TECHNICAL REPORT

ISO/TR 5658-1

First edition
1997-12-15

Reaction to fire tests — Spread of flame —

Part 1: Guidance on flame spread

Essais de réaction au feu — Propagation du feu —

Partie 1: Guide sur la propagation de la flamme

ISO

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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 Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.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 5658-1, which is a Technical Report of type 3, was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 1, *Reaction to fire*.

ISO 5658 consists of the following parts, under the general title *Reaction to fire tests — Spread of flame*:

— *Part 1: Guidance on flame spread* (Technical Report)

— *Part 2: Lateral spread on building products in vertical configuration*

— *Part 3: Lateral ignition of and flame spread on building products in vertical configuration (LIFT) method* (Technical Report)

— *Part 4: Intermediate-scale spread of flame with vertically oriented specimens*

Annex A of this Technical Report is for information only.

Introduction

The rate and extent of flame spread are important properties to be characterized when evaluating the reaction-to-fire hazards of construction products. Historically, there have been many approaches taken to the measurement of flame spread and most of these have evolved with little fundamental justification. This Technical Report describes different modes of flame spread and proposes some theoretical principles to assist with the relevant application of the data obtained from flame spread tests.

Many flame spread tests measure the rate and extent of the flame front as the flame moves over the surface of large-area, flat products such as linings on walls, ceilings and floors. Usually the orientation of the test specimen is related to the end-use application (for example, exposed face upwards for floor-coverings). This requirement for end-use relevance is satisfied by ISO 5658-2 and ISO/TR 5658-3 when wall-linings are to be evaluated.

Flame spread over construction products is related to the fire scenario. ISO/TC 92/SC 1 have concentrated on development of tests to simulate flame spread in rooms and along corridors. Other important scenarios where flame spread data are required are facades (both front and behind), shafts, stairs and roofs; much of the theoretical guidance given in this Technical Report may be applied to these scenarios even though ISO test procedures may not yet be available.

Flame spread can also occur over non-planar products (e.g. pipes) and within assemblies (e.g. along joints or inside air-gaps). Whilst this Technical Report concentrates on the theory pertinent to flat products, some of the theory outlined may be applied to improve the understanding of these more complex situations (see clause 8, flame spread within assemblies).

Flame spread initiated by removal of flaming drops or debris is not treated in this Technical Report. Empirically derived tests for these secondary flame spread phenomena are available (see ref. [34]).

NOTE — Flame spread can be reduced and sometimes eliminated due to melting and dripping; these effects are also not treated in this Technical Report.

Reaction to fire tests — Spread of flame —

Part 1:
Guidance on flame spread

1 Scope

This Technical Report provides guidance on flame spread tests for construction products. It describes the principles of flame spread and classifies different flame spread mechanisms.

The results of small-scale flame spread tests (e.g. ISO 5658-2 [31], ISO/TR 5658-3 [32] and ISO 9239-1 [35]) and large-scale tests (e.g. ISO 9705 [13]) may be used as components in a total hazard analysis of a specified fire scenario. The theoretical basis of these tests is explained so that relevant conclusions or derivations may be made from the test results.

2 Principles of flame spread

Flammability of room surfaces is a major concern of all building regulations. The primary room surfaces in question are any combustible linings used on the walls or ceilings, along with floor coverings. To understand the role of bench-scale tests in assessing this hazard, the dominant fire effects must be placed in context.

The ceiling can show a very rapid fire spread and a high contribution to hazard. Recent research suggests that the least combustible materials should be allocated to the ceiling in order to minimize fire hazard. There is not universal agreement on this point, however, and some studies conclude the opposite (see reference [25]). For almost any fire scenario, flame spread along the ceiling is wind-aided, that is, the air-flow and the flame spread are both in the same direction.

For common fire scenarios, flame spread on walls will be upward, that is wind-aided, in the vicinity of the fire source. In other parts of the walls, flame spread will be downward, that is opposed-flow, since entrained air is moving upwards, opposite to the direction of flame motion. Much of the wall can, however, be directly ignited by submersion into the layer of hot gases forming below the ceiling. This ignition does not involve a flame spread process at all, but it is directly accelerated by ceiling flammability.

Flame spread on floors is generally ignorable within a room since it is very limited until quite late in a fire. Flame spread on floors in corridors, however, can be of major concern. This flame spread is usually caused by a room fire impinging on the adjacent corridor and igniting the flooring. There will usually be some prevailing air flow direction within a corridor. Flame spread can then proceed either in the wind-aided direction, or as opposed flow. Commonly, flame spread in both directions can occur simultaneously on corridor flooring materials.

In principle, two different bench-scale test methods would be required to represent the two fundamentally different flame spread processes of wind-aided spread and opposed-flow spread. The flame spread rates are not similar in these two processes. Wind-aided spread tends to be much more rapid since a large amount of virgin combustible can be the flame tip, whereas in the opposite direction the heating of the material is limited to a very small heating zone. Research studies have shown, however, that a test solely dedicated to examining wind-aided spread is not necessary [26].

Theory and experiments both reveal that wind-aided flame spread can be directly predicted once the heat release rate and the ignitability behaviