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Reaction to fire tests — Determination of fire parameters of materials, products and assemblies using an intermediate-scale heat release calorimeter (ICAL)

Essais de réaction au feu — Détermination, à l'aide de calorimètre à échelle intermédiaire à dégagement de chaleur (ICAL), des paramètres relatifs au feu des matériaux, produits et ouvrages

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 14696, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 1, *Reaction to fire*.

This document is being issued in the Technical Report (type 2) series of publications (according to subclause G.3.2.2 of part 1 of the ISO/IEC Directives, 1995) as a "prospective standard for provisional application" in the field of fire safety because there is an urgent need for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the ISO Central Secretariat.

A review of this Technical Report (type 2) will be carried out not later than three years after its publication with the options of: extension for another three years; conversion into an International Standard; or withdrawal.

Annexes A to D form a normative part of this Technical Report. Annexes E and F are for information only.

Reaction to fire tests — Determination of fire parameters of materials, products and assemblies using an intermediate-scale heat release calorimeter (ICAL)

1 Scope

This Technical Report provides a method for measuring the response of materials, products and assemblies exposed in vertical orientation to controlled levels of radiant heating with an external igniter.

This test method is used to determine the ignitability, heat release rates, mass loss rates, and visible smoke development of materials, products and assemblies under well ventilated conditions.

The heat release rate is determined by measurement of the oxygen consumption as determined by the oxygen concentration and flow in the exhaust product stream as specified in 11.1. Smoke development is quantified by measuring the obscuration of light by the combustion product stream.

Specimens are exposed to heating fluxes ranging from 0 kW/m^2 to 50 kW/m^2. Hot wires are used as the ignition source.

This test method has been developed for material, product or assembly evaluations, mathematical modelling and design purposes. The specimen are tested in thicknesses and configurations representative of actual end product or system uses.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this Technical Report. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this Technical Report are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 9705, *Fire tests — Full scale room test for surface products*.

ISO/IEC Guide 52:1990, *Glossary of fire terms and definitions*.

3 Terms and definitions

For the purposes of this Technical Report, the terms and definitions given in ISO/IEC Guide 52 and the following apply.

3.1
assembly
fabrication of materials or composites, for example sandwich panels

NOTE This may include an air gap.

3.2
composite
combination of materials which are generally recognized in building construction as discrete entities, for example coated or laminated materials

3.4
flashing
existence of flame on or over the surface of the specimen for periods of less than 1 s

3.5
heating flux
incident flux imposed externally from the heater on the specimen at the initiation of the test

3.6
heat release rate
heat evolved from the specimen, per unit of time and area

3.7
ignition
onset of sustained flaming as defined in 3.15

3.8
irradiance (at a point of a surface)
quotient of the radiant flux incident on an infinitesimal element of surface containing the point, by the area of that element

3.9
material
single substance or uniformly dispersed mixture, for example metal, stone, timber, concrete, mineral fibre, polymers

3.10
orientation
plane in which the exposed face of the specimen is located during testing, either vertical or horizontal facing up

3.11
oxygen consumption principle
proportional relationship between the mass of oxygen consumed during combustion and the heat released

3.12
product
material, composite or assembly about which information is required

3.13
specimen
representative piece of the product which is to be tested together with any substrate or treatment

3.14
smoke obscuration
reduction of light transmission by smoke, as measured by light attenuation

3.15
sustained flaming
existence of flame on or over most of the specimen surface for periods of over 10 s

3.16
transitory flaming
existence of flame on or over the surface of the specimen for periods of between 1 and 10 s

4 Symbols and abbreviations

A	Cross sectional area of duct (m^2)
E	Net heat released for complete combustion of propane, per unit of oxygen consumed (12,78 MJ/kg O_2)
E_{CO}	Net heat released for incomplete combustion, per unit of CO consumed
$E_{propane}$	Net heat released for complete combustion of propane, per unit of oxygen consumed (12,73 MJ/kg of O_2)
$E_{methane}$	Net heat released for complete combustion of methane, per unit of oxygen consumed (12,51 MJ/kg of O_2)
f_x	Yield of gas x (kg/kg)
$f(Re)$	Reynolds number correction
I	Transmitted beam intensity (cd)
I_0	Beam intensity before attenuation (cd)
k	Smoke extinction coefficient (m^{-1})
k_c	Velocity profile shape factor (non-dimensional)
L_p	Light path length of beam through smoky environment (m)
M_a	Molecular mass of incoming air (kg/kmol)
M_{CO}	Molecular mass of carbon monoxide (kg/kmol)
M_{CO_2}	Molecular mass of carbon dioxide (kg/kmol)
M_{dry}	Molecular mass of dry air (29 kg/kmol)
M_e	Molecular mass of exhaust gases (kg/kmol)
M_{H_2O}	Molecular mass of water (kg/kmol)
M_{N_2}	Molecular mass of nitrogen (kg/kmol)
M_{O_2}	Molecular mass of oxygen (32 kg/kmol)
m	Specimen mass (kg)
$\dot{m}_e$	Mass flow in exhaust duct (kg/s)
OD	Optical density (non-dimensional)
Δp	Pressure drop across the orifice plate or bidirectional probe (Pa)
q	Total heat released (MJ)

$\dot{q}$	Heat release rate (kW)
RSR	Rate of smoke release (m^2/s)
TSR	Total smoke released (m^2)
T_e	Combustion gas temperature at the photodetector (K)
T_s	Duct temperature (near photodetector) (K)
t	Time (s)
$\dot{V}_e$	Volumetric flow in exhaust duct (at measuring location of mass flow) (m^3/s)
$\dot{V}_s$	Volumetric flow at location of smoke meter (value adjusted for smoke measurement calculations) (m^3/s)
Δt	Sampling time interval (s)
$X_{CO,e}$	Measured mole fraction of CO in exhaust flow (non-dimensional)
$X_{CO,i}$	Measured mole fraction of CO in incoming air (non-dimensional)
$X_{CO_2,e}$	Measured mole fraction of CO_2 in exhaust flow (non-dimensional)
$X_{CO_2,i}$	Measured mole fraction of CO_2 in incoming air (non-dimensional)
$X_{O_2,e}$	Measured mole fraction of O_2 in exhaust flow (non-dimensional)
$X_{O_2,i}$	Measured mole fraction of O_2 in incoming air (non-dimensional)
$[x]$	Concentration of gas x (kg/kg)
α	Combustion expansion factor (non-dimensional; normally a value of 1,105)
ρ	Density of air at the temperature in exhaust duct (kg/m^3)
ρ_0	Density of air at 273,15 K: 1,293 (kg/m^3)
ϕ	Oxygen depletion factor (non-dimensional)

5 Principle

5.1 This test method is designed to measure the heat release rate from a 1 m^2 specimen in a vertical orientation. The specimen is exposed to a uniform heat flux from a gas fired radiant panel up to 50 kW/m^2 and uses electrically heated wires for ignition. Heat release measured by this test method is based on the observation that, generally, the net heat of combustion is directly related to the amount of oxygen required for combustion (see references [2,3]). The primary measurements are oxygen concentrations and exhaust flow. Burning may be either with or without ignition wires used at the top and bottom of the specimen.

5.2 Additional measurements include the mass loss rate of the specimen, the time to sustained flaming and the light intensity of a light beam having traversed the smoky duct. The apparatus can be used to measure additional properties discussed in informative Annex F.

6 Apparatus

Where dimensions are stated in the following description, they shall be considered mandatory and shall be followed within nominal tolerance of ± 5 mm on the radiant panel and specimen holder assemblies. An exception to this tolerance is the placement of the screen in front of the ceramic burner and which shall be ± 0,5 mm. The tolerances permitted in the exhaust system of ISO 9705 [9] are permissible.

The apparatus shall consist of the following components:

— a radiant panel assembly (Figure 1) located in the vertical orientation;

— a specimen holder (Figure 2);

— an exhaust collection system,

— weighing platform,

— gas laminar flow meter, and

— a data acquisition system.

A general layout of the whole test assembly is shown in Figure 3.

6.1 Radiant panels

The panel consists of a hollow 50 mm by 50 mm square steel tubing which supports 3 rows of adjustable, ceramic-faced, natural gas burners[1)] comprised of three burners per row (Figure 1). The tubing has typical residential water hose connections provided at the bottom of the tubing to facilitate water cooling.

The left and right burners in each row are made up of four modules each and the centre burners are comprised of one module. A module consists of 4 vertically stacked ceramic elements 12,7 mm deep by 95 mm high by 158 mm wide. The centre burners consist of one module each. The modules are comprised of a plenum space in which the natural gas is injected at a controlled rate by the burner's control system. Combustion air is aspirated into the plenum space through the gas and air injection port.

The face of each burner is covered with stainless steel cloth type floating screen (mesh per linear 25,4 mm – 4 x 4, wire diameter 1,19 mm, width opening 5,16 mm) for higher surface temperature and safety. The screens shall be carefully installed to allow for elongation of screens and supporting rods. This will allow the distance between the burners and screens to remain constant when heated. The optimum distance between the surface of the burners and the outer surface of the screen is 20 mm. The rows of gas burners on the panel shall be separated by a distance of 93 mm from each other and also attached to the support tubing at the locations indicated in Figure 1.

Natural gas of net heating value at least 49 MJ/kg shall be supplied to the unit through a control system provided with a safety interlock. All gas pipe connections to the burners must be sealed with a gas pipe compound resistant to liquified petroleum gases. A drip leg shall be installed in the gas supply line going to each heater to minimize the possibility of any loose scale or dirt within the gas supply line from entering the burner's control system.

Ignition of the burners shall be accomplished by individual, automatic spark igniters and pilot flames. The spark igniters are used to ignite the pilot flames which in turn are used to ignite the burners after pilot flame temperature sensors have reached a required value. The pilot remains on until the burners are extinguished.

An opening of at least 25 mm shall be provided at the vertical centreline between the rows of burners.

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1) A modified RAY-TEC burner unit, RT132, from Modine Manufacturing company, 1500 Dekoven Avenue, Racine, Wisconsin 53403, USA, has been found suitable for this application.

6.2 Radiant panel constant irradiance controller

The irradiance from the radiant panel assembly shall be capable of being held at a preset level by means of regulating the flow of natural gas to the burners (see annex E.2 for more information). The flow of the gas is regulated using an automatic flow controller, motorized valve and a thermocouple located on the surface of a ceramic burner. The irradiance is directly proportional to the temperature on the surface of the ceramic burners. Gas flow shall be continuously measured to calculate the heat released from the radiant panel assembly. This value is needed in computations of the heat release rate from the specimen.

6.3 Specimen holder assembly components

6.3.1 Specimen holder

The specimen holder assembly is shown in Figure 2 and is capable of holding a specimen up to 150 mm thick. (A thicker specimen holder is necessary to accomodate specimens thicker than 150 mm.) The top portion of the assembly is removable to facilitate specimen insertion. Prior to starting the test the specimen shall be protected from the radiant panel heat flux exposure by the water cooled shield (6.4). A drip tray, 300 mm wide x 50 mm deep x 914 mm long, shall be attached to the floor of the specimen holder directly below the specimen frame to contain limited amounts of materials that melt and drip. Two wire igniters described in 6.5 are attached to the specimen holder. A gas stream blocking plate (6.6) is mounted at the bottom of the specimen.

6.3.2 Weighing platform

The general arrangement of the specimen holder and the weighing platform is indicated in Figure 2. The weighing platform[2)] shall be capable of weighing the specimen to an accuracy of 1 g. The platform shall be protected from the radiant panel assembly by an insulation board cover as shown in Figure 2.

