NFPA 271

Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

2001 Edition

NFPA, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101
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This edition of NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter,* was prepared by the Technical Committee on Fire Tests and acted on by NFPA at its May Association Technical Meeting held May 13–17, 2001, in Anaheim, CA. It was issued by the Standards Council on July 13, 2001, with an effective date of August 2, 2001, and supersedes all previous editions.

This edition of NFPA 271 was approved as an American National Standard on August 2, 2001.

Origin and Development of NFPA 271

Earlier editions of NFPA 271 were published as NFPA 264 and were first available in 1992. NFPA 264 was very closely related to and derived from NFPA 264A, *Standard Method of Test for Heat Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*. This document was based on the methods of measuring rates of heat release using an oxygen consumption calorimeter developed at the National Institute of Standards and Technology by Dr. Vytenis Babrauskas, et al. This document provided a general methodology for measuring the heat release rates of a variety of materials in a variety of end uses. It was intended that this approach be adopted and customized for the testing of specific products and materials. This bench-scale approach provides a mechanism for deriving information that can be used for product and material evaluation, mathematical modeling, and design purposes, as well as for research and development purposes.

The 1995 edition of NFPA 264 reflected changes that were both editorial and technical in nature. The technical revisions included standardization of the horizontal position as the orientation for testing of specimens. The horizontal orientation provides greater repeatable and reproducible results. The vertical orientation details were located in Annex D and are intended to be used more for research purposes. The definition of sustained flaming was revised from existence of flame for 10 seconds to existence of flame for 4 seconds in order to coordinate with other documents.

The 1998 edition of NFPA 264 was renumbered as NFPA 271. The designation was changed for coordination purposes. This placed this document in rotation with other documents that use the oxygen consumption calorimeter. The changes to the 1998 edition were only minor in nature. They included updating the document to the latest terminology used in the industry and the current laboratory processes, and some editorial clarification. A new section pertaining to the radiation shield was added.

The 2001 edition is a complete revision that incorporates the layout and provisions of the NFPA *Manual of Style*, 2000 edition. Minor revisions include updating ignition circuit applications in Sections 2.7 and D.10, identifying the type of radiation shield not permitted, and correcting the heat release calibration in Section 5.3.

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This list represents the membership at the time the Committee was balloted on the final text of this edition. Since that time, changes in the membership may have occurred. A key to classifications is found at the back of the document.

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

Information on referenced publications can be found in Chapter 2 and Annex G.

Chapter 1 Administration

1.1 Scope.

1.1.1* This test method shall measure the response of materials exposed to controlled levels of radiant heating, with or without an external igniter.

1.1.2 This test method shall be used to determine the ignitability, heat release rate, mass loss rates, effective heat of combustion, and visible smoke development of materials and products.

1.1.3* This test method tests the specimen in the horizontal orientation.

1.2 Purpose.

1.2.1* This test method shall provide measurements of the behavior of material and product specimens under a specified radiant heat exposure in terms of the rate of heat release, effective heat of combustion, mass loss rate, time to ignition, and smoke production.

1.2.2 The data obtained for a specific test shall describe the rate of heat and smoke release of the specimen when exposed to the specific conditions and procedures used in performing that test.

1.2.3 Release rate measurements shall provide a quantitative measure of specific changes in performance caused by product modification.

1.3 Application.

1.3.1 Significance.

1.3.1.1 This test method shall be considered useful for the following:

(1) Evaluations of materials or products
(2) Mathematical modeling
(3) Design of new materials or products
(4) Research and development

1.3.1.2 Types of materials suitable for testing with this method shall include specimens from an end-use product and the various components used in the end-use product.

1.3.1.3 Release rates for a given material depend on how the material is used, its thickness, and the method of mounting.

1.3.1.4 Other factors, some of which cannot be controlled, that can also affect the heat release rate for a given material include the orientation of the material (vertical, horizontal, or otherwise), the types of joints or other methods used for installation, the way the material reacts to fire (melts and drips, recedes, chars, pyrolyzes, intumesces, or flames), and the use of fire retardants.

1.3.1.5 This standard shall not purport to address all safety problems associated with its use. The user of this standard shall be responsible for establishing appropriate safety and health practices and for determining the applicability of regulatory limitations prior to use.

1.3.2* Test Limitations. This test method shall test the specimen in the horizontal orientation.

1.3.2.1 This test method shall not apply to end-use products that do not have planar, or nearly planar, external surfaces.

1.3.2.2 The test data shall be invalid if any of the following occurs:

(1) The specimen undergoes explosive spalling
(2) The specimen swells to the point where it touches the spark plug prior to ignition
(3) The specimen swells to the point where it touches the heater base plate during combustion

1.3.2.3 If delamination of the specimen occurs, the test results shall be considered suspect, and this shall be described in the test report.

1.3.2.4* This test method shall be performed in a controlled environment under controlled laboratory conditions in order to obtain material properties data for use in evaluating the fire hazard of materials.

1.3.2.4.1 These data alone do not describe the fire hazard of a material's specific end use or predict its response to real fires.

1.3.2.4.2 The data obtained by this test method have not yet been correlated with the real-world fire performance for most materials.

1.3.2.4.3 Thus, caution shall be used when utilizing such data to evaluate the full-scale fire performance of the end use of materials tested in accordance with this method.

1.3.3 Summary of Test Method.

1.3.3.1 This test method shall be based on the observation that the net heat of combustion is directly related to the amount of oxygen necessary for combustion: approximately 13.1×10^3 kJ of heat are released per 1 kg of oxygen consumed.

1.3.3.2 Specimens in the test shall be combusted in ambient air conditions while being subjected to a predetermined external radiant heat flux, which ranges from 0 kW/m^2 to 100 kW/m^2. Combustion shall be initiated with or without a spark ignition.

1.3.3.3 The primary measurements, as a function of time, shall be oxygen concentration and exhaust gas flow rate (for assessing heat release rate).

1.3.3.3.1 Additional measurements shall include specimen mass, for assessing mass loss rate and smoke obscuration, both of them as a function of time, and time to sustained flaming, which is a measure of ignitability.

1.3.3.3.2 The test method is also suitable for other measurements.

1.3.3.4* This test method shall be intended to determine the heat evolved by a product or material when exposed to an external radiant heat source.

1.3.3.4.1 It also determines the effective heat of combustion, mass loss rate, time to sustained flaming, and smoke production.

1.3.3.4.2 These properties shall be determined on small-size specimens that are representative of the intended end-use materials.

1.3.3.5 The rate of heat release shall be determined by measurement of the oxygen consumption, which is determined by the oxygen concentration and the flow rate in the exhaust product stream.

1.3.3.5.1 The effective heat of combustion shall be determined from a concomitant measurement of specimen mass loss rate in combination with the heat release rate.

1.3.3.5.2 Smoke development shall be determined from the obscuration of light by the combustion product stream.

1.3.3.6 This test method shall be applicable to various categories of products and shall not be limited to a single fire scenario.

1.3.3.7* Specimens shall be exposed to heating fluxes in the range of 0 kW/m^2 to 100 kW/m^2 in a horizontal orientation.

1.3.3.7.1 External ignition, where used, shall be by electric spark.

1.3.3.7.2 The value of the heating flux and the use of external ignition shall be specified by the relevant material or performance standard or by the test sponsor for research and development purposes.

1.3.3.8 Ignitability shall be determined as a measurement of time from initial exposure to time of sustained flaming.

1.4 Units.

1.4.1 The values stated in SI units shall be regarded as the standard.

1.4.2 Unless otherwise stated, all dimensions included in the test and figures shall be mandatory and shall be followed within nominal tolerances of 1 mm. Dimensions in figures that are not followed by an asterisk (*) shall be considered nonmandatory.

1.5 Symbols. The following symbols are used in this standard:

A_s = nominal specimen exposed surface area (0.01 m^2)

C = calibration constant for oxygen consumption analysis (m$^{1/2}$kg$^{1/2}$K$^{1/2}$)

$-dm/dt$ = required mass loss rate

$\Delta H_c/r_0$ = net heat of combustion (kJ/kg)

$\Delta H_{c,eff}$ = effective heat of combustion (kJ/kg)

I = actual beam intensity

I_0 = beam intensity with no smoke

k = smoke extinction coefficient (m^{-1})

L = extinction beam path length (m)

m = specimen mass (kg)

m_f = final specimen mass (kg)

m_i = initial specimen mass (kg)

$\dot{m}$ = specimen mass loss rate (kg/s)

ΔP = orifice meter pressure differential (Pa)

q'' = total heat release (kJ/m^2)

$\dot{q}$ = heat release rate (kW)

$\dot{q}''$ = heat release rate per unit area (kW/m^2)

t_0 = stoichiometric oxygen/fuel mass ratio

t = time (s)

t_d = oxygen analyzer delay time (s)

Δt = sampling time interval (s)

T_e = absolute temperature of gas at the orifice meter (K)

$\dot{v}$ = volume exhaust flow rate measured at the location of the laser photometer (m^3/s)

X_{O_2} = oxygen analyzer reading, mole fraction of O_2

$X_{O_2}^0$ = initial value of oxygen analyzer reading

$X_{O_2}^1$ = oxygen analyzer reading, before delay time correction

s_f = specific extinction area, for shmoke (m^2/kg)

Chapter 2 Referenced Publications (Reserved)

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter shall apply to the terms used in this standard. Where terms are not included, common usage of the terms shall apply.

3.2 NFPA Official Definitions.

3.2.1 Shall. Indicates a mandatory requirement.

3.2.2 Should. Indicates a recommendation or that which is advised but not required.

3.2.3 Standard. A document, the main text of which contains only mandatory provisions using the word "shall" to indicate requirements and which is in a form generally suitable for mandatory reference by another standard or code or for adoption into law. Nonmandatory provisions shall be located in an annex, footnote, or fine-print note and are not to be considered a part of the requirements of a standard.

3.3 General Definitions.

3.3.1 Heat of Combustion.

3.3.1.1 Effective Heat of Combustion. The measured heat release divided by the mass loss for a specified time period.

3.3.1.2* Net Heat of Combustion. The oxygen bomb calorimeter value for the heat of combustion, corrected for the gaseous state of product water.

3.3.2 Heat Release Rate. The heat evolved from the specimen, per unit of time.

3.3.3 Heating Flux. The incident radiant heat flux imposed externally from the heater on the specimen at the initiation of the test.

3.3.4 Ignitability. The propensity for ignition, as measured by the time to sustained flaming, in seconds, at a specified heating flux.

3.3.5 Orientation. The plane in which the exposed face of the specimen is located during testing (i.e., horizontally facing the heater).

3.3.6 Oxygen Consumption Principle. The expression of the relationship between the mass of oxygen consumed during combustion and the heat released.

3.3.7 Smoke Obscuration. The reduction of light transmission by smoke, as measured by light attenuation.

3.3.8 Sustained Flaming. The existence of flame on or over the surface of the specimen for periods of at least 4 seconds.

3.3.9 Visible Smoke. The obscuration of transmitted light caused by combustion products released during the test.

Chapter 4 Test Apparatus

4.1 General. The test apparatus shall consist of the following components:

(1) A conical-shaped radiant electric heater
(2) Specimen holders
(3) An exhaust-gas system with oxygen-monitoring and flow-measuring instrumentation
(4) An electric ignition spark plug
(5) A data collection and analysis system
(6) A load cell for measuring specimen mass loss

4.1.1 A general view of the apparatus shall be as shown in Figure 4.1.1.

4.1.2 A cross-sectional view of the heater shall be as shown in Figure 4.1.2.

4.1.3 An exploded view of the horizontal orientation shall be as shown in Figure 4.1.3.

4.2 Conical Heater.

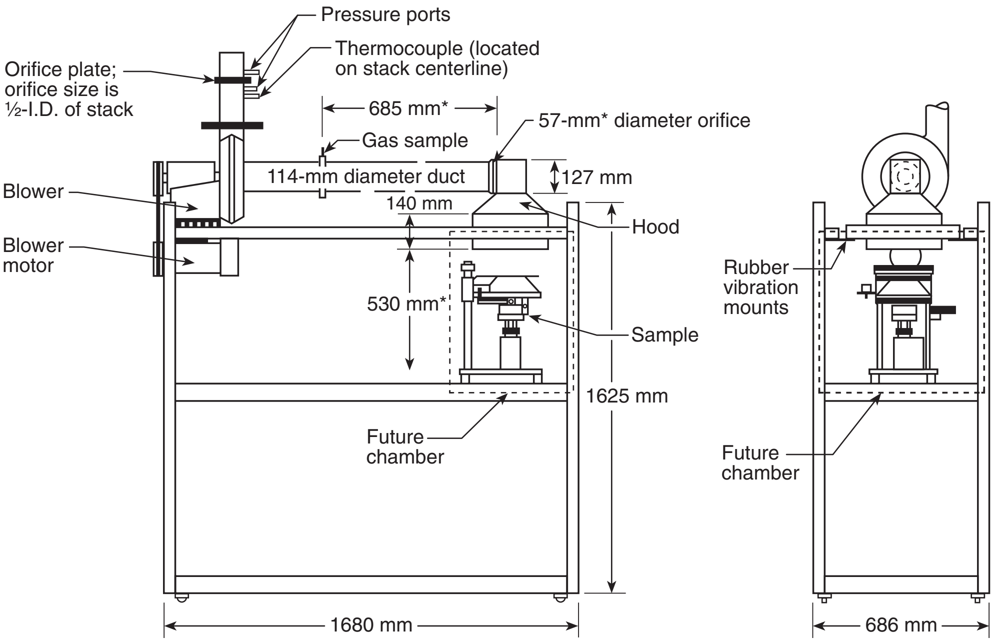
4.2.1 The active element of the heater shall consist of an electrical heater rod, rated at 5000 W at 240 V, tightly wound into the shape of a truncated cone as shown in Figure 4.1.2.

4.2.2 The heater shall be encased on the outside with a double-wall stainless steel cone packed with a refractory fiber material of approximately 100 kg/m^3 density.

4.2.3* The heater shall be mounted in a horizontal orientation.

4.2.4 The heater shall be capable of producing irradiances on the surface of the specimen of up to 100 kW/m^2.

4.2.5 The irradiance shall be uniform within the central 50-mm × 50-mm area of the specimen to within 10 percent.



*Indicates a critical dimension

FIGURE 4.1.1 Overall view of apparatus.

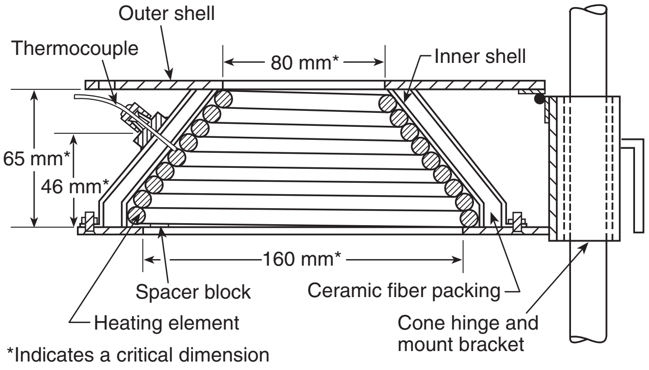


FIGURE 4.1.2 Cross-sectional view of heater.

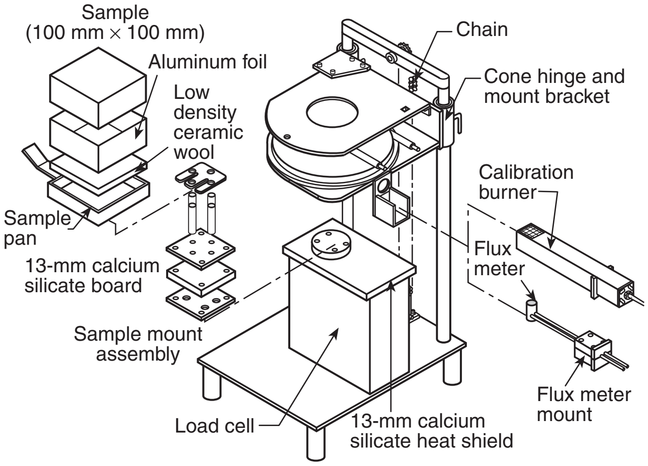


FIGURE 4.1.3 Exploded view, horizontal orientation.

4.2.6 The irradiance from the heater shall be capable of being held at a preset level by means of a temperature controller and three Type K stainless steel–sheathed thermocouples, symmetrically dispersed and in contact with, but not welded to, the heater element as shown in Figure 4.1.2.

4.2.7 The thermocouples shall be of equal length and wired in parallel to the temperature controller.

4.2.8 The standard thermocouples shall be sheathed, 1.5 mm to 1.6 mm O.D., with an unexposed hot junction. Alternatively, either 3-mm O.D. sheathed thermocouples with an exposed hot junction or 1-mm O.D. sheathed thermocouples with unexposed hot junction shall be suitable for use.

4.2.9 Radiation Shield.

4.2.9.1 The cone heater shall be provided with a removable radiation shield to protect the specimen from the heat flux prior to the start of the test.

4.2.9.2 The shield shall be made of noncombustible material, with a total thickness not to exceed 12 mm.

4.2.9.3 The shield shall be either one of the following:

(1) Water-cooled and coated with a durable matte black finish of surface emissivity, $e = 0.95 \pm 0.05$
(2) Not water-cooled, with a metallic reflective top surface
(3) Not water-cooled, with a ceramic, nonmetallic, surface that minimizes radiation transfer to the specimen surface

4.2.9.4 The shield shall be equipped with a handle or other suitable means for insertion and removal in accordance with 7.2.3.

4.2.9.5 The cone heater base plate shall be equipped with the means for holding the shield in position and allowing its insertion and removal in accordance with 7.2.3.

4.3 Temperature Controller.

4.3.1 The temperature controller for the heater shall be capable of holding the element temperature steady to within 2°C.

4.3.2 An acceptable system shall be a three-term controller (proportional, integral, and derivative) and a thyristor unit capable of switching currents up to 25 A at 250 V.

4.3.3 The controller shall have a temperature input range of 0°C to 1000°C, a set scale capable of being read to 2°C or better, and automatic cold junction compensation.

4.3.4 The controller shall be equipped with a safety feature so that, in the event of an open circuit in the thermocouple line, it causes the temperature to fall to near the bottom of its range.

4.3.5 The thyristor unit shall be of the zero crossing type and not of the phase angle type.

4.3.6 The heater temperature shall be monitored by a meter capable of being read to 2°C or better.

4.4 Exhaust System.

4.4.1 The exhaust-gas system shall consist of a high-temperature centrifugal exhaust fan, a hood, intake and exhaust ducts for the fan, and an orifice plate flowmeter as shown in Figure 4.4.1.

