The Cone Calorimeter

28

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Introduction

Chapter 27 describes the history and development of techniques for measuring heat release rate (HRR). This chapter outlines features and details of today's preferred instrument for measuring bench-scale HRR—the cone calorimeter. Other cone calorimeter measuring functions are

1. Effective heat of combustion
2. Mass loss rate
3. Ignitability
4. Smoke and soot
5. Toxic gases

The cone calorimeter is based on the concept of oxygen consumption calorimetry, which is also presented in Chap. 27.

This chapter provides both an introduction to and description of cone calorimeter measurement technology. The cone calorimeter has recently assumed a dominant role in bench-scale fire testing of various products; therefore, an emphasis will be placed on the *why* of various design features. When conducting tests, the cone calorimeter operator needs to consult several other documents. Testing will presumably be in conformance with either ISO 5660 [1] or ASTM E1354 [2]. In addition, the "User's Guide for the Cone Calorimeter" [3] should be consulted. This chapter does not emphasize the operational aspects documented in these references but instead provides the reader with an overall feel for the equipment. Space is not available in this handbook to fully discuss the applications of cone calorimeter data, apart from the review of data given in Chap. 26. Extensive guidance on using cone calorimeter data is given in a textbook on this subject [4]. It also provides example data compilations and information on using cone calorimeter data for predictions of fires.

Summary of Features

A schematic view of the cone calorimeter is shown in Fig. 28.1. Figure 28.2 shows a commercial instrument, and Fig. 28.3 identifies some of the major components. The more salient operational features and limits of the apparatus are

Specimen size	100 × 100 mm, thickness of 6–50 mm
Specimen orientation	Horizontal, face up (standard testing) or vertical (reserved for exploratory studies)
Specimen back-face conditions	Very low loss insulating ceramic fibrous material
Load cell live load capacity	500 g
Load cell tare capacity	3.5 kg
Load cell resolution	0.005 g
Ignition	Electric spark
Heating flux range	0–110 kW · m^{-2}
Flux uniformity, horizontal	Typically 2 %
Flux uniformity, vertical	Typically 7 %

(continued)

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Sensing principle	Oxygen consumption, only
Maximum instantaneous output	In excess of 20 kW
Normally calibrated range	0–12 kW
Linearity over 0–12 kW range	5 %
Noise intrinsic to oxygen meter	20 ppm O_2
Noise in HRR measurement, over 0–12 kW range	2.5 %
Smoke meter operating range	0–20 m^{-1} (linear)
Smoke meter resolution	0.01 m^{-1}
Soot sampler mass fraction range	0–1 part in 200 (of exhaust gas flow)

Uses of Cone Calorimeter Data

Cone calorimeter data are primarily used for four purposes:

1. comparative evaluation of materials;
2. obtaining of thermophysical constants (fire properties) of materials;
3. as input data to fire models or engineering calculation;
4. for regulatory compliance.

Comparative Evaluation of Materials

Comparative evaluation of materials is the easiest and simplest use of cone calorimeter data. This, in fact, is also where the largest amount of published literature involving cone calorimeter data is found, of which the fire retardants field is a prominent example. There have been hundreds of papers published examining fire retardant formulations with the use of the cone calorimeter. For such studies, modeling or large-scale testing is inappropriate, since the

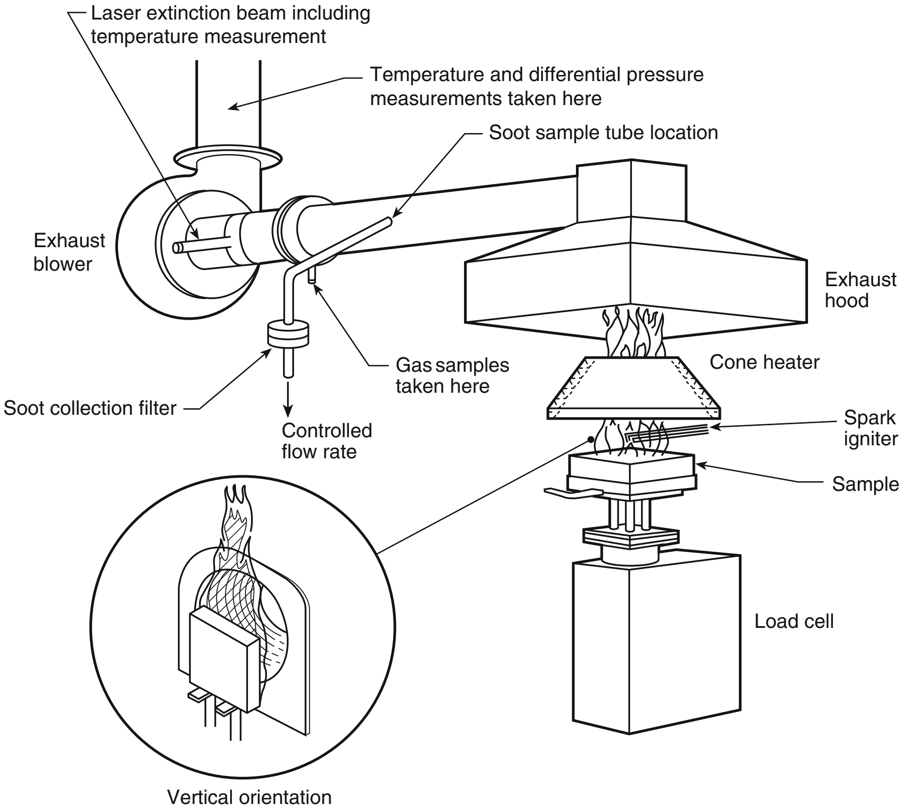


Fig. 28.1 Schematic view of the cone calorimeter

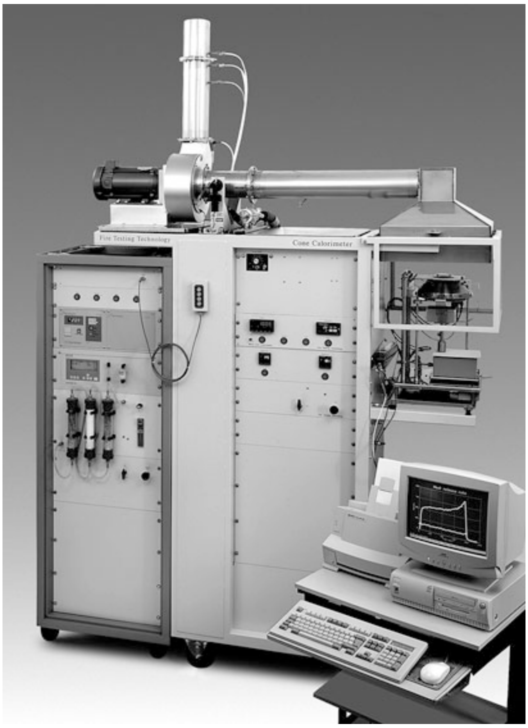
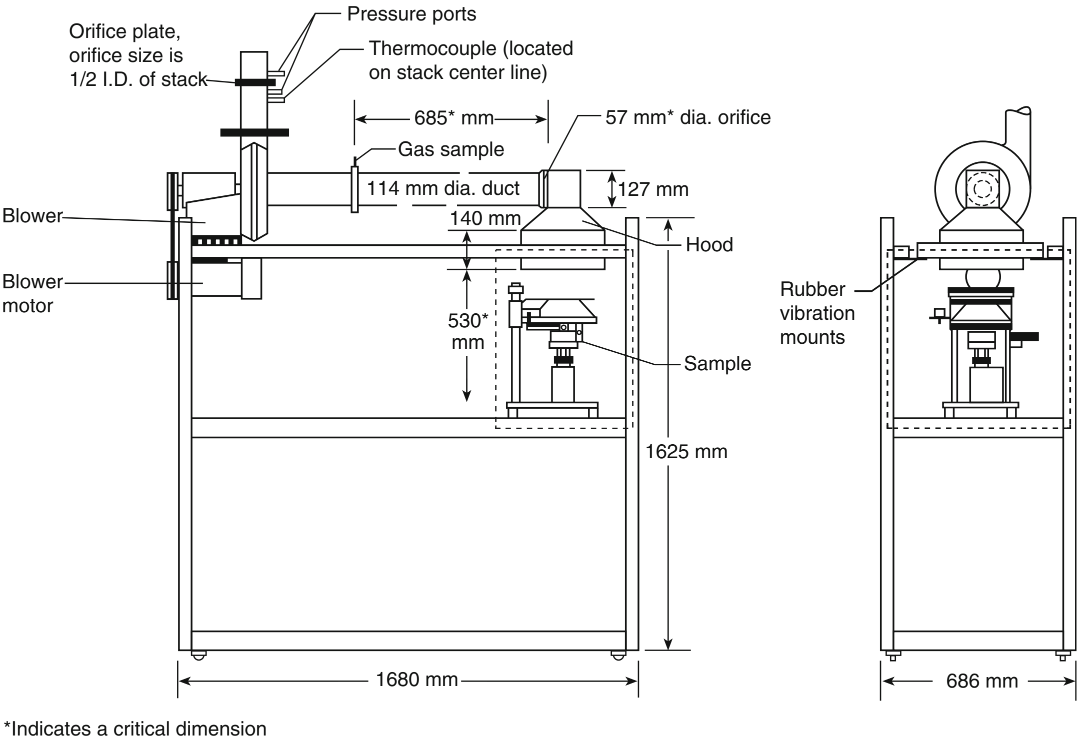


Fig. 28.2 A commercial cone calorimeter (Photo courtesy Fire Testing Technology, Ltd.)

same polymer formulation can be used for a wide array of products. Thus, cone calorimeter data are normally used and a comparative evaluation is made. Most commonly, candidate materials are evaluated simply by comparing their peak HRR values. This approach is not adequate if flame spread in the real-life environment is significant, i.e., if the material is not quickly ignited over its entire face. For taking flame spread into account, albeit in a simplified way, Babrauskas [5] proposed in 1984 that the variable $\dot{q}''/t_{ig}$ be used, which is the ratio of the HRR value to the ignition time. The ignition time was shown to be correlated to flame spread rate, thus, this hazard parameter increases with both increasing HRR and increasing propensity for rapid flame spread. A reasonable semi-quantitative prediction of the time to flashover was possible using this ratio for various wall lining materials. Petrella [6] later proposed a modified rating system where $\dot{q}''/t_{ig}$ is plotted on one axis, while total heat released is plotted on the other. Materials of better performance have both a low $\dot{q}''/t_{ig}$ value and a low total heat release. The most refined scheme



*Indicates a critical dimension

Fig. 28.3 View of major components of the cone calorimeter which is still simple is the one put forth in 1991 by Cleary and Quintiere [7]. They introduced a parameter *b*:

$$b = 0.01\dot{q}''_{avg} - 1 - \frac{t_{ig}}{t_b} \tag{28.1}$$

where $\dot{q}''_{avg}$ = average HRR (kW m^{-2}) at a 50 kW m^{-2} irradiance, t_{ig} = ignition time (s), and t_{b} = duration of flaming (s). They showed that materials which show $b < -0.4$ have negligible propensity to spread fire, while those with progressively higher values show increased hazard in full-scale applications. The Cleary/Quintiere *b* is not to be confused with Spalding's B number, sometimes use to characterize hazards of burning liquids.

Obtaining Thermophysical Constants of Materials

The HRR of materials cannot be computed from some ostensibly simple material fire properties, but is rather a complex relationship governed by chemical (reaction kinetics), thermal (heat transfer properties), and mechanical (cracking, delamination, etc.) properties. Thus, in general, it is not possible to deduce some underlying material fire properties from HRR data. However, the situation is more amenable for ignition data, where it is possible to obtain fire properties from cone calorimeter data. This topic is treated at length in the *Ignition Handbook* [8], but here the most useful computation will be identified. For thermally thick materials, Janssens derived the relationship:

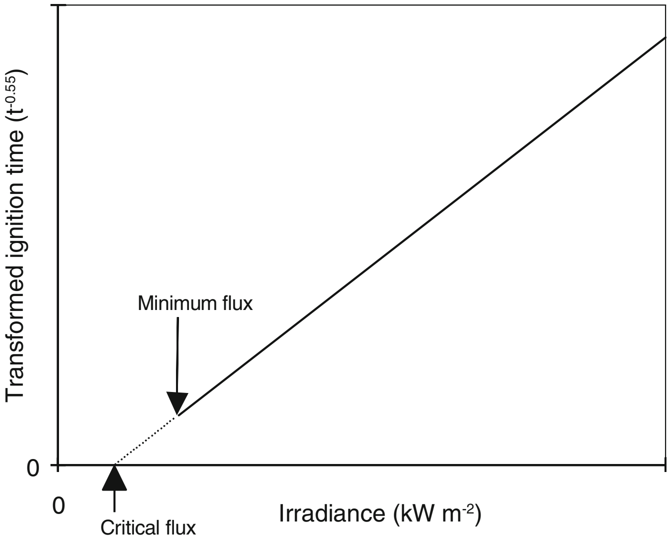
$$\dot{q}''_e = \dot{q}''_{cr}\left[1 + 0.73\left(\frac{\lambda\rho C}{h^2_{eff}t_{ig}}\right)^{0.55}\right] \tag{28.2}$$

According to this, if experimental data are plotted (Fig. 28.4) such that $\dot{q}''_e$ is put on the x-axis and $t_{ig}^{-0.55}$ on the y-axis, then the data will fall in a straight line, with the x-axis intercept being $\dot{q}''_{cr}$. Here $\dot{q}''_e$ = irradiance (kWm^{-2}), $\dot{q}''_{cr}$ = x-axis intercept, t_{ig} = ignition time (s), and $\lambda\rho C$ is the thermal inertia (kJ^2 m^{-4} s^{-1} K^{-2}) of the specimen. From such a plot, the value of thermal inertia can be computed, which is an effective fire property of importance in both ignition and flame spread problems.

Input Data for Fire Models or Calculations

A number of correlational schemes for making engineering calculations on various types of commodities have been developed which are

Fig. 28.4 The main variables of the ignitability plot



based on Cone Calorimeter data. These are reviewed in Chap. 26. For more refined models, i.e., zone or CFD models for room fires, the application is more difficult. This is because the HRR is strongly a function of the irradiance. But in most real fires, the irradiance received by any particular locale is a dynamic function of time and is not a constant. Because of this difficulty, it has become more common for modern-day computer codes, e.g., FDS, to adopt a pyrolysis model, rather than using small-scale experimental HRR data as an input. A pyrolysis model effectively is a scheme where the HRR of a small area of material is computed from some sort of input data. But, as discussed above, for realistic materials there generally is no simple series of expression that would be able to predict the HRR, based on the input of a modest collection of constants. Even if the constants can be defined, they must in turn be obtained from experiments, and this is already known to be difficult in the first place. CFD models however may have an option to input small-scale HRR data; typically in that case the HRR at a fixed irradiance is used. Capote et al. [9] illustrated such an approach in modeling train fires with FDS. Aksit et al. [10] described use of cone calorimeter input data for modeling cable tray fires with SOFIE, while Andersson [11] described a more general effort with SOFIE. Tsai et al. [12] described a proprietary CFD model using cone calorimeter data; the model was used solely for calculating ignition behavior of materials.

For zone fire models, the most successful example has been the BRANZfire model of Wade [13–15]. Lattimer et al. [16] described a module for CFAST based on cone calorimeter input data. Janssens and Dillon [17] described a simple room fire model based on cone calorimeter data. Cone calorimeter data have also been used in an application simpler than room fires, the prediction of upward flame spread on vertical panels [18–23].

For some models, it is necessary to know the total heat flux incident on the specimen, not just the external heat flux; the total heat flux is comprised of the external heat flux, plus the flame flux. Hostikka and Axelsson [24] showed an interesting example of CFD modeling by predicting the flame flux in the cone calorimeter.

Regulatory Compliance

The New Zealand building code specifies use of the ISO version of the cone calorimeter standard, ISO 5660 [1], for external wall cladding products. The Building Code of Australia uses cone calorimeter testing to assess fire retardant treated wood for use in bushfire-prone areas. The building code of Japan uses cone calorimeter testing extensively, as a primary measure of the fire performance of surface lining materials [25]. In their application, tests are run at 50 kW m^{-2} irradiance for a duration of 5, 10, or 20 min, depending on the classification sought. In each case, a peak HRR value below 200 kW m^{-2} must be found, with the total heat release being less than 8 MJ m^{-2}, with the latter being a particularly onerous requirement. Taiwan has also adopted similar provisions. IMO, the International Maritime Organization, which provides the regulations for constructing of sea-going vessels, uses cone calorimeter testing for acceptance of “fire restricting material” for high-speed craft in the case of furniture and related materials.

Operating Principle

It is emphasized at this point that the cone calorimeter has been designed to use *only* oxygen consumption calorimetry as its measurement principle [26]. Other calorimeters that on occasion use oxygen consumption principles, for example, the Factory Mutual Research Corporation (FMRC) flammability apparatus (Chap. 27), sometimes incorporate a sensible enthalpy flow measurement technique to arrive at the *convective component* of the heat release rate. In the design of the cone calorimeter, such an approach was deemed to be misleading. The implicit assumption behind this type of measurement is that the fraction of the total heat release being manifest as the sensible flow enthalpy is a property of the material being tested. Such is not, in fact, the case. The convective fraction is dependent on details of the apparatus design and also on the scale of the specimen [27].

Where high-quality results are required, such as in the cone calorimeter, current-day practice demands that a paramagnetic oxygen analyzer be used. The various manufacturers use measuring schemes that differ in detail, but all rely on the same paramagnetic principle whereby the sensing element is sensitive to the partial pressure of oxygen in the cell. The most significant interferents to this detection principle are NO and NO_2, both of which show a strong paramagnetic response, but not as strong as that of oxygen. Interferents are never a problem in fire testing, however, since O_2 levels measured are 10–21%, whereas concentrations of NO_x are rarely above 100 ppm.

Unlike in applications where oxygen levels are monitored as simply one of many indications of fire hazard, in HRR work it is essential that the instrumentation be designed for the highest possible resolution. Thus, both the ASTM and ISO standards specify that the short-term noise + drift of the oxygen analyzer must be less than or equal to 50 ppm O_2. The best-grade commercial instruments are able to meet a 20 ppm O_2 limit. In addition, the standards provide a significant amount of detail on the layout of the gas sampling system, including desiccation, mass flow control, and bypass flows. All of these aspects have to be in conformance with the specifications for good repeatability and reproducibility performance (see Fig. 28.3) to be achieved.

Because the detection principle responds to oxygen partial pressure, there needs to be a compensation for changes in atmospheric pressure, either with a mechanical back-pressure regulator or by measuring the pressure and correcting electrically. Without compensation, there can be significant error in the calculated heat release rate. Carbon dioxide, the other major component expected to be in the oxygen analyzer, causes less than 0.3 % error in the oxy-gen reading. Extensive practice advice on selecting, setting up, and calibrating oxygen analysis systems is given in Twilley and Babrauskas [3] and in Babrauskas and Grayson [4].

The Radiant Heater

After establishing the operating principle, the next most important feature is the type of heater. In general, such a heater should be able to achieve adequately high irradiances, have a relatively small convective heating component, present a highly uniform irradiance over the entire exposed face of the specimen, and be designed so as not to change its irradiance when the main voltage varies, when heater element aging occurs, or when the apparatus retains some residual heat from the exposure given to a prior specimen.

Range of Heat Fluxes Needed for Testing A room fire burning near its maximum rate can show gas temperatures over 1000 °C, producing corresponding irradiances to walls and contents of 150 $kW \cdot m^{-2}$. Testing under such extreme conditions may not be required; nonetheless, if postflashover fires are to be simulated, irradiances of over 75 $kW \cdot m^{-2}$ should be available, and preferably closer to 100 $kW \cdot m^{-2}$. A significant convective component would negate the purpose of having a radiant ignition test. Rather low convective fluxes can be achieved for specimens oriented horizontally, face up, and with the prevailing airflow being upwards. For vertical specimens, orientation is considered, and it becomes evident that a boundary layer will normally be expected to develop that will add some convective component. The convective boundary layer component is not uniform over the height of a specimen; thus it is seen that better uniformity can also be expected under conditions where the convective component is minimized.

Choice of Heater Type In a real fire, the ignition source is, in most cases, in the vicinity of a combustible. The radiation spectrum depends on the size of the fire. A very small fire can show a substantial fraction of its radiation at wavelengths characteristic of H_2O, CO_2, and other combustion products [28]. For larger fires—certainly for room fires reaching a hazardous condition—the radiation from the soot tends to dominate. The result is an approximation to a graybody radiation [29]. For such a graybody radiation the temperature is typically in the vicinity of 1000 °C [30]. Experimentally, heater choices for test apparatuses have included gas-fired panels, electric resistance heaters, flames, and high-temperature lamps. Electrical heaters tend to have a near-graybody characteristic and, assuming a dull or oxidized surface condition, a high emissivity. Gas-fired panels derive a substantial portion of their radiation from the ceramic face; thus, while there are discrete molecular wavelength peaks, overall the radiation shows a graybody continuum, typically in the range of 700–1000 °C [31]. High-temperature lamps, which have been used by several investigators [28, 32], typically have radiating temperatures of 2200–3000 °C. The spectral distribution of such a source—further limited by a translucent enclosure—is much different from one operating at 1000 °C. Whether this change in spectral characteristics is important depends on the surface of the material to be ignited. For a material with a radiant absorbance independent of wavelength, this source variation would not matter. Hallman, however, has reported data for a large number of plastics and shows that although there are some specimens with negligible wavelength dependence to their absorbance, the majority shows strong variations [28]. Hallman also measured ignition times of plastics with both a flame source and high-temperature lamps. The effect on ignition times ranges from negligible to more than an order of magnitude, depending on the specimen. For a general-purpose test, flames would probably be the least desirable source of heating. For a bench-scale test, flame size has to be kept small. This means that such flames are optically thin, their emissivity is low, and higher heat fluxes cannot be achieved unless a strong convective component is added.

Design Details Once an electrical radiant heater had been decided upon, design details were also influenced by work at NIST with earlier types of calorimeters. One of the primary requirements of the heater is that it not change the irradiance impressed on the specimen when the specimen ignites. This undesired event is, of course, exactly what happens with several of the older types of calorimeters. The specimen's flames directly heat nearby ironwork, which, in turn, radiates to the specimen. The heater, which had been viewing a cold specimen prior to ignition, also starts to view a hot flame afterwards. The result is that its efficiency increases drastically, giving a rise to its radiating temperature. Based on these observations, guidelines were formulated so that the specimen must, as much as possible, view only

1. A temperature-controlled heater
2. A water-cooled plate
3. The open-air, ambient-temperature environment

Reliance on item 2 increased costs significantly; thus, it was more desirable to use only items 1 and 3. Prior to the development of the cone calorimeter, fire test apparatuses typically controlled the power (or fuel rate) into the heater, but did not maintain it at a fixed temperature.

