Users’ Guide for the
Fire Propagation Apparatus (FPA)
ASTM E-2058

Issued by:

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IMPORTANT NOTE

This guide does not purport to replace or overrule any sections of ASTM E 2058, FM 4910 or any relating standard to this apparatus. It is recommended that this standard, or the most recent version, is read in conjunction with this guide.

Users finding difficulties with these procedures, or encountering anomalous conditions not described in the documentation are urged to contact Fire Testing Technology Limited. User comments are specifically invited, and will be incorporated into future editions of this guide. Telephone: +44 (0)1342 323600 or Fax: +44 (0)1342 323608.
## Contents

1. The FTT Fire Propagation Apparatus (FPA) .............................................. 1
   1.1 Introduction ......................................................................................... 1
   1.2 Scope ................................................................................................. 2
   1.3 Calculations ....................................................................................... 4
   1.4 Services ............................................................................................. 5
   1.5 Safety Precautions and Procedure ..................................................... 6

2. Apparatus ............................................................................................ 8
   2.1.1 Infrared (IR) Heating System ....................................................... 8
   2.1.2 Load Cell System .......................................................................... 8
   2.1.3 Ignition Pilot Flame ....................................................................... 8
   2.1.4 Gas Analysis System .................................................................. 9
      2.1.4.1 Carbon Dioxide/Carbon Monoxide Analysers ..................... 9
      2.1.4.2 Inlet-Air Oxygen Analyser .................................................... 9
      2.1.4.3 Exhaust Oxygen Analyser ..................................................... 11
   2.1.5 Combustion Air Distribution System ............................................ 11
   2.1.6 Water Cooled Shield .................................................................. 11
   2.1.7 Exhaust System ............................................................................ 11
      2.1.7.1 Test Section Instruments ....................................................... 11
   2.1.8 Specimen holders ........................................................................ 12

3. Calibration ........................................................................................... 13
   3.1 Radiant Flux Heater ......................................................................... 13
      3.1.1 Positioning of Radiant Flux Heaters ........................................ 13
   3.2 Gas Analyser Calibration ................................................................ 13
      3.2.1 Carbon Dioxide/Carbon Monoxide Analysers ....................... 14
      3.2.2 Oxygen Analyser ..................................................................... 14
      3.2.3 Load Cell .................................................................................. 15
      3.2.4 Heat Release Calibration ........................................................ 16
   3.3 Conditioning ...................................................................................... 18

4. Testing Procedure ................................................................................ 19
   4.1 Specimen size and preparation ....................................................... 19
      4.1.1 Ignition and Combustion Tests of horizontal specimens .......... 19
   4.2 Rectangular sample for vertical fire propagation test ....................... 20
4.3 Cable sample for vertical fire propagation test ............................................................ 21
4.4 Procedure 1: Ignition Test ........................................................................................ 22
4.5 Procedure 2: Combustion Test .............................................................................. 23
4.6 Procedure 3: Fire Propagation Test ....................................................................... 25

5. Calculations .............................................................................................................. 28
   5.1 Report .................................................................................................................. 29
      5.1.1 Procedure 1: Ignition Test ........................................................................... 29
      5.1.2 Procedure 2: Combustion Test ................................................................... 29
      5.1.3 Procedure 3: Fire Propagation Test ............................................................. 29

6. Terminology ............................................................................................................. 31
   6.1.1 Definitions ....................................................................................................... 31
   6.1.2 Nomenclature ............................................................................................... 31

7. References ............................................................................................................... 33
1. The FTT Fire Propagation Apparatus (FPA)

1.1 Introduction

Fire Testing Technology Ltd. manufactures the Factory Mutual Research Corporation (FMRC) Fire Propagation Apparatus (FPA), a heat release calorimeter, which can be used to quantify the ignition, heat release (chemical, convective, and overall), mass loss, effective heat of combustion, and fire propagation performance of materials (Figure 1.1). This is done by developing a series of combined fire-test-response parameters, related to the propensity of materials to support fire propagation. The generation of combustion products such as smoke, specific toxic species and corrosive gases can also be quantified by attaching optional additional analytical equipment to the basic apparatus.

Figure 1.1: - Fire Testing Technology Fire Propagation Apparatus

The use of this apparatus has its basis in fundamental research, by Dr. Archibald Tewarson and others[^1-6]. It has now resulted in FMRC developing standards. FM Standard 4910 (“Clean Room Materials Flammability Test Protocol: Test Standard, Class Number 4910”, September 1997), addresses materials to be used in Cleanrooms, but it was preceded by standards for other materials and products, including electrical cables (“Cable Fire Propagation Specification Test Standard, Class Number 3972”, July 1989) and mine belts (“Class 1 Conveyor Belting Approval Standard, Class Number 4998”, August 1995).
1.2 Scope

The FPA is a calorimeter which enables the ignition, heat release, and fire propagation performances of materials to be quantified by use of a series of parameters (these parameters are listed and defined below). Generation of combustion products such as smoke, specific toxic species and corrosive gases can be quantified by use of additional analytical equipment to the basic apparatus.

Three tests that are commonly used in conjunction with the apparatus are:

1. An Ignition test (determines CHF and TRP);
2. A Combustion test (determines EHC); and,
3. A Fire Propagation Test (determines FPI).

The parameters used to quantify the fire performance are:

1. The Critical Heat Flux (CHF), the minimum heat flux at or below which no ignition occurs, kW·m\(^{-2}\);
2. The Thermal Response Parameter (TRP), a material property giving the resistance to ignition upon exposure to a prescribed heat flux, kW·s\(^{1/2}\)·m\(^{-2}\);
3. The Fire Propagation Index (FPI), the propensity of a material to support fire propagation beyond the ignition zone in terms of the chemical heat release rate during upward fire propagation in an elevated O\(_2\) environment, simulating the radiant heat flux emitted from real fire flaming, m\(^{5/3}\)·kW\(^{-2/3}\)·s\(^{1/2}\); and,
4. The Effective Heat of Combustion (EHC), the energy generated by chemical reactions per unit mass of fuel vaporised, kJ·kg.

The ignition and combustion test methods involve the use of horizontal specimens subjected to a controlled, external radiant heat flux which can be set from 0 up to 65 kW·m\(^{-2}\). The third test method, the fire propagation test, involves the use of vertical specimens subjected to ignition near the base of the specimen from an external radiant heat flux and a pilot flame. Both the combustion and fire propagation tests can be performed using either normal air or other gaseous mixtures, such as air with added nitrogen or air enriched with up to 40% oxygen.

The ignition test method involves the use of horizontal specimens subjected to a controlled, external radiant heat flux, which can be set from 0 up to 65 kW·m\(^{-2}\). This test method is used to determine: (a) the time required for ignition of horizontal test specimens by a pilot flame as a function of the magnitude of a constant, externally applied radiant heat flux and (b) the time to initial fuel vaporization. The surface of the test specimens is coated with a thin layer of a carbon black and activated charcoal mixture to ensure complete absorption of the radiant heat flux from the infrared heating system. (It should be pointed out that the coating mixture does not itself undergo sustained flaming).