6.3.3 Specimen holder trolley

A trolley, as shown in Figure 3, shall be provided to hold the specimen holder and weighing platform so that the specimen can be moved to a predetermined location in front of the radiant panel at the beginning of a test. The trolley shall be placed on tracks or guides to facilitate exact specimen placement with respect to the radiant panel. The trolley tracks shall be located perpendicular to the plane of the radiant panel so that the specimen is moved directly toward the radiant panel. The specimen is inserted in the holder when the trolley is at a sufficient distance from the radiant panel. The trolley tracks shall be long enough to move the specimen holder to a distance of 6 m from the radiant panel if necessary.

6.4 Specimen shield

A water cooled shield (Figure 4) shall be provided to absorb the thermal energy from the radiant panels prior to testing. The shield is constructed so that a preset water flow will maintain a shield temperature on the unexposed face below 100 °C. The shield shall be positioned directly in front of the radiant panel assembly at a distance of 150 mm. The mounting method used shall accommodate removing the shield in less than 2 s.

6.5 Wire igniters

Two 0,81 mm Chromel wires (from Type K thermocouple wires) are used as igniters. One wire is positioned horizontally, spanning the full width of the specimen, 80 mm above the bottom exposed edge of the specimen and 15 mm from the specimen surface. The other wire is positioned horizontally, spanning the full width of the specimen, 20 mm above the top exposed edge of the specimen and 15 mm from the specimen's vertical plane. A spring, protected from the radiant heat, shall be attached to one end of the wires to compensate for the wire expansion during the test. It shall remain under tension throughout the test so that the igniter wire remains in position. When used, sufficient electrical power shall be applied to the wire that will produce an orange glow. Low voltages, up to 30 V, shall be used for safety reasons. More information about the choice of the wire igniters is given in annex E.3.

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2) A Sartorius Model F150S Electromagnetic Scale, has been found suitable for this application.

6.6 Gas stream blocking plate

A thin steel plate which projects 10 cm out from the specimen surface shall be attached to the specimen holder perpendicularly to the specimen surface along the lower exposed specimen edge. Information about the gas stream interrupting projection plate is given in annex E.5.

6.7 Heat flux meter

The total heat flux meter shall be of the Schmidt-Boelter (thermopile) type, with a design range of about 50 kW/m^2. The target receiving radiation, and possibly to a small extent convection, shall be flat, circular, approximately 12,5 mm in diameter, and coated with a durable matt-black finish. The target shall be water cooled. Radiation shall not pass through any window before reaching the target. The instrument shall be robust, simple to set up and use, and stable in calibration. The instrument shall have an accuracy of within ±3% and a repeatability of within ±0,5 %.

6.8 Heat flux calibration panel

A panel to establish the heat flux/distance relationship shall be constructed from nominal 12 mm to 13 mm thick calcium silicate board of nominal density 600 kg/m^3 to 850 kg/m^3. The panel shall be the same size as a specimen (1000 x 1000 mm) and shall have holes with diameters to accomodate the heat flux meter (6.7). Five rows and columns of holes (25 holes total) shall be drilled with their centres 224 mm apart and 52 mm from the edges on all sides of the panel.

6.9 Exhaust collection system

Construct the exhaust collection system with the following minimal requirements: a blower, steel hood, duct, bidirectional probe, thermocouple(s), oxygen measurement system, smoke obscuration measurement system (white light lamp and photocell/detector or laser) and combustion gas sampling and analysis system. Construct the exhaust collection system as shown in Figure 5 and as explained in annex A.1.

Ensure that the system for collecting the smoke (which includes gaseous combustion products) has sufficient exhaust capacity and is designed in such a way that all of the combustion products leaving the burning specimen are collected. Design the capacity of the evacuation system such that it will exhaust minimally all combustion gases leaving the specimen (see annex A.1).

Place probes for sampling of combustion gas and for measurement of flow in accordance with clause 7.

Make all measurements of smoke obscuration, gas concentrations or flows at a position in the exhaust duct where the exhaust is uniformly mixed so that there is a nearly uniform velocity across the duct section.

If the straight section before the measuring system is at least 8 times the inside diameter of the duct the exhaust is considered to be uniformly mixed. If a measuring system is positioned at a distance of less than 8 diameters, demonstrate the achievement of equivalent results.

7 Minimum requirements for exhaust duct instrumentation

NOTE Additional information is found in annex B.

7.1 Flow

Measure the flow in the exhaust duct by means of a bidirectional probe [12] or an equivalent measuring system with an accuracy of at least ± 6% (see annex B for further details). The response time to a stepwise change of the duct flow shall not exceed 5 s, to reach 90 % of the final value.

7.2 Combustion gas analysis

7.2.1 Sampling line

Construct the sampling line tubes of a material not influencing the concentration of the combustion gas species to be analysed. The following sequence of the gas train has been shown to be acceptable: sampling probe, soot filter, cold trap, gas stream pump, vent valve, plastic drying column and carbon dioxide removal columns (if used), flow controller and oxygen analyser (see Figure 6 and annex B for further details). Alternative designs of the sampling line must give equivalent results. The gas train shall also include appropriate spanning and zeroing facilities.

7.2.2 Oxygen measurement

Measure the oxygen concentration with an accuracy of at least ± 0,04% of full scale in the output range of 0 to 25 vol % oxygen, or ±0,01 vol % oxygen, in order to have adequate measurements of heat release rate. Take the combustion gas sample from the end of the sampling line. Calculate the time delay, including the time constant of the instrument; it is a function of the exhaust duct flow. This time delay shall not exceed 60 s (see annex B for further details).

7.2.3 Carbon monoxide and carbon dioxide measurement

Measure the combustion gas species with an instrument having an accuracy of at least ± 0,1 vol % for the carbon dioxide and ± 0,02 vol % for carbon monoxide. A suitable output range is 0 to 1 vol % for carbon monoxide and 0 to 6 vol % for carbon dioxide. Take the combustion gas sample from the end of the sampling line. Calculate the time delay, including the time constant of the instrument; it is a function of the exhaust duct flow. It shall be a maximum of 60 s (see annex B for further details).

7.2.4 Smoke obscuration measurement

Install an optical system for measurement of light obscuration across the centreline of the exhaust duct. Determine the optical density of the smoke by measuring the light transmitted with a photometer system consisting of a white light source and a photocell/detector or a laser system for measurement of light obscuration across the centreline of the exhaust duct.

One photometer system found suitable consists of a lamp, lenses, an aperture and a photocell. See Figure 7 and annex B for further details. Construct the system so that soot deposits on the optics during a test do not reduce the light transmission by more than 5 %.

Alternatively, instrumentation constructed using a 0,5 mW to 2,0 mW helium-neon laser, instead of a white light system is also acceptable. See Figure 8 and annex B.4 for further details. It has been shown that white light and laser systems will give similar results [17].

8 Significance and use

8.1 This test method is used primarily to determine the heat release rate of materials, products and assemblies. Other parameters determined are mass loss rate, the time to ignition, and smoke and gas production. These properties are determined on a sample which may be an assembly of materials or products that are tested in their end-use thickness. Therefore, the heat release rate of a wall assembly, for instance, can be determined.

8.2 Representative joints and other characteristics of an assembly shall be included in a specimen when these details are part of the normal design.

8.3 This test method is applicable to end-use products not having an ideally planar external surface. The radiant flux field shall be adjusted to be that which is desired at the average distance of the surface from the radiant panel.

9 Test specimens

9.1 Size and preparation

9.1 Test specimen's dimensions shall be 1 000 by 1 000 mm and up to 150 mm in thickness[3]. They shall be representative of the construction of the end-use product. Materials and assemblies of normal thickness 150 mm or less shall be tested using their full thickness.

9.2 If a product is designed to normally have joints in a field application, then that specimen shall incorporate the joint detail. The joint shall be centred in the specimen's vertical or horizontal centreline as appropriate. The specimen shall also be tested without a joint detail if the design does not include a joint.

9.3 The edges of the specimen shall be covered with 12 mm ceramic wool blanket to eliminate the gap between the holder and the specimen.

9.2 Conditioning

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

NOTE Constant mass is considered to be reached when two successive weighing operations, carried out at an interval of 24 h, do not differ by more than 0,1 % of the mass of the test piece or 1 g, whichever is the greater.

10 Calibration of apparatus

Calibrate all instruments carefully with standard sources after initial installation. Among the instruments to be calibrated are load cells or weighing platforms, smoke meters, flow or velocity transducers and gas analysers.

10.1 Heat flux/distance relationship

10.1.1 Ignite the radiant panel and allow it to come to equilibrium as indicated by its constant heat release rate.

10.1.2 A curve of average flux measurements over the specimen surface versus specimen distance from the radiant panels shall be generated. The calibration panel shall be placed in the same position as a specimen and the flux meter inserted from the unexposed face through the holes. The target face of the flux meter shall extend 15 mm toward the radiant panel from the exposed surface of the calibration panel to minimize the convective heat transfer contribution. After the calibration panel has come to equilibrium, the flux measurements shall be made with the target face of the flux meter at the following distances, in millimetres, away from the radiant panel: 300, 400, 600, 800, 1 000, 2 000, 3 000, 4 000, 5 000 and 6 000.

10.1.3 No individual flux measurement shall deviate from the average at each of the distances by more than ±5 %.

10.1.4 The curve generated in 10.1.2 shall be used to determine the distance from the radiant panel for a desired radiant heat flux exposure.

10.1.5 Calibration shall be performed every three months or more frequently if any significant changes to equipment are made or if calibration is suspect.

10.2 Heat release

10.2.1 Perform the calibration of the heat release instrumentation in the exhaust duct by burning propane or methane gas and comparing the heat release rates calculated from the metered gas input, and those calculated from the measured oxygen consumption. The value of net heat of combustion for propane is 46,5 MJ/kg and for methane 50 MJ/kg . Position the calibration burner in the same location where the specimen is to be placed during a 35 kW/m^2 exposure test. Measure the gas flow at a pressure of 101 kPa $\pm$ 5 kPa (standard atmospheric pressure, measured at the flow gauge) and a temperature of 20 °C $\pm$ 5 °C.

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[3] If specimens of thickness greater than 150 mm are to be tested, a suitable specimen holder needs to be constructed.

10.2.2 The calibration source for the test shall be a gas burner with a nominal 0,3 m by 0,3 m porous top surface of a refractory material. The top surface of the burner through which the gas is supplied shall be located horizontally, 0,3 m off the floor. The burner shall be supplied with natural grade propane (95 % purity) or methane (98 % purity). The gas for the burner flame shall not be premixed with air. The gas flow to the burner shall be measured with an accuracy of at least ±3 %. The heat output to the burner shall be kept constant and controlled within ±5 % of the prescribed value.

The burner may be ignited by a pilot burner or a remotely controlled spark igniter. Burner controls shall be provided for automatic shut-off of the gas supply if flameout occurs.

NOTE A burner may be constructed with a 25 mm thick porous ceramic-fiber board over a 152 mm plenum; or alternatively a minimum 100 mm layer of sand can be used to provide the horizontal surface through which the gas is supplied. The sand burner may be preferable for economic reasons. This type of burner is shown in Figure 10.

10.2.3 Another suitable calibration burner is a pipe, with an inner diameter of 100 mm $\pm$ 1,5 mm, supplied with gas from beneath as described in ISO 9705 [9]. The gas for the burner flame shall not be premixed with air.

10.2.4 Obtain a minimum of two calibration points. Obtain a lower heat release rate value of 250 kW and a higher heat release rate of 600 kW.

