Canada has shown differences in a horizontal furnace as high as 100% during the first 10 min (**61**,**62**). When the four different temperature sensors were used to control this furnace, the total heat flux measured at 1 h with a Gardon Gauge heat flux sensor ranged from 116 to 136 kW/m^2; the average value was 125 kW/m^2 ± 8 % (**61**).

X3.2.8.1 All of these results show there can be large uncertainties in the estimated thermal exposure (or heat transfer or heat flux) between nominally identical standardized tests. This make it very difficult to use estimated heat flux data in the development of engineering models of fire performance and performance based building codes. Quantitative heat flux measurements can reduce the uncertainty.

X3.2.9 The challenges involved in estimating the heat flux from a single temperature measurement, such as the E119 Shielded TC or the Plate Thermometer or the DFT Front Face, are outlined in a report (**63**). The report describes the development of a thermal response model for the Sandia Heat Flux Gauge (SHFG), a single thermocouple sensor design, along with an evaluation of the uncertainty of the heat flux estimates obtained from it.

X3.2.9.1 The SHFG design uses a 1.6 mm, Inconel sheathed thermocouple attached to a 0.25 mm stainless steel or Inconel plate. The plate is mounted on the end of a 10-15 cm long pipe that is filled with ceramic fiber insulation.

X3.2.9.2 For the SHFG, the steady-state heat flux measurement uncertainty was approximately 10 %. Under dynamic conditions, the uncertainty ballooned to over 35 %. The dynamic errors are attributed to "missing physics" in the sensor response model (**63**).

X3.2.9.3 One final note, Temperature is a scalar variable and a Primary Unit in the SI System;. Heat Flux is a vector quantity and it is a Derived Unit. As a result, they should be measured separately just as Current (a Primary Unit) and Voltage (a Derived Unit) are in electrical systems.

X3.3 *Comparing Fire Resistance Test Exposures*—Just as simultaneous temperature and heat flux boundary conditions cannot be specified for a surface of a solid, reports by Sultan (**61**,**62**) and Janssens (**18**) have shown it is difficult to measure one parameter in a fire resistance test (such as the furnace temperature) and calculate the other (thermal exposure). Part of the difficulty involves deciding how many and what simplifying assumptions are allowed. Due to a smaller number of assumptions, heat flux estimates in fire resistance test furnaces, where there is good understanding of the overall conditions, should in general be more accurate than those in an uncontrolled environment, such as an actual room burn or forest fire.

X3.3.1 *Directional Flame Thermometers*—Quantitative heat flux measurements are needed in fire safety tests to support the development and validation of engineering models for fire protection materials and structural assemblies. Water-cooled or passive sensors can be used for this task. The water-cooled sensors are the direct reading Schmidt-Boelter or Gardon Gauge designs that are used in some E5 Methods (ASTM Methods for these sensors have been developed by E21.08). A proven type of passive sensor for these measurements is called a Directional Flame Thermometer (DFT). DFT are passive or uncooled heat flux sensors that have much higher temperature capability than the water cooled ones and are very rugged. These characteristics simplify installation in a wide range of fire applications.

X3.3.1.1 DFTs have been used for over 20 years to help define heat transfer inside and outside a wide variety of fires. DFTs have been used to obtain quantitative heat flux measurements from large pool fires, spill fires with cross-winds, rocket launch accidents, fire resistance tests and others.

X3.3.1.2 DFTs are thermocouple based sensors. There are two metal plates, usually Inconel 600, with a layer of ceramic fiber insulation material lightly compressed in between. A 12 by 25 mm strip of Nickel foil is formed over the tip of the thermocouple and spot welded to the unexposed surface of each plate; this provides a good thermomechanical attachment of the thermocouples. These two temperature measurements provide the data necessary for using a numerical thermal model of the sensor with advanced data analysis techniques to quantify the thermal exposure in fire tests.

X3.3.1.3 Early work on Directional Flame Thermometers (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 a quasi-steady condition in times as short as a minute. As a result, Pool Fire DFTs were designed with 1.6 mm plates to provide rapid equilibration with the fire; initial heating rates were approximately 30 K/s. The heat flux measurements made with DFTs have been used to support the development of engineering models (**64**,**65**,**66**).

X3.3.2 Based on the recommendations from NIST following the WTC Investigation, recent work has focused on the use of Pool Fire and Furnace DFT designs for making quantitative heat flux measurements in standardized fire resistance tests to support the development and validation of engineering models. This preliminary work is very encouraging.

