Designation: E 1529 – 00

An American National Standard

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

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 E 119, the only available standardized test for fire resistant construction, However, the exposure specified in Test Methods E 119 does not adequately characterize large hydrocarbon pool fires. Test Methods E 119 is intended to be representative of building fires where the primary fuel is solid in nature, and where 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 E 119. 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 more closely approximates 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 may be useful for testing other items such as piping, electrical circuits in conduit, floors or decks, and cable trays. Because failure criteria and test specimen descriptions are not provided in these test methods, testing these types of items will require appropriate specimen details and end-point or failure criteria.

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

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

1.5.2 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.

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

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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 Construction Assemblies.

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

1.5.5 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.

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

1.5.7 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.

1.6 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 5is acceptable.

1.7 The values stated in inch-pound units are to be regarded as the standard. The values given in parentheses are for information only.

1.8 *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..*

1.9 *This standard does not purport to address all of the safety problems, 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.*

1.10 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:*

B 117 Practice for Operating Salt Spray (Fog) Apparatus[2]

D 822 Practice for Conducting Tests on Paint and Related Coatings and Materials Using Filtered Open-Flame Carbon-Arc Exposure Apparatus[3]

E 119 Test Methods for Fire Tests of Building Construction and Materials[4]

E 176 Terminology Relating to Fire Standards[4]

E 511 Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Gage[5]

2.2 *Code of Federal Regulations:*

46 CFR 164.007 Structural Insulations[6]

3. Terminology

3.1 *Definitions*—Refer to Terminology E 176 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, ¾h, 1 h, 1½h, etc.

4.1.1 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.

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

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[2] *Annual Book of ASTM Standards*, Vol 03.02.

[3] *Annual Book of ASTM Standards*, Vol 06.01.

[4] *Annual Book of ASTM Standards*, Vol 04.07.

[5] *Annual Book of ASTM Standards*, Vol 15.03.

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

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 column specimens includes temperature limits for steel columns. These limits are intended to define the temperature above which a steel column with an axially applied design allowable load would fail structurally. 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 and may or may not be restrained against longitudinal thermal expansion, depending on the intended use. 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.

CONTROL OF FIRE TEST

6. Fire Test Exposure Conditions

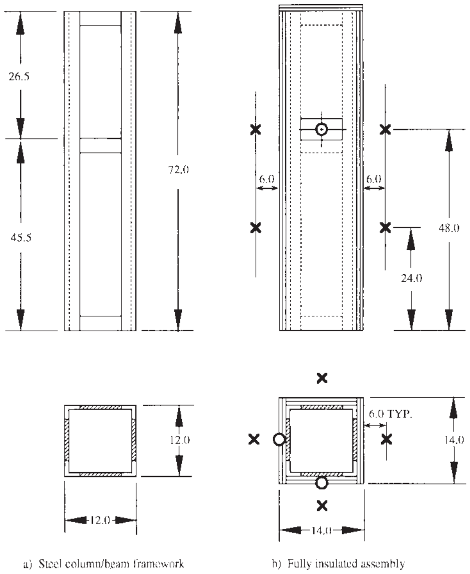
6.1 Expose the test specimen to heat flux and temperature conditions representative of total continuous engulfment in the luminous flame regime of a large free-burning fluid-hydrocarbon-fueled pool fire. See Appendix X1 for the rationale for selection of this condition. Essential conditions are specified 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 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.

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.



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.

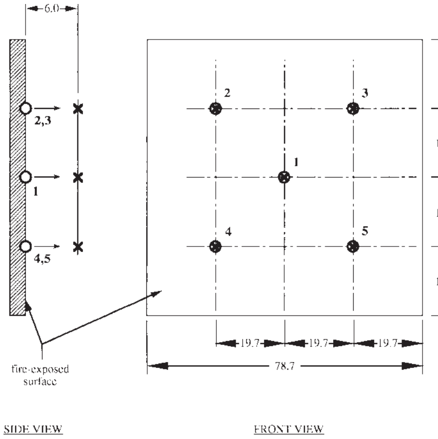
NOTE 4—All dimensions are in inches.

FIG. 1 Calibration Assembly for Beams and Columns

7. Heat Flux Measurements

7.1 Measure the total heat flux as specified in 6.2 using a circular foil heat flux gage (often called a Gardon gage after the developer) as specified in Annex A1.

7.1.1 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



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

fabricated from noncombustible materials. The dimensions and instrumentation are shown in Fig. 1.[7]

7.1.2 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.

7.1.3 All measurements made within 1 min (that is, recorded time ±30 s) shall be considered as having been made at the same time.

7.2 At all times after the first 5 min of the test, the total heat flux shall be:

7.2.1 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 ± 25 %).

7.2.2 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 ± 5 %) (158 kW/m ^{2} ± 8 kW/m^2).