The combustion test method also involves the use of horizontal specimens, and they too are subjected to a controlled, external radiant heat flux, which can be set from 0 up to 65 kW·m\(^{-2}\). The test method is used to determine the chemical and convective heat release rates when the horizontal test specimen is exposed to an external radiant heat flux. The test can be performed
using either normal air or other gaseous mixtures, such as air with added nitrogen or air enriched with up to 40% oxygen.

The third test method, the fire propagation test, involves the use of vertical specimens subjected to ignition near the base of the specimen from an external radiant heat flux and a pilot flame. It is used to determine the chemical heat release rate of a burning, vertical specimen during and after upward fire propagation initiated by a heat flux near the base of the specimen. Chemical heat release rate is derived from the release rates of carbon dioxide and carbon monoxide. Observations are also made of the flame height on the vertical specimen during fire propagation. This test can also be performed using either normal air or other gaseous mixtures, such as air with added nitrogen or air enriched with up to 40% oxygen.

The fire propagation test method is different from other test methods assessing heat release or flame spread, such as the cone calorimeter (ASTM E1354 or ISO 5660), the Ohio State University calorimeter (ASTM E906) or the lateral ignition and flame spread test (LIFT, ASTM E1321 or ISO 5658) by virtue of producing laboratory measurements of the chemical heat release rate during and after the actual process of self-sustained, upward fire propagation on a vertical test specimen. The LIFT apparatus gives results during lateral/horizontal, while the cone calorimeter and Ohio State University calorimeter give measurements of the rate of heat release from materials fully involved in flaming combustion, using oxygen consumption calorimetry and thermopile calorimetry, respectively. Moreover, these calorimeters generally use an external radiant flux, rather than the flames from the burning material itself, to characterize fire behavior.

Materials intended to be analysed in the Fire Propagation Apparatus are test specimens originating from an end-use product or the various components contained in the end-use product. Results from the laboratory procedures provide input to fire propagation and fire growth models, risk analysis studies, building and product designs and materials’ research and development.

The ignition test is performed to determine the time required from the application of an externally applied heat flux, in the presence of a pilot flame, to a horizontal test specimen until ignition of that specimen. The lighted pilot flame, at a 10 mm flame length, is positioned 10 mm above the test specimen surface and 10 mm from the perimeter of the test specimen. The external radiation is supplied by an infrared heater, the voltage of which is set to produce the desired incident heat flux, with the initial value recommended to be 30 kW/m². The test specimen is protected from external radiation prior to the test by a water-cooled shield, which is removed to expose the sample to the external heat flux. The exposure is continued until sustained flaming (existence of flame on or over most of the specimen surface for at least a 4 s duration) occurs, or until 15 mins have elapsed without ignition (whichever comes first). The procedure is then repeated for other heat flux exposures, at higher or lower incident heat fluxes, as needed, until sufficient data is obtained to permit assessment of the critical heat flux for ignition and the thermal response parameter (a minimum of four heat fluxes is needed).

The combustion test is conducted to measure the chemical and convective heat release rates, and the mass loss rate, and use them to determine the effective heat of combustion of a horizontal specimen. Smoke obscuration data are also determined during this test (at three different wavelengths). In this test, exposure of the horizontal test specimen, at a
recommended incident heat flux of 50 kW·m$^{-2}$, continues beyond ignition. The test end point is 2 min after flames can no longer be seen. In the test, information is obtained not only at the time when vapors are first observed coming from the test specimen, and the time at ignition, but also visual observations of the flame height, flame color and smokiness, any unusual flame or specimen behavior and flame extinction time. Simultaneously, time-based data is obtained on:-

- mass flow rate of overall exhaust (kg·s$^{-1}$);
- mass flow rate of carbon monoxide (kg·s$^{-1}$);
- mass flow rate of carbon dioxide (kg·s$^{-1}$);
- mass loss rate of test specimen (kg·s$^{-1}$);
- differential pressure in the exhaust duct (Pa);
- temperature in the exhaust duct (K);
- mass of smoke particulates (g); and,
- extinction coefficient (m$^{-1}$).

The fire propagation test is performed to determine the fire propagation index of a material through measurement of the chemical heat release rate of a vertical test specimen during and after upward fire propagation. The test set-up is similar to that in the combustion test, except that the mass of the test specimen is not measured. In this case, the incident heat flux is set at 50 kW·m$^{-2}$ and the oxygen concentration of the incoming air at 40% oxygen, to simulate the radiant heat flux from the material flames in real fires. Measurements during this test method are similar to those made during the combustion test method, except for test specimen mass or smoke obscuration information.

Additional instrumentation can be used to measure a corrosion index, such as the Average Corrosion Index (ACI), which gives an indication of corrosion damage caused by the combustion products from a burning material by exposing a metal sensor to the gases generated during the test and then leaving it in a still environment for several hours to monitor corrosion. The ACI is measured by removing the corrosion probe from the duct 30 mins after the end of the test, placing it in an environmentally controlled chamber at 23 °C and 60 ± 5% relative humidity, and then monitoring the metal loss (as a corrosion indicator) every 5 min for at least 16 hrs.

1.3 Calculations

The parameters to be reported are calculated based on the following concepts:

$$\text{FPI} = 1000[0.42 \text{ Chemical HRR/Test Specimen Width}]^{1/3}/\text{TRP}$$

$$\text{Chemical HRR} = 13,300(\text{Added Generation Rate of CO}_2) + 11,100(\text{Added Generation Rate of CO})$$

$$\text{EHC} = \sum [\text{Chemical HRR} \times \text{Scan Period}] / \text{Mass Loss}$$

$$\text{Convective HRR} = \text{Mass Flow Rate} \times C_p \times (\text{Duct Temperature Increase})$$

$$\text{Smoke Yield} \propto \sum [\text{Volumetric Flow Rate} \times \text{Extinction Coefficient} \times \text{Scan Period}] / \text{Mass Loss}$$
ACI: ratio of an average corrosion rate to an average combustion product concentration in the exhaust duct.

1.4 Services

1. Extraction. A hood system is required which can:-
   • Remove the maximum of 300l·s\(^{-1}\) from the exhaust stack, while being de-coupled from it [that is, the FPA exhaust stack should empty into a collection hood, rather than being directly plumbed into the building exhaust]; and,
   • Remove any smoke drifting up due to specimen insertion or removal; and allow burned specimens to be temporarily placed in a safe location. The requirement for a de-coupled configuration is to avoid introducing pressure fluctuations from the building ventilation system or from the outside weather. In practice, thus, the actual rated capacity will have to be, in excess of 300l·s\(^{-1}\) coming from the exhaust itself.

2. Electrical power. Electrical power providing 277VAC 60 Hz 160A at the instrument must be available. Two additional 110VAC 60Hz 20A supplies are also required. One is a dirty supply (for fan, pump etc.) and the other a clean supply (for analysers etc.). Separate mains supply is required for the computer and printer. All supplies are to be switched and fused.