The Conical Shape The cone calorimeter derives its name from the conical shape of the heater (Fig. 28.5). The decision had been made to use an electric resistance heater, running at a realistic maximum temperature of about 950 °C, but its material and shape still had to be determined. Based on poor experiences with exposed-wire resistance heaters and with silicon carbide rod–type heaters, the tube heater was chosen. The tube heater consists of a resistive wire element inside a protective tube, swaged over a packing of inorganic insulation. The tube is made of Incoloy™ and can be bent to a desired shape.

To determine the best shape, the conical heater used in the ISO 5657 ignitability apparatus [33] was examined. This seemed to be a promising shape. The proper shape had to have a hole in the middle, since otherwise a hot spot would occur at the sample center, where the radiation view factor is the highest. The same

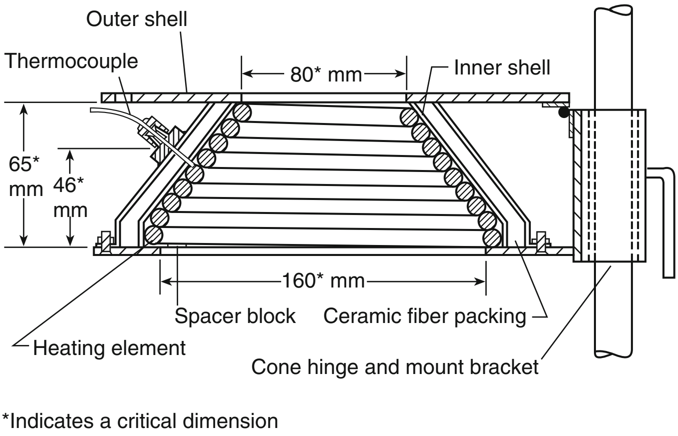


Fig. 28.5 Cross-sectional view through the cone heater

heater had to serve in both horizontal and vertical orientations. In the horizontal orientation, it was essential that all the products of combustion flow out the hole in the middle, and not "splash" on the heater coil itself, nor escape from the underside. The original ISO 5657 design proved to be unsuitable in the former respect. It also had problems with durability and assembly. Thus a totally new design was created, which, however, looked superficially similar to the ISO 5657 cone. With the actual cone calorimeter design, the flames from the specimen do not splash on the heater coil. Instead, a sheath of cold air is pulled up, surrounding the flame plume. Thus, there is not a concern that any surface reactions occur on the heater coil.

The space between the inner and outer cones is packed with refractory fiber. This arrangement helps keep the outside of the unit cool and also helps bring the heater up to operating temperature rapidly.

Emissivity of the Heater The emissivity was characterized by Janssens [34]. The heater coil, once installed and operated a few times, becomes essentially radiatively black. The emissivity itself cannot be directly measured; however, it is possible to compute an approximate view factor, F, for the cone heater. The possibility of measurements is based on a simultaneous determination of the heater surface temperature and the heat flux falling on the heat flux meter, with the meter held in place at the same location where a specimen is situated. Over the range of fluxes of 10–90 $\text{kW} \cdot \text{m}^{-2}$, Janssens determined the $\varepsilon \times F$ product to be 0.73, with F being computed as 0.78. Then, solving for ε gives $\varepsilon = 0.91$. Since the temperatures of the heater closely resemble those in room fires, and the emissivity approaches 1.0, this means that the spectral distribution is likely to be very close to that expected from room fires (neglecting the molecular radiation contribution from CO_2 and H_2O). It is important that the heater element be kept in good repair, in order that expected uniformity be achieved. Aging may cause the coil windings to separate and sag. If this occurs, poorer uniformity has been shown to occur [35].

Convective Fraction of the Heating Flux During the development of the cone calorimeter at NIST, a study was conducted to determine the fraction of the heating flux accounted for by the convective contribution [36]. When measured with respect to a water-cooled heat flux meter, the results showed that, in the horizontal specimen orientation, the convective contribution was immeasurably small. In the vertical orientation, the fraction was typically 8–12 %. Janssens later remeasured the vertical configuration [34] using a more accurately calibrated heat flux meter and found that, even for the vertical orientation, the convective transfer is immeasurably small. Thus, it can be stated that the objective of having a test method where the heating is primarily radiant was successfully met. For modeling of test results, however, one may be more interested in the possibility of convective heat transfer to a specimen that is heated, or even burning, not to a calibration meter constrained by its water-cooling jacket at near-room temperature. Janssens also made some determinations of such actual specimen heating. The direction of the heat transfer was such as to represent a heat loss from the specimen in all cases. A single convective heat transfer coefficient could not be derived, however, since the value was dependent on the irradiance level from the heater. Janssens's results could be represented by:

Irradiance from heater (kW·m^{-2})	Convective heat transfer coefficient h_c (W·m^{-2}·K^{-1})
20	9.0
40	18.0
60	27.0

For practical work, Janssens recommended that an average value of $h_c = 13.5$ W · m^{-2}·K^{-1} should be appropriate for work over the common irradiance range of 20–40 kW · m^{-2}. The actual details of this small amount of convective heat transfer are pertinent only to certain specialized studies. For most work, it is entirely adequate to assume that the specimen heating is entirely radiative.

Uniformity of the Heating Flux The uniformity of the heating flux over the face of the specimen in the cone calorimeter has been described [36]. Over the range of irradiances from 25 to 100 kW · m^{-2}, the ratio of the flux at the specimen center to average flux varied only from 1.00 to 1.06. The peak deviations from average were typically 2 % in the horizontal orientation and 7 % in the vertical. Deviations are higher in the vertical orientation, since the effect of convective fluxes, due to the boundary layer flow, is more pronounced there. Additional measurements have been made in the specimen-depth plane. Control of the surface of the specimen was a special concern to the designers of the ISO apparatus, where a special compressive loading mechanism is provided that attempts to relevel the exposed surface, in case the specimen recedes due to melting. In the cone calorimeter, measurements have been made in the horizontal orientation using a small, 6-mm-diameter Gardon-type heat flux gauge. A flux mapping was obtained starting at the initial surface, and progressing down to the maximum depth of a specimen, which is 50 mm. A normal aluminum foil rectangular specimen wrap was used for these tests, but without any specimen. The results show that, at heating fluxes of both 25 and 50 kW · m^{-2}, the deviations over the entire specimen depth are less than 10 %, and can, therefore, be neglected (Fig. 28.6). At the lower depths, reflection from the aluminum foil probably assists in maintaining this uniformity.

Orientation of the Heater and Specimen The normal orientation of the specimen should be

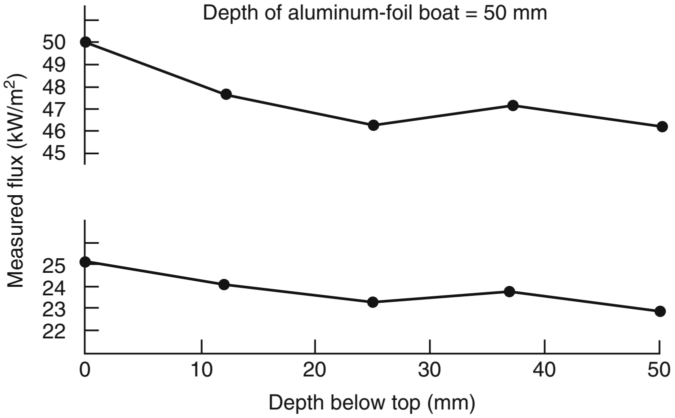


Fig. 28.6 Measured flux at various positions below the top surface of a specimen

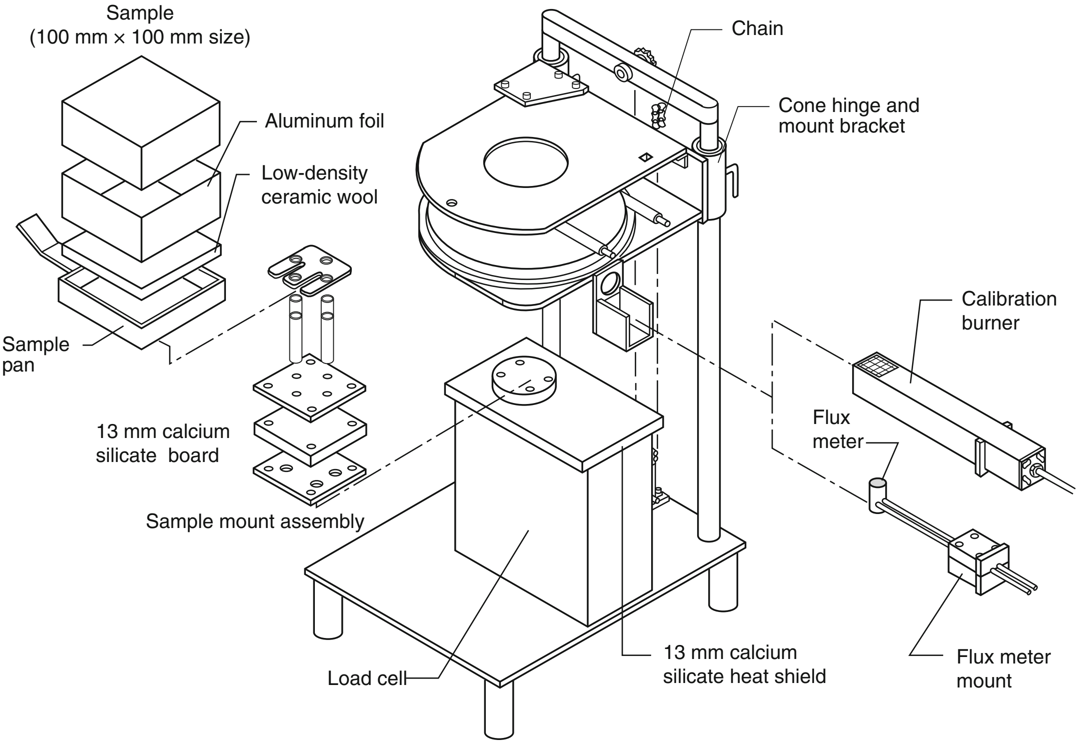


Fig. 28.7 Heater in the horizontal (standard) orientation

horizontal, face up, with the heater being parallel, face down. This allows thermoplastics, liquids, and other melting or dripping samples to be successfully tested. Because it was considered desirable to allow testing in a vertical orientation for certain application exploratory studies, provision was made to swing the heater 90° into a vertical orientation. Vertical orientation testing may be preferable when probing the flame regions or measuring specimen surface temperatures is desired. Figures 28.7 and 28.8 show the comparative horizontal and vertical heater orientations, respectively. It is especially emphasized that no standard testing should be specified for the vertical orientation, *even for products that are normally used in a vertical orientation*. The ASTM standard [2] was amended in 1992 to clarify that the vertical orientation is only for special research studies and not for product testing.

The Shutter

The original NIST design for the Cone Calorimeter did not include a shutter. The operator would just quickly drop the specimen holder on top of the mount plate at the top of the load cell. This was satisfactory for most building products and plastics. However, in 1993 researchers at SP (Technical Research Institute of Sweden) found that there were some reproducibility issues when testing upholstered furniture specimens that ignited very quickly. Thus, they designed a shutter (originally described as "heat shield" and later as "radiation shield") to be interposed between the heater and the specimen surface; this was originally described in a 1996 SP report [37]. The use of a shutter makes it possible to (a) get the load cell to equilibrate before commencing exposure, and (b) provide an nearly step-function initiation of radiant heat flux to the specimen.