4.4.2 The exhaust system shall be capable of developing flows from 0.012 m^3/s to 0.035 m^3/s.

4.4.3 A restrictive orifice (57-mm I.D.) shall be located between the hood and the duct to promote mixing.

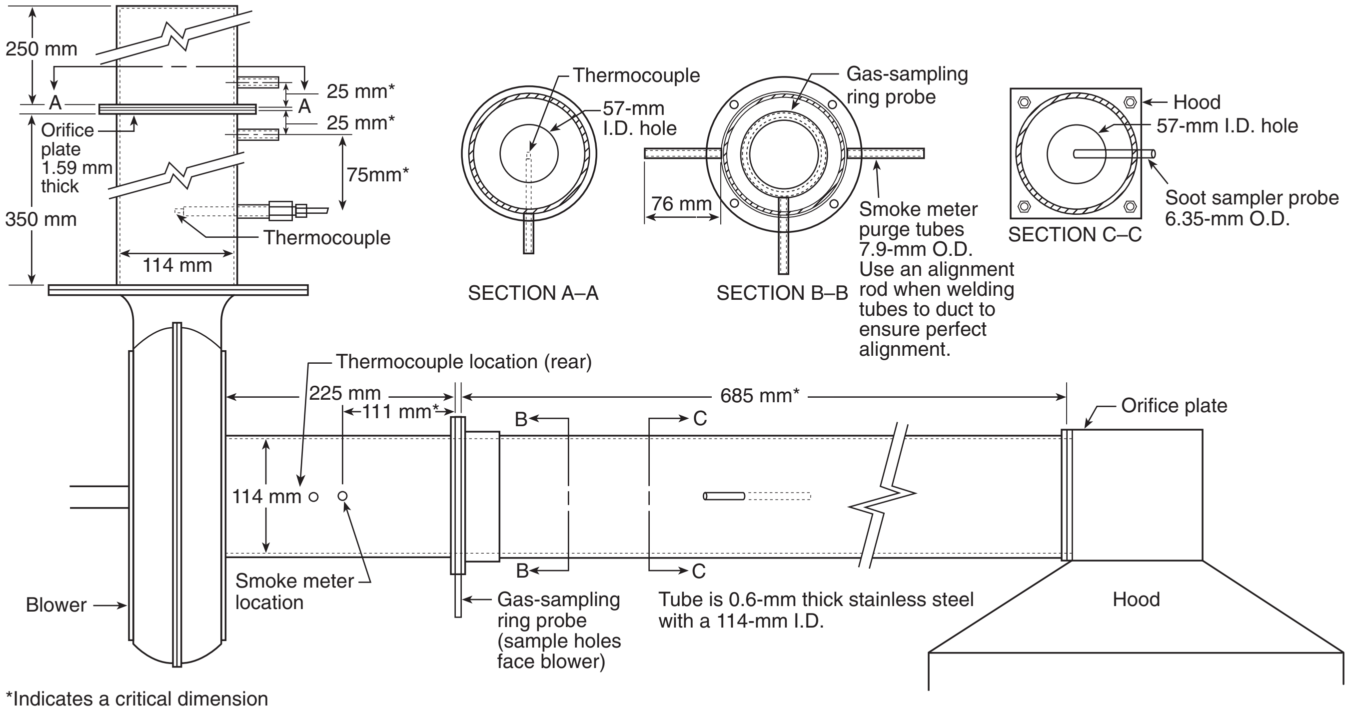
4.4.4 A ring sampler for gas sampling shall be located in the fan intake duct 685 mm from the hood as shown in Figure 4.4.1.

4.4.5 The ring sampler shall contain 12 holes to average the stream composition, with the holes facing away from the flow to avoid soot clogging.

4.4.6 The temperature of the gas stream shall be measured using a 1.0-mm to 1.6-mm O.D. sheathed-junction thermocouple or a 3-mm O.D. exposed-junction thermocouple positioned in the exhaust stack on the centerline and 100 mm upstream from the measuring orifice plate.

4.4.7 The flow rate shall be determined by measuring the differential pressure across a sharp-edged orifice (57-mm I.D.) in the exhaust stack at a location at least 350 mm downstream from the fan.

4.4.8 For other features, the geometry of the exhaust system shall not be considered critical. The undisturbed inflow distances to the gas-sampling probe and the measuring orifice shall be sufficient for the flow to be uniformly mixed.



*Indicates a critical dimension
(Not to scale)

FIGURE 4.4.1 Exhaust system.

4.5 Load Cell.

4.5.1 The arrangement of the specimen holders on the load cell shall be as indicated in Figure 4.1.3.

4.5.2 The load cell shall have an accuracy of 0.1 g and a measuring range of 500 g.

4.6 Specimen Mounting.

4.6.1 The horizontal specimen holder shall be as shown in Figure 4.6.1.

4.6.2* The bottom of the horizontal specimen holder shall be lined with a layer of low-density (nominal density 65 kg/m^3) refractory fiber blanket with a thickness of at least 13 mm.

4.6.3 The distance between the bottom surface of the cone heater and the top of the specimen shall be adjusted to 25 mm.

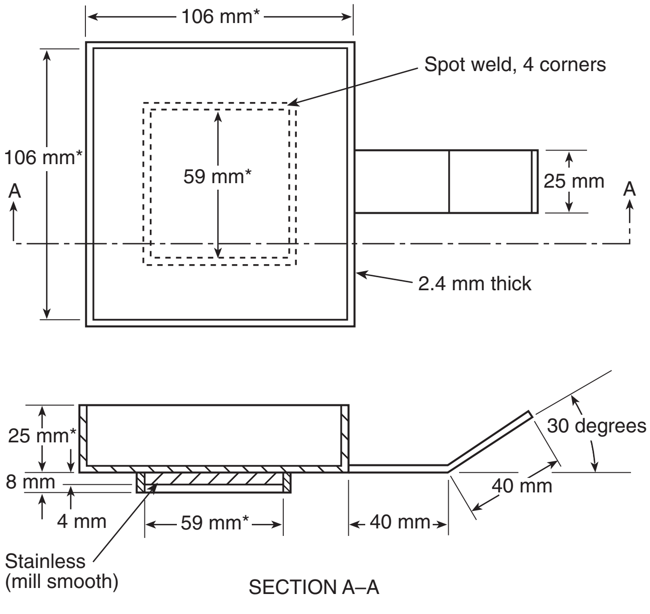
4.6.4 A retainer frame and a wire grid, as shown in Figure 4.6.4(a) and Figure 4.6.4(b), respectively, shall be used when testing intumescing specimens to reduce unrepresentative edge-burning of composite specimens and for retaining specimens prone to delamination. Other techniques shall be permitted to be utilized if documented in the test report.

4.7 Ignition Circuit.

4.7.1 External ignition shall be accomplished by a spark plug powered from a 10-kV transformer or by a 10-kV spark generator.

4.7.2 The length and location of the spark plug or spark generator electrode shall be such that the spark shall have a gap of 3 mm.

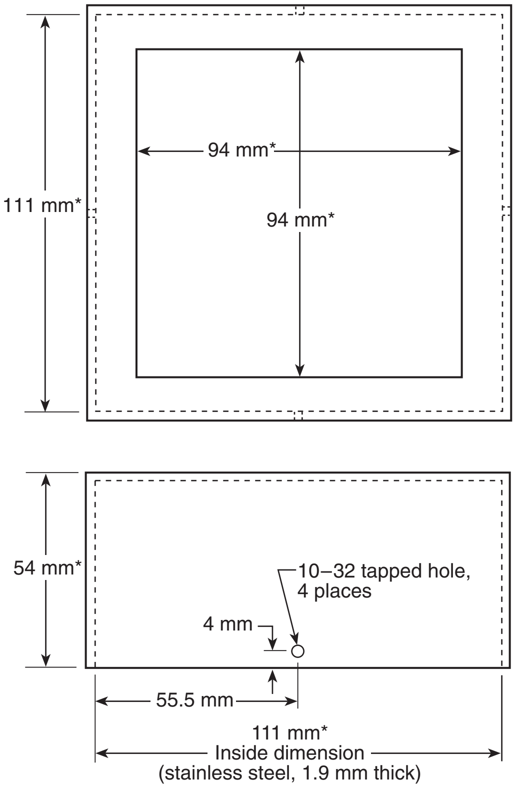
4.7.3 Spark gap shall be located 13 mm above the center of the specimen in the horizontal orientation.



*Indicates a critical dimension

FIGURE 4.6.1 Horizontal specimen holder.

4.7.4 If a spark plug and transformer is used, the transformer shall be of a type specifically designed for spark ignition use. The transformer shall have an isolated (ungrounded) secondary to minimize interference with the data transmission lines.



*Indicates a critical dimension

FIGURE 4.6.4(a) Optional retainer frame.

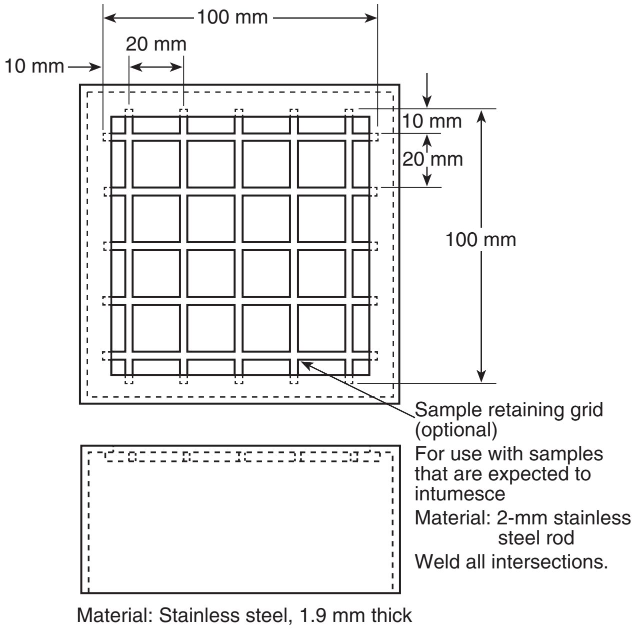


FIGURE 4.6.4(b) Optional wire grid.

4.7.5 The igniter shall be removed when sustained flaming is achieved for a period of 4 seconds.

4.8 Ignition Timer. The timing device for measuring time to sustained flaming shall be capable of recording elapsed time to the nearest second and shall be accurate to within 1 second in 1 hour.