3. Water supply. Pressure regulated clean water with a flow rate of 2.0l·min\(^{-1}\) allowing each IR heater to receive at least 0.34l·min\(^{-1}\) at <50lb·in\(^{2}\). The inlet temperature should not exceed 70°F (22°C) above dew point. A supply is also necessary for the water cooled shield which should be adequate to prevent a temperature increase of the shield (approximately 3.0l·min\(^{-1}\)).

4. Air Supply. Pressure regulated clean, oil-free shop air at a flow rate of 1.5m\(^3\)·min\(^{-1}\) allowing each IR heater to receive at least 0.3m\(^3\)·min\(^{-1}\).

4. Drain. A drain line is required to handle the water being provided.

6. Calibration gas of CO/CO\(_2\) which should be in the range of 80/90% of the analyser's full scale with a flow of 3.5l·min\(^{-1}\) at a maximum pressure 5 psi. Recommended ranges are 2500ppm CO\(_2\) and 400ppm CO. A 6 mm internal diameter pipe connector is required.
7. **Oxygen free Nitrogen** is required to:-
   - Zero the oxygen analyser with a maximum flow of 3.5 l·min⁻¹ at a maximum pressure of 5psi. A 6 mm internal diameter pipe connector is required.
   - Supply the air distribution chamber at a flow rate of 20 l·min⁻¹ allowing flaming in the combustion zone to be extinguished.

8. **Drying Agents.** Agent for removing water: Drierite is the preferred agent (or silica gel may be used).

IF CERTAIN OPTIONS HAVE BEEN SELECTED THE FOLLOWING SERVICES WILL BE NEEDED:

1. **Total Hydrocarbon Analyser**
   - **Fuel Gas** of 40% Hydrogen, 60% Nitrogen mixture at a flow rate of 80 ml·min⁻¹.
   - **Calibration Gas** is methane. The concentration can be 0 to 4 ppm CH₄ through 0 to 1000 ppm CH₄ at the user’s discretion with a flow rate of 0.5 to 2.0 l·min⁻¹.

2. **Methane.** For the calibration burner, methane gas of at least 99.5% purity with a maximum flow of 25 l·min⁻¹ at a maximum pressure of 2 bar (30 lb·in⁻²) and with a 6 mm internal diameter pipe connector is required.

1.5 **Safety Precautions and Procedure**

1. Some specimens may produce severe flaming during a test. Therefore, adequate means of extinguishing the specimen should be available. A recommended mean of extinguishment is compressed nitrogen which can be directed to the burning area along with any other means such as fire extinguishers etc.

2. This test method may involve hazardous materials, operations and equipment. Therefore, we specifically exclude any liability whatsoever for claims arising from use or misuse of this equipment. It is the responsibility of whoever uses the equipment to consult and establish appropriate health and safety practices and determine the applicability of regulatory limitations prior to use.

3. All service inputs must be made secure. A pure oxygen supply is connected at the service inputs. This gas is highly flammable and extreme care should be taken when using it.

4. The equipment must be supervised at all times.

5. To reduce the glare #2 green welding glasses should be worn at all times when using the infrared heating system and the safety practices provided in the heaters manual should be performed in conjunction with the measures listed here.

6. This equipment must only be operated by authorised personnel who are fully conversant with the safety requirements. The operator must have a thorough knowledge of the chemical properties of the materials under test and what combustion products can be expected from them.
7. Care should be taken to avoid contact with hot surfaces produced from the burning of the material. It is recommended that heat-protective gloves (not household rubber) be worn when working in burner area and when removing a specimen holder.

8. The products of pyrolysis and burning of the materials under test may be carcinogenic, toxic, or otherwise hazardous. An auxiliary breathing device and protective glasses may have to be worn before opening the chamber door. It may be noted that highly corrosive residues may permeate and degrade heat-protective gloves. Butyl gloves must be worn underneath the heat-protective gloves for complete protection in such cases.

9. The installation, siting and provision of services to the equipment must have the approval of the Safety Officer.

10. All normal laboratory safety precautions must be followed.

11. The exhaust system must be checked for proper operation before testing and must be discharged away from intakes for the building ventilation system. Provisions must be made for collecting and venting any combustion products that fail to be collected by the exhaust system.
2. Apparatus

The apparatus (Figure 2.1) consists of the following components: an infrared heating system, a load cell system, an ignition pilot flame and timer, a product gas analysis system, a combustion air distribution system, a water-cooled shield, an exhaust system, test section instruments, calibration instruments and a digital data acquisition system.

2.1.1 Infrared (IR) Heating System

The IR Heating System consists of four 241 mm long heaters and a power controller.

Each of the four IR heaters contain six tungsten filament tubular quartz lamps in a compact reflector body that produces up to 510 kW·m$^{-2}$ of radiant flux in front of the quartz window that covers the lamps. The reflector body is water-cooled and the lamp chamber, between the quartz window and reflector, is air-cooled for prolonged life. The emitter of each lamp is a 127 mm long tungsten filament in an argon atmosphere enclosed in a 9.5 mm outer diameter clear quartz tube. The emitter operates at approximately 2205°C (4000°F) at twice rated voltage, with spectral energy peaks at 1.15 and 0.89 micron. Wavelengths greater than about 2 microns are absorbed by the quartz bulb envelope and heater front window, which are air-cooled.

The power controller maintains the output voltage required by the heater array despite variations in load impedance through the use of phase angle power control to match the hot/cold resistance characteristics of the tungsten/quartz lamps. The controller also incorporates average voltage feedback to linearise the relationship between the voltage set by the operator and the output voltage to the lamps.

2.1.2 Load Cell System

The load cell system consists of a load cell, which has an accuracy of 0.1 g, and a measuring range of 0-1000 g; a 6.35 mm diameter stainless steel shaft, at least 330 mm long, resting on the load cell support point; a 100 mm diameter, 1.5 mm thick aluminium load platform connected to the upper end of the stainless steel shaft by a collar; and two low friction, ball-bushing bearings that guide the shaft as it passes through the top and bottom, respectively, of the air distribution chamber. The stainless steel shaft shall incorporate, at the lower end, a threaded adjustment rod to compensate for horizontal test specimens of different thickness.

2.1.3 Ignition Pilot Flame

The ignition pilot consists of an ethylene/air (60/40 by volume) flame adjusted for a 10 mm length. The pilot flame is anchored at the 50 mm long, horizontal end of a 6.35 mm OD, 4.70 mm ID stainless steel tube. In the horizontal tube section a 4-hole ceramic insert produces a stable flame and prevents flashback. The pilot flame tube is able to be rotated and elevated to position the horizontal flame at specified locations near the specimen.
2.1.4 Gas Analysis System

The gas analysis system consists of a gas sampling system (connected to the air and water supply system) and gas analysis instruments, as described below.