10.2.5 Take measurements at least once every 6 s and start 1 min prior to ignition of the burner. Determine the average heat release rate over a period of at least one minute by (a) the oxygen consumption method and (b) calculating the heat release rate from the gas mass flow and the net heat of combustion. A correct factor of heat released per oxygen consumed for the calibration gas ($E_{propane}$=12,78 MJ per kg O_2; $E_{methane}$=12,51 MJ per kg O_2) must be used in the oxygen consumption method (equation D.4). The difference between the two values shall not exceed 5 %. This comparison shall be made only after steady state conditions have been reached.

10.2.6 Calibration shall be performed every three months or more frequently if any significant changes to equipment are made or if calibration is suspect.

10.2.7 When calibrating a new system, or when modifications are introduced, check the response time of the measuring system by the following test sequence:

Time	Burner output
0 min to 5 min	0 kW
5 min to 10 min	250 kW
10 min to 15 min	600 kW
20 min to 25 min	0 kW

The response of the system to a stepwise change of the heat output from the burner shall be a maximum of 12 s to 90 % of final value.

10.2.8 Perform the calibration described in 10.2.4, 10.2.5 and the calibration described in 10.2.7 at a duct air flow corresponding to oxygen concentration between 20,2 % and 20,4% with the radiant panel in operation only.

10.2.9 The change in measured heat release rate, comparing time average values over 1 min, shall not be more than 10 % of the actual heat output from the burner.

10.3 Mass loss

Perform the calibration by loading the weighing platform with known masses corresponding to the measuring range of interest, to ensure that the requirements of accuracy in 6.3.2 are fulfilled. Carry out this calibration daily, prior to testing.

10.4 Smoke obscuration

Calibrate the smoke meter initially to read correctly for two neutral density filters of significantly different values, and also at 100 % transmission. The use of neutral density filters at 0,5 and 1,0 values of optical density has been shown to be satisfactory for this calibration. Once this calibration is set, only the zero value of extinction coefficient (100 % transmission) needs to be verified each day, prior to testing. Investigate any excessive departure from the zero line at the end of a test, and correct it.

10.5 Gas analysis

Calibrate gas analysers daily, prior to testing (see ASTM E800 standard guide for further guidance).

10.6 Heat flux meter

The calibration of the heat flux meter shall be checked whenever a recalibration of the apparatus is carried out by comparison with an instrument (of the same type as the working heat flux meter and of similar range) held as a reference standard and not used for any other purpose. The reference standard shall be fully calibrated at a standardizing laboratory at yearly intervals.

11 Procedure

11.1 Preparation

11.1.1 Open the water valve to the steel tubing which supports the radiant panel and adjust the water flow to the flow previously determined to be sufficiently high that water exiting the frame will not exceed 50 °C temperature.

11.1.2 Position the specimen holder assembly remote to the desired test location.

11.1.3 Place the water cooled shield in front of the radiant panel assembly and adjust the water flow to the flow previously determined to be sufficiently high that water exiting the shield will not exceed 50 °C temperature.

11.1.4 Establish a duct air flow previously determined to correspond to oxygen concentration between 20,2 % and 20,4 % with the radiant panel in operation only.

11.1.5 Turn on the flow of gas to each of the radiant panels and ignite them.

11.1.6 Allow the burners to operate for 30 min prior to testing.

11.1.7 Adjust, if necessary, the water flows from 11.1.1 and 11.1.3, and the duct flow from 11.1.4 to the required values.

11.1.8 Turn on all sampling and recording devices and calibrate the analysers.

11.1.9 Insert the specimen into the specimen holder. The specimen shall be placed in the specimen holder by removing the top specimen holder cap section, inserting the specimen and replacing the top cap.

11.1.10 Switch on the wire igniters.

11.2 Procedure

11.2.1 Move the specimen trolley to the location necessary for the desired flux exposure.

11.2.2 Collect baseline data for 2 min after the signal from the weighing platform settles down to equilibrium.

11.2.3 Remove the water cooled specimen shield in not more than 2 s and start the timer marking the beginning of the test.

11.2.4 Record the times when flashing or transitory flaming occur. When sustained flaming occurs, record the time and turn off the igniters. If the flame extinguishes after turning off the igniters, turn on the igniters again within 5 s and do not turn the igniters off until the entire test is completed. Report these events in the test report.

11.2.5 If the duct flow is not sufficient to collect all the fire gases, then the duct flow shall be increased.

11.2.6 Record all important events during the test like cracking, melting, collapse of all or part of the specimen, deformations and intumescing.

11.2.7 Collect data until 2 min after sustained flaming occurs on the unexposed side of the specimen or a predetermined time period.

11.2.8 Unless otherwise specified in the material or performance standard make three determinations and report as specified in clause 13.

12 Calculations

The specimen heat release rate is calculated by subtracting the radiant panel assembly heat release rate (baseline) from the total heat release rate. The radiant panel heat release rate contribution measured by the natural gas flow rate shall be multiplied by a factor of 1,05, to take into account the correct factor of heat released per oxygen consumed for natural gas ($E_{methane}$=12,51).

Considerations for heat release measurements are presented in annex C. Calculate heat release data, using the equations presented in annexes D.1 and D.2. The testing laboratory shall choose one of the equations in annex D.1 to calculate heat release, based on the gas analysers installed.

Calculate mass loss rate using the procedures in annex D.4.

Calculate smoke release data using the equations in annex D.3.

The exposed surface area of the specimen is 0,84 m^2. Use 0,84 m^2 to calculate parameters per unit surface area.

13 Test report

Include the following information in the test report:

13.1 Descriptive information

a) Name and address of the testing laboratory.

b) Specimen identification code or number.

c) Date and identification number of the report.

d) Name and address of the test sponsor.

e) Name of product manufacturer or supplier, if known.

f) Composition or generic identification.

g) Density, or mass per unit surface area, total mass, thickness of the main components in the specimen, thickness of the specimen, moisture content of materials if appropriate and mass of combustible portion of specimen, if known.

h) Description of the specimen, if different from the product.

i) Details of specimen preparation by the testing laboratory.

j) Details of special mounting methods used.

k) Heating flux and exhaust system flow.

l) Type of gas used for radiant panel.

m) Number of replicates tested under the same conditions. (This shall be a minimum of three except for exploratory testing.)

n) Conditioning of the specimens.

o) Date of test.

p) Test number and any special remarks.

13.2 Test results (see also annex F)

Table of numerical results containing:

a) Time to sustained flaming (s)

b) Peak heat release rate (kW), and the time at which it occurred (s)

c) Average heat release rate values for the first 60 s, 180 s, 300 s after ignition, or for other appropriate periods (kW)

d) Total heat released (MJ)

e) Peak rate of smoke release (m^2/s), and the time at which it occurred

f) Average rate of smoke release values for the first 60 s, 180 s, 300 s after ignition, or for other appropriate periods (m^2/s)

g) Total smoke released (m^2)

h) Total mass loss (kg)

i) Percentage of mass loss (%)

j) Equation used to calculate heat release rate

k) Average yield of carbon monoxide (kg CO/kg fuel) (optional)

13.3 Graphical results

a) Plot of heat release rate vs. time

b) Plot of rate of smoke release vs. time (optional)

c) Plot of mass loss vs. time (optional)

d) Plot of mass loss rate vs. time (optional)

e) Plots of the duct temperature vs. time (optional)

f) Plot of mass flow in the exhaust duct vs. time (optional)

g) Plot the heat release rate vs. time from the radiant panel (baseline) (optional)

13.4 Descriptive results

a) Photographs or videotape of the fire development.

b) All available information requested in 11.2.6.

14 Test limitations

The test data may have limited validity if any of the following occur:

a) The specimen melts sufficiently to overflow the drip tray.

b) Explosive spalling occurs.

15 Hazards

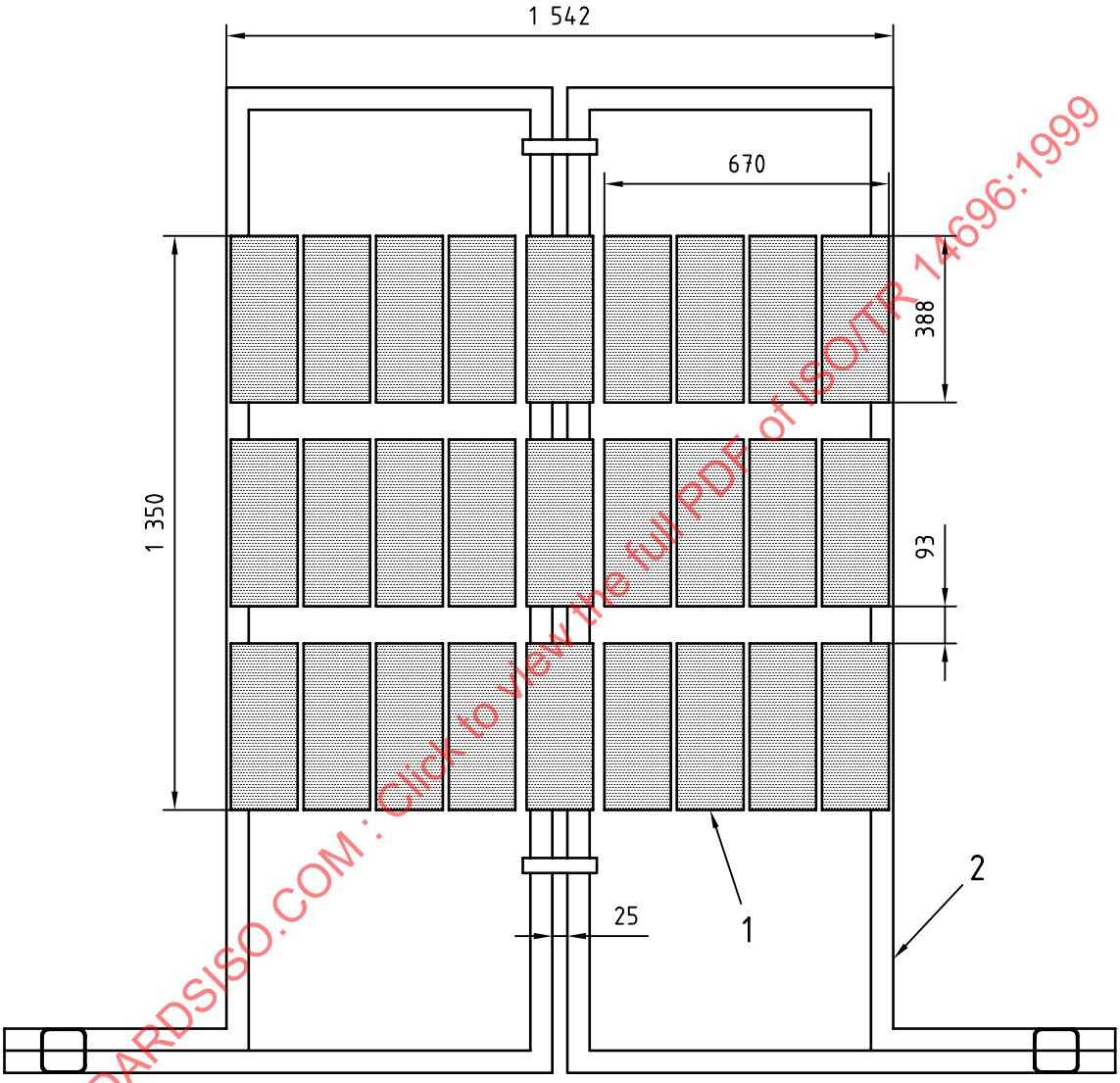
The test procedures involve high temperatures and combustion processes. Therefore hazards may exist for burns, ignition of extraneous objects or clothing and for inhalation of combustion products. The operator shall use protective gloves and clothes while removing the specimen shield and while moving the specimen trolley toward or away from the radiant panels. The construction of a viewing wall with windows is recommended for laboratories with small spaces where the operator and viewers cannot move far enough away from the area of the radiant panel.