4.9* Gas Sampling. Gas-sampling arrangements such as shown in Figure 4.9 shall incorporate a pump, a filter to prevent entry of soot, a cold trap to remove most of the moisture, a bypass system set to divert all flow except that required for the oxygen analyzer, a further moisture trap, and a trap for CO_2 removal where CO_2 is not measured. If CO_2 is removed, an additional moisture trap is required downstream from the CO_2 trap.

4.10 Oxygen Analyzer.

4.10.1 The analyzer shall be of the paramagnetic type with a range of 0 percent to 25 percent O_2.

4.10.2 The analyzer shall exhibit a linear response and drift of not more than 50 ppm O_2 (root-mean-square value) over a period of ½ hour.

4.10.3 The stream pressure shall be regulated upstream of the analyzer to allow for flow fluctuations, and the readings from the analyzer shall be compensated with an absolute pressure regulator to allow for atmospheric pressure variations.

4.10.4 The analyzer and the absolute pressure regulator shall be located in a constant-temperature environment.

4.10.5 The oxygen analyzer shall have a 10 percent to 90 percent response time of less than 12 seconds.

4.11 Smoke Obscuration Measuring System.

4.11.1 The smoke-measuring system, as shown in Figure 4.11.1, shall consist of a helium–neon laser, silicon photodiodes as main beam and reference detectors, and appropriate electronics to derive the extinction coefficient and to set the zero reading.

4.11.2 The system shall be designed to be resiliently attached to the exhaust duct by means of refractory gasketing at the location shown in Figure 4.4.1. This can be achieved either by using an optical bench or by split toke mounting in two pieces that are rigidly fastened together.

4.11.3 The meter shall be located in place by means of two small-diameter tubes welded onto each side of the exhaust duct. These tubes shall serve as part of the light baffling for the air purging and shall also allow for any smoke that enters despite the purge flow to be deposited on tube walls before reaching the optical elements.

4.12 Heat Flux Meter.

4.12.1 The total heat flux meter shall be of the Gardon (foil) or Schmidt-Boetler (thermopile) type, with a design range of 100 kW/m^2.

4.12.1.1 The target receiving radiation shall be flat, circular, approximately 12.5 mm in diameter, and coated with a durable matte black finish.

4.12.1.2 The target shall be water-cooled.

4.12.1.3 Radiation shall not pass through any window before reaching the target.

4.12.1.4 The instrument shall be robust, simple to set up and use, and stable in calibration.

4.12.1.5 The instrument shall have an accuracy within 3 percent and a repeatability within 0.5 percent.

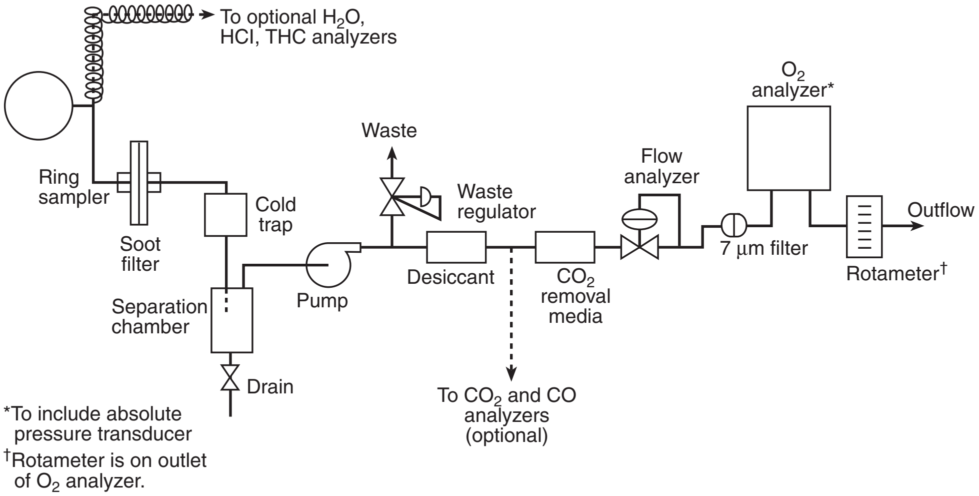


FIGURE 4.9 Gas analyzer instrumentation.

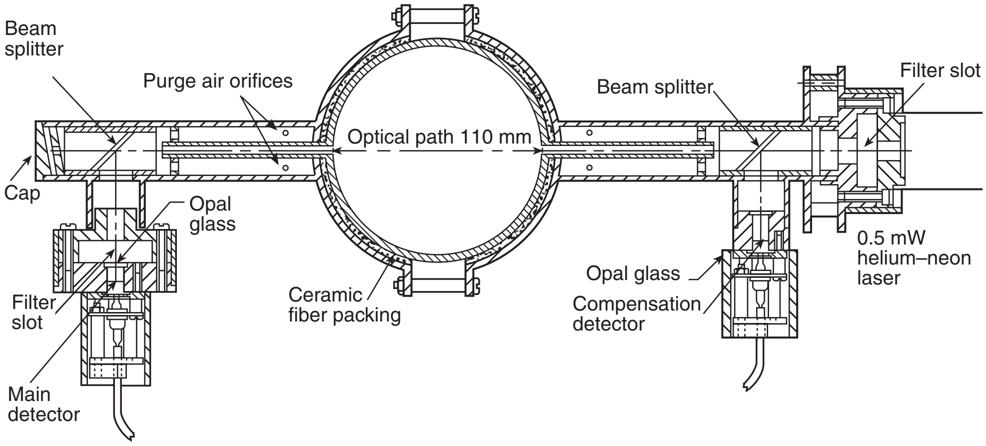


FIGURE 4.11.1 Smoke obscuration measuring system.

4.12.2 The calibration of the heat flux meter shall be checked whenever the apparatus is recalibrated by comparison with an instrument (of the same type as the working heat flux meter and of similar range) used only as a reference standard. The reference standard shall be fully calibrated at a standardizing laboratory at yearly intervals.

4.12.3 This meter shall be used to calibrate the heater temperature controller as shown in Figure 4.1.3. The meter shall be positioned at a location equivalent to the center of the specimen face during the calibration.

4.13 Calibration Burner.

4.13.1 A calibration burner shall be used to calibrate the rate of heat release apparatus as shown in Figure 4.1.3. The burner shall be constructed from a square-sectional brass tube with a square orifice covered with wire gauze through which the gas diffuses as shown in Figure 4.13.1.

4.13.2 The tube shall be packed with ceramic fiber to improve uniformity of flow.

4.13.3 The calibration burner shall be connected to a metered supply of methane with a purity of at least 99.5 percent.

4.14 Optical Calibration Filters. Glass neutral density filters of at least two different values and accurately calibrated at the laser wavelength of 0.6328 micrometers shall be provided.

4.15 Digital Data Collection.

4.15.1 The data collection system used shall have facilities for the recording of the output from the O_2 analyzer, the orifice meter, the thermocouples, the load cell, and the smoke-measuring system.

4.15.2 The data collection system shall have an accuracy corresponding to at least 50 ppm O_2 for the oxygen channel, 0.5°C for the temperature-measuring channels, and 0.01 percent of full-scale instrument output for all other instrument channels.

4.15.3 The system shall be capable of recording data for at least 1 hour at intervals not exceeding 2 seconds.

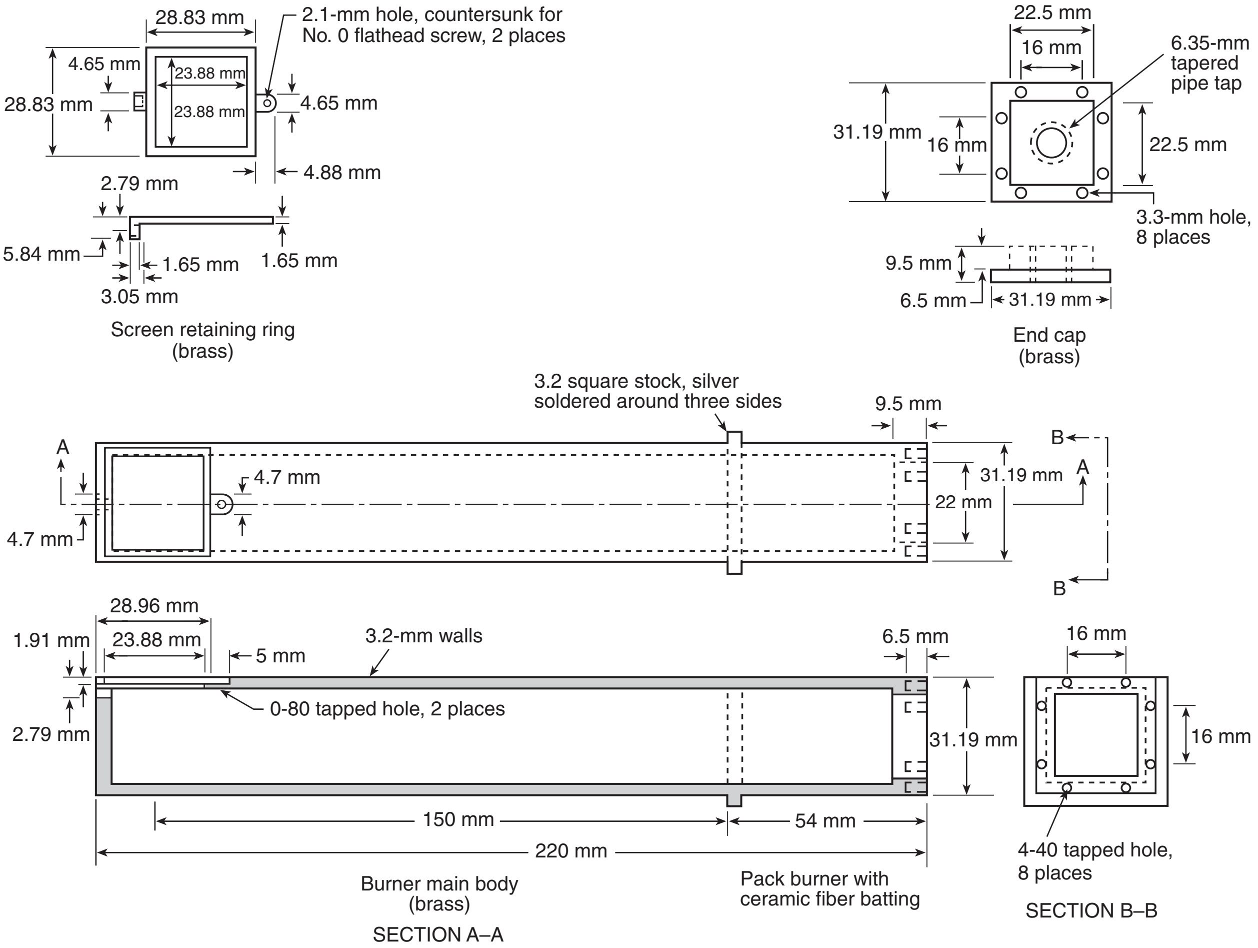


FIGURE 4.13.1 Calibration burner.

Chapter 5 Calibration of Equipment

5.1 Heater Flux Calibration.

5.1.1 The temperature controller shall be set at the required flux by using the heat flux meter at the start of the test day or after changing to a new flux level.

5.1.2 A specimen or specimen holder shall not be used when the heat flux meter is inserted into the calibration position.

5.1.3 The cone heater shall be operated for at least 10 minutes, and it shall be ensured that the controller is within its proportional band before the calibration is begun.

5.2 Oxygen Analyzer Calibration.

5.2.1 Preliminary Calibration.

5.2.1.1 The oxygen analyzer delay time shall be determined by setting a methane flow rate to the calibration burner that is equivalent to 5.0 kW. The heater shall not be turned on for this calibration.

5.2.1.2 The output of the analyzer shall be recorded on a data acquisition device or on a strip chart recorder as the methane supply, turned on and ignited, reaches a steady value and then returns to baseline after the supply is cut off. The temperature for the exhaust orifice meter shall be recorded at the same time.

5.2.1.3 The turn-on delay shall be determined from the difference between the time at which the temperature reading reaches 50 percent of its ultimate deflection and the time at which the oxygen reading reaches 50 percent of its ultimate deflection. The turn-off delay shall be determined similarly at turn-off.

5.2.1.4 The delay time shall be the average of the turn-on delay and turn-off delay.

5.2.1.5 The delay time value, t_d, subsequently shall be used to time-shift all the oxygen readings.

5.2.1.6 If the oxygen analyzer is equipped with an electric response time adjustment, it shall be set so that at turn-off there is just a trace of overshoot when switching rapidly between two different calibration gases.

5.2.1.7 Scan Timing.

5.2.1.7.1 The timing of the scans by the data collection system shall be calibrated with a timer accurate to within 1 second in 1 hour.

5.2.1.7.2 The data output shall show event times correct to within 3 seconds.

5.2.2 Operating Calibrations.

5.2.2.1 At the start of testing each day, the oxygen analyzer shall be zeroed and calibrated. For zeroing, the analyzer shall be fed with nitrogen gas using the same flow rate and pressure as for the sample gases.

5.2.2.2 Calibration shall be achieved similarly using ambient air and adjusting for a response of 20.95 percent.

5.2.2.3 Analyzer flow rates shall be monitored and set to be equal to the flow rate used when testing specimens.

5.2.2.4 After each specimen has been tested, a response level of 20.95 percent obtained using ambient air shall be verified.

5.3* Heat Release Calibration.

5.3.1 The heat release calibration shall be performed each day at the start of testing.

5.3.2 Methane with a purity of at least 99.5 percent shall be introduced into the calibration burner at a flow rate corresponding to 5 kW based on the net heat of combustion of methane (50.0×10^3 kJ/kg) using a precalibrated flowmeter. The flowmeter used shall be a dry test meter, a wet test meter, or an electronic mass flow controller.

5.3.3 If an electronic mass flow controller is used, it shall be calibrated periodically against a dry test meter or a wet test meter.

5.3.4 The test meter shall be equipped with devices to measure the temperature and pressure of the flowing gas so that appropriate corrections to the reading are made. If a wet test meter is used, the readings also shall be corrected for the moisture content.

5.3.5 The exhaust fan shall be set to the speed to be used for subsequent testing. The required calculations are provided in Chapter 8.

5.4* Load Cell Calibration. The load cell shall be calibrated with standard weights in the range of test specimen weight on each day of testing or when the load cell mechanical zero requires adjustment.

5.5* Smoke Meter Calibration. The smoke meter initially shall be calibrated to read correctly for two different value neutral density filters and also at 100 percent transmission.

Chapter 6 Test Specimens

6.1 Specimen Size. Test specimens shall be 100 mm × 100 mm, shall be up to 50 mm thick, and shall be cut to be representative of the construction of the end-use product.

6.2 Specimen Testing. For testing, the sides and bottom of each of the specimens shall be wrapped in a single layer of aluminum foil (0.025 to 0.040 mm thick), with the shiny side facing the specimen.

6.2.1 Composite specimens shall be exposed in a manner typical of the end-use condition. They shall be prepared so that the sides are covered with the outer layer(s).

6.2.2* Composite and intumescing materials shall be mounted using techniques that hold them in place within the specimen holder during combustion. The exact mounting and retaining method used shall be specified in the test report.

6.3 Conditioning. Specimens shall be conditioned to moisture equilibrium (constant weight) at an ambient temperature of 23°C ±3°C and a relative humidity of 50 percent ±5 percent.

Chapter 7 Test Procedure

7.1 Preparation.

7.1.1 Traps.

7.1.1.1 The CO_2 trap and the final moisture trap shall be checked.

7.1.1.2 The absorbents shall be replaced when they are no longer effective.

7.1.1.3 Any accumulated water in the cold trap separation chamber shall be drained.

7.1.1.4 The normal operating temperature of the cold trap shall be 0°C or lower.

7.1.2 Power. The power to the cone heater and the exhaust blower shall be turned on each test day. Power to the oxygen analyzer, load cell, and pressure transducer shall not be turned off on a daily basis.

7.1.3* Exhaust Flow. An exhaust flow rate at a value of $0.024\ m^3/s \pm 0.002\ m^3/s$ shall be set.

7.1.4 Calibration. The required calibration procedures specified in Chapter 5 shall be performed.

7.1.5 Holder. An empty specimen holder with refractory blanket in place shall be placed in the horizontal orientation during warm-up and in between tests to avoid excessive heat transmission to the load cell.

7.1.6 Ignition. Where external ignition is used, the spark plug holder shall be positioned in the location appropriate to the orientation being used.

7.2 Procedure.

7.2.1 When the test is ready to be performed, the empty specimen holder shall be removed.

7.2.2 The radiation shield shall be inserted, and the specimen, within the horizontal holder, shall be positioned in place. The holder shall initially be at room temperature.

7.2.3* The radiation shield shall remain in place until load cell equilibrium, but for no longer than 10 seconds total if the shield is not water-cooled.

7.2.4 Data Collection.

7.2.4.1 Data collection shall be initiated on removal of the radiation shield, which is the start of the test.

7.2.4.2 The data collection intervals shall be 2 seconds or less.

7.2.5 The ignition shall be conducted in the following sequence:

(1) Start the ignition timer.
(2) Move the spark igniter into place.
(3) Turn on the power to the spark igniter.

This sequence shall be accomplished within 2 seconds of the removal of the radiation shield.

7.2.6* Flaming.

7.2.6.1 When flashing or transitory flaming occurs, the times shall be recorded.

7.2.6.2 When flaming is sustained for a period of 4 seconds, the exceeding time at which the sustained flaming started shall be recorded, the spark igniter shall be turned off, and the spark ignition shall then be removed.

7.2.6.3 If the flame self-extinguishes in less than 60 seconds after the spark is turned off, the spark igniter shall be reinserted and shall be turned on.

7.2.6.3.1 If flaming reoccurs, the test shall be stopped, the test data shall then be discarded, and the test shall then be repeated without removing the spark igniter until the entire test is completed.

7.2.6.3.2 The events described in 7.2.6.3.1 shall be included in the test report.

7.2.7 Data shall be collected until 2 minutes after any flaming or other signs of combustion cease, until the average mass loss over a 1-minute period has dropped below 150 g/m^2 or until 60 minutes have elapsed, whichever occurs first.

7.2.8 Holder.

7.2.8.1 The specimen holder shall be removed.

7.2.8.2 The empty specimen holder shall be replaced.

7.2.9* After the start of the test, if the specimen does not exhibit sustained flaming within 15 minutes, the test shall be ended. If sustained flaming was not observed, the report shall indicate that there was no ignition. *(See also Section 9.1)*

7.2.10 Unless otherwise specified in the material or performance standard, three determinations shall be made and reported as specified in Chapter 9. The 180-second mean heat release rate readings shall be compared for the three specimens. If any of these mean readings differ by more than 10 percent from the average of the three readings, then an additional set of three specimens shall be tested. In such cases, the averages for the set of six readings shall be reported.

7.3 Safety Precautions.

7.3.1 The operator shall use protective gloves for insertion and removal of test specimens because the test procedures involve high-temperature and combustion processes and, therefore, hazards exist for burns, ignition of extraneous objects or clothing, and inhalation of combustion products. Neither the cone heater nor the associated fixtures shall be touched while hot except with the use of protective gloves.