The arrangement is shown in Figure 2.2. It consists of a sampling probe (6.35 mm OD with 14 holes) in the test section duct, primary and secondary filters to prevent entry of soot, a condenser operating at temperatures in the range -5°C to 0°C to remove liquids, a tube containing an indicating desiccant (10-20 mesh) to remove most of the remaining moisture, a filter to prevent soot from entering the analysers (if not already removed), a sampling pump that transports the flow through the sampling line, system flow meters, needle valves and manifolds to direct the flow to individual analysers (CO, CO₂, O₂).

2.1.4.1 Carbon Dioxide/Carbon Monoxide Analysers

The carbon dioxide analyser enables measurements from 0 to 15,000 ppm and the carbon monoxide analyser enables measurements from 0 to 500 ppm concentration levels. Drift is not more than ±1% of full scale over a 24 hr period and precision is 1% of full-scale. The 10% to 90% of full-scale response times are less than 10 s.

2.1.4.2 Inlet-Air Oxygen Analyser

This analyser has a 10% to 90% of full-scale response time of 10 s or less, an accuracy of 0.05% of full-scale, a drift of not more than ±50 ppm O₂ over one-half hour and a 0% to 100% range.
Figure 2.2: - Plumbing Schematic
2.1.4.3 Exhaust Oxygen Analyser

An additional oxygen analyser is used to measure the depletion of oxygen in the combustion products. This analyser has the same specifications as the inlet-air analyser.

2.1.5 Combustion Air Distribution System

This system consists of an air distribution chamber and air supply pipes. The air distribution chamber is an aluminium chamber containing eight discharge tubes arranged in a circle of 165 mm inside diameter. Each tube is aluminium and built to distribute inlet gases (air, O\textsubscript{2}, N\textsubscript{2}, etc.) to three sets of screens (stainless steel woven wire cloth of 10, 20 and 30 mesh from bottom to top, respectively), for producing a uniform air flow. Inlet air flows downward through the eight discharge tubes, disperses on the bottom plate, then rises through the mesh screens toward the aluminium support cylinder.

An aluminium cylinder extends from the air distribution chamber up to the load platform and contains a step to support a quartz pipe. Above the load platform elevation, the quartz pipe supplies oxidant to the specimen flame while allowing radiant energy from the IR heating system to reach the specimen surface. A second shorter length of quartz tube sits above the first connected via a stainless steel flange. The aluminium support cylinder is rigidly attached to the distribution chamber, but the quartz pipe is removable.

2.1.6 Water Cooled Shield

To prevent the specimen from being exposed to the IR heaters during the one minute heater stabilisation period, there is a shield consisting of two aluminium cylinders welded together with an inlet and outlet for water circulation. An electrically actuated, pneumatic piston raises the shield to cover the specimen during test preparation and lowers the shield within 1 s to expose the specimen at the start of a test.

2.1.7 Exhaust System

The exhaust system consists of the following main components: an intake hood, a mixing duct, a test section, duct flanges and a high temperature blower to draw gases through the intake funnel, mixing duct and test section at variable flow rates up to 0.25 m\textsuperscript{3}/s. The intake funnel, mixing duct and test section are coated internally with a resin enamel over a suitable primer to form a three layer coating that will withstand temperatures of at least 200°C.

2.1.7.1 Test Section Instruments

Test Section Thermocouple Probe - A thermocouple probe (1.5mm diameter), inserted through a test section port, is positioned such that the exposed, type K measurement bead is at the centre of the test section, at the axial position of the gas sampling port. The thermocouple probe is for measurement of gas temperature with a time response (in the specified exhaust flow) of no more than one second and an accuracy of 1.0°C.

Averaging Pitot Probe and Pressure Transducer - An averaging Pitot probe (Platon Flo-Bar), inserted through a test section measures the mass flow rate of the gas stream using six openings, five facing upstream and one downstream designed for compatibility with the test section diameter. The differential pressure generated by the probe is measured with an electronic pressure transducer (electronic manometer). The measured differential pressure is proportional to the square of the flow rate.
Heat Flux Gauge - For calibration of the IR heating system, a Gardon type total heat flux gauge is supplied, having a nominal range of 0 to 100 kW·m⁻² and a flat, 6 to 8 mm diameter sensing surface coated with a durable, flat-black finish. The body of the gauge is cooled by water above the dew point of the gauge environment. The calibration of the heat flux gauge should be performed monthly through the use of a black-body oven calibration facility that compares the gauge response to that of a NIST-traceable optical pyrometer. Alternatively, the gauge can be compared with the output to that of a reference standard.

Agilent Data Logger - The outputs from the CO, CO₂, inlet O₂, exhaust O₂, the load cell, the test section duct thermocouple and the electronic pressure transducer are digitally recorded at 1 s intervals. The data is time shifted for the gas concentrations to account for delays within the gas sampling lines and respective instrument response times. The data collection system is accurate to within ±1°C for temperature measurement and ±0.01 percent of full-scale instrument output for all other channels. The system is capable of recording data for at least 1 hr at 1 s intervals, although test duration typically is between 8 and 15 mins.

2.1.8 Specimen holders

Two types of specimen holder are supplied: horizontal circular and vertical. The horizontal circular holder is a 0.099 m (3.9 in) diameter aluminium dish. The vertical specimen holder is a 0.485 m (19 in) high x 0.133 m (5.2 in) wide ladder rack. A horizontal square holder consisting of two layers of “2 mil” (0.05 mm thickness) aluminium foil moulded to the sides and base of a square specimen can also be used.
3. Calibration

3.1 Radiant Flux Heater

Calibrate IR heaters at the start of the test day. Clean the quartz windows, lamps and back reflective surfaces of the heaters to keep them free of any impurity build up or scratches. Horizontally position the heat flux gauge sensing surface, at a location equivalent to the centre of the top surface of a horizontal specimen. Place the quartz pipe in position, as required, and check that the water and air cooling for the IR heaters is at an adequate level, (the heaters will not operate if this is not the case). Record IR heater voltage settings and measured radiant flux levels for planned tests checking that the water cooling required by the heat flux gauge is flowing, (should be the case if the IR heater water cooling is flowing). The controls for the IR heater are shown on Figure 3.1.

**Figure 3.1: - Lamp Control Panel**

![Lamp Control Panel](image)

3.1.1 Positioning of Radiant Flux Heaters

At least annually, check the position of the IR heaters. Set the heater voltage at 90% of the maximum value. Horizontally position the heat flux gauge sensing surface and measure the heat flux at each of five locations, corresponding to each corner and the centre of a square, horizontal specimen, at an elevation equivalent to that of the specimen top surface. Adjust the position of each IR heater symmetrically and repeat these heat flux measurements, if necessary, until there is at most a 5% mean deviation of the five readings from the average value. Then, position the heat flux gauge to locations equivalent to the vertical axis at the centre of a square specimen. Measure the heat flux at elevations of 10 mm and 20 mm above and below that equivalent to the specimen top surface. Check that the heat flux at these four elevations is within 5% of the value at the elevation of the specimen face.