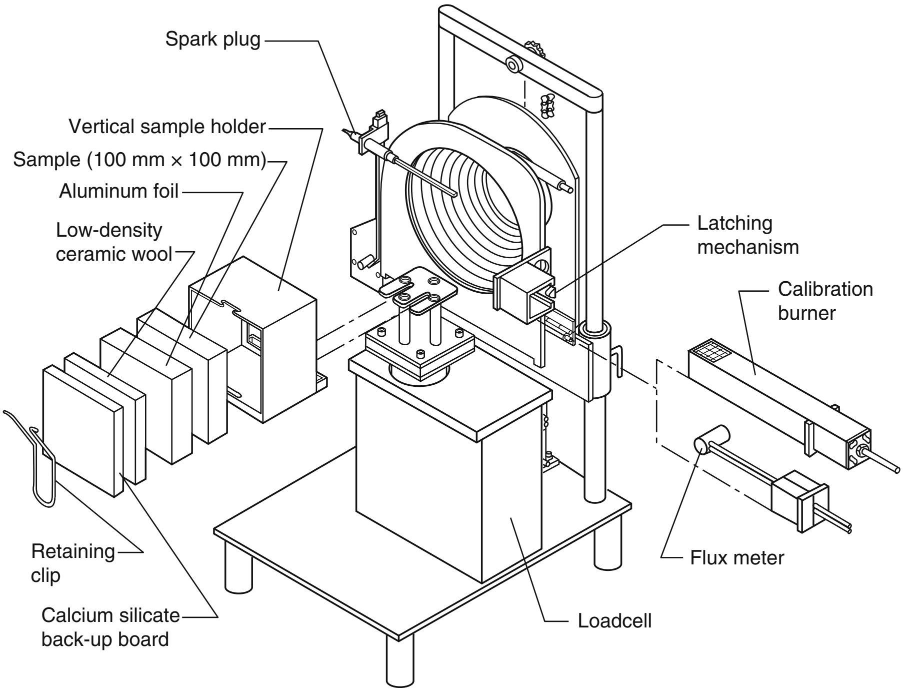


Fig. 28.8 Heater in the vertical orientation

However, with the use of a shutter there is potentially a different type of error that is introduced. A shutter will reflect some heat back to the heater, and will also rise in temperature and reradiate heat flux to the heater. Both of these would cause the heater's temperature to rise. The solution adopted by ASTM [2] and ISO [1] standards was that the shutter should be in place for no longer than 10 s prior to start of test, and that it be either water-cooled with a black coating, or else not water-cooled, but with made of ceramic material or made of reflective metal. The reflective metal option is the least satisfactory, because, while radiation towards the specimen gets eliminated by reflection, the reflection towards the heater does cause its temperature to rise. Thus, the best accuracy is attained with a minimal duration of the shutter's closure. This change was made in the 1997 edition of ASTM E 1354 and in the second edition (2002) of ISO 5660-1.

Airflow

The feasible airflow rate through the system is bound by certain limits. It must not be so fast that ignition results are improperly affected. It must also not be so slow that products of combustion spill out of the hood. If this were a closed system, one would also be concerned about airflow being so slow that the air/fuel ratio drops into the fuel-rich regime. The standard cone calorimeter, however, has been designed for ambient air testing, and this consideration does not apply.

Systematic guidance in this area was not available. However, as an example of the effect of airflow, measurements were made at NIST using the OSU apparatus. Specimens of black polymethyl methacrylate (PMMA) were exposed in the horizontal orientation to a heating flux of 35 $\mathrm{kW \cdot m^{-2}}$. With an airflow rate of 12 $\mathrm{L{\cdot}s^{-1}}$ through the combustion chamber, the ignition time was 209 s. When the airflow rate was doubled to 24 $\mathrm{L{\cdot}s^{-1}}$, the specimen ignition time increased to 403 s. By contrast, Table 28.1 shows comparative results with the cone calorimeter; it can be seen a flow rate of 24 $\mathrm{L{\cdot}s^{-1}}$ was found to be satisfactory. That flow rate was also about a factor of 2 greater than the minimum at which no spill out of the hood occurs.

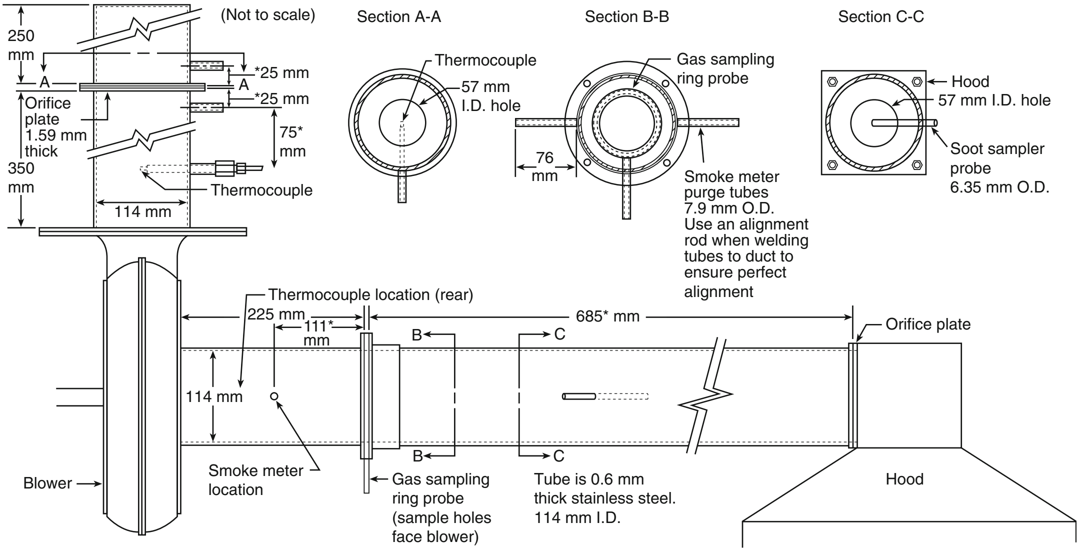
The exhaust system uses a high-temperature cast-iron blower to exhaust the gases and an

Table 28.1 Effect of exhaust hood airflow on ignition times in the cone calorimeter[a]

Material	Thickness (mm)	Orientation	Fan setting	Ignition time[b] (s)
PMMA	13	Horizontal	No fan	71
PMMA	13	Horizontal	24 L·s^{-1}	76
PMMA	13	Horizontal	41 L·s^{-1}	67
PMMA	13	Vertical	No fan	86
PMMA	13	Vertical	24 L·s^{-1}	84
PMMA	13	Vertical	41 L·s^{-1}	77
Redwood	13	Horizontal	No fan	23
Redwood	13	Horizontal	24 L·s^{-1}	24
Redwood	13	Horizontal	41 L·s^{-1}	31
Redwood	13	Vertical	No fan	22
Redwood	13	Vertical	24 L·s^{-1}	27
Redwood	13	Vertical	41 L·s^{-1}	29

[a] At an irradiance of 35 kW · m^{-2}

[b] Typical ignition time scatter was on the order of ±10 % ($1\sigma, N = 3$)



*Indicates a critical dimension

Fig. 28.9 Exhaust duct

orifice plate flowmeter (Fig. 28.9). The orifice plate flowmeter is instrumented with a differential pressure transducer and a thermocouple. For specialized studies, where the entire combustion system is glass enclosed [38], it is possible to go to flow rates below 12 L·s^{-1}. With such enclosed systems, accurate measurements can be made down to about 9 L·s^{-1} using the standard orifice plate. For lower flow rates, down to about 5 L·s^{-1}, the standard orifice plate is replaced by one with a smaller opening.

Means of Ignition

In some cases no external ignition source is desired, and specimen testing is to be done solely on the basis of autoignition. In most cases, however, an external ignition source is desirable. This ignition source should, in general, not impose any additional localized heating flux on the specimen. Apparatus designs have been developed, with impinging pilots that can, in some cases, produce such high localized heat fluxes as to burn a hole through the specimen at the point of impingement, yet not ignite it outside of that region [39]. Applications for such devices tend to be specialized, since the general objective of radiant ignition testing is to produce data that can be analyzed in the context of an assumed one-dimensional heat flow. A design using an impinging pilot has an additional difficulty. Since most of the specimen face is not yet heated to the ignition temperature when ignition first begins in the vicinity of the pilot, no unique ignition time can be determined. Instead, there is a significant time spread between when ignition first occurs at the initial location, to when the final portions of the face have been ignited.

The ignitor should reliably ignite a combustible gas mixture in its vicinity. Thus, the location of the ignitor must be chosen so that it is near the place where maximum evolution of pyrolysate gases is expected. Some materials are highly fire-retardant treated, and, when heated, emit vapors that tend to extinguish a pilot flame. The ignitor has to be designed so as not to be extinguished by fire-retardant compounds coming from the specimen, nor by airflows within the test apparatus.

The ISO 5657 apparatus was designed with a “dipping” gas pilot, which is periodically thrust for a short while down close to the specimen face, then retracted. This solution, however, introduces an uncertainty into ignition times and provides further complexity. A gas pilot, based on experience, also requires oxygen premix to achieve a flame that is both small and resistant to blowout [40]. With products high in fire retardant, even such precautions are not likely to lead to a reliable pilot; thus, for instance, the ISO 5657 apparatus uses a second pilot to reignite the main pilot. Pilot stability also tends to be crucially dependent on the physical condition of the pilot tube tip, and significant maintenance can be necessary. Finally, if used in a heat release apparatus, a gas pilot can add noise to the baseline of the heat release measurement. Experimental efforts at the National Bureau of Standards (NBS) had success using the NBS-II calorimeter, a more tractable alternative (i.e., electric spark ignition). This spark plug arrangement for ignition was successful, and so a similar electric pilot was designed for the cone calorimeter. The location of the ignitor should be at the place where the lower flammable limit is expected to first be reached when the specimen begins its pyrolysis. It should, however, not be so close to the specimen surface that minor swelling of the specimen would interfere with the ignition function. In the cone calorimeter, the ignitor locations were chosen so that, when testing in the horizontal orientation, the spark plug gap is located 13 mm above the *center* of the specimen; in the vertical orientation, the spark plug gap is located at the specimen plane and 5 mm above the *top* of the specimen holder.

The actual spark plug arrangement is shown in Fig. 28.10. The spark plug is provided by a special-purpose 10-kV ignition transformer. The spark plug is moved in and out by remote control, operated by an air motor that rotates the shaft on which the spark plug rests. A reversible lock bar is used to adjust the spark-plug-to-heater distance when changing from the horizontal to the vertical orientation (the spark gap is 13 mm away from the heater baseplate in the horizontal orientation, but 25 mm away in the vertical).

Specimen Area and Thickness

Both specimen area and thickness may be expected to have some effect on the ignitability and the heat release rate. The main practical size and thickness limitations come from the fact that the specimens to be tested should exhibit primarily one-dimensional heat transfer. Thus, the configuration should be such that excessive edge effects are not seen. If the specimen thickness is such that it is thermally thick (the heat wave penetration depth being less than the physical depth), then further increases in thickness are not expected to change ignitability results. For thinner specimens, however, there can be expected to be a thickness effect, and the backing or substrate material’s thermophysical properties can be of importance.