8. Furnace Pressure Measurement

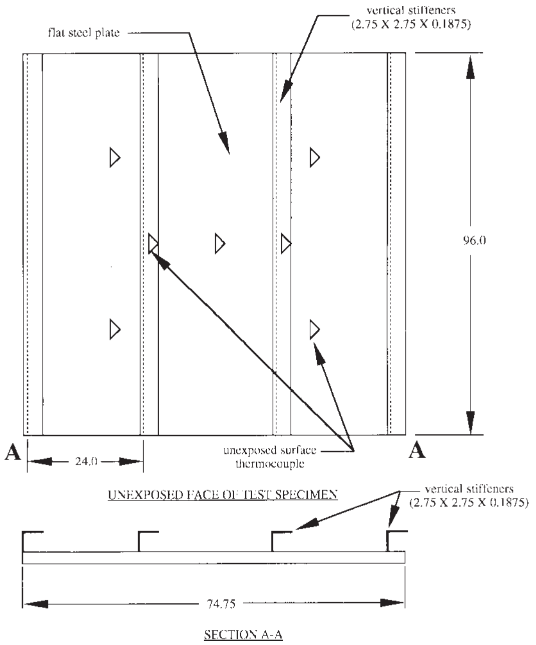
8.1 When testing any assembly that forms part of the wall of a test furnace (for example, walls, ceilings, floors, bulkheads, decks, doors, etc.), the furnace pressure shall be measured. The procedure is adapted from the differential pressure section of Test Method E 814.

8.2 Measure the gage 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 of Test Method E 814; this design is shown in Fig. 4 of Test Method E 814. The probe tips are to be manufactured from stainless steel or other suitable material.



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. 3 Design of Steel Fire-Containment Wall Test Specimen

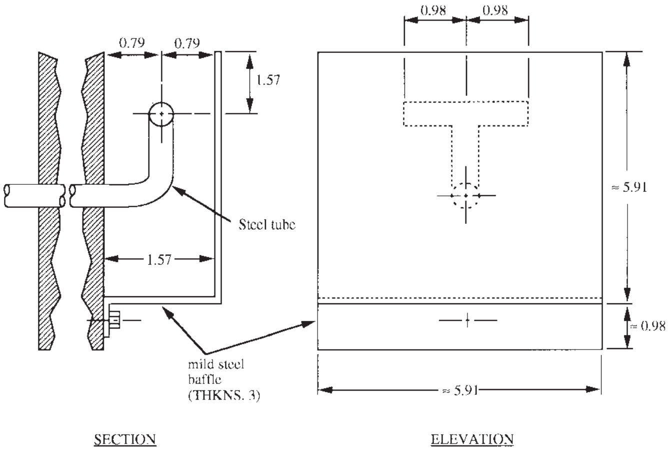


FIG. 4 Static Pressure-Measuring Device Dimensions in Millimetres

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. Gas Temperature Measurement

9.1 Measure the temperature of the gases adjacent to and impinging on the calibration or test specimens, as specified in

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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.

6.3, using factory manufactured 0.25-in. outside diameter (OD), inconel-sheathed, Type K, chromel-alumel thermocouples. The time constant, in air, of the thermocouple assemblies shall be less than 60 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.

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 Measure the gas temperature at least once every 3 min at each required measurement site. Data shall be recorded within ±30 s of the 3 min intervals to satisfy the minimum requirement.

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)

10. Test Facility Design

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

10.1.1 It is consistent with the approach of Test Methods E 119,

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 19.6.2.

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 7.2.

11.2.2.2 *Gas Temperature*—See 9.1-9.3.

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*—See 6.3 and Section 9a.

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 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.

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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).

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 accomodate 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 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. These tests may also be applicable to other materials and assemblies. This is left to those interested parties involved to determine. Further, because it is recognized that accelerated aging/weathering testing is an art and not a science, preconditioning tests prior to aging/weather exposure (for example, tensile stressing of brittle materials), additional exposure environments may be required for some fire protection materials for structural steel, and for other materials and assemblies, if the parties involved have a particular concern about a particular material or an assembly in a particular environmental exposure.

NOTE 1—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 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 16.5.

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 D 822. 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 day for 72 h, followed by an immediate exposure to −40 ± 5°F (−40± 3°C) for 24 h, and then an immediate 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 B 117.

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 This procedure may be used for the testing of other than steel columns 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 may 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 (650°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 2). The ends of the beam shall be simply supported and the beam shall not be restrained against longitudinal thermal expansion.

NOTE 2—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 E 119, 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.

16.2 *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 3—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 2).

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 (650°C), for a period equal to that for which classification is desired.

16.2.6 See 5.3.2.

16.2.7 *Piping*—This procedure may be used for the testing of items other than steel beams, such as piping. Because failure criteria are not provided in these test methods for these types of assemblies, 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.

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. 3. When the actual construction will contain one or more joints, the specimen shall be tested with at least one joint.

NOTE 4—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 6.5.

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 on drawing in Fig. 3:

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.

17.5.2 Place the thermocouples used for temperature measurement on the unexposed surface in accordance with Test Methods E 119. Also, see Fig. 3, Note 3.