The water cooled shield placed in front of the radiant panel assembly dramatically lowers the heating of the laboratory space. Additionally, it lowers the potential for harm to operators working in the area.

16 Precision and bias

The task group is actively pursuing the development of data regarding the precision and bias of this test method. Results from an ICAL study [18] including some repeatability data are available.

Dimensions in millimetres

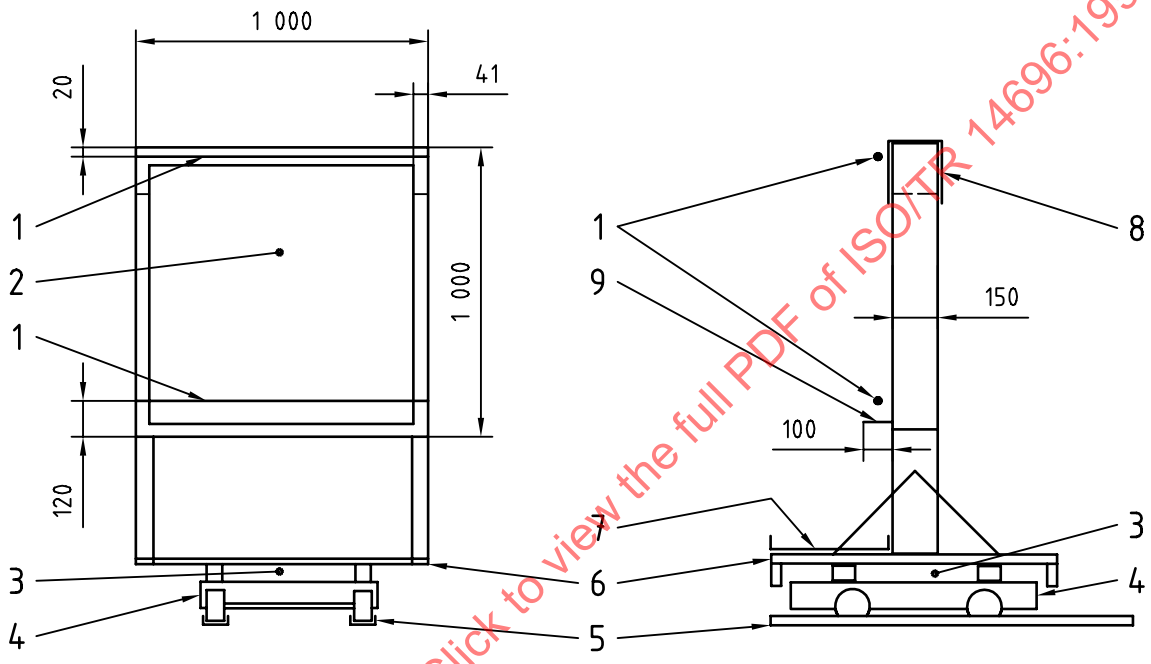


Key

1 Radiant heaters
2 Water-cooled steel frame

Figure 1 — Radiant panel assembly

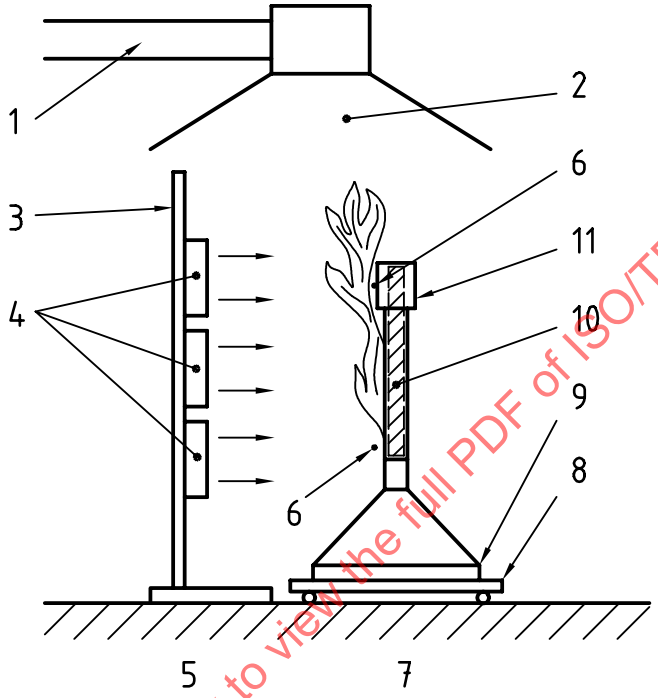
Dimensions in millimetres



Key

1 Wire igniters
2 Exposed surface
3 Air space
4 Scale
5 Wheels and tracks
6 Calcium silicate heat shield
7 Drip tray
8 Removable top cap
9 Gas stream interrupting projection plate

Figure 2 — Specimen holder

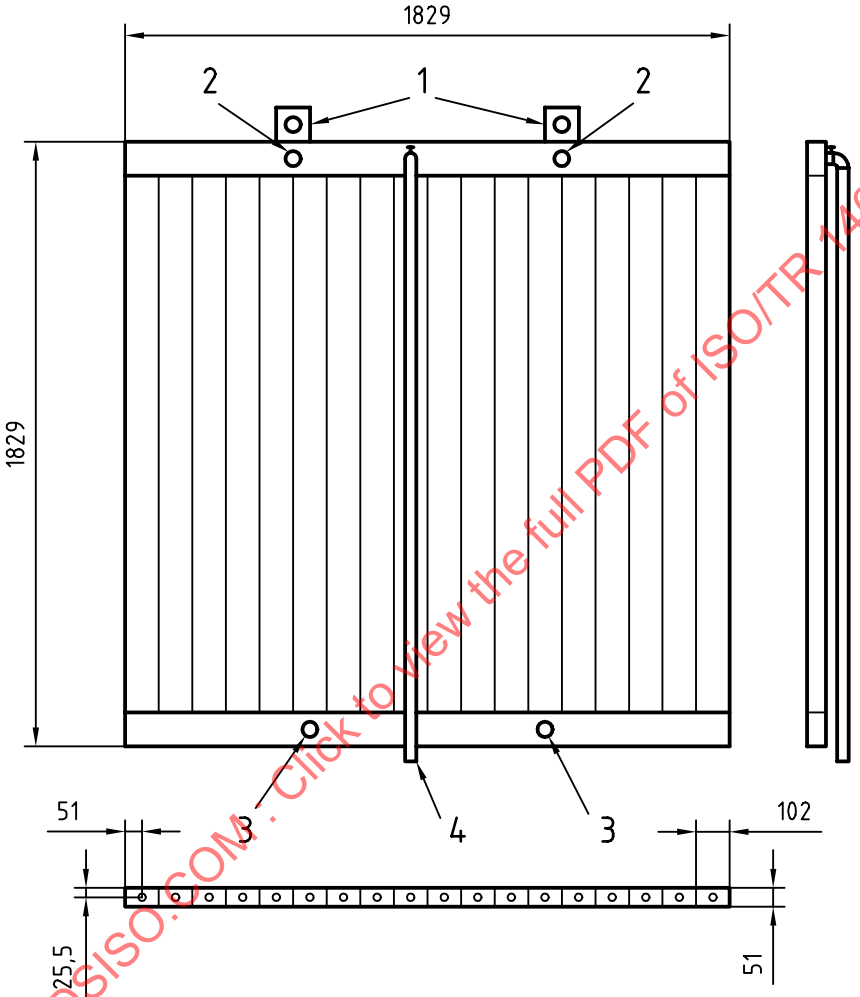


Key

1 Gas sampling port
2 Collection hood
3 Water-cooled supporting frame
4 Radiant heat units
5 Radiant panel
6 Wire igniter
7 Specimen holder
8 Trolley
9 Weighing platform
10 Specimen
11 Top cap of sampler holder