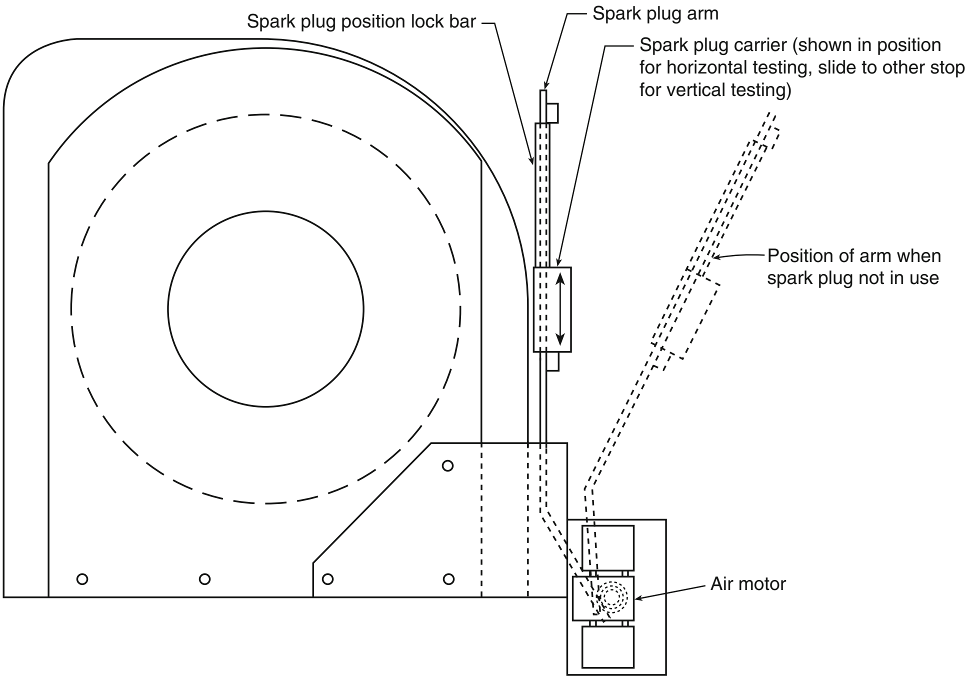


Fig. 28.10 Spark plug, carrier, and air motor

Specimen Area Janssens [34] studied in some detail the general problem of area effect on ignition. The effect is seen to be smaller when irradiances are high rather than low. The exact magnitude of the effect is also dependent on the specimen's thermophysical properties. For specimens of area 0.01 m^2 or larger, however, his results show an increase in ignition time of only about 10 % over what would be seen with a specimen of infinite area. Later, Nussbaum and Östman [41] studied specimens in an experimental apparatus somewhat similar to the cone calorimeter, but accommodating 200 × 200 mm specimens. Their comparison of the ignition times of these larger specimens against the standard 100 × 100 mm ones shows that quadrupling the specimen area decreases the ignition time by about 20 %.

For heat release rate, the specimen size affects the measurement, since flame volume is larger over larger specimens; consequently the flame radiation tends to approach a value of higher emissivity. Nussbaum and Östman also examined heat release rates from larger specimens; the differences were generally of the same order of magnitude as the repeatability of the results. Babrauskas, in commenting on these data [42], discussed tests on larger size, horizontal PMMA samples, where each doubling of the specimen's area increased the heat release rate, per unit area, by about 10 %. The more general treatment of the horizontal specimen, of course, is as a liquid pool. Chapter 26 gives details on the size effect for burning pools. It can be seen that the diameter has to be greater than about 1 m before the specimen area effect becomes negligible.

The effect of specimen size for vertical samples was examined at Factory Mutual Research Corporation (FMRC) in a series of experiments on PMMA walls [43, 44]. The FMRC studies showed little size effect for specimen heights up to 200 mm; beyond 200 mm there was approximately a linear dependence of $\dot{q}''$ on the height. This was true up to the maximum height tested, that is, 3.56 m. Unlike horizontal pools, the rate of heat release was not leveling off at even these sizes, and estimates suggested that the specimen size would have to be increased by another order of magnitude before a leveling off would be seen.

The conclusion from the above studies was that 100 × 100 mm was a suitable size for bench-scale testing, but that the bench-scale $\dot{q}''$ rates will always be somewhat lower than for full-scale fires.

Specimen Thickness The cone calorimeter is intended for testing actual commercial products. Thus the specimen thickness should be, as much as possible, the thickness of the finished product. There are limitations at both ends of the scale, however. The instrument is restricted to testing specimens not thicker than 50 mm. For products that in their finished state are greater than 50 mm thick, it can readily be seen that, for almost any realizable combination of thermophysical properties and incident radiant fluxes, a 50 mm specimen is thermally thick, and increasing thickness would not change the ignition times [45, 46]. By making calculations for various densities and heat fluxes, it was found that for particleboard the minimum thickness required to ensure that the specimen is thermally thick can be represented by

$$\ell = 0.6 \frac{\rho}{\dot{q}''} \tag{28.3}$$

where

$\ell = \text{Thickness (mm)}$

$\rho = \text{Density} \left(\text{kg} \cdot \text{m}^3\right)$

$\dot{q}'' = \text{Heat flux} \left(\text{kW} \cdot \text{m}^2\right)$

This is probably a reasonable rule of thumb for other materials as well. The proportionality of the required thickness to $\rho/\dot{q}''$ is derived from classical heat conduction theory by equating the time for the front surface to reach ignition temperature to the time the rear surface's temperature begins to rise, assuming that the thermal conductivity is proportional to the density. Numerical calculations were necessary to determine a suitable constant because of the impact of front surface heat losses.

For materials that are not thermally thick at the time of ignition, the nature of the backing material or substrate can influence the measured value of the ignition time. In the cone calorimeter, the substrate is a blanket of refractory ceramic fiber material, having a nominal density of 65 $\text{k} \cdot \text{gm}^{-3}$. In use, the material assumes a more compacted density of roughly 100 $\text{kg} \cdot \text{m}^{-3}$. Whenever possible, materials whose thicknesses are less than the minimum suggested in the above formula should be mounted on that substrate material over which they will actually be used. As a practical guide for testing unknown commercial samples, it is desirable to specify that any specimens less than 6 mm thick should always be considered as needing to be tested over their in-use substrate.

Fabrics are a special case. Thin fabrics are sometimes used for constructing air-supported structures; these should be tested with an air space in back, simulating the usage conditions. A special holder has been constructed that allows the fabrics to be pulled taut and held above a dead-air space (Fig. 28.11).

Sample Testing Specifications

Specimen Orientation and Specimen Holders

The specimen holders in Figs. 28.12 and 28.13 show the two specimen holders, respectively. With proper precautions, the horizontal orientation can be used for testing liquids and melting materials, whereas the vertical orientation's small melt trough can only catch a very small amount of molten material. Also, some specimens, when tested in the vertical orientation, show a tendency to lose physical strength and fall out of the holder, which does not happen in the horizontal orientation.

In the vertical orientation, there are several layers of rigid millboard behind the blanket, sufficient in thickness to fill out the depth of the specimen holder. The specimen is wrapped in a single sheet of aluminum foil, covering the sides and bottom. The aluminum foil serves to limit the flow of molten material and prevent it from seeping into the refractory blanket.

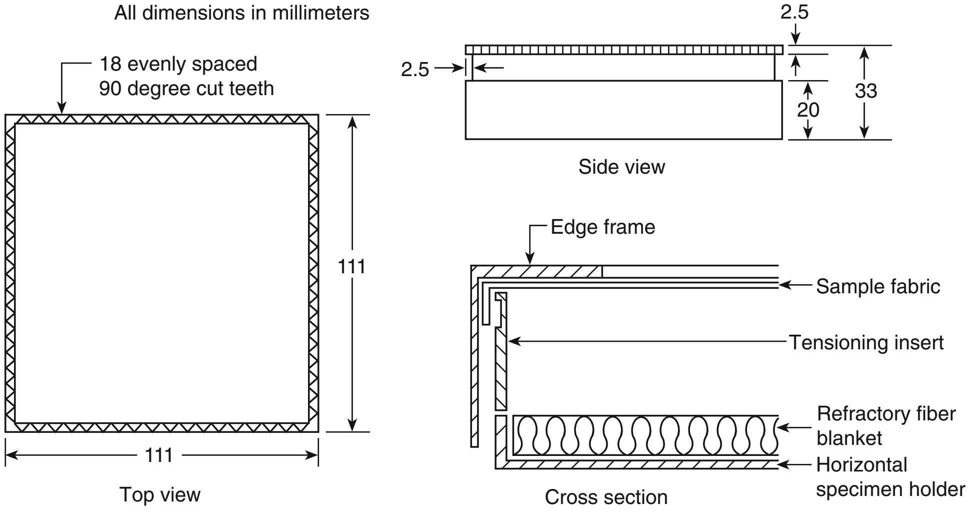
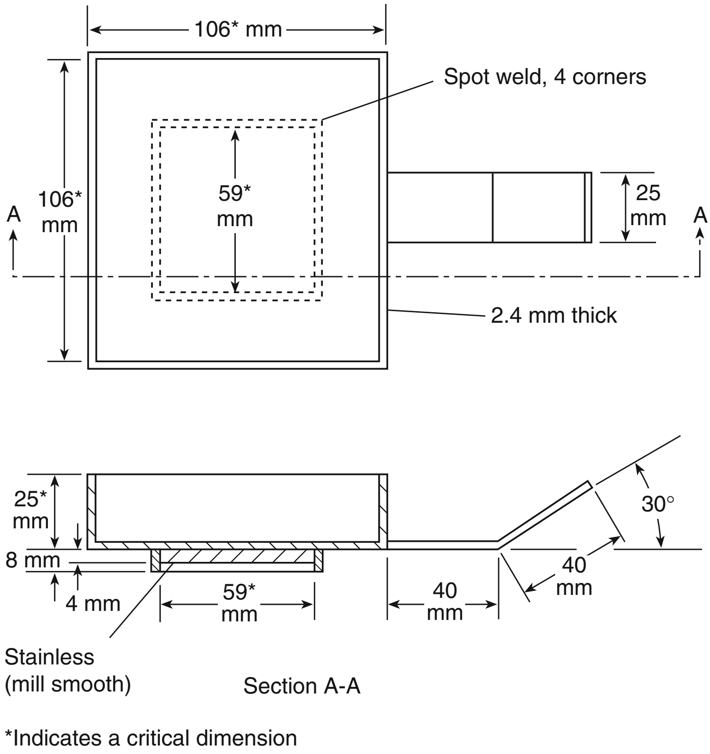


Fig. 28.11 Special holder for testing fabrics and similar thin materials

Fig. 28.12 Horizontal orientation specimen holder



Load Cell

Many ancillary measurements made in the cone calorimeter (such as yields of various gas species) require the use of a load cell. Transducers had been tried in various earlier apparatuses, but most suffered because they were not designed for purely single-axis linear motion. That is, if the weight of the specimen was not well balanced, or differential heating stresses occurred, it was