X3.3.2.1 Using the measured temperature histories from the two thermocouples in a DFT enables a calculation of heat flux over the entire test duration The heat flux calculations use simple and more involved techniques. The Furnace DFT design uses 3 mm thick, Inconel plates to enable the use of slug or thin-skin calorimeter measurement techniques for early times (< 5 min). Quasi-steady analyses for used for later times (>15 min). Nonlinear inverse heat conduction technique are used to cover the middle period (5 < time < 15 min) or the entire duration (**11**,**12**).

X3.3.2.2 The early time heat flux can be calculated from the front plate (furnace side) temperature measurements using slug calorimeter techniques (ASTM E457) or thin-skin calorimeter techniques (ASTM E459). Using these calorimeter analysis techniques for a large DFT like sensor with a 304 stainless steel plate 1.6 mm thick, heat fluxes were obtained in spill fire ignition experiments with a duration of about 30-60 s (**9**,**67**).

X3.3.3 The nonlinear (temperature dependent), inverse heat conduction analysis uses a one dimensional, transient thermal model of the DFT with the measured plate temperature histories. Detailed, post-test, inverse analysis uses a fully nonlinear inverse code, such as IHCP1D (Beck, 1999). The full inverse analysis is being used to develop sets of linear digital filter functions to provide real-time readout of heat flux during a fire resistance test. These convolution type, digital filter functions can be easily programmed into modern data acquisition systems.

X3.3.4 In a project sponsored by the US Coast Guard using IMO A754 marine fire resistance test methods, the ASTM E457 and E459 approaches along with an advanced thin-skin technique (Carslaw & Jaeger, 1959) were used for DFTs with 1.6 or 3.2 mm thick, Inconel face plates. The analysis was effective and showed peak heat flux exposures of 30-40 kW/m^2 in vertical furnaces and 25-30 kW/m^2 in horizontal furnaces during the rapid heating portion of these fire resistance tests, approximately the first 5 min (**11**,**12**). The effective time for this type analysis depends on the plate thickness. In this test, it was approximately useful for ~250-300 s for the 1.6 mm plates and longer for the 3 mm thick plates.

X3.3.4.1 In the Coast Guard sponsored work, the non-linear, inverse heat conduction analysis code (IHCP1D) was also used to calculate the net heat transfer rates to the front face of the various DFTs as well as a large, actively cooled, Furnace Characterization Unit (FCU) over the entire test duration of up to one hour (**11**,**12**). These inverse calculations showed good agreement with the total heat fluxes calculated with the simplified, early and late time DFT analysis techniques. In a wall furnace test, measurements made with the two different DFT designs and the FCU showed integrated total heat flux exposures over one hour that differed by less than 3 %.

X3.3.5 The late time analysis calculates energy storage in both plates and the heat transfer through the DFT using the temperature dependent, thermal conductivity of the ceramic fiber insulation layer that separates the two Inconel plates. An alternative calculation uses the Reradiation Differential between the Front and Back Plates; while not quite as accurate, it is much easier to calculate. Using the Conduction Heat Transfer or the Reradiation Differential as part of an energy balance for the DFT Front Plate, an "Effective Furnace Radiation Temperature" can be calculated. Because the "effective furnace blackbody radiation temperature" calculation accounts for energy storage in the plate and heat loss off the back-face of the DFT to the test assembly, it provides a more accurate measure of total thermal exposure than either the E119 Furnace Thermocouples or the Plate Thermometers.

X3.3.5.1 For steady-state or quasi-steady state conditions, DFT thermal 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 circuit performance is not fully specified without knowing at least two of these three parameters (temperature drop, heat flux or thermal resistance).

X3.3.5.2 For dynamic thermal experiments like fires or fire safety tests, the appropriate electrical analog is a resistance-capacitance or RC network circuit. The electrical capacitance is replaced by the volumetric heat capacity.

X3.3.5.3 Detailed, post-test analysis of DFT data uses a Nonlinear Inverse Heat Conduction Code (**7**,**8**). Newly developed Inverse Digital Filters provide either real-time heat flux readouts during a test or quick-look capabilities for large data sets (**16**,**17**).