Figure 3 — Intermediate-scale calorimeter

Dimensions in millimetres

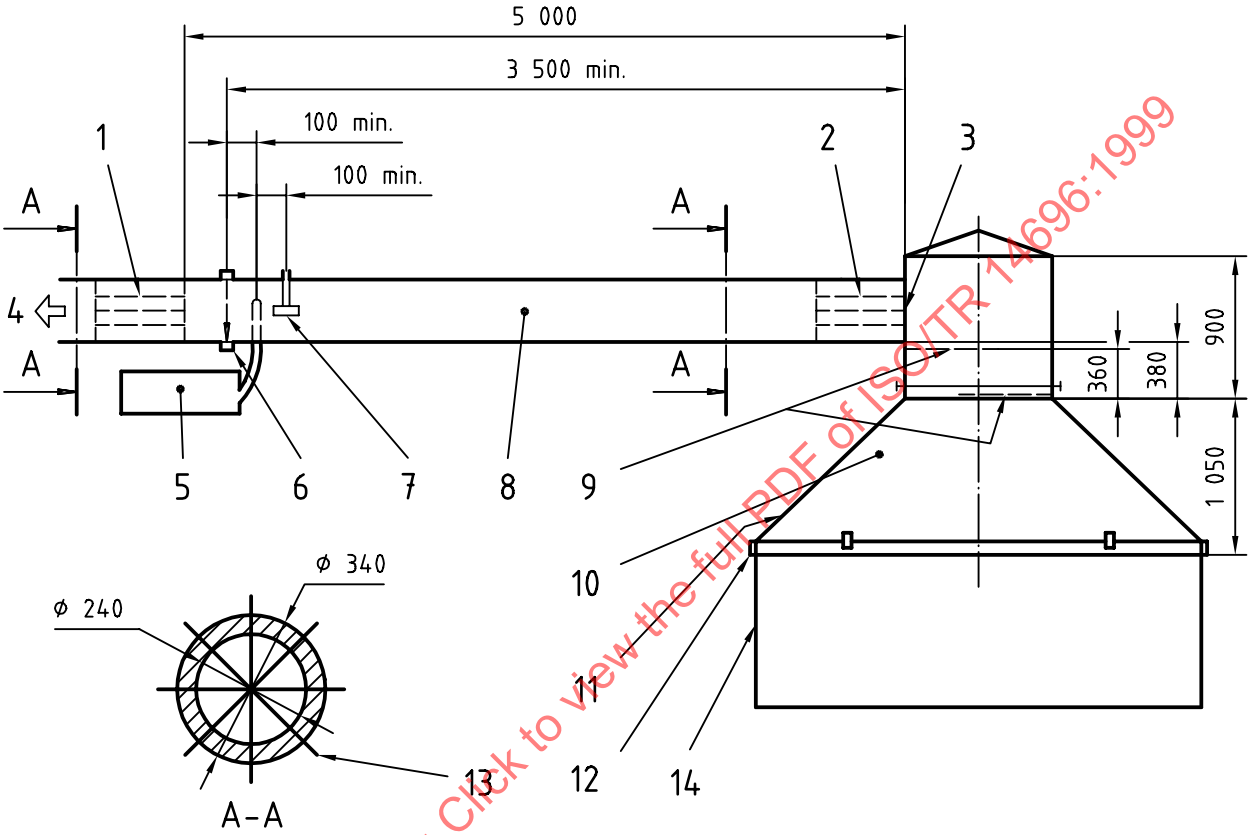


Key

1 Support trolley attachment points
2 Water outlet
3 Water inlet
4 Emergency vent line

Figure 4 — Heat shield

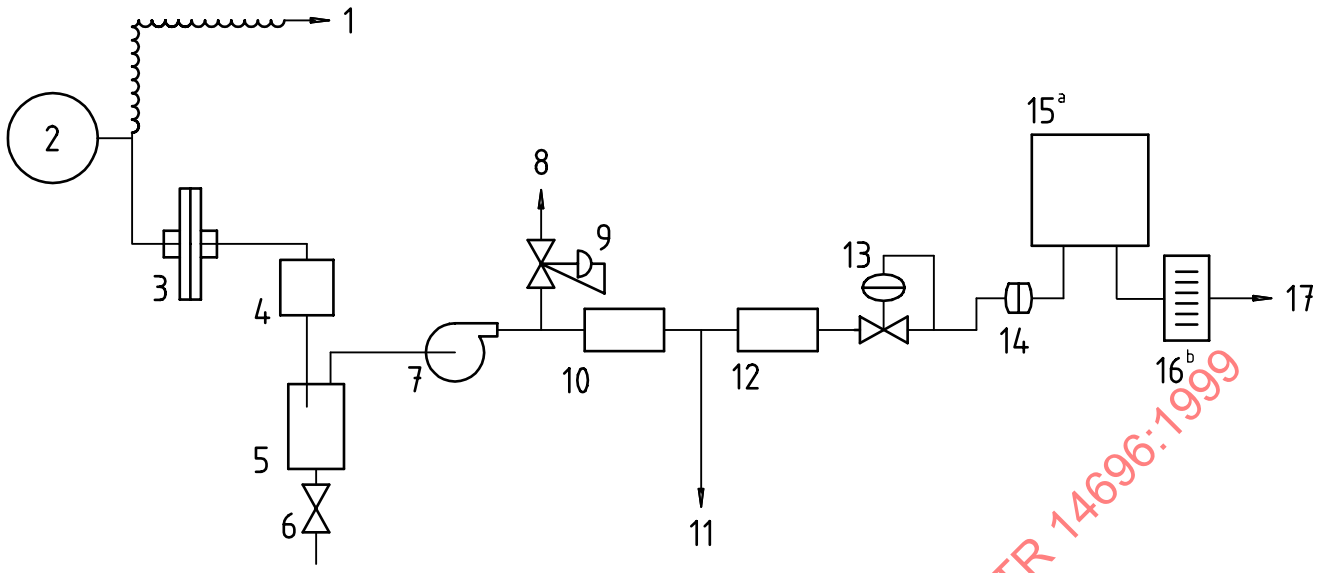
Dimensions in millimetres



Key

1 Guide
2 Guide vanes
3 Opening, Ø 400 mm
4 To exhaust
5 Gas analysis
6 Lamp, photocell system
7 Bidirectional probe
8 Exhaust duct
9 Steel plates, 2 mm x 500 mm x 900 mm
10 Hood of 2 mm thick steel plates
11 Opening, 3 100 mm x 2 400 mm
12 Steel frame of profile 50 mm x 100 mm x 3,2 mm
13 4 steel plates, 395 mm x 400 mm
14 Steel plates (optional), 1 000 mm x 2 400 mm

Figure 5 — Collection hood and exhaust

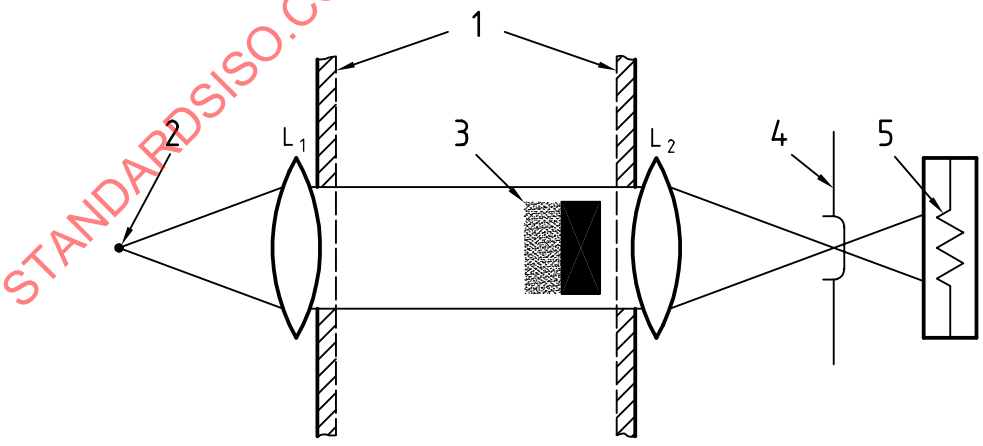


Key

1 Gas sampling probe
2 Exhaust duct
3 Soot filter
4 Cold trap
5 Separation chamber
6 Drain
7 Pump
8 Waste
9 Waste regulator
10 Desiccant
11 To optional CO_2 and CO analysers
12 CO_2 removal media
13 Flow controller
14 Filter, 7µm
15 Oxygen analyser
16 Rotameter

[a] Includes absolute pressure transducer.
[b] Rotameter is attached to outlet of oxygen analyser.

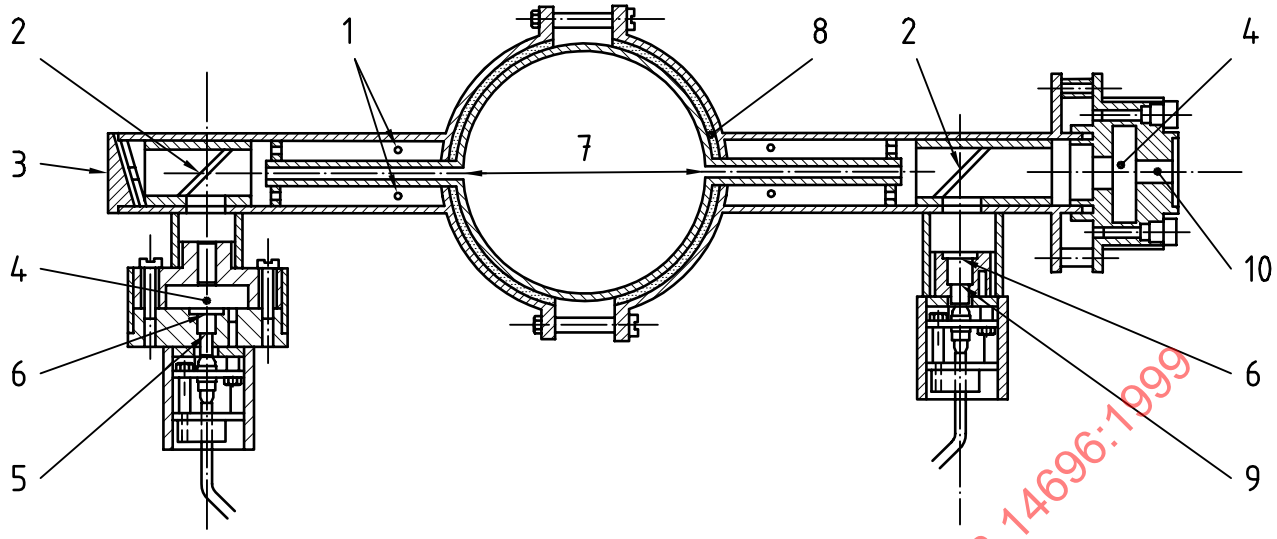
Figure 6 — Schematic of gas sampling train



Key

1 Walls of exhaust duct
2 Lamp
3 Smoke particles
4 Aperture
5 Detector

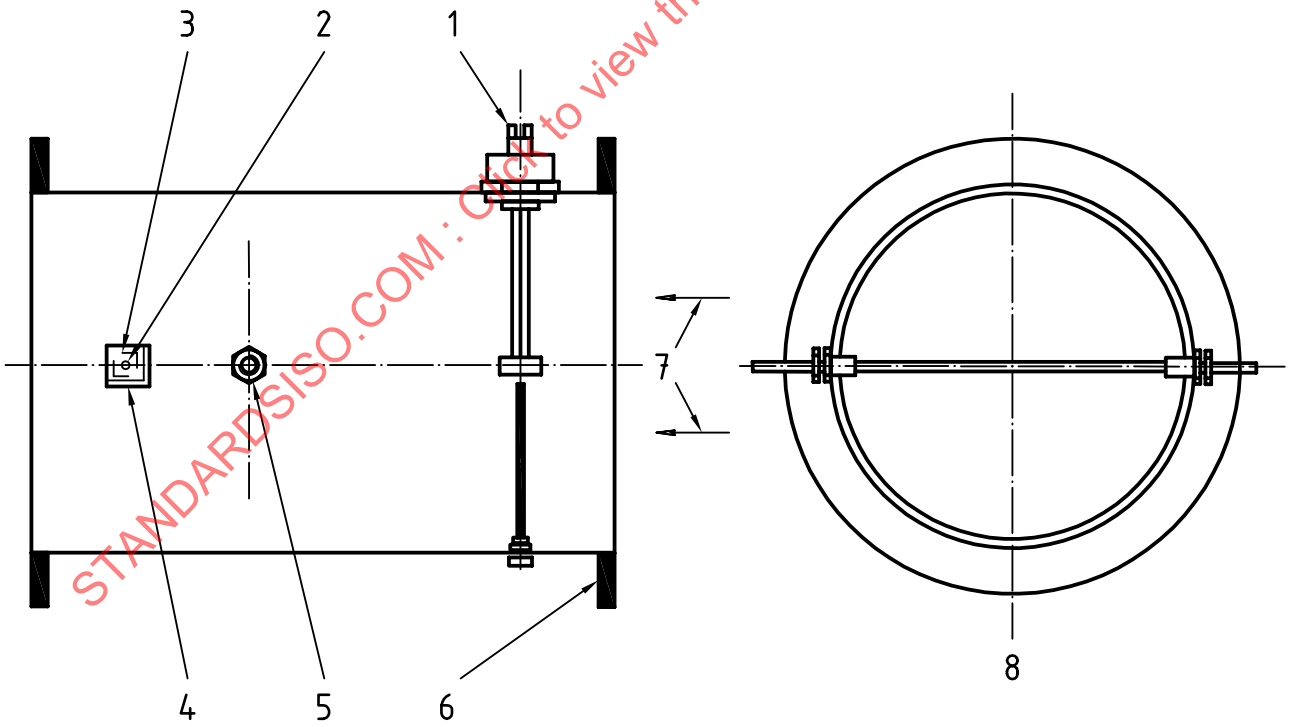
Figure 7 — White light optical system



Key

1 Purge air orifices
2 Beam splitter
3 Cap
4 Filter slot
5 Main detector
6 Opal glass
7 Optical path
8 Ceramic fibre packing
9 Compensation detector
10 0,5 mW helium-neon laser