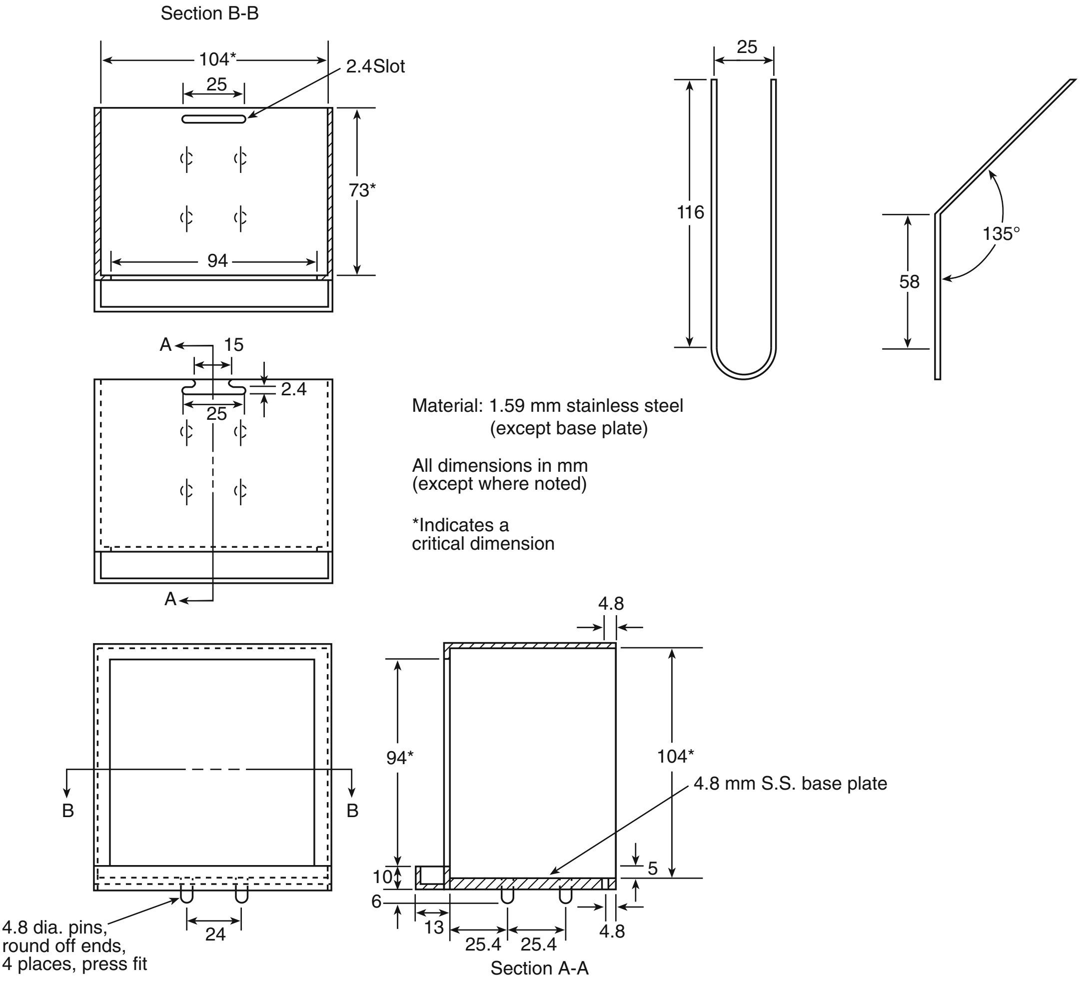


Fig. 28.13 Vertical orientation specimen holder

likely that a mechanical moment (or *torque*) would be applied to the device, with the transducer then being prone to jamming. For the cone calorimeter, a commercial-design load cell was found that permits only up-and-down axial motion while being insensitive to torques or forces from other directions.

The load cell has to accommodate two differently oriented specimen holders and may need to hold additional fixtures. All of these can have substantial—and different—weights, yet must allow accurate mass determination for low-density specimens. The solution adopted was a weighing system that has a large (3.5 kg) mechanical tare adjustment range, along with a sensitive weighing range (500 g). A resolution of 0.005 g is readily achievable.

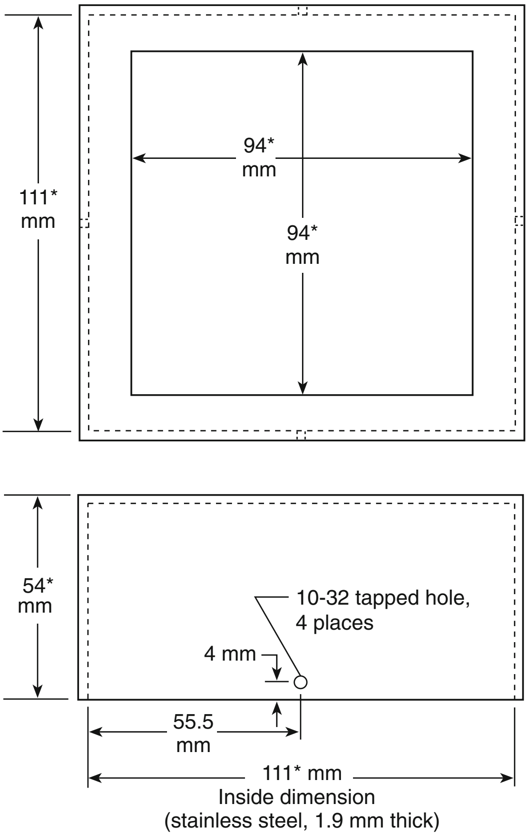
Figures 28.7 and 28.8 show, respectively, how the horizontal and vertical orientation specimen holders are accommodated on the load cell. The horizontal holder has a square recess on the bottom and simply is placed straight down. The vertical holder is more conveniently inserted directly toward the heater, correctly locating the specimen by four mounting pins on the bottom. In both cases there is a positive specimen location, and the operator does not have to be concerned with how far to insert the holder.

Edge Conditions

Edge Effects In an apparatus such as the cone calorimeter, it is desired that the small-scale test specimen would behave, as much as is possible, like a correspondingly sized element of the full-scale object. If one is dealing with relatively large, flat, full-scale objects, then heat and mass transfer will occur only in the direction perpendicular to the exposed face. There will be no heat or mass flow along either of the face directions. The guidance to be derived from this conceptual model in designing the bench-scale test environment is clear: there should be a minimum of heat or mass transfer at the specimen edges. The aluminum foil used to wrap the specimen usually serves to minimize any mass transfer that may occur. The heat transfer situation, however, is more complicated.

In the vertical specimen orientation, the specimen has to be restrained against falling out; therefore, the vertical specimen holder incorporates a small lip extending 3 mm along the edges. In the horizontal orientation, no special measures need to be taken against falling out. Thus, for many specimens it is satisfactory to simply cover the edges and bottom with aluminum foil, leaving the top exposed in its entirety.

Some categories, however, present special problems—specimens that either have a propensity to ignite first along the outside edge or that, when ignited, burn disproportionately vigorously near the edges. Such behavior is often found with wood specimens and with certain composites. This problem is alleviated by using a stainless steel edge frame for the horizontal orientation, which like the vertical holder provides a 3 mm lip around the edge of the specimen face (Fig. 28.14).



*Indicates a critical dimension

Fig. 28.14 Edge frame for the horizontal specimen holder

Specimens showing unrepresentative edge burning can be viewed as having a spurious heat gain along the edges when compared against a hypothetical ideal situation of exactly zero heat loss or gain at the edges. When an edge frame is applied, the opposite situation can tend to result, that is, an observed net heat loss from the specimen [47]. The ideal situation of a specimen prevented from showing unrepresentative increased edge burning but equally not sustaining any losses to an edge frame may be difficult to approach in practice. This is still a topic of active study at several institutions.

In some cases, an edge frame is needed for thermostructural reasons. Some specimens, especially certain composites, can show pronounced edge warping and curling when subjected to heat. The burning of such a specimen would be highly nonuniform if its edges were not held down with an edge frame. In many cases, an edge frame is all that is required. In some cases, however, additional measures such as a wire grid (see below) are required.

Intumescing Samples Intumescence is a common difficulty with fire test specimens, either before ignition or during the burning. The simplest solution used in the cone calorimeter,

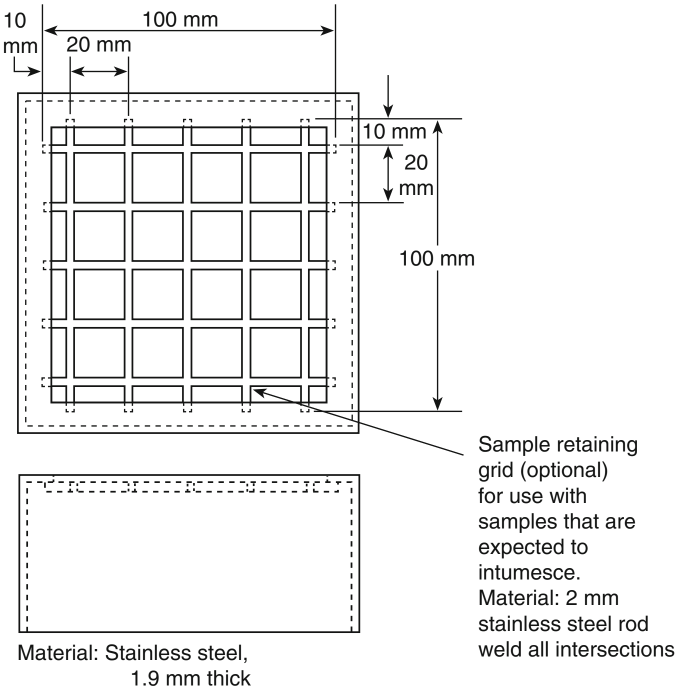


Fig. 28.15 Wire grid

sufficient in many, but not all, cases, is a wire grid placed on top of the specimen. Figure 28.15 shows a medium-weight grid. To minimize effects on measurements, the grid weight should be the smallest possible consistent with providing adequate mechanical restraint to the tested specimen. Effects on measurements will be negligible if the average grid mass is less than 0.6 $\text{kg} \cdot \text{m}^{-2}$ of specimen face area. This mass corresponds to quite a thin, small grid and will practically be usable only in occasional cases. Additional guidance is given in the NBS "User's Guide for the Cone Calorimeter" [3], but testing laboratories will, on occasion, be required to devise their own special schemes for mounting and restraint.

Smoke Measurement

One of the most essential ancillary measurements performed with the cone calorimeter is smoke obscuration. Widespread dissatisfaction with older, closed-box types of smoke tests [48, 49] caused by the large number of both practical and theoretical difficulties were successfully resolved by developing a flow-through smoke measuring system, using a helium-neon laser as the light source and a sophisticated quasi-dual-beam measuring arrangement. Figure 28.16 shows the overall arrangement of the laser photometer. It is mounted on the exhaust duct at the location shown in Fig. 28.9. A thermocouple is also mounted nearby, since the calculations require a determination of the actual volume flow rate in the duct at the photometer location. The user should consult Geake [49] for details explaining the operation of the laser photometer. Briefly, the light from the laser goes, via two beam splitters, into two detectors. The light reaching the compensation detector is not attenuated by smoke; its signal serves as the reference to cancel out fluctuations in laser output power. The main beam detector measures a signal that is attenuated by the smoke. The optical path is purged by a minute flow of room air through a purge system. The flow is maintained by the pressure differential in the exhaust duct.

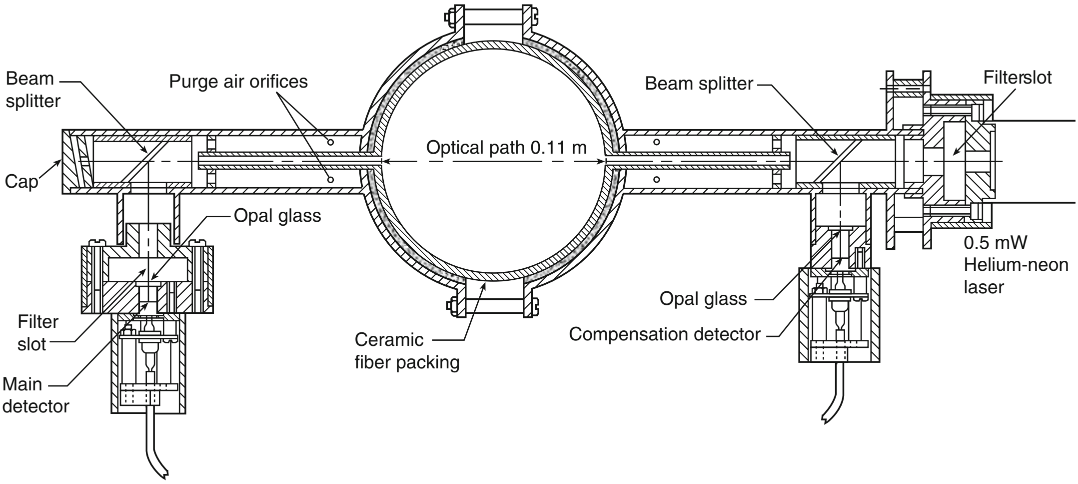


Fig. 28.16 Laser photometer

For certain research purposes, it is advantageous, in addition to obtaining optical smoke obscuration measurement, also to record the gravimetric soot yield by measuring grams of soot evolved per gram of specimen burned. A soot mass sampler is connected to the port indicated in section C-C of Fig. 28.9, and a known mass fraction of the exhaust duct flow is passed through a measuring filter and is weighed before and after the test.