X3.4 *Results from Directional Flame Thermometer Applications*—Although they have been used in a wide variety of fires, the focus is on quantitative heat flux measurement results obtained with DFTs in fire resistance tests. A summary over the past decade is given below; it is followed by more detailed information. The measurement results include:

X3.4.1 *Total heat flux in horizontal furnace tests*—(using Plate Thermometer control) with either low losses (fairly uniform temperature and radiosity in the furnace volume) or when there are high losses (horizontal test with uninsulated, metal ceiling - losses 25-30 kW/m^2) — In the high loss test, estimates made from Plate Thermometer measurements were 25 % low, those from an E119 TC were 44 % low (**17**,**60**).

X3.4.2 The net (almost total) heat flux exposure during the fast temperature ramp (first 5 min) using 3 DFT or DFT-like sensor designs with 3 different response times; the 3 measurements generally agreed within a couple percent over the first 250 s before the thinnest one rolled off due to its faster temperature rise; these results demonstrate that the dynamic response characteristics of the individual temperature sensors are not very important (**12**).

X3.4.3 The net heat flux to a test unit with a metal surface over the entire test duration (done in conjunction with measurements of the exposed surface temperature of the test unit); there was very good agreement between estimates made using DFT data and those calculated for the metal test unit with a nonlinear inverse heat conduction code (**12**).

X3.4.4 Comparing total heat flux exposures in five IMO A754 tests conducted in four different vertical and horizontal furnaces; the standard deviation of the thermal exposure is about 10 % for times greater than 10 min (95 % confidence interval about ±20 %); for times between 0 and 10 min, the standard deviation is 2-3X higher.

X3.4.5 The repeatability of the total heat flux exposure in a single furnace within a few percent, just as ISO has shown temperature repeatability using Plate Thermometers (**11**).

X3.4.6 *The heat flux in real-time using the new Inverse Heat Conduction*—Digital Filter Function technique; agreement between a full nonlinear inverse heat conduction analysis and the filter function calculations was very good over an hour long test, except for the first peak, which occurred about 100 s after ignition, in an oscillating signal (**16**,**17**).

X3.4.7 *Cold wall heat fluxes*—This result is based on work at the Southwest Research Institute. This work showed that Schmidt-Boelter heat flux sensors (water-cooled) and DFTs provide comparable "cold wall" heat flux measurements in an E119 test of 70 min duration. The data analysis which involves corrections for both the radiative and convective components of the heat transfer, is complicated by the fact that the surface temperature histories of the two sensors are very different. The radiative correction is fairly straight forward because the sensor emissivities are known. Correction of the convective component is much more difficult. Bare wire thermocouples were used to get a better measure of the gas temperature. Then estimates were made about the convective heat transfer coefficients to make the convective corrections. (**16**,**18**)

X3.4.8 *Comparative heat flux measurements*—showed how changing the control sensor design or the furnace design changes the thermal exposure (**61**,**62**). Thermal exposures during the first 10 min of the test varied by a factor of 2 (100 %); at the end of an hour, the spread was approximately 16 %.

X3.4.9 Partial results from a US Coast Guard sponsored project involving the IMO A754 marine fire resistance tests were reported in the proceedings of a 2001 ASTM E5 Symposium (**11**,**68**). In the IMO A754 tests, there were DFTs with 1.6 mm plates sitting 10 cm in front of a Furnace Characterization Unit (FCU), which had 5 mm thick face plates and was actively cooled. In some of these tests, there were additional DFTs with 3 mm plates mounted on the walls, ceilings or floors of the furnace to aid modeling.

X3.4.9.1 Prior to running the furnace fire resistance tests, a number of preliminary tests were run with a well controlled, radiant heat source known as Dial-a-Fire at Sandia National Laboratories. During these tests, unexposed surface heat losses in the FCU were measured with Kapton Film thermopile sensors that were adhesively bonded. There was good agreement between these measurements and the values calculated with the nonlinear inverse heat conduction code. (**11**,**68**).

X3.4.9.2 In a horizontal furnace, good agreement was shown in early time heat fluxes obtained from all three sensor designs. During the first 5 min, the net heat flux curves from all three sensors (two DFT designs and the FCU) overlapped. These results were obtained even though the "nominal sensor time constants" for temperature measurements varied by more than a factor of 3 (**11**).