3.2 Gas Analyser Calibration

Calibrate the carbon dioxide, carbon monoxide and oxygen analysers before the first Combustion or Fire Propagation Test of the day. The analysers need to be turned on at least two hours prior to this procedure being performed using the switch indicated in Figure 3.2.
### 3.2. Carbon Dioxide/Carbon Monoxide Analysers

Calibrate the CO\(_2\) and CO analysers for measurement of combustion gases by establishing a down scale calibration point and an upscale calibration point. Perform the upscale calibration with a “span gas” at the upper end of the range that will be used during actual sample analysis and use a “zero gas” for the down-scale calibration point at the lower end of the analyser range. Use nitrogen as the “zero gas” reference source by turning on nitrogen cylinder to give 3.5 l·min\(^{-1}\) (at 5psig) for CO/CO\(_2\). Zero the analysers. Span each analyser with its appropriate gas for the corresponding range. The necessary valves for performing this procedure are indicated in Figure 3.3.

### 3.2.2 Oxygen Analyser

Calibrate the oxygen analyser for measurement of inlet oxygen concentration (and the optional oxygen analyser for combustion gases) by establishing a low calibration point and a high calibration point. Perform the upscale calibration with a “span gas” at the upper end of the range that will be used during actual sample analysis and use a “zero gas” for the down-scale calibration point at the lower end of the analyser range. To calibrate the analyser, open the zero gas span gas at 3.5 l·min\(^{-1}\) (at 5psig), set the analyser to zero, close the zero gas and open the span gas at the same flow rate and then set the upper end of the analyser range. Re-span and re-zero several times, if necessary. The necessary valves for performing this procedure are indicated in Figure 3.3.
3.2.3 Load Cell

The load cell must be checked before each test.

Insert the sample holder which is going to be used for the test and wait for the digital meter to stabilise and then press the Tare button (Figure 3.2) so that 0.0 g is displayed. With a weight similar in range to the specimen being tested, place this on the sample holder and confirm that the digital meter and the computer are recording the value.

In order for the software to record the mass of the specimen correctly, the load cell controller maximum mass, $m_{\text{max}}$ must be set to greater than the mass of the specimen. For example, if your specimens weigh around 75 g then set the maximum to 100 g, if your specimens weigh around 25g then set the maximum to 50 g. At this maximum the signal sent to the computer, must be 10 Volts and at zero mass 0 Volts must be sent to the computer. The sequence Table 3.1 in shows how to set the maximum output.
Table 3.1: - Load Cell Controller Set-Up

<table>
<thead>
<tr>
<th>PUSH</th>
<th>DISPLAY</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MENU×17</td>
<td>OT.SC.OF</td>
<td></td>
</tr>
<tr>
<td>MIN</td>
<td>READ 1</td>
<td></td>
</tr>
<tr>
<td>MAX/MIN</td>
<td>00000.0</td>
<td>READ 1 must be 00000.0</td>
</tr>
<tr>
<td>MENU</td>
<td>OUTPT1</td>
<td></td>
</tr>
<tr>
<td>MAX/MIN</td>
<td>00.0000</td>
<td>OUTPT1 must be 00.0000</td>
</tr>
<tr>
<td>MENU</td>
<td>READ 2</td>
<td></td>
</tr>
<tr>
<td>MAX/MIN</td>
<td>$m_{\text{max}}$</td>
<td>Enter maximum mass here (for example 00100.0)</td>
</tr>
<tr>
<td>MENU</td>
<td>OUTPT2</td>
<td></td>
</tr>
<tr>
<td>MAX/MIN</td>
<td>10.0000</td>
<td>OUTPT2 must be 10.0000</td>
</tr>
<tr>
<td>MENU</td>
<td>STORED RESET2</td>
<td></td>
</tr>
</tbody>
</table>

If a PC is connected, in the software choose Calibrate | Mass and in the Mass FSD field enter the maximum mass you entered into the controller, $m_{\text{max}}$. Ensure that the Volts FSD field is 10. Press OK and then place a weight on the load cell and ensure that the screen agrees with the instrument when viewing the Status screen.

3.2.4 Heat Release Calibration

Calibrate the heat release rate measurement process at least monthly to ensure correct functioning of the Fire Propagation Apparatus. Check that the measured effective heat of combustion of acetone is within ± 5% of the reference value of 27,900 kJ·kg$^{-1}$ and that the measured total delay (or lag) time of the gas analysers is less than 20 s.
- Do not use the IR heaters or the pilot.
- Perform the rest of the required calibration procedures as described in this section.
- Check that inlet air flow is set at 200 l·min$^{-1}$ on the inlet air control panel (Figure 3.5)
- Start the data acquisition program.
- Place 100.0 ml of acetone in a specimen dish 0.097 m (3.8 in.) diameter on the load cell.
- Ignite the acetone using a match 30 s after the start of data acquisition.
- End data acquisition 2 mins after the end of visible flaming.
- Determine the effective heat of combustion.
- Determine the delay time for the gas analysers by computing the difference between the time when the test section duct gas temperature reaches 50% of its steady-state value and the time when the reading of each analyser reaches 50% of its steady-state value.

Alternatively (if supplied) the instrument can be calibrated with the methane burner at a methane flow rate equivalent to 5kW. FPACalc automatically determines the flow coefficient during this calibration.
Figure 3.4: Heat Release Test for Acetone in FPA.

Figure 3.5: Inlet Air Control
3.3 Conditioning

Condition specimens to moisture equilibrium (constant weight) at an ambient temperature of 23 ± 3°C and a relative humidity of 50 ± 5% for 24 hrs.
4. Testing Procedure

Three types of tests are generally conducted: ignition, combustion and vertical fire propagation. The procedures of these tests are described below. The procedures followed here are, in general, consistent with the procedures in Approvals’ test standards as well as in ASTM E-2058 and NFPA287.

4.1 Specimen size and preparation

4.1.1 Ignition and Combustion Tests of horizontal specimens

Circular and square horizontal sample holders are generally used, depending on the test standard that is being followed. The horizontal square holder consists of two layers of 2-mil (0.05 mm thickness) aluminium foil moulded to the sides and bottom of a square solid and foam sample. The maximum thickness of a foam sample can be 0.1m (4 in). The horizontal circular holder is a 0.099 m (3.9 in) diameter and 0.025 m (1 in) deep aluminium dish for solid and liquid samples.

Cut samples from essentially planar materials or products to be 102 by 102 mm (4 by 4 in) square or 97 mm diameter circular in shape (see Figure 4.1). Samples should have a thickness of no less than 3 mm and no more than 25 mm and be representative of the end-use material or product. When the Ignition Test is paired with a Fire Propagation Test for the purpose of computing a Fire Propagation Index, the sample thickness must be identical in both tests.

Figure 4.1: - Demonstration of Cut Samples.