Calibration Equipment

Two basic calibrations are needed: (1) the calibration of the temperature controller for the conical heater and (2) the actual heat release rate calibration. The temperature controller is calibrated using a Schmidt-Boelter-type heat flux meter equipped with a locating collar and inserted in place of the specimen, with its face where the specimen face would be located. No specimen holder is used for this operation. Figures 28.7 and 28.8 show the insertion of the heat flux meter.

The heat release rate is calibrated with a calibration burner inserted into the same bracket used for the heat flux meter (Fig. 28.17). The calibration burner, however, instead of being inserted facing the heater, is inserted so that the discharge opening faces upward. Calibration is accomplished by controlling the flow of high-purity methane going to the burner and comparing it to a known value and using the net heat of combustion for pure CH_4 as 50 MJ · kg^{-1}.

The laser photometer is calibrated by neutral-density glass filters. These are inserted into a filter slot in front of the main beam detector. An auxiliary filter slot is provided in front of the laser. This serves to check the correct balancing of the dual-beam system’s common mode rejection ratio.

The NBS “User’s Guide to the Cone Calorimeter” [3] details how calibrations are performed.

Miscellaneous Details

Ring Sampler

The combustion products flowing through the exhaust system can be heavily laden in soot, which would cause rapid clogging of the oxygen measurement system if precautions were not taken. The most important precaution is the specially designed ring sampler (Fig. 28.18), which is installed in the exhaust duct with the intake holes facing away from the direction of airflow. A number of small holes are used so as to provide a certain degree of smoothing with respect to duct flow turbulence.

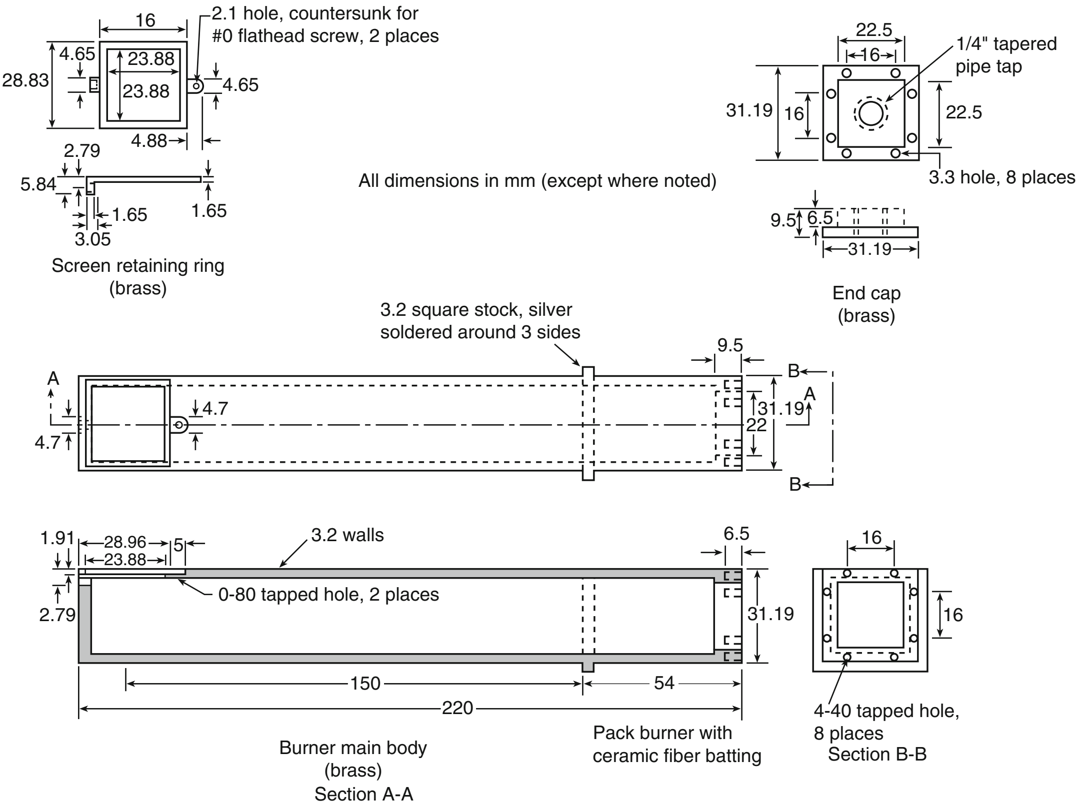


Fig. 28.17 Calibration burner

Additional Gas Analyzers

Many users of cone calorimeters provide not just an oxygen analyzer but also additional gas analyzers to help determine combustion chemistry and toxicity. CO and CO_2 analyzers are simply fitted into the same sampling line serving the oxygen analyzer. Other analyzers, for example, H_2O, HCI, and total unburned hydrocarbons, require a completely separate, heated sampling line system. Such a system also needs to have a heated soot filter at the front.

Special Issues with Product Testing

The cone calorimeter has been used for studying a very wide range of products and materials. In this section, some items of interest are considered where special care needs to be exerted in configuring the samples or in testing.

Liquids

The HRR of liquids is generally not the quantity of interest to regulators and other individuals charged with enforcing fire safety provisions for liquids. In addition, there is no easy way to scale from bench-scale results to large-scale applications. However, some research studies on liquids using the cone calorimeter have been reported. In such studies, use of a circular dish is generally more convenient than using a square specimen. For example, Hayakawa et al. [50] used a 113 mm diameter dish, while Iwata et al. [51] used a 90 mm dish. Liu et al. [52] conducted a study of liquids in the cone calorimeter, accompanied by water mist extinguishment. A number of other studies [53–57] have been reported.

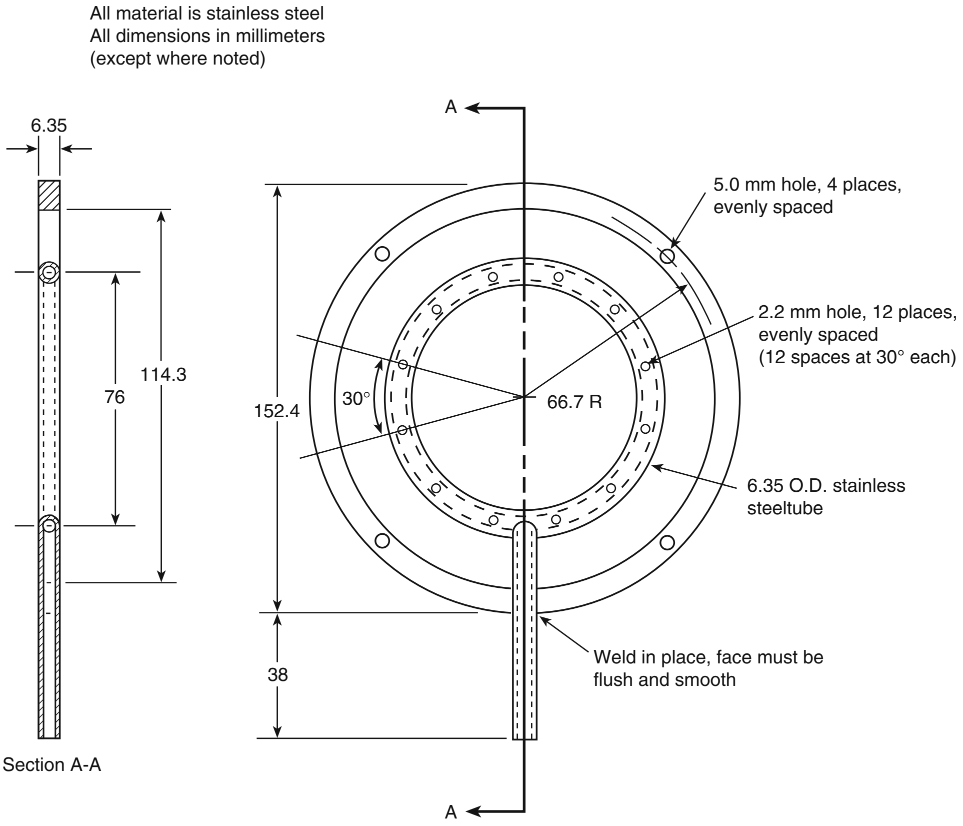


Fig. 28.18 Ring sampler

Electrical Cables

In testing electric cables, pyrolysis gases have a pronounced tendency to flow along the length of the cable interior and burn only at the edges rather than uniformly over the surface. For such specimens, it has often been found useful to coat the cable ends with a sodium silicate cement, such as Insa-Lute Adhesive Cement Paste No. 1, produced by the Sauereisen Cements Co. When the ends are sealed in such a manner, a knife puncture must be made in the face of each piece of cable to avoid pressure buildup and rupture.

Even though electrical cables are circular rather than flat, it has been found that they can be successfully tested in the cone calorimeter. Normally, 100 mm long cable sections are cut and placed side by side, filling up the specimen holder. For this to be practical, the diameter should not be excessive, say less than 15 mm or so.

ASTM has issued a standard [58] on the testing of electrical cables with the cone calorimeter. In the ASTM standard, the cables may either be cut into sections, or else the insulation material alone is to be tested as a flat plaque. The latter will generally not be practical, since cable manufacturers do not produce the plastic in this form. The ASTM standard also permits the ends to be sealed, or unsealed, when actual cable sections are tested.

Grayson et al. [59] documented the results of the FIPEC research program, where electrical cable testing and modeling was done using a wide array of techniques. A very extensive cone calorimeter testing effort is described in this connection. The FIPEC researchers concluded that the best results are obtained when the ends are sealed, except for very small cables

(<4 mm dia.). The sealing did not affect the magnitude of the results, but did improve the repeatability. They also conducted plaque tests on some individual materials.

Intumescing Materials

Intumescing materials can present special problems for testing. Most substances do not intumesce significantly during testing. The exceptions are, of course, intumescent coatings, but also some grades of PVC show a strong tendency to intumesce, as do some a few other materials. The first problem encountered is if the specimen rises sufficiently to contact the spark plug and cause a short. More extreme intumescing can actually result in contacting the heater coil, although this has rarely been seen. Apart from problems with the spark plug (which can be avoided by improvising another ignition arrangement), there is the issue of flux non-uniformity—as the specimen surface rises, it encounters a locale with higher radiant flux.

The original solution for intumescing materials, incorporated into the ASTM [2] and ISO [1] standards, has been to provide a wire retaining grid, which is placed on top of the specimen and held down the edge frame. This generally sufficiently reduces the intumescence to eliminate technical problems. However, this has caused concern for some manufacturers, who considered that their product may not able to achieve the optimal performance that it might in its end-use application, where a thicker layer of intumesced material would be developed.