Figure 8 — Smoke obscuration measuring system

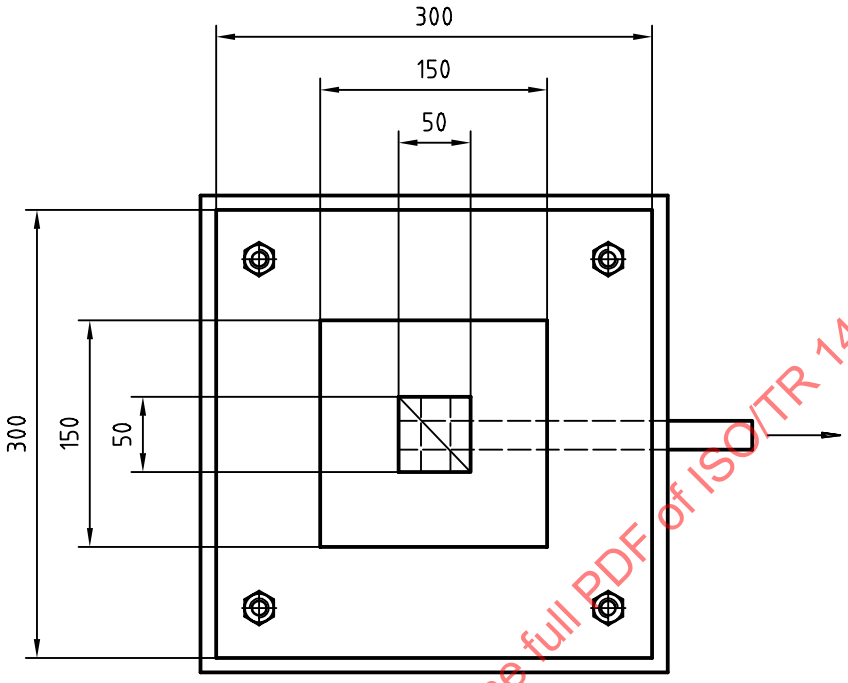


Key

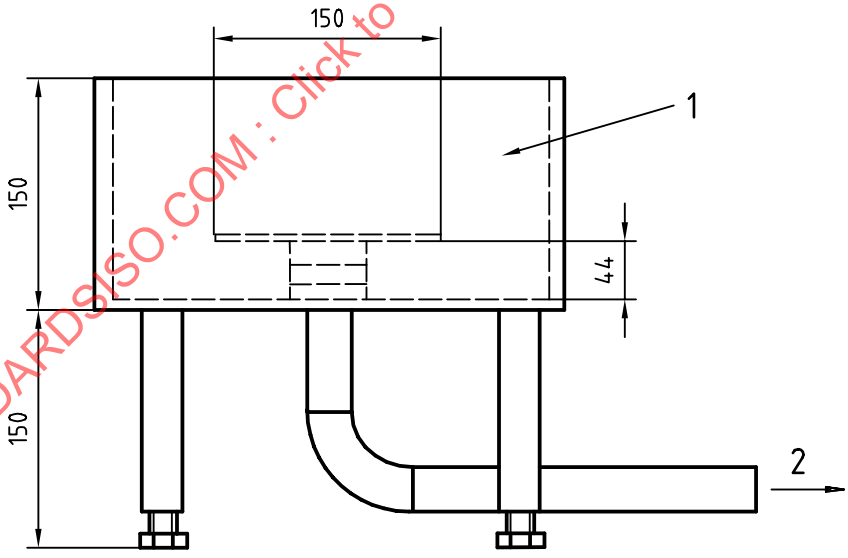
1 Bidirectional probe
2 Laser extinction beam
3 Laser optics
4 Laser source
5 Gas sampling probe
6 Flow thermocouple
7 Flow direction
8 View of gas sampling probe (holes downstream to reduce clogging)

Figure 9 — Laser beam and other instrumentation in exhaust duct

Dimensions in millimetres



NOTE Shown without sand.



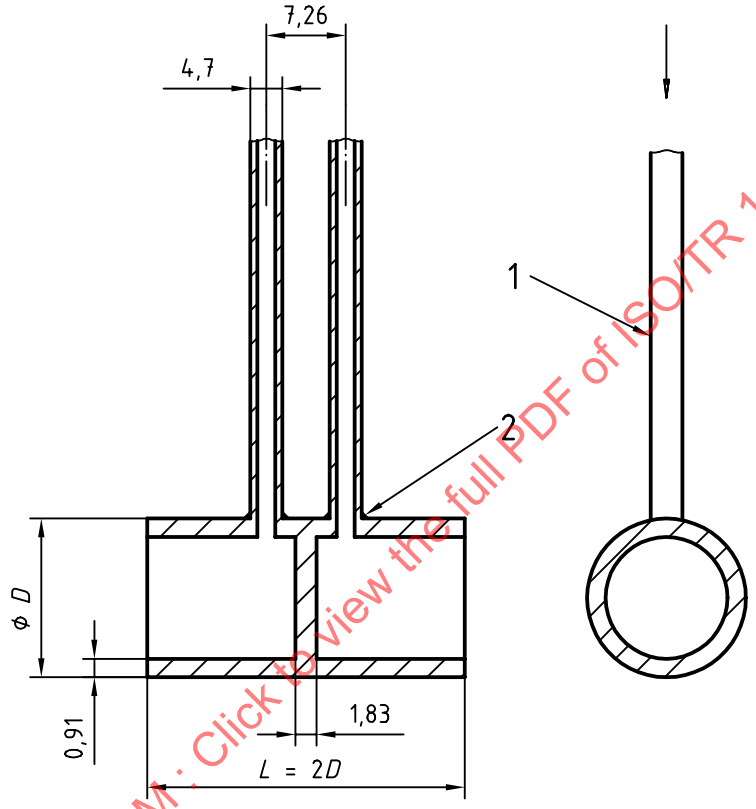
Key

1 Space filled with silica sand

2 Propane fuel

Figure 10 — Sand burner

Dimensions in millimetres

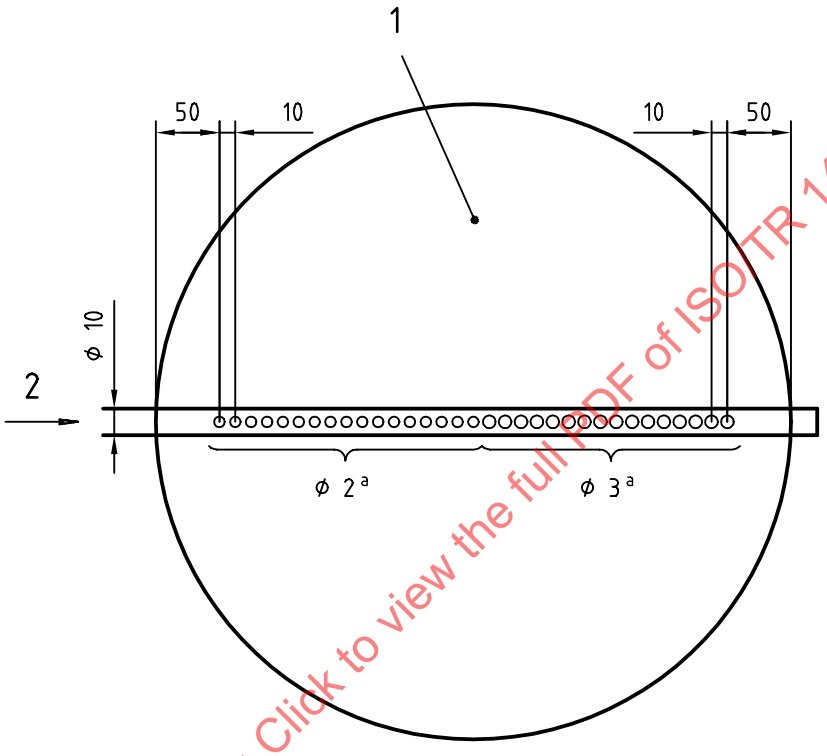


Key

1 Variable-length support tube (to Δp instrument)
2 Weld

Figure 11 — Bidirectional probe

Dimensions in millimetres

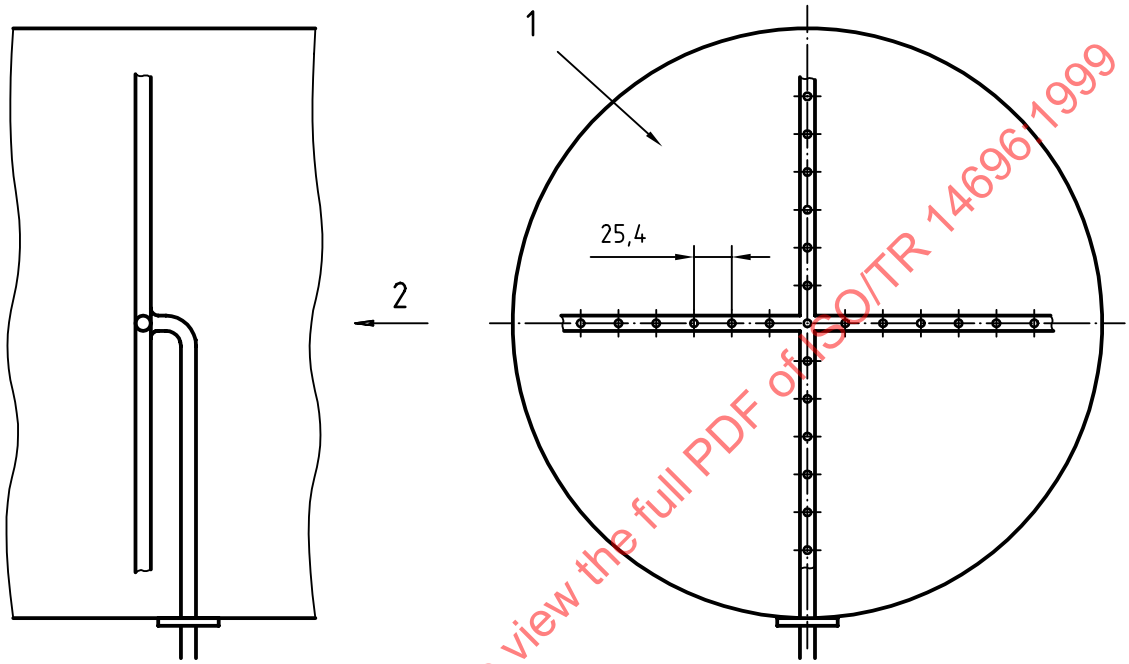


Key

1 Exhaust duct
2 Sample flow

[a] Holes on downstream side of flow

Figure 12 — Horizontal gas sampling probe



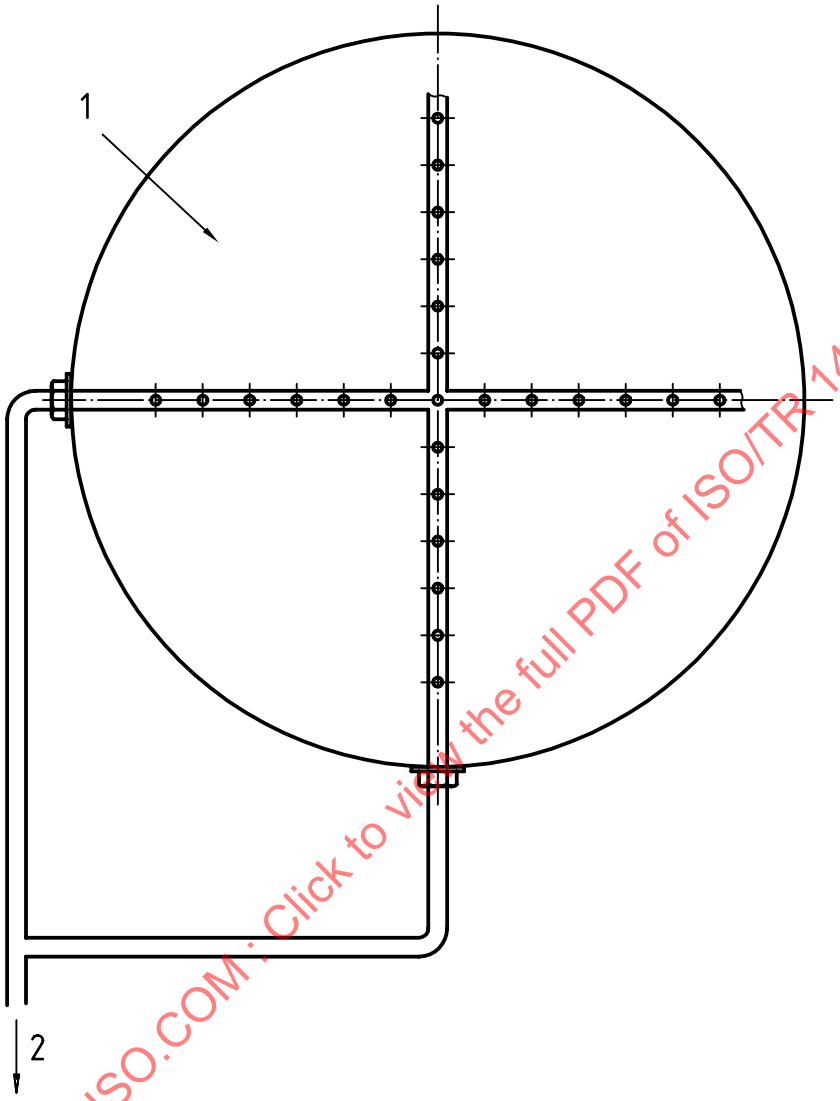
Key

1 ½ in OD SS tube

2 Air flow

NOTE Small holes (centre, 9), 2,4 mm (3/32 in) diameter; large holes (outer, 16), 3,2 mm (1/8 in) diameter; distance between holes 25,4 mm (1 in).