For testing, place square or circular sample in the respective square or circular holder. Granular (or melting materials) or cable samples are tested in the circular holder, with the cable samples cut to cover the centre and at least 20 mm on each side of the centre of the
circular aluminium dish. It is suggested that an appropriate sample holder should be used according to the specific standard. Depending on the sample and the test standard, the exposed top surface of the sample either should be sprayed with a single coat of flat black paint that is designed to withstand temperatures of 540 ± 10°C or uniformly covered with 0.11 mg/mm² of a 50/50 carbon black/activated charcoal (50-200 mesh) mixture. Coat 4 by 4 in. (100 by 100 mm) by maximum 4 in. (100 mm) thick foam samples with carbon black/activated charcoal and expose the coated surfaces to the heat flux. If paint coating is used, make sure to condition the sample at a temperature of 23 ± 3°C and a relative humidity of 50 ± 5% for 48 hrs prior to testing. Place the holder containing the sample on a 13 mm thick, calcium silicate board (density 700-750 kg/m³, thermal conductivity 0.11-0.13 W/m K) having the same dimensions as the holder, as shown in Figure 4.2, just before a test is to be performed. The samples should be mechanically restrained using 24-gage nickel/chromium wire, as shown in Figure 16.

**Figure 4.2: Samples in round aluminium dish and in square aluminium foil dish with calcium silicate boards.**

**4.2 Rectangular sample for vertical fire propagation test**

The vertical sample holder (for rectangular sample) is a 0.485 m (19 in.) high and 0.133 m (5.2 in.) wide ladder rack. The vertical cable holder is 0.825 m high and can support a cable sample 0.81 m (32.5 in.) long and up to 51 m (2 in.) diameter. The detail schematics of both holders are given in ASTM-2058 Standard.

Cut samples from essentially planar materials or products to be 101.6 mm in width and 305 mm in height (4 by 12 in.). Samples should have a thickness of no less than 3 mm and no more than 13 mm and be representative of the end-use material or product.

Place ceramic paper (density 190-200 kg/m³) of 3.2 mm (0.125 in.) thickness to cover the sides and back surface of the specimen and then wrap the sample, with the ceramic paper, in two layers of aluminium foil of “2 mil” (0.05 mm) thickness to expose only the front surface to be tested.

Wrap the covered and exposed width of the sample securely with one turn of #24 gage nickel/chromium wire at distances of 50 mm from each end and at the midpoint of the 305 mm length of the sample.
Place the bottom of the sample on the metal base-plate of the vertical holder with the covered (back) surface of the sample against the ladder rack. When a collection dish is used for melting material the bottom of the sample should at the top of the collection dish.

Wrap one turn of #24 gage nickel/chromium wire securely around the sample, the ladder rack and the threaded rods at distances of 100 and 200 mm from the bottom of the sample to keep the sample firmly in contact with the vertical sample holder (see Figure 4.3).

Figure 4.3: Vertical Sample Holder in the FPA.

4.3 Cable sample for vertical fire propagation test

The vertical holder as specified in ASTM-2058 Standard should be used for the cable. Cut 813 mm (32 in) length of cable and cover the bottom 203 mm (8 in) with 2-mil (0.05 mm thickness) aluminium foil. Place the cable in the centre of the holder with lower end on the steel plate. Secure the cable (at 3 or 5 locations) by 24-gage nickel-chromium wires and centre the cable by tightening the three bolts in the steel tube. Figure 4.4 shows a cable with the holder in the FPA.
4.4 Procedure 1: Ignition Test

The ignition test is performed to determine the Thermal Response Parameter (TRP), and the Critical Heat Flux (CHF) of a material.

Verify that nitrogen for flame extinguishment is available for flow at $100 \pm 10$ litres/minute and that pilot flame gases (ethylene to air ratio 60:40) are regulated to give specified flame length when needed.

Figure 4.5: Ignition Test Setup in the FPA.

Place the 13 mm thick calcium silicate board supporting the appropriate horizontal specimen holder in position (centred) on the aluminium load platform (confirm that there is no quartz pipe in place, to insure natural air flow).

Turn on the exhaust blower.

Light the pilot flame and adjust for a 10 mm flame length.
Move the lighted pilot flame to a position 10 mm above the specimen surface and 10 mm from the perimeter of the specimen.

Turn on air and water to cool the infrared radiant heaters.

Raise the water-cooled shield surrounding the specimen holder to prevent specimen exposure to external heat flux.

Set the IR heater voltage to produce 30 kW/m$^2$ and allow for 1 min of stabilisation.

Lower the water-cooled shield to expose the sample to the external heat flux. Simultaneously start a timer.

Record the time to ignition as the time from exposure to the external heat flux until a sustained flame is established for at least a 4 s duration.

Introduce nitrogen to extinguish flames.

When the specimen has cooled sufficiently to be safely handled, remove the specimen to a ventilated environment.

Repeat this procedure for infrared heater settings of 35, 40, 45, 50, 55 and 60 kW·m$^{-2}$.

If the specimen ignites at 30 kW·m$^{-2}$ within 15 mins, then repeat the same procedure at 25, 20, 15 and 10 kW·m$^{-2}$ (in that order) until there is no ignition for 15 mins.

4.5 Procedure 2: Combustion Test

The combustion test is conducted to determine the Effective Heat of Combustion (EHC) and to measure the chemical and convective heat release rates ($Q_{\text{chem}}$ & $Q_c$).

Place the 13 mm thick calcium silicate board supporting the appropriate horizontal specimen holder in position (centred) on the aluminium load platform.

Verify that the gas sampling system is removing all water vapour and similarly condensable combustion products. If the sampling system flow meter indicates less than 10 litres/min, then replace sampling system filter elements.

Install fresh indicating desiccant and soot filter in the gas sampling line.

Ignite the flame in the hydrocarbon gas analyser and check the Flame Out indicator on the front panel to assure that there is flame ignition.

Verify that nitrogen for flame extinguishment is available for flow at 100±10 litres/min and that pilot flame gases (ethylene to air ratio 60:40) are regulated to give specified flame length when needed.
Turn on gas sampling pump to oxygen, carbon monoxide, carbon dioxide and hydrocarbon gas analysers (which are powered on at all times to maintain constant internal temperatures); set correct flow rates for each instrument.

Perform required calibration procedures as specified in Section 3.

**Figure 4.6: Combustion Test Setup in the FPA.**

![Combustion Test Setup in the FPA](image)

Turn on the exhaust and air-supply blowers servicing the apparatus.

Light the pilot flame and adjust for a 10 mm flame length.

Move the lighted pilot flame to a position 10 mm above the specimen surface and 10 mm from the perimeter of the specimen.

Turn on air and water to cool the infrared radiant heaters.

Install the quartz pipe on the mounting step in the aluminium oxidant supply pipe.

Raise the water-cooled shield to cover the specimen.

Check that inlet air flow is set at 200 litres/min.

Set the IR heater voltage to produce the desired radiant exposure of the specimen surface and allow the IR heaters to stabilise for 1 min.

Start data acquisition system.

At 30 s, lower the cooling shield to expose specimen to infrared radiant heaters.