A procedure was suggested [60] whereby the specimen surface is placed at 60 mm below the base of the heater, instead of 25 mm, in order to allow ample height for expansion. This however also has drawbacks. The heat flux uniformity at such a spacing becomes poor across the face of the specimen. In addition, if a tall hemispherical or elongated configuration is allowed to arise, there is very limited heat flux incident upon the sloped sides of such a specimen.

Low HRR Materials and Noncombustibility

Many building codes, including all in North America, have long taken the stance that materials are to be divided into two kinds: combustible and noncombustible. This kind of categorical yes/no distinction basically reflects the fire knowledge of the nineteenth century, and not the twenty-first, where fire safety engineering is acknowledged to be a profession capable of quantitative assessment of hazards. While codes have numerous and complex provisions on this subject, the most important application, by far, is in regards to materials that are used as either structural members or as lining materials, e.g., wall or ceiling linings. Babrauskas and Janssens recently examined this question in detail [61]. It was concluded that the concept of noncombustibility has no reasonable relationship to life safety, as pertains to sub-surface construction materials, that is, everything except the surface materials. The HRR of surface materials, on the other, is crucial to life safety. But noncombustibility is not useful metric for hazard. It was recommended that a solution which is consistent with fire safety engineering concepts and is presented in a practical way is the Cleary/Quintiere calculation of the '*b*' parameter, in Equation 28.1. A comparison to large-scale room fire test results showed a very good ability of this parameter to distinguish materials which led to hazardous fire conditions, versus ones which did not.

In addition, low HRR materials may show up in the form of composites, where the top layer is highly resistant to burning, while the layer (s) underneath are less so. Such constructions present issues which are discussed in the next section.

Composites

The cone calorimeter is inherently designed to be able to test composite products, provided the layers are can adequately be represented by an assembly no more than 50 mm deep. In practice, this allows for a reasonable representation of products which are even much thicker, provided that there are not additional layers which are both deep and producing a high HRR. In some cases, however, special precautions need to be taken.

For example, upholstered furniture composites cannot be tested in a representative manner unless the outer layers are constrained to stay in place, instead of crumpling due to exposure to heat. In view of this need, a special test method, ASTM E 1474 [62], was developed for preparing and testing such composites.

Some high-pressure laminates explosively delaminate when subjected to heating. These can only be tested if the use of the wire grid and edge frame eliminates this problem, which it normally does. Another special category of products are ones where the surface layer has a low HRR, while layers underneath show a much higher HRR. If tested simply as a cut specimen, the edges are likely to get involved early, and this may produce unrepresentative burning. The problem was studied by Canadian researchers [63, 64] who developed a special holder which protects the edges of such specimens. The latter was incorporated into the Canadian CAN/ULC S135 standard [65].

Measurements Taken with the Cone Calorimeter

The relevant ISO [1] or ASTM [2] standards mandate certain minimum variables to be recorded. In practice, it is normally desired to make the data from the test be as complete as possible. Cone calorimeter data are normally handled as data tables and files standardized according to the Fire Data Management System (FDMS) prescription [66]. A complete set of data from the cone calorimeter are illustrated there. Here the more important of these are given, somewhat augmenting the ISO and ASTM set. Note that most items must be reported for each test run, and a complete test consists of three runs.

Identification	Various data items must be included here
Preparation	Any nonstandard specimen preparation details must be reported
Test number	Serial number of test; also information on testing laboratory, operator, and so forth
Irradiance	The heating flux set for the test ($\text{kW} \cdot \text{m}^{-2}$)
Exhaust flow rate	Recorded for completeness, usually the standard value of 24 $\text{L} \cdot \text{s}^{-1}$
Orientation	Horizontal or vertical
Spark ignition	Yes or no
Edge frame	Yes or no
Wire grid	Yes or no
Area of specimen	(m^2), since may be nonstandard in special cases
Specimen initial mass	(g)
Specimen final mass	(g)
Time to ignition	According to the ISO and ASTM standards, "sustained flaming" (s)
Time to flameout	(s)
Peak $\dot{q}''$	($\text{kW} \cdot \text{m}^{-2}$)
Peak $\dot{m}''$	($\text{g} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$)
Total q''	($\text{MJ} \cdot \text{m}^{-2}$)
O_2 consumption	($\text{kJ} \cdot \text{kg}^{-1}$); this is set to a specific constant value if known, otherwise to 13,100
Effective heat of combustion	($\text{MJ} \cdot \text{kg}^{-1}$), reported for period of entire test run
Specific extinction rate	($\text{m}^2 \cdot \text{kg}^{-1}$), reported for period of entire test run
Average mass loss rate	Computed over period starting when 10 % of the ultimate specimen mass loss rate has occurred and ending at the time when 90 % of the ultimate specimen mass loss has occurred ($\text{g} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$)
Average $\dot{q}''$ (60 s)	Computed for the first 60 s after ignition ($\text{kW} \cdot \text{m}^{-2}$)
Average $\dot{q}''$ (180 s)	Computed for the first 180 s after ignition ($\text{kW} \cdot \text{m}^{-2}$)
Average $\dot{q}''$ (300 s)	Computed for the first 300 s after ignition ($\text{kW} \cdot \text{m}^{-2}$)

Note in the above 60, 180, and 300 s averages that, if the test is ended before having burned, say, 300 s, a proper average can still be correctly computed (i.e., at the end of the averaging period a number of zeroes are used for data points past the end of the test). Since users are often confused by this point, it must be emphasized: it is not sensible to report an "average heat-release rate" without specifying the time interval. The reason has to do with the question of determining the end of the test. The ISO and ASTM standards specify that the end of the test is considered to be

1. After all flaming and other signs of combustion cease
2. While there may still be vestigial combustion evidence, but the mass loss rate has become very small (less than 150 g·m^{-2} being lost during any 1 min)
3. 60 min have elapsed

These rules are needed for establishing some uniformity among testing laboratories. They do not, however, mean that it is technically sound to compare the average of one material that may have burned for 10 min with another that may have burned for 5 min. It is technically sound, however, to compare their burning over the first one, three, and so forth, minutes of test.

Further information on the form, units, and usage of fire properties measured in the cone calorimeter can be found in Babrauskas [67]; specific information on the smoke and soot properties measured in the cone calorimeter is given in Babrauskas and Mulholland [48].

Repeatability and Reproducibility

The repeatability, r, and reproducibility, R, of the cone calorimeter were studied in two sets of interlaboratory trials, one sponsored by ISO and one by ASTM. According to the ISO instructions [68], the definitions of repeatability and reproducibility were taken as

$$r = 2.8\sigma_r$$
$$R = 2.8\sigma_R$$

where σ_r is the repeatability standard deviation, σ_R is the reproducibility standard deviation, and the 2.8 factor comes from specifying the probability level of 95 %.

From the results of the interlaboratory trials, values for r and R were calculated for six variables. These variables, chosen as being representative for the test results, were t_{ign}, $\dot{q}''_{\max}$, $\dot{q}''_{180}$, q_{tot}'', $\Delta h_{c,\text{eff}}$, and σ_f. A linear regression model was used to describe r and R as functions of the mean overall replicates and overall laboratories for each of the six variables. The regression equations given below also indicate the range of mean values over which the fit was obtained.

The results for time to sustained flaming, t_{ign}, in the range of 5–150 s were

$$r = 4.1 + 0.125 t_{\text{ign}}$$
$$R = 7.4 + 0.220 t_{\text{ign}}$$

The results for peak heat release rate, $\dot{q}''_{\max}$, in the range of 70–1120 kW · m^{-2} were

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

The results for 180 s average heat release rate, $\dot{q}''_{180}$, in the range of 70–870 kW · m^{-2} were

$$r = 23.3 + 0.037 \dot{q}''_{180}$$
$$R = 25.5 + 0.151 \dot{q}''_{180}$$

The results for total heat released, $\dot{q}''_{\text{tot}}$, in the range of 5–720 MJ · m^{-2} were

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

The results for effective heat of combustion, $\Delta h_{c,\text{eff}}$, in the range of 7–40 kJ · g^{-1} were

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

The results for average specific extinction area, σ_f, in the range of 30–2200 m^2 · kg^{-1} were

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

A comparison of the cone calorimeter repeatability and reproducibility to the values obtained for the ISO 5657 radiant ignition test showed the cone calorimeter results to be about a factor of 2 better.

Fig. 28.19 The NIST controlled-atmosphere cone calorimeter

Special Cone Calorimeters

The standard cone calorimeter has been designed to use room air for combustion. All standard testing is done under such conditions. For special combustion studies, however, it can be of interest to explore the burning of materials at oxygen levels other than 21 %. Such a unit, constructed at NIST, is described in Babrauskas et al. [38]. This controlled-atmosphere unit has already been used for studies of the burning of materials in air supplies with less than 21 % oxygen, with N_2 or CO_2 being mixed into the air stream (Fig. 28.19). It has also been used for pyrolysis studies under pure nitrogen flow conditions. In principle, it could also be used for studies of enriched-oxygen atmospheres; however, the necessary safety procedures for handling high-concentration oxygen streams are required. A unit for handling O_2 mixtures greater than 21 % has been constructed for NASA, but data are not yet available from it. A controlled-atmosphere unit is also appropriate for use when airflow rates of less than 12 L·s^{-1} are required.

All of the present cone calorimeter designs, both standard and otherwise, have been designed for use only under ambient pressures. There is interest at this time from at least one research group to design and construct a unit for aerospace studies that would function under nonambient pressures.

Nomenclature

$\boldsymbol{b}$	Parameter
$\boldsymbol{F}$	View factor (-)
$\boldsymbol{h_c}$	Convective heat transfer coefficient (W · m^{-2}·K^{-1})
ℓ	Thickness (mm)
$\dot{m}''$	Mass loss rate (g · s^{-1} · m^{-2})
$\dot{q}$	Total energy released per unit area (MJ · m^{-2})
$\boldsymbol{q''}$	Total energy released per unit area (MJ m^{-2})
$\dot{q}''$	Heat flux (kW·m^{-2})
$\dot{q}''_{180}$	180 s average heat release rate (kW · m^{-2})
$\dot{q}''_{avg}$	Average heat release rate (kW m^{-2})
$\dot{q}''$	Irradiance (kW m^{-2})
$\dot{q}''_{\max}$	Maximum heat release rate (kW m^{-2})
$\dot{q}''_{\text{tot}}$	Total heat released (MJ · m^{-2})

$\dot{q}''_{cr}$	Critical heat flux (kW m^{-2})
$\boldsymbol{r}$	Repeatability (units dependent on quantity investigated)
$\boldsymbol{R}$	Reproducibility (units dependent on quantity investigated)
$\boldsymbol{t}_{\mathbf{b}}$	Duration of flaming (s)
$\boldsymbol{t}_{\mathbf{ig}}$	Ignition time (s)
$\boldsymbol{\Delta h}_{\boldsymbol{c},\mathbf{eff}}$	Effective heat of combustion (MJ · kg^{-1})
$\boldsymbol{\varepsilon}$	Emissivity (-)
$\boldsymbol{\lambda\ \rho\ C}$	Thermal inertia ($kJ^2\ m^{-4}\ s^{-1}\ K^{-2}$)
$\boldsymbol{\rho}$	Density (kg·m^{-3})
$\boldsymbol{\sigma_r}$	Repeatability standard deviation (units dependent on quantity investigated)
$\boldsymbol{\sigma_R}$	Reproducibility standard deviation (units dependent on quantity investigated)
$\boldsymbol{\sigma_f}$	Average specific extinction area (m^2 · kg^{-1})

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