7.3.2 The exhaust shall be checked for proper operation before testing and shall discharge into a building exhaust system with adequate capacity.

7.3.3 Provision shall be made for collecting and venting any combustion products that fail to be collected by the normal exhaust system of the apparatus.

Chapter 8 Calculations

8.1* General. The equations in this section shall assume that only O$_2$ is measured, as indicated on the gas analysis system in Figure 4.9.

8.2* Calibration Constant Using Methane.

8.2.1 The methane calibration shall be performed prior to the day's testing, to check for the proper operation of the instrument and to compensate for minor changes in mass flow determination.

8.2.2* The calibration constant, *C*, shall be determined from the following equation:

$$C = \frac{5.0}{1.10\left(12.54 \times 10^3\right)} \left(\frac{\sqrt{\Delta P}}{T_e} \right) \left[\frac{X^0_{O_2} - X_{O_2}(t)}{1.105 - 1.5 X_{O_2}(t)} \right]$$

8.3 Calculations for Test Specimen. The calculations in this section shall be used for various applications. The applicable material or performance standard shall be consulted for additional calculations.

8.3.1 Heat Release.

8.3.1.1 Prior to performing other calculations, the oxygen analyzer time shift shall be determined by the following equation:

$$X_{O_2}(t) = X^1_{O_2}(t + t_d)$$

8.3.1.2 The heat release rate then shall be determined by the following equation:

$$\dot{q}(t) = \frac{\Delta \mathrm{H}_c}{r_0}(1.10) C \sqrt{\frac{\Delta P}{T_e}} \left[\frac{X^0_{O_2} - X_{O_2}(t)}{1.105 - 1.5 X_{O_2}(t)} \right]$$

8.3.1.3 The value of $\Delta H_c/r_0$ for the test specimen shall be set to equal 13.1 × 10^3 kJ/kg, unless a more accurate value is known for the test material. The heat release rate per unit area shall be determined as follows:

$$q''(t) = \frac{q(t)}{A_s}$$

where:
A_s = 0.01 m^2

When the optimal retainer frame and wire grid as shown in Figure 4.8.4(a) and Figure 4.8.4(b) are used, $A_s = 0.0088$ m^2.

8.3.1.4 The total heat released during combustion, $\dot{q}''$, shall be determined by summation:

$$\dot{q}'' = \sum\nolimits_i \dot{q}'' i(t) \Delta t$$

The summation shall begin with the first reading after the last negative rate of heat release reading that occurs at the beginning of the test and shall continue until the final reading recorded for the test.

8.3.2 Mass Loss Rate and Effective Heat of Combustion.

8.3.2.1 The required mass loss rate, $-dm/dt$, shall be computed at each time interval using five-point numerical differentiation. The following equations shall be used:

(1) For the first scan ($i = 0$):

$$-\left(\frac{dm}{dt}\right)_{i=0} = \frac{25m_0 - 48m_1 + 36m_2 - 16m_3 + 3m_4}{12\Delta t}$$

(2) For the second scan ($i = 1$):

$$-\left(\frac{dm}{dt}\right)_{i=1} = \frac{3m_0 + 10m_1 - 18m_2 + 6m_3 - m_4}{12\Delta t}$$

(3) For any scan for which $1 < i < n - 1$ (n = total number of scans):

$$-\left(\frac{dm}{dt}\right)_{i} = \frac{-m_{i-2} + 8m_{i-1} - 8m_{i+1} + m_{i+2}}{12\Delta t}$$

(4) For the next to the last scan ($i = n - 1$):

$$-\left(\frac{dm}{dt}\right)_{i=n-1} = \frac{-10m_n - 3m_{n-1} + 18m_{n-2} - 6m_{n-3} + m_{n-4}}{12\Delta t}$$

(5) For the last scan ($i = n$):

$$-\left(\frac{dm}{dt}\right)_{i=n} = \frac{-25m_n + 48m_{n-1} - 36m_{n-2} + 16m_{n-3} - 3m_{n-4}}{12\Delta t}$$

8.3.2.2 The average effective heat of combustion shall be determined as follows, with the summation taken over the entire test length:

$$\Delta H_{c,eff} = \frac{\Sigma_i \dot{q}_i(t)\Delta t}{m_i - m_f}$$

A time-varying value also shall be determined as follows:

$$\Delta H_{c,eff}(t) = \frac{\dot{q}_i(t)}{-(dm/dt)}$$

8.3.3 Smoke Obscuration.

8.3.3.1 The extinction coefficient, k, shall be determined by the smoke meter electronics as follows:

$$k = \left(\frac{1}{L}\right)\ln\left(\frac{I_0}{I}\right)$$

8.3.3.2 The average specific extinction area obtained during the test shall be as follows:

$$\sigma_{f(avg)} = \frac{\Sigma_i \dot{v}_i k_i \Delta t_i}{m_i - m_f}$$

Chapter 9 Report

9.1 Required Information. The test report shall include the following information unless otherwise specified in the relevant material or performance standard:

(1) Specimen identification code or number
(2) Manufacturer or submitter
(3) Date of test
(4) Operator
(5) Composition or generic identification
(6) Specimen thickness
(7) Specimen mass
(8) Specimen color(s) and description
(9) Details of specimen preparation by the testing laboratory
(10) Test orientation, specimen mounting, and whether the retainer frame, the wire grid, or other special mounting procedure was used
(11) Heating flux and exhaust system flow rate
(12) Number of replicate specimens tested under the same conditions (A minimum of three specimens shall be tested, unless exploratory testing only is intended.)
(13) Time to sustained flaming(s). If sustained flaming was not observed during the test *(see 7.2.9)*, the report shall state "No ignition."
(14) Heat release rate (per unit area) curve (kW/m^2)
(15)*Peak $\dot{q}''$ and average $\dot{q}''$ values for the first 60 seconds, 180 seconds, and 300 seconds after ignition, or for other appropriate periods (For specimens that do not show sustained flaming, the above quantities, tabulated for periods beginning with the first reading after the last negative rate of heat release reading that occurs at the beginning of the test, shall be reported.)
(16) Total heat released by the specimen (MJ/m^2) (The total heat shall be computed beginning with the first reading after the last negative rate of heat release reading that occurs at the beginning of the test and continuing until the final reading recorded for the test.)
(17) Average $\Delta H_{c,eff}$ for the entire test (MJ/kg)
(18) Curve of $\Delta H_{c,eff}$ (MJ/kg) (This information is optional.)
(19) Mass remaining after test (g)
(20) Sample mass loss (kg/m^2), which is the average specimen mass loss rate (g/m^2·s) computed over the period that begins when 10 percent of the ultimate specimen mass loss occurs and that ends when 90 percent of the ultimate specimen mass loss occurs
(21) Smoke obscuration, which shall be reported as the average specific extinction area (m^2/kg)
(22) Values determined for Section 9.1, nos. (l2), (15), (16), and (20), averaged for all specimens
(23) Additional observations, including times of transitory flaming or flashing, if any
(24) Difficulties encountered in testing, if any
(25) Duration of test and the criteria used to end the test
(26) Data recording interval(s)
(27) Calculation method used for heat release

Annex A Explanatory Material

Annex A is not a part of the requirements of this NFPA document but is included for informational purposes only. This annex contains explanatory material, numbered to correspond with the applicable text paragraphs.

A.1.1.1 Conducting tests without piloted ignition is best kept for research and development.

A.1.1.3 Testing of materials in the horizontal orientation is currently preferred, especially for regulatory purposes, since such testing is much more reproducible and repeatable than when performed in the vertical orientation and generally appears to provide a more severe exposure condition. Where using the vertical orientation, it is more difficult to control the pyrolysates that evolve from the material's surface for the purpose of external ignition using the point source spark ignition. Convective heat flow along the exposed surface of the sample is also a complicating factor.

A.1.2.1 Determine the relationship of the behavior of materials and products to radiant heat flux exposure by testing specimens in a series of exposures over as broad a range of incident radiant heat fluxes as possible.

A.1.3.2 Testing of materials in the horizontal orientation is currently preferred, especially for regulatory purposes, because such testing is much more reproducible and repeatable than that performed in the vertical orientation and generally appears to provide a more severe exposure condition. When using the vertical orientation, it is more difficult to control the pyrolysates that evolve from the material's surface for the purpose of external ignition using the point source spark ignition. Convective heat flow along the exposed surface of the sample is also a complicating factor.

A.1.3.2.4 It cannot be assumed that the behavior of materials tested in accordance with this method will be replicated in a real fire situation. The response of a material to a real fire is affected by many factors, including the specific end-use of the material, the environment in which it is used, and the fire condition to which it might be exposed.

A.1.3.3.4 Additional information on testing is provided in Annex E.

A.1.3.3.7 Additional information on heating flux and the use of external ignition can be found in E.2.3.

A.3.3.1.2 Net Heat of Combustion. For additional information, see ASTM D 3286, *Standard Test Method for Gross Calorific Value of Coal and Coke by the Isoperibol Bomb Calorimeter.*

A.4.2.3 Because the geometry of the heater is critical, the dimensions shown in Figure 4.1.2 should be adhered to closely.

A.4.6.2 A suitable method for adjusting the distance between the bottom surface of the cone heater and the top surface of the specimen is to use a sliding cone height adjustment as shown in Figure 4.1.2, if provided.

A.4.9 The removal of CO_2 produces water, and this should be removed. If an optional CO_2 analyzer is used instead of removing CO_2 from the oxygen analyzer stream, the equations used to calculate the rate of heat release are different from those for the standard case indicated in Chapter 8. The appropriate equations are provided in Annex C.

A.5.3 Calibration can be permitted to be performed with or without the cone heater operating but should not be performed during heater warm-up.