Record the time when vapours are first observed coming from the test specimen, the time at ignition, flame height, flame colour/smokiness, any unusual flame or specimen behaviour and flame extinction time.
Maintain the position of the pilot flame to be a 10 ± 5 mm height above the exposed surface of any specimen that regresses or expands during the test period.

Terminate the test by introducing nitrogen 2 mins after the end of visible flaming or if flames reach 35 ± 10 mm above the rim of the collection funnel for more than 30 s.

When the specimen has cooled sufficiently to be safely removed from the specimen holder, weigh the residue and record the result.

Repeat the above procedures to give a total of three chemical heat release rate and mass loss rate determinations.

4.6 Procedure 3: Fire Propagation Test

The fire propagation test is performed to determine the Fire Propagation Index (FPI) of a material, through measurement of the chemical heat release rate of a vertical specimen during upward fire propagation.

Verify that nitrogen for flame extinguishment is available for flow at 100 ± 10 litres/min and that pilot flame gases (ethylene to air ratio 60:40) are regulated to give specified flame length when needed.

Turn on gas sampling pump to oxygen, carbon monoxide, carbon dioxide and hydrocarbon gas analysers (which are powered on at all times to maintain constant internal temperatures); set correct flow rates for each instrument.

Perform required calibration procedures as specified in 3.

Turn on the exhaust and air-supply blowers servicing the apparatus.

Light the pilot flame and adjust for a 10 mm flame length.

Move the lighted pilot flame to a position 10 mm above the specimen surface and 10 mm from the perimeter of the specimen.

Turn on air and water to cool the infrared radiant heaters.

Remove the stainless steel load cell shaft and the ball-bushing bearings from the air distribution chamber and replace with the appropriate vertical specimen holder, with specimen installed, such that the bottom edge of the vertical specimen that is to be exposed to IR heating is at an elevation equivalent to that of the top surface of a horizontal specimen.

Light the pilot flame and adjust for a 10 mm flame length.

Turn on a grade oxygen cylinder to provide oxygen for the inlet-air.

Turn on air and water to cool the infrared radiant heaters.
Install the quartz pipe on the mounting step in the aluminium oxidant supply pipe.

Raise the water-cooled shield surrounding the specimen holder to prevent pre-exposure to external heat flux.

Move the pilot flame to a position 75 mm from the bottom of the specimen and 10 mm away from the specimen surface

Figure 4.7: Setup for Vertical Fire Propagation Test in the FPA

Check that the inlet air/oxygen flow is set at 200 l·min⁻¹ and that the inlet oxygen concentration is 40% by volume, based on the calibrated inlet oxygen analyser.

Set the IR heater voltage to produce 50 kW·m⁻² and allow to stabilise for one minute.

Start data acquisition program.

At 30 s, lower the water-cooled shield to expose the lower portion of the vertical sample to the external heat flux from the infrared radiant heaters. Simultaneously start a timer.

After preheating the base area of the specimen for 1 min, move the pilot flame into contact with the specimen surface to initiate fire propagation (if ignition and fire propagation has not already occurred) and then move the pilot flame away from the specimen.

Measure the chemical heat release rate as a function of time during fire propagation, using the Combustion Test Procedures.

Record the time when vapours are first observed coming from the test specimen, the time at ignition, flame height at 1 min intervals, flame characteristics such as colour, and the time at flame extinction.
Terminate the test by introducing nitrogen 2 mins after the end of visible flaming or if flames reach $35 \pm 10$ mm above the rim of the collection funnel for more than 30 s or if the specimen undergoes noticeable structural deformation.

Repeat the above procedures to give a total of three heat release rate determinations.
The thermal response parameter (TRP) is determined from the slope of a straight-line regression fit to data on external heat flux (from the IR heaters) vs. the inverse of the square root of time-to-ignition. Data is from the four highest external heat fluxes (e.g., 45, 50, 55 and 60 kW·m\(^{-2}\)) in the Ignition Test. The standard deviation (standard error) of the slope due to data scatter must be within 10% of the regression fit slope. Obtain additional data if this standard deviation is too large.

The critical heat flux (CHF) is determined from the intercept with the ordinate of a straight-line regression fit to data on external heat flux (from the IR heaters) vs. the inverse of time-to-ignition. Data is from the four lowest heat fluxes (e.g., 30, 25, 20, 15 kW·m\(^{-2}\)) in the Ignition Test. The standard deviation (standard error) of the intercept due to data scatter must be within 10% of the regression fit intercept. Obtain additional data if this standard deviation is too large.

The fire propagation index (FPI) is determined by using the expression:

\[
\text{FPI} = 1000 \frac{(0.42 \dot{Q}_{\text{chem}})}{W}^{\frac{1}{3}} / \text{TRP}
\]  

where the chemical heat release rate, \(\dot{Q}_{\text{chem}}\), is measured during the Fire Propagation Test.

The chemical heat release rate is determined from the following expression:

\[
\dot{Q}_{\text{chem}} = 13,300 (\dot{G}_{\text{CO}_2} - \dot{G}_{\text{CO}_2}^0) + 11,100 (\dot{G}_{\text{CO}} - \dot{G}_{\text{CO}}^0)
\]

where \(\dot{G}_{\text{CO}_2}\) and \(\dot{G}_{\text{CO}}\) are the generation rates (kg·s\(^{-1}\)) of \(\text{CO}_2\) and \(\text{CO}\), respectively, and where \(\dot{G}_{\text{CO}_2}^0\) and \(\dot{G}_{\text{CO}}^0\) are the corresponding measurements before ignition of the specimen.

The generation rates of \(\text{CO}_2\) and \(\text{CO}\) are determined from the following expressions:

\[
\dot{G}_{\text{CO}_2} = A_d K (P_{\text{atm}} / 101,000)^{\frac{1}{2}} (2 \ast 353 \Delta p_m / T_d)^{\frac{1}{2}} \ast 1.52 X_{\text{CO}_2}
\]

\[
\dot{G}_{\text{CO}} = A_d K (P_{\text{atm}} / 101,000)^{\frac{1}{2}} (2 \ast 353 \Delta p_m / T_d)^{\frac{1}{2}} \ast 0.966 X_{\text{CO}}
\]

\(\Delta H_{\text{eff}}\) is determined from the following expression:

\[
\Delta H_{\text{eff}} = \frac{Q}{M_{\text{loss}}}
\]

where \(Q\) is the cumulative heat generated during the Combustion Test, based on a summation over all data scans of the product of \(\dot{Q}_{\text{chem}}\), from Eq 2, and \(\Delta t\), the time between scans; and where \(M_{\text{loss}}\) is the change in measured specimen mass (by laboratory balance) resulting from the Combustion Test.
The convective heat release rate, \( \dot{Q}_c \), is determined from the following equation:

\[
\dot{Q}_c = \dot{m}_d \ c_p \ (T_d - T_a) = A_d \ K \ (P_{atm} / 101,000)^{1/2} (2 \times 353 \ \Delta p_m / T_d)^{1/2} \ c_p \ (T_d - T_a)
\]  

(6)

where \( c_p \) (kJ/kg•K) is the specific heat of air, \( T_d \) (K) is the gas temperature in the test section duct during the Combustion Test and \( T_a \) (K) is the gas temperature in the test section duct just before pilot flame ignition occurs. The specific heat, \( c_p \), is corrected for temperature as follows:

\[
c_p = 1.00 + 1.34 \times 10^{-4} \ T_d - 2590 / T_d^2
\]  

(7)

5.1 Report

5.1.1 Procedure 1: Ignition Test

Report the following information:

1. Specimen identification code or number.
2. Manufacturer or name of organisation submitting specimen.
3. Date of test.
4. Operator and location of apparatus.
5. Composition or generic identification of specimen.
6. Specimen thickness and dimensions of specimen surface exposed to IR heaters (mm).
7. Specimen mass (kg).
8. Details of specimen preparation.
9. Specimen orientation, specimen holder and description of special mounting procedures.
10. Room temperature (°C) and relative humidity (%).
11. Exhaust system flow rate (litre/min).
12. Radiant flux from IR heating system applied to test specimen (kW·m\(^{-2}\)).
13. Time when vapours are first observed coming from the test specimen (s).
14. Time at which there is ignition and sustained flaming (s).
15. Thermal response parameter, TRP (kW·s\(^{1/2}\)·m\(^{-2}\)).
16. Critical heat flux, CHF (kW·m\(^{-2}\)).
17. Additional observations (including times of transitory flaming, flashing, or melting).

5.1.2 Procedure 2: Combustion Test

In addition to 5.1.1.1 - 5.1.1.12, report the following information:

1. Chemical, and convective heat release rates per unit specimen area (kW·m\(^{-2}\)).
2. Generation rates of carbon monoxide, and carbon dioxide (kg·s\(^{-1}\)).
3. Specimen mass loss rate (kg·s\(^{-1}\)).
4. Effective heat of combustion, \( \Delta H_{eff} \) (kJ·kg\(^{-1}\)).
5. Specimen mass remaining after test (kg).
6. Number of replicate specimens tested under the same conditions.

5.1.3 Procedure 3: Fire Propagation Test

In addition to 5.1.1.1 - 5.1.1.12, report the following information:
Chemical heat release rate (kW).
Flame height (m).
Chemical heat release rate per unit exposed width or circumference of specimen (kW·m⁻¹)
Thermal response parameter from the Ignition Test (kW·s⁻¹/₂·m⁻²).
Fire propagation index (m⁵/₃·kW⁻²/₃·s⁻¹/₂).
Number of replicate specimens tested under the same conditions.
6. Terminology

6.1.1 Definitions

critical heat flux, \( CHF \), \((kW\cdot m^{-2})\), \( n \) - the maximum heat flux applied to a specimen for which there is no ignition.

effective heat of combustion, \( EHC \), \((kJ\cdot kg^{-1})\), \( n \) - the energy generated by chemical reactions per unit mass of fuel vaporised.

fire propagation index, \( FPI \), \((m^{5/3}\cdot kW^{2/3}\cdot s^{-1/2})\), \( n \) - the propensity of a material to support fire propagation beyond the ignition zone, determined in part by the chemical heat release rate during upward fire propagation in air containing 40% oxygen.

thermal response parameter, \( TRP \), \((kW\cdot s^{1/2}\cdot m^{-2})\), \( n \) - a parameter characterising resistance to ignition upon exposure of a specimen to a prescribed heat flux.

6.1.2 Nomenclature

- \( A_d \) cross sectional area of test section duct \((m^2)\)
- \( CHF \) Critical Heat Flux \((kW/m^2)\)
- \( c_p \) specific heat of air at constant pressure \((kJ/kg \ K)\)
- \( D o_2 \) mass consumption rate of oxygen \((kg/s)\)
- \( EHC \) Effective Heat of Combustion \((kJ/kg)\)
- \( FPI \) Fire Propagation Index \((m^{5/3}/kW^{2/3}/s^{1/2})\)
- \( \dot{G}_{co} \) mass flow rate of CO in test section duct \((kg/s)\)
- \( \dot{G}_{co2} \) mass flow rate of \( CO_2 \) in test section duct \((kg/s)\)
- \( \dot{G}_j \) mass flow rate of compound \( j \) in test section duct \((kg/s)\)
- \( \Delta H_{co} \) heat of complete combustion per unit mass of CO \((kJ/kg)\)
- \( \Delta H_{co2} \) heat of complete combustion per unit mass of \( CO_2 \) \((kJ/kg)\)
- \( \Delta H_{eff} \) effective heat of combustion \((kJ/kg)\)
- \( \Delta H_{o2} \) heat of complete combustion per unit mass of oxygen \((kJ/kg)\)
- \( \Delta H_T \) net heat of complete combustion per unit mass of fuel vaporised \((kJ/kg)\)
- \( K \) flow coefficient of averaging Pitot tube \([\text{duct velocity}/(2\Delta p_{m}/\rho)^{1/2}]\) (-)
- \( k_{CO2} \) stoichiometric \( CO_2 \) to fuel mass ratio, for conversion of all fuel carbon to \( CO_2 \) (-)
- \( k_{CO} \) stoichiometric CO to fuel mass ratio, for conversion of all fuel carbon to CO (-)
- \( k_{O2} \) stoichiometric ratio of mass of oxygen consumed to mass of fuel burned (-)
- \( MW_j \) ratio of the molecular weight of compound, \( j \), to that of air (-)
- \( M_{loss} \) ultimate change in specimen mass resulting from combustion \((kg)\)
- \( m_d \) mass flow rate of gaseous mixture in test section duct \((kg/s)\)
- \( P_{atm} \) atmospheric pressure \((Pa)\)
- \( \Delta p_m \) pressure differential across averaging Pitot tube in test section duct \((Pa)\)
- \( Q \) cumulative heat released during Combustion Test \((kJ)\)
\( \dot{Q}_{\text{chem}} \) chemical heat release rate (kW)
\( \dot{Q}_c \) convective heat release rate (kW)
\( T_a \) gas temperature in test section duct before ignition (K)
\( T_d \) gas temperature in test section duct (K)
\( TRP \) Thermal Response Parameter (kW•s^{1/2}/m^2)
\( t \) time (s)
\( t_{\text{ign}} \) ignition time (s)
\( \Delta t \) time between data scans (s)
\( \dot{\nu} \) total volumetric flow rate in test section duct (m^3/s)
\( W \) horizontal width of a flat specimen or the circumference of a cable specimen (m)
\( X_j \) measured analyser reading for compound, j, or mole fraction of compound, j (-)
\( X_{\text{CO}_2} \) measured carbon dioxide analyser reading or mole fraction of carbon dioxide (-)
\( X_{\text{CO}} \) measured carbon monoxide analyser reading or mole fraction of CO (-)
\( \rho \) gas density in test section duct (kg/m^3)

Superscripts

\( \cdot \) per unit time (s^{-1})
\( 0 \) before ignition of the specimen

Subscripts

\( d \) test section duct
\( j \) fire product
7. References