Figure 13 — Cross-type sampling probe



Key

1 SS tube, 12,7 mm OD

2 To filter and gas analysers

NOTE Small holes (centre, 9), 2,4 mm (3/32 in) diameter; large holes (outer, 16), 3,2 mm (1/8 in) diameter; distance between holes 25,4 mm (1 in).

Figure 14 — Cross-type gas sampling probe

Annex A
(normative)

Design of hood and exhaust duct

A.1 Collect the combustion gases from the burning specimen by means of a hood. A system is described below which has been tested in practice and proven to fulfill the specifications given in the method.

A.2 The following bottom dimensions of the hood have been found satisfactory: 3,1 m by 2,4 m, with a height of the hood itself of 1,0 m, see Figure 5. A vertical skirt on the hood will help assure all the fire gases are collected at the least duct flow. The hood feeds into a plenum having a 0,9 m by 0,9 m cross sectional area. The plenum has a height of 0,9 m. The maximum acceptable plenum height is 1,8 m, depending on building constraints. A system with different dimensions is acceptable, provided equivalence has been demonstrated. Design and manufacture the hood so that no leakage exists.

A.3 In the plenum chamber, it has been found that the incorporation of two plates approximately 0,5 m by 0,9 m in size, see Figure 5, is a satisfactory way to increase mixing of the combustion gases. Alternative gas mixing methods are acceptable, if equivalence has been demonstrated.

A.4 Connect an exhaust duct to the plenum chamber. The inner diameter of the exhaust duct is 0,4 m to 1,0 m. To facilitate flow measurements, guide vanes, if needed are located at both ends of the exhaust duct, Figure 5. Alternatively, the rectilinear part of the exhaust duct must have such a length that a fully developed flow profile is established at the point of measurement. Connect the exhaust duct to an evacuation system.

A.5 Design the capacity of the evacuation system so as to exhaust minimally all combustion gases leaving the specimen. This requires an exhaust capacity of at least 2,7 kg s^{-1} (about 8,000 m^3h^{-1} at standard atmospheric conditions) corresponding to a driving under pressure of about 2 kPa at the end of the duct. Provide a means to control the exhaust flow from about 0,5 kg s^{-1} up to maximum flow as stated above during the test process. Ensure that the measurement system has sufficient sensitivity for measuring low rates of heat release. Mixing vanes in the duct are an adequate means of solving the problem if concentration gradients are found to exist.

A.6 An alternative exhaust system design is acceptable if it is shown to produce equivalent results. Equivalency is demonstrated by meeting the calibration requirements under clause 10. Exhaust system designs based on natural convection are unacceptable.

Annex B
(normative)

Instrumentation in exhaust duct

B.1 Flow measurement

B.1.1 One technique for measuring the flow is a bidirectional probe located at the centreline of the duct. The probe shown in Figure 11 consists of a stainless steel cylinder 44 mm long and with an inner diameter of 22 mm. The cylinder has a solid diaphragm in the centre, dividing it into two chambers. The pressure difference between the two chambers is measured by a differential pressure transducer.

B.1.2 Use a differential pressure transducer with an accuracy of at least ± 0,25 Pa and of the capacitance type. A suitable range of measurement is 0 Pa to 150 Pa.

B.1.3 Place one thermocouple within 152 mm of the bidirectional probe. Use an Inconel sheathed thermocouple, type K Chromel-Alumel. The wire gauge shall be in the range 24 AWG (0,51 mm diameter) to 30 AWG (0,36 mm diameter). Place the thermocouple wire, within 13 mm of the bead, along expected isotherms to minimize conduction errors. Use an insulation between the Chromel and Alumel wires that is stable to at least 1 100 °C. Ensure that the thermocouple does not disturb the flow pattern around the bidirectional probe.

B.2 Sampling line

B.2.1 Locate the sampling probe in a position where the exhaust duct flow is uniformly mixed. Construct the probe with a cylindrical cross section so as to minimize disturbance of the air flow in the duct. Collect the combustion gas specimens across the entire diameter of the exhaust duct (see Figure 12).

B.2.2 Remove the particulates contained in the combustion gases with inert filters, to the degree required by the gas analysis equipment. Carry out the filtering procedure in more than one step. Cool the combustion gas mixture to a maximum of 4°C. The combustion gas specimens taken to each analyser shall be completely dried.

B.2.3 Transport the combustion gases by a pump. Use a pump which does not allow the gases to contact oil, grease or similar products, all of which can contaminate the gas mixture. A diaphragm pump (coated with polytetrafluoroethylene) is suitable. Alternate pumps shown to have the same effect are acceptable, but they have often been shown to need frequent replacement.

B.2.4 Suitable sampling probes are shown in Figures 12, 13 and 14. These sampling probes are of the bar and cross type. Ring type sampling probes are also acceptable, although they do not collect gas samples across the full diameter of the duct. Turn the intake of the sampling probe downstream to avoid soot clogging the probe.

B.2.5 A suitable pump has a capacity of 10 l min^{-1} kPa to 50 l min^{-1} kPa (minimum), as gas analysis instrument consumes about 1 l min^{-1}. A pressure differential of at least 10 kPa, as generated by the pump, reduces the risk of smoke clogging the filters.

B.2.6 Install a soot filter, capable of removing all particles > 25 µm in size.

B.2.7 A refrigerated column is the most successful approach to cool and dry the gases. Provide a drain plug to remove the collected water from time to time. Alternative devices are also acceptable.

B.2.8 If carbon dioxide is to be removed, use carbon dioxide removal media, as indicated in Figure 6.

B.3 Combustion gas analysis

B.3.1 Oxygen concentration

Use an oxygen analyser, meeting the specifications under 7.2.2, preferably of the paramagnetic type.

B.3.2 Carbon monoxide and dioxide concentration

Analysers found suitable are non-dispersive infrared analysers.

B.3.3 Time shift

Gas concentration measurements require the use of appropriate time shifts in order to account for gas transit time within the sampling system.

B.4 Smoke obscuration

B.4.1 White light system

B.4.1.1 One suitable light measuring system[4] based on white light has the following components: a lamp, plano convex lenses, an aperture, a photocell and an appropriate power supply. Mount lenses, lamp and photocell inside two housings, located on the exhaust duct, diametrically opposite each other. It has been found that a system consisting solely of a white light and a photocell, along the exhaust duct, across from each other and at an angle to the vertical, is satisfactory in some cases.

B.4.1.2 Use a lamp of the incandescent filament type, which operates at a colour temperature of 2,900 K ± 100 K. Supply the lamp with stabilized direct current, stable within ± 0,2 % (including temperature, short term and long term stability). Centre the resultant light beam on the photocell.

B.4.1.3 Select the lens system such that the lens L_2, according to Figure 7, has a diameter, d, chosen with regard to the focal length, f, of L_2 so that $d/f \geq 0{,}04$.

B.4.1.4 Place the aperture in the focus of lens L_2 according to Figure 7.

B.4.1.5 Use a detector with a spectrally distributed response according to the CIE photopic curve and linear within 5 % over an output range of at least 3,5 decades. Check this linearity over the entire range of the instrument periodically with calibrated optical filters.

B.4.1.6 Design a system that is easily purged against soot deposits. The use of holes in the periphery of the two housings is a means of achieving this objective.

B.4.2 Laser system

B.4.2.1 An acceptable alternative system for measurements of smoke obscuration uses a laser beam. An 0,5 mW to 2,0 mW helium-neon laser beam is projected across the exhaust duct. Couple the two halves of the device rigidly together (see Figure 8).

---

[4] The system described below is an example of a light measuring system that has been found to be satisfactory:

lenses: plano convex, diameter 40 mm, focal length 50 mm;

lamp: Osram Halo Stars, 64410: 6 V, 10 W, or equivalent;

photocell: United Detector Technology, PIN 10 AP, or equivalent;

voltage supply: Gresham Lion Ltd, Model G x 012, or equivalent.

B.4.2.2 If a laser is used for smoke measurement, a suitable means of mounting it together with the combustion gas sampling probes is shown in Figure 9.

Annex C
(normative)

Considerations for heat release measurements

C.1 Measurement of heat release rate by oxygen consumption

C.1.1 In 1917, Thornton [2] showed that for a large number of organic fuels, a more or less constant net amount of heat is released per unit of oxygen consumed for complete combustion. Huggett [3] obtained an average value for this constant of 13,1 MJ/kg of O_2. This value may be used for practical applications and is accurate, with very few exceptions, to within ± 5%.

C.1.2 Thornton's rule indicates that it is sufficient to measure the oxygen consumed in a combustion system in order to determine the net heat released. This is particularly useful for full-scale fire test applications. For example, for compartment fires, the oxygen consumption technique is much more accurate and easier to implement than methods based on measuring all the terms in a heat balance of the compartment.

C.1.3 Perhaps the first application of the O_2 consumption principle in fire research was by Parker [4] using ASTM E84 tunnel test. Later, Sensenig applied it to an intermediate scale room test [5]. During the late seventies and early eighties, the O_2 consumption technique was refined at the National Institute for Standards and Technology (NIST, formerly National Bureau of Standards). A paper by Parker [6] gives equations to calculate heat release rate by O_2 consumption for various applications. The technique is now used extensively in many laboratories all over the world, both in bench-scale [7] and full-scale [8,9] fire test applications.

C.1.4 The objective of this section is to provide a comprehensive set of equations and guidelines to determine the heat release rate in ICAL fire tests based on the O_2 consumption principle. The approach followed here is somewhat different from Parker [6] as the emphasis is on intermediate-scale fire test applications and the use of volumetric flows is avoided. Volumetric flows require specification of temperature and pressure. Various investigators have used different combinations of reference pressure and temperature. This leads to confusion, which is greatly minimized if mass flows are used.

C.1.5 The basic requirement is that all combustion products shall be collected in a hood and removed through an exhaust duct. At a distance downstream of the hood sufficient for adequate mixing, both flow and composition of the combustion gases are measured. It is assumed here that it is not possible to measure the air flow into the system, as this is generally the case for full-scale fire tests. The differences in treatment and equations to be used are mainly due to the extent to which combustion gas analysis is made. At least O_2 shall be measured. However, heat release rate measurements will be more accurate by measuring CO_2 and CO additionally.

C.1.6 It must be emphasized that the analysis is approximate. The following list describes the main simplifying assumptions made.

a) The amount of energy released by complete combustion per unit of oxygen consumed is taken as: E = 13,1 MJ/kg of O_2.

b) All combustion gases are considered to behave as ideal gases, in other words 1 mole of any gas is assumed to occupy a constant volume at the same pressure and temperature.

c) Incoming air consists of O_2, CO_2, H_2O, and N_2. All "inert" gases, which do not take part in the combustion reaction, are considered as nitrogen.

d) O_2, CO_2, and CO are measured on a dry basis, in other words water vapour is removed from the specimen before combustion gas analysis measurements are made.