A.5.4 The load cell mechanical zero might have to be adjusted when using the edge frame or if the apparatus was not last used in the horizontal orientation.

A.5.5 Once this calibration is set, only the zero value of the extinction coefficient (100 percent transmission) normally needs to be verified prior to each test.

A.6.2.2 Such mounting techniques include the use of an edge frame as shown in Figure 4.6.4(a), wire grid, or other special mounting procedure suitable to the specimen being tested. Figure 4.6.4(b) shows a wire grid suitable for several types of intumescing specimens.

A.7.1.3 Under room temperature conditions, this volume flow rate corresponds to a mass flow rate of approximately 30 g/s.

A.7.2.3 The radiation shield should remain in place for a sufficient time to ensure stability of operation.

A.7.2.6 The time of sustained flaming to be reported is the time at which the flaming initially is observed, not when the 4-second period that defines sustained flaming has elapsed.

A.7.2.9 Testing should be stopped if explosive spalling or excessive swelling occurs. The procedures described in Chapter 7 might be useful in mitigating these effects.

A.8.1 Appropriate equations for cases where additional gas analysis equipment (CO_2, CO, H_2O) is used are provided in Annex C.

A.8.2 A calibration differing more than 5 percent from the previous calibration is not normal and suggests instrument malfunction.

A.8.2.2 Here 5.0 corresponds to 5.0 kW of methane supplied, 12.54×10^3 is the ratio $\Delta H_c / r_0$ for methane, 1.10 is the ratio of oxygen to air molecular weight, and the other variables are as provided in 1.3.3.

A.9.1(15) Certain specimens do not show visible, sustained flaming but do indicate positive rate of heat release values.

Annex B Precision and Bias

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

B.1 Precision.

B.1.1 Interlaboratory trials were conducted by ASTM Committee E.5 to determine the repeatability and reproducibility of this test method. The results were analyzed in conjunction with the results of a parallel set of interlaboratory trials sponsored by the International Organization for Standardization (ISO). The complete results have been placed on file at ASTM headquarters as a research report, *Report to ASTM on Cone Calorimeter Inter-Laboratory Trials* (request RR: E05-1008). The results obtained for repeatability and reproducibility are provided below; further details of the interlaboratory trials are provided in Section B.2.

B.1.2 The following definitions of repeatability (r) and reproducibility (R) should be used:

$$r = f\sqrt{2\sigma_r}$$
$$R = f\sqrt{2\sigma_R}$$

where:
σ_r = repeatability standard deviation
σ_R = reproducibility standard deviation

The coefficient $\sqrt{2}$ derived from the fact that r and R refer to the difference between two single test results, and f, which equals approximately 2, corresponds to the probability level of 95 percent being taken. These products then are rounded off as follows:

$$r = 2.8S_r$$
$$R = 2.8S_R$$

For calculations, the sample-based standard deviation estimates, S, are substituted for the population standard deviations, σ, since the latter are not known.

B.1.3 For the materials tested, values for repeatability, *r,* and reproducibility, *R,* have been calculated for six variables. These variables, chosen as representative of the test results, are as follows:

$$t_{ig}, \dot{q}''_{max}, \dot{q}''_{180}, \dot{q}''_{tot}, \Delta H_{c,eff}, \sigma_f$$

A linear regression model was used to describe *r* and *R* as a function of the mean overall replicates and overall laboratories for each of the six variables. The regression equations are provided. The range of mean values over which the fit was obtained is also indicated. The results for time to sustained flaming, t_{ig}, in the range of 5 seconds to 150 seconds were as follows:

$$r = 4.1 + 0.125t_{ig}$$
$$R = 7.4 + 0.220t_{ig}$$

The results for peak heat release rate, $\dot{q}''_{max}$, in the range of 70 kW/m^2 to 1120 kW/m^2 were as follows:

$$r = 13.3 + 0.131\dot{q}''_{max}$$
$$R = 60.4 + 0.141\dot{q}''_{max}$$

The results for 180-second average heat release rate, $\dot{q}''_{180}$, in the range of 70 kW/m^2 to 870 kW/m^2 were as follows:

$$r = 23.3 + 0.137\dot{q}''_{180}$$
$$R = 25.5 + 0.151\dot{q}''_{180}$$

The results for total heat released, $\dot{q}''_{tot}$, the range of 5 MJ/m^2 to 720 MJ/m^2 were as follows:

$$r = 7.4 + 0.068\dot{q}''_{tot}$$
$$R = 11.8 + 0.088\dot{q}''_{tot}$$

The results for peak effective heat of combustion, $\Delta H_{c,eff}$, in the range of 7 kJ/g to 40 kJ/g were as follows:

$$r = 1.23 + 0.050\Delta H_{c,eff}$$
$$R = 2.42 + 0.055\Delta H_{c,eff}$$

The results for average specific extinction area, σ_f, in the range of 30 m^2/kg to 2200 m^2/kg were as follows:

$$r = 59 + 0.076\sigma_f$$
$$R = 63 + 0.215\sigma_f$$

B.2 Bias. For solid specimens of unknown chemical composition, as used in building materials, furnishings, and common occupant fuel load, it has been documented that the use of the oxygen consumption standard value of $\Delta H_c/r_0 = 13.1 \times 10^3$ kJ/kg oxygen results in an expected error band of 5 percent compared to true value. For homogeneous materials with only a single pyrolysis mechanism, this uncertainty can be reduced by determining ΔH_c from oxygen bomb measurements and r_0 from ultimate elemental analysis. For most testing, this is not practical, because specimens might be composite and nonhomogeneous and might exhibit several degradation reactions. Therefore, for unknown samples, a 5 percent accuracy limit is recommended. For reference materials, however, careful determination of $\Delta H_c/r_0$ can reduce this source of uncertainty substantially.

Annex C Calculation of Heat Release with Additional Gas Analysis

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

C.1 Introduction. The equations used to calculate heat release rate assume CO_2 is removed from the gas sample in a chemical scrubber before O_2 is measured. Some laboratories are equipped to measure CO_2; in such a case, it is not necessary to remove the CO_2 from the O_2 line. The advantage in this case is that the chemical scrubbing agent, which is costly and necessitates careful handling, can be avoided.

In this annex, equations are provided that should be used when CO_2 is measured but not scrubbed out of the sampling lines. Two cases are considered. In the first case, part of the dried and filtered sample stream is diverted into infrared CO_2 and CO analyzers. To avoid condensation, the measurement of H_2O concentration in the flow of combustion products necessitates a separate sampling system with heated filters, heated sampling lines, and a heated analyzer.

C.2 Symbols. The following symbols are used in this annex:

C = calibration constant for oxygen consumption analysis (m$^{1/2}$kg$^{1/2}$K$^{1/2}$)
$\Delta H_c/r_0$ = net heat of combustion (kJ/kg)
M_a = molecular weight of air (kg/kmol)
M_e = molecular weight of the combustion products (kg/kmol)
$\dot{m}_e$ = exhaust duct mass flow rate (kg/s)
ΔP = orifice meter pressure differential (Pa)
$\dot{q}''$ = heat release rate per unit area (kW/m^2)
t_d = oxygen analyzer delay time (s)
t_d^1 = delay time of the CO_2 analyzer (s)
t_d^2 = delay time of the CO analyzer (s)
t_d^3 = delay time of the H_2 analyzer (s)
T_e = absolute temperature of gas at the orifice meter (K)
$X_{CO_2}^0$ = initial CO_2 reading (mole fraction)
X_{CO}^0 = initial CO reading (mole fraction)
$X_{H_2O}^0$ = initial H_2O reading (mole fraction)
$X_{O_2}^a$ = ambient O_2 reading (mole fraction)
$X_{CO_2}^1$ = CO_2 reading before delay time correction (mole fraction)
X_{CO}^1 = CO reading before delay time correction (mole fraction)
$X_{H_2O}^1$ = H_2O reading before delay time correction (mole fraction)
X_{CO_2} = CO_2 reading after delay time correction (mole fraction)
X_{CO} = CO reading after delay time correction (mole fraction)
X_{H_2O} = H_2O reading after delay time correction (mole fraction)
ϕ = oxygen depletion factor

C.3 Where CO_2 and CO Are Measured. As in the case of the oxygen analyzer, measurements of CO_2 and CO should be time-shifted to take into account the transport time in the sampling lines, as follows:

$$X_{O_2}(t) = X^1_{O_2}\left(t + t_d\right)$$
$$X_{CO_2}\left(t\right) = X^1_{CO_2}\left(t + t^1_d\right)$$
$$X_{CO}\left(t\right) = X^1_{CO}\left(t + t^2_d\right)$$

C.3.1 In this case, the delay times, t^1_d and t^2_d, for the CO_2 and CO analyzers, respectively, are usually different (smaller) than the delay time, t_d, for the O_2 analyzer.

The exhaust duct flow is calculated as follows:

$$\dot{m}_e = C\sqrt{\frac{\Delta P}{T_e}}$$

C.3.2 The rate of heat release now can be determined as follows:

$$\dot{q} = 1.10\left(\frac{\Delta H_c}{r_0}\right)X^a_{O_2}\left[\frac{\phi - 0.1721 - \phi\left(X_{CO}/X_{CO_2}\right)}{(1-\phi)+1.105\phi}\right]\dot{m}_e$$

C.3.3 The oxygen depletion factor, ϕ, is calculated as follows:

$$\phi = \frac{X^0_{O_2}\left(1 - X_{CO_2} - X_{CO}\right) - X_{O_2}\left(1 - X^0_{CO_2}\right)}{X^0_{O_2}\left(1 - X_{CO_2} - X_{CO} - X_{O_2}\right)}$$

C.3.4 The ambient mole fraction of oxygen is calculated as follows:

$$X^a_{O_2} = \left(1 - X^0_{H_2O}\right)X^0_{O_2}$$

The second value in the denominator of the value in brackets in the equation in C.3.2 is a correction factor for incomplete combustion of some carbon to CO instead of CO_2. In fact, the value of X_{CO} is usually very small, so that it can be disregarded in the equations in C.3.2 and C.3.3. The practical implication of this correction factor is that a CO analyzer generally does not result in a noticeable increase in accuracy of heat release rate measurements. Consequently, the equations can be used, even if no CO analyzer is present, by setting $X_{CO} = 0$.