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; temperature; heat flux; thermal shock

ANNEX

(Mandatory Information)

A1. TOTAL HEAT FLUX SENSOR ("CALORIMETER")

A1.1 *General Description*—For measurement of total heat flux, a water-cooled circular foil "Gardon Gage" heat flux sensor shall be used. A general description of this type of gage is given in Test Method E 511, which was developed by ASTM Subcommittee E21.08. While it is used to make total heat flux measurements, this device 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 (which is the water-cooled circular foil). This millivolt output is self-generating and is directly proportional to the total heat flux.

A1.2 *Specifications*:

A1.2.1 *View Angle*—180°.
A1.2.2 *Accuracy*—±3 % of reading (radiative fluxes only).
A1.2.3 *Linearity*—±2 % of full range.
A1.2.4 *Repeatability*—±½ %.
A1.2.5 *Response Time*—0.5 s or less.
A1.2.6 *Surface Coating Absorptivity*—To be specified by the manufacturer for a 2500°R (1390 K) blackbody radiation spectrum.

A1.3 *Calibration:*

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

A1.3.1 Each instrument shall have a certified calibration, for the range of intended use, directly traceable to the National Institute for Standards and Technology (NIST). The instrument shall have a certified recalibration, for the range of intended use, directly traceable to the NIST 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.

A1.3.2 Prior to each use, recalibrate each instrument in accordance with procedures that are either directly or indirectly traceable to NIST.

A1.4 *Operation*—Because condensation on the surface of the sensor can cause faulty readings, the temperature of the sensor should be kept above 120°F (50°C) or above the dew point of the local environment, whichever is greater. This can be accomplished by using a sensor with an attached thermocouple and varying the flow rate or temperature of the water.

A1.5 *Mounting and Use*—Sensors shall be mounted in the calibration fixtures such that there is no direct flame or high velocity jet impingement. The water cooling must be capable of maintaining foil edge temperature less than 300°F (150°C).

A1.6 *Acceptable Sensors*—Several sensors[10] have been verified by their manufacturers to meet the requirements of A1.1 and A1.2.

A1.7 *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 from the three manufacturers listed below. 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.

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[10] Model C-1300A ASYMPTOTIC Water-Cooled Calorimeter, a registered trademark of HY-CAL Engineering, 12105 Los Nietos Rd., Santa Fe Springs, CA 90670; Model 1000-1 Circular Foil Water-Cooled Calorimeter by Thermogage, Inc., 330 Alleghany St., Frostburg, MD 21532; and Model 64-20-18 Water-Cooled Heat Flux Transducer by Medtherm Corp., P.O. Box 312, Huntsville, AL 35804.

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 E 119*—Prior to the development of these test methods, Test Methods E 119 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 E 119 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 E 119, 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 E 119 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 **(5)**.

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 **(5-9)**. 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 E 119 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 E 119 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 **(11-18)** 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 E 119 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 E 119 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 E 119 fire **(19-22)**. Indeed Norway now specifies firewalls on offshore platforms rated per a hydrocarbon fire **(23)**.

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 **(5, 6, 20, 24-27)** that have shown that materials can perform quite differently in Test Methods E 119 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 E 119 rating **(20)**.

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 **(21)**. 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 **(12, 14)**. 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 **(6, 9), 11, 12, 14, 17)**. Radiant heat transfer to an object is defined by the Stefan-Boltzmann equation as follows:

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

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 $0 \leq \epsilon \leq 1$), the case where $\epsilon = 1$ 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) **(12, 15-18)**, 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 = $\sigma\epsilon_f F_{sf}(T_f^4 - T_s^4)$, *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).

(*a*) Bader of Sandia **(11)** 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).

(*b*) Canfield and Russell of the U.S. Navy **(12)** mapped the temperature and radiant heat flux (using Gardon gages) 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)).

(*c*) NASA and Avco **(13)** measured total heat flux in a 48 by 54-ft (14.6 by 16.5-m) pool fire using a Gardon gage. The maximum total heat flux measured was 50 600 Btu/ft^2·h (160 kW/m^2).

(*d*) Brown of the FAA **(16)** also used Gardon gages 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.

(*e*) Mansfield of NASA **(14)** also used Gardon gages. 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.

(*f*) In a series of tests at Sandia National Laboratories **(17, 18, 28)**, 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:

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

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 **(9, 29-33)** 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 **(17)**. Reference **(19)** 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. References **(18, 29-33)** 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 **(14)**: "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 **(23)**. The 20-ft (6.1-m) height at which the 38 ft/s (11.6 m/s) value was reported **(17)** or the 41 ft/s (12.6 m/s) value reported in **(18)** during low winds are therefore at the approximate average height of HPI concern. It should be noted that the data reported **(18)** 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 **(15, 17, 18)**, it was selected for two reasons:

(a) (*a*) 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 **(12, 15, 17, 18)**. The selected range is in the middle of the broader range.

(b) (*b*) 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) **(12, 15)**. 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 **(31)**:

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 **(15)**, 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" **(30)**. 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 E 119 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 **(34)**. 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 **(35)**.

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