X3.4.9.3 In the 2008 ASTM E5 Symposium, Keltner, et al (**17**) showed a comparison of the net heat flux to the FCU calculated with Beck's IHCP1D inverse heat conduction code (**8**) using three, in-depth FCU temperature measurements with the heat flux calculated from the DFT net heat flux and the DFT hot-face and FCU surface temperature measurements. From the DFTs and the FCU measurements, the paper also showed the total heat flux exposures calculated by adding reradiation to the net heat flux. For the two approaches, the integrated total heat flux exposures differed by less than 1 % over the nearly hour long test.

X3.4.10 Janssens (**18**) presented a comparison of methods for measuring thermal exposure in fire resistance tests at the ISO Workshop on Heat Transfer Calculations and Measurements in Fire Safety Engineering – Furnace Characterization and Control. It showed very good agreement between cold-wall heat fluxes measured with water-cooled, Schmidt-Boelter heat flux sensors and those calculated from DFT heat fluxes and gas temperatures measured with bare-wire thermocouples. Those estimated from Plate Thermometer temperature histories were lower than the Schmidt-Boelter or DFT values.

X3.4.11 In the 2008 ASTM E5 Symposium, Sultan (2008) demonstrated the differences between the furnace temperature control sensors (ASTM E119 Shielded Thermocouple, ISO 834 Plate Thermometer, ASTM E1529 Directional Flame Thermometer and bare, beaded thermocouple). The paper also demonstrated that changing the furnace control sensor also changed the thermal exposure during the test. The differences were largest during the initial fast ramp, when the measured heat flux varied by more than 100 % between the various sensors.

X3.4.12 A 2008 ASTM paper showed a comparison of the total heat flux measurements (thermal exposure) from 5 IMO A754 fire resistance tests run in 4 different furnaces lined with ceramic fiber insulation (**17**). Although all are controlled to the same time temperature curve using the same temperature sensor, the coefficient of variance of the total heat flux values starts out in the 20-30 % range. From 10 min after ignition to the end of the test, it is approximately 10 %.

X3.5 Measurement Applications to Performance Based Models

X3.5.1 Work to date has focused more on making the heat flux measurements in fire resistance tests than on how they would be applied for studying ignition of materials, fire propagation or structural response calculations. Discussed below is an approach for meeting NIST's request for quantitative heat flux measurements to support the development and validation of engineering models for fire protection materials and structural assemblies.

X3.5.2 To obtain the net heat fluxes, the two DFT plate temperature measurements are fed into a nonlinear inverse heat conduction code (or the new Inverse Filter Functions (IFF)). The calculation, which uses a dynamic thermal model of the sensor, returns the net heat flux to the DFT hot-face. The net heat flux is what crosses the exposed surface of the sensor – that is, the absorbed heat flux minus the re-radiated flux. The calculation also returns the flux conducted into the insulation layer and the net heat flux at the back surface (facing the test unit).

X3.5.3 The total heat flux (fire exposure) is calculated by adding the net flux and reradiation from the face. In an earlier paper, results from a vertical furnace lined with fire brick demonstrated that the total heat flux versus time curves obtained from the DFTs and the FCU agreed closely except at very early times, when convection and condensation might be important (**11**). The integrated heat flux values over the test period also agreed closely.

X3.5.4 Using the net heat flux to the DFT and the DFT hot-face temperature, an Effective Furnace Radiation Temperature (EFRT) can be calculated. The EFRT approach is similar to the Adiabatic Surface Temperature calculations based on Plate Thermometer data (**15**). However, the Effective Furnace Radiation Temperature is a more accurate measure because it includes any energy storage in the DFT plates and transmission through the DFT.

X3.5.5 The EFRT is used to calculate an equivalent blackbody heat flux. Earlier work has shown that the total heat fluxes (fire exposure) obtained from sensors with very different temperature histories (two DFT designs and the FCU with plate thicknesses of 1.6, 3.2 and 5 mm respectively) agree closely (**17**). As a result, the net heat flux to another test object is obtained by using its surface temperature, from either measurements or models, to calculate the reradiation and subtracting it from the total heat flux. As heat flux is a vector quantity, a DFT used for this purpose should be mounted close to the surface and point in the same direction as the surface.

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SUMMARY OF CHANGES

Committee E05 has identified the location of selected changes to this standard since the last issue (E1529-14a) that may impact the use of this standard. (Approved Nov. 1, 2016.)

(1) Paragraphs A1.2.1 and A1.2.2 were revised.

(2) Note A1.1 was added.

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