C.4 Where H_2O Also Is Measured. In an open combustion system, such as is used in this method, the flow rate of air entering the system cannot be measured directly but is inferred from the flow rate measured in the exhaust duct. An assumption regarding the expansion due to combustion of the fraction of the air that is fully depleted of its oxygen needs to be made. This expansion depends on the composition of the fuel and the actual stoichiometry of the combustion. A suitable average value for the volumetric expansion factor is 1.105, which is accurate for methane.

This value is already incorporated within the equation in C.3.2 for $\dot{q}$. For cone calorimeter tests, it can be assumed that the exhaust gases consist primarily of N_2, O_2, CO_2, H_2O, and CO; thus, measurements of these gases can be used to determine the actual expansion. (It is assumed that the measurements of O_2, CO_2, and CO correspond to a dry gas stream, while the H_2O measurement corresponds to total stream flow.) The mass flow rate in the exhaust duct is then more accurately provided by the following equation:

$$\dot{m}_e = \sqrt{\frac{M_e}{M_a}}C\sqrt{\frac{\Delta P}{T_e}}$$

C.4.1 The molecular weight, M_e, of the exhaust gases is calculated as follows:

$$M_e = \left[4.5 + \left(1 - X_{H_2O}\right)\left(2.5 + X_{O_2} + 4X_{CO_2}\right)\right]4$$

C.4.2 Using 28.97 as the value for M_a, the heat release rate is calculated as follows:

$$\dot{q}\left(t\right) = 1.10\left(\frac{\Delta H_c}{r_0}\right)\left(1 - X_{H_2O}\right)\left[\frac{X^0_{O_2}\left(1 - X_{O_2} - X_{CO_2}\right)}{1 - X^0_{O_2} - X^0_{CO_2}} - X_{O_2}\right]\dot{m}_e$$

C.4.3 The H_2O readings used in the equation in C.4.2 are time-shifted in a way similar to that for the equations in Section C.3 for the other analyzers:

$$X^0_{H_2O}\left(t\right) = X^1_{H_2O}\left(t + t^3_d\right)$$

Additional background on these computations is given in note 15 in Annex E.

Annex D Testing of Specimens in the Vertical Orientation

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

D.1 Introduction. This annex is provided so that the user of this standard has access to a standardized methodology for testing specimens in a vertical orientation using the same apparatus specified in this standard. Although the recommended method of testing specimens is in the horizontal orientation, especially for the purpose of regulating the use of materials, it is believed that testing specimens in the vertical orientation might be useful for research and development purposes. With time and experience, this method of testing might be found suitable for more widespread use.

D.2 Purpose. This test method allows testing of the specimen in the vertical position.

D.3 Basis of Test Method. This alternative test method using the vertical orientation of the test specimen is based on the text of Chapters 1 through 9. To accommodate the vertical orientation of the specimen, the wording has been revised as necessary, and section and paragraph numbers in parentheses have been provided for quick reference.

D.4 Test Limitations.

D.4.1 *(See 1.3.2.)* The test data should be considered to be invalid if any of the following occur:

(1) The specimen experiences an explosive spalling.
(2) The specimen swells to the point where it touches the spark plug prior to ignition.
(3) The specimen swells to the point where it touches the heater base plate during combustion.
(4) In the vertical orientation, the specimen melts sufficiently to overflow the melt-trough.

D.4.2 If delamination of the specimen occurs, the test results should be considered suspect, and this should be described in the test report.

D.5 Exposure. *(See 1.3.3.5.)* Specimens should be exposed to heating fluxes ranging from 0 kW/m^2 to 100 kW/m^2 in a vertical orientation. External ignition, where used, should be by electric spark. The value of the heating flux and the use of external ignition should be specified by the relevant material or performance standard *(see E.2.3)* or by the test sponsor for research and development purposes.

D.6 Definition.

D.6.1 Orientation. *(See 3.3.5.)* The plane in which the exposed face of the specimen is located during testing (i.e., vertically facing the heater).

D.7 Test Apparatus. *(See Section 4.1.)* The test apparatus should consist of the following components:

(1) A conical-shaped radiant electric heater
(2) Specimen holders
(3) An exhaust-gas system with oxygen-monitoring and flow-measuring instrumentation
(4) An electric ignition spark plug
(5) A data collection and analysis system
(6) A load cell for measuring specimen mass loss

A general view of the apparatus is shown in Figure 4.1.1, and an exploded view of the vertical orientation is shown in Figure D.7.

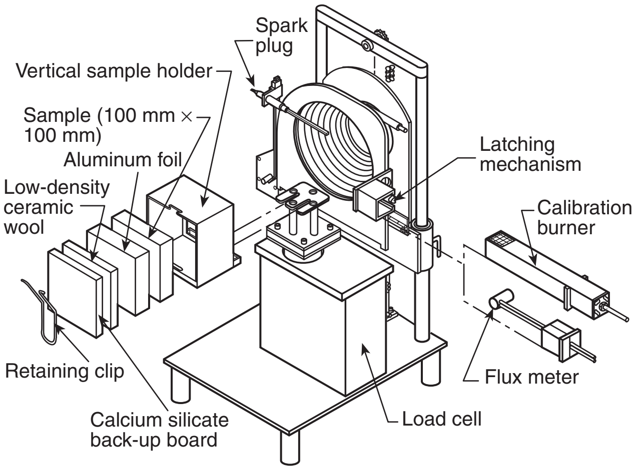


FIGURE D.7 Exploded view, vertical orientation.

D.8 Heater. *(See 4.2.3.)* The heater should be mounted in a vertical orientation. The heater should be capable of producing irradiances on the surface of the specimen of up to 100 kW/m^2. The irradiance should be uniform within the central 50-mm × 50-mm area of the specimen to within 10 percent.

D.9 Specimen Holder. *(See 4.6.1.)* The vertical specimen holder is shown in Figure D.9 and includes a small drip trap to contain a limited amount of molten material. A specimen should be installed in the vertical specimen holder by backing it with a layer of refractory fiber blanket (nominal density 65 kg/m^3). The thickness of the refractory fiber blanket depends on the specimen's thickness but should be at least 13 mm. A layer of rigid, ceramic fiber millboard should be placed behind the fiber blanket layer. The millboard thickness should be such that the entire assembly is rigidly bound together once the retaining spring clip is inserted behind the millboard. In the vertical orientation, the cone heater height should be set so the center of the heater lines up with the specimen center.

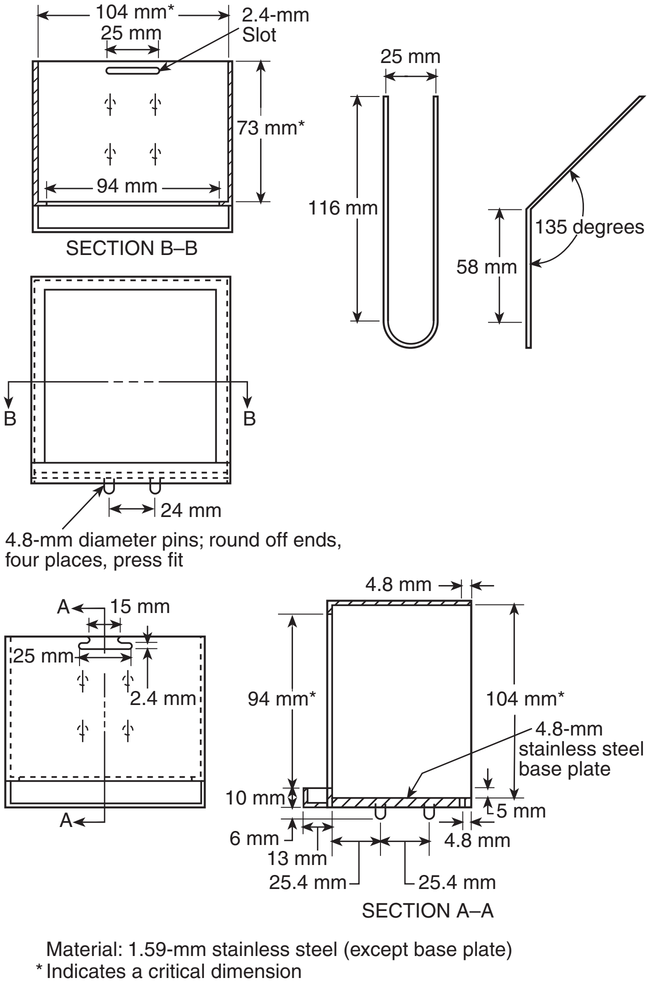


FIGURE D.9 Vertical specimen holder.

D.10 Ignition Circuit. *(See Section 4.7.)* External ignition should be accomplished by a spark plug powered from a 10-kV transformer, or by a 10-kV spark generator. The length and location of the spark plug or spark generator electrode should be such that the spark has a gap of 3 mm and that the spark gap is located 5 mm above the top of the holder and in the plane of the specimen face in the vertical orientation. If a spark plug and transformer is used, the transformer should be of a type specifically designed for spark ignition use. The transformer should have an isolated (ungrounded) secondary to minimize interference with the data transmission lines. The igniter should be removed when sustained flaming is achieved for a period of 4 seconds.