C.1.7 In the analysis to follow, initial emphasis will be placed on the flow measurement. Equations to calculate flow are applicable, unless otherwise indicated, irrespective of the configuration of the combustion gas analysis system. In subsequent sections, distinction is made between various combustion gas analyser combinations.

C.2 Flow measurements

C.2.1 The mass flow rate through the duct is obtained from the velocity measured with a bi-directional probe at one point in the duct, usually along the centreline. The flow is then calculated using a predetermined shape of the velocity profile in the duct. The latter is obtained by measuring velocity at a sufficient number of representative points over the diameter or cross section of the duct prior to any fire tests. Detailed procedures to obtain this profile are described in reference [11]. Usually, conditions in intermediate-scale fire tests are such that the flow in the duct is turbulent, resulting in a shape factor k_c (=ratio of the average velocity to the velocity along the centreline) close to unity.

C.2.2 Due to considerable soot production in many fires, pitot static tubes cannot be used because of the potential for clogging of the holes. In order to deal with this problem, a more robust bidirectional probe was designed by McCaffrey and Heskestad [12]. This involves measuring the differential pressure across the probe and the centreline velocity and is valid in the range of Reynolds numbers, *Re*:

$$40 < Re < 3\,800$$

In many intermediate-scale fire test applications, duct diameter and flow are such that the Reynolds number is:

$$Re > 3\,800$$

In this case $f(Re)$ is taken as a constant (1,08), which greatly simplifies the calculations (equation D.1). Further details of this and of all other calculations discussed in this annex and in annex D are found in a paper by Janssens [13]. For additional details, see also ISO 9705.

C.3 Heat release rate measurement if only oxygen is measured

C.3.1 In this case all water vapour and CO_2 are eliminated by the use of appropriate filtering media. This leads to the assumption that the specimen combustion gas only consists of O_2 and N_2. This is approximately true provided CO production is negligible which is usually the case due to the abundant availability of oxygen. As the composition of the incoming air is unlikely to change during a test, and as the temperatures in building fires are usually not high enough to generate noticeable amounts of nitrogen oxides by nitrogen fixation, the mole fraction of O_2 in the air as measured by the analyser prior to a test can be written on the basis of O_2 and N_2 exclusively. The mole fraction of O_2 in the exhaust combustion gases, as measured by the oxygen analyser, can be written likewise. As nitrogen is conserved and does not participate in the combustion reactions, the equations are derived on the basis of its conservation.

C.3.2 In this case the heat release rate (in kW) is calculated as a function of the heat released per unit of oxygen consumed (E, 13,1 MJ/kg of O_2), the ratio of the molecular weight of oxygen (M_{O_2}, 32,0 kg/kmol) and molecular weight of the incoming air (M_a, generally taken as 28,97 kg/kmol) and the mass flow of the incoming air (in kg/s). The flow measured is that of the mixture of combustion gases and the incoming air within the exhaust duct and not that of the incoming air. In order to find a relation between the two, it is necessary to define the oxygen depletion factor. The oxygen depletion factor is the fraction of the incoming air which is fully depleted of its oxygen (equation D.4). It has been demonstrated (see Appendix in ASTM E1354), that the heat release rate is a function of E, M_{O_2}, M_a, and the oxygen depletion factor, plus the expansion factor.

The expansion factor has to be assigned and a recommended value is 1,105, the value for methane. The value for propane is 1,084, carbon in dry air is 1,0 and hydrogen is 1,21.

C.3.3 The resulting equation D.5 is expected to be accurate to within $\pm$ 5 % provided combustion is complete and all carbon is converted to CO_2. Errors will be larger if CO or soot production is considerable or if a significant amount of the combustion products are other than CO_2 and H_2O. It is unlikely that these errors will be of concern for the ICAL tests since O_2 is not limited.

C.4 Heat release rate measurement if oxygen and carbon dioxide are being measured

This case is similar to that covered in the former section. If is now assumed that only water vapour is trapped before the sample reaches the combustion gas analysers. Again, the equations are derived on the basis of conservation of N_2. The mole fraction of CO_2 in the incoming air is taken to be 440 ppm. A new equation is now needed, of course, for the oxygen depletion factor, equation D.7. Again the equation for heat release rate (equation D.5) is accurate to within $\pm$ 5% provided combustion is complete and all carbon is converted to CO_2.

C.5 Heat release rate measurement if oxygen, carbon dioxide and carbon monoxide are being measured

This case reverts to that covered in C.4 if CO production is negligible. Taking CO into account, however, changes the equations. It means that a new oxygen depletion factor is required, equation D.8, as well as a new heat release rate equation altogether, equation D.9.

C.6 Conclusions

C.6.1 Depending on the configuration of combustion gas analysers and the type of flow measurement, one of the following procedures shall be used to calculate heat release rate.

C.6.2 Case 1: Only O_2 is measured.

Calculate the mass flow of the exhaust combustion bases.

Calculate the oxygen depletion factor.

Calculate the heat release rate.

C.6.3 Case 2: Both O_2 and CO_2 are measured.

Calculate the mass flow of the exhaust combustion gases as in C.6.2.

Calculate the new oxygen depletion factor.

Calculate the new heat release rate.

C.6.4 Case 3: O_2 and CO_2 and CO are measured.

Calculate the mass flow of the exhaust combustion gases as in C.6.2.

Calculate the new oxygen depletion factor.

Calculate the new heat release rate.

C.6.5 The following numerical values are recommended for use in the equations:

a) Energies:

E = 13,1 MJ/kg of O_2, E_{co} = 17,6 MJ/kg of O_2, $E_{propane}$=12,78 MJ/kg of O_2, $E_{methane}$=12,51 MJ/kg of O_2.

b) Molecular weights

M_a = 29 kg/kmol (cases 1,2 & 3), M_{CO} = 28 kg/kmol, M_{CO_2} = 44 kg/kmol, M_{dry} = 29 kg/kmol, M_e = 29 kg/kmol (cases 1,2 & 3), M_{H_2O} = 18 kg/kmol, M_{N_2} = 28 kg/kmol, M_{O_2} = 32 kg/kmol.

c) Expansion factor = 1,105 (cases 1,2 & 3).

C.6.6 If a CO_2 analyser is used, this eliminates the need for removal of CO_2 from the combustion gas sample. This is mainly of practical importance as the scrubbing agent used to remove CO_2 usually requires careful handling and is rather expensive. If a significant amount of CO is produced (for example at or beyond flashover in ventilation controlled room fires), accuracy of the heat release rate measurement is improved if CO is measured.

C.6.7 The presence of a water vapour analyser simplifies the analysis and improves accuracy even more. Unfortunately, implementation of a water vapour analyser is not straightforward because sampling lines, filters, etc. must be heated to avoid condensation. Thus, the use of a water vapour analyser precludes the need to estimate the expansion factor. However, for this Technical Report, the use of water analysers is not recommended.

Annex D
(normative)

Measurement equations

D.1 Heat release rate

D.1.1 The equation to calculate mass flow rate is:

$$m_e = 26{,}54 \frac{A k_c}{f(Re)} \sqrt{\frac{\Delta p}{T_e}} \quad \text{(D.1)}$$

The function of the Reynolds number correction, $f(Re)$, is taken to be 1,08 as described in C.2.

D.1.2 Case 1 : Only O_2 is measured.

Calculate the mass flow according to the equation in D.1 and the oxygen depletion factor according to equation D.2:

$$\Phi = \frac{X_{O_2,i} - X_{O_2,e}}{\left[1 - X_{O_2,e}\right] X_{O_2,i}} \quad \text{(D.2)}$$

Then, calculate the heat release rate (q) according to equation D.3:

$$q = E \frac{M_{O_2}}{M_a} \frac{\Phi}{1 + \Phi(\alpha - 1)} \dot{m}_e X_{O_2,i} \quad \text{(D.3)}$$

If only O_2 is measured, equation D.4 simplifies to equation D.4:

$$q = 1{,}10\, E\, C \left[\frac{X_{O_2,i} - X_{O_2,e}}{1{,}105 - 1{,}5\, X_{O_2,e}} \right] \quad \text{(D.4)}$$

D.1.3 Case 2: Only O_2 and CO_2 are measured.

Calculate the mass flow according to equation D.1 and the oxygen depletion factor according to equation D.5:

$$\Phi = \frac{X_{O_2,i}\left[1 - X_{CO_2,e}\right] - X_{O_2,e}\left[1 - X_{CO_2,i}\right]}{X_{O_2,i}\left[1 - X_{O_2,e} - X_{CO_2,e}\right]} \quad \text{(D.5)}$$

and the heat release rate according to equation D.3.

D.1.4 Case 3: O_2 and CO_2 and CO are measured.

Calculate the mass flow according to equation D.1, the moisture content of the incoming atmosphere according to equation D.3 and the oxygen depletion factor according to equation D.6.

$$\Phi = \frac{X_{O_2,i}\left[1 - X_{CO_2,e} - X_{CO,e}\right] - X_{O_2,e}\left[1 - X_{CO_2,i}\right]}{X_{O_2,i}\left[1 - X_{O_2,e} - X_{CO_2,e} - X_{CO,e}\right]} \quad \text{(D.6)}$$

Finally calculate the heat release rate according to equation D.7:

$$q = \left[E\,\Phi - \left[E_{CO} - E\right] \frac{1-\Phi}{2} \frac{X_{CO_2,e}}{X_{O_2,e}} \right] \frac{M_{O_2}}{M_a} \cdot \frac{\dot{m}_e}{\left[1+\Phi\,(\alpha-1)\right]} X_{O_2,i} \qquad \text{(D.7)}$$

D.2 Total heat release equations

Determine the total heat released during combustion, q, by summation as follows:

$$q = \sum_i \dot{q}_i\,(t)\,\Delta t \qquad \text{(D.8)}$$

where the summation begins with the first reading after exposure and continues until the final reading of the test.

D.3 Smoke measurement equations

Optical density (OD) (equation D.9):

$$\mathrm{OD} = \log(I_0 / I) \qquad \text{(D.9)}$$

Extinction coefficient (k) (equation D.10):

$$k = \left(1/L_p\right) \ln\left[I_0/I\right] \qquad \text{(D.10)}$$

The volumetric flow is calculated as the product of the mass flow and the density of air, at the corresponding temperature. Thus, both the volumetric flow and the density of air must undergo temperature corrections. The volumetric duct flow q_V is adjusted because it is measured in the exhaust duct, but required at the temperature near the photodetector, as shown in equation D.11:

$$\dot{V}_s = \dot{V}_e \left(\frac{T_s}{T_e}\right) \qquad \text{(D.11)}$$

The density of air is adjusted between the literature value, measured at 273,15 K, and the value at the temperature in the exhaust duct, as shown in equation D.12:

$$\rho = \rho_0 \frac{273{,}15}{T_e} \qquad \text{(D.12)}$$

Then, the final equation for the volumetric flow is D.13:

$$\dot{V}_s = \frac{\dot{m}_e}{\rho_0} \cdot \frac{T_e}{273{,}15} \qquad \text{(D.13)}$$

Rate of smoke release (RSR) is defined by equation D.14:

$$\mathrm{RSR} = \dot{V}_s\, k \qquad \text{(D.14)}$$

Total smoke released (TSR) is defined by equation D.15:

$$\mathrm{TSR} = \int \mathrm{RSR}\, \mathrm{d}t \qquad \text{(D.15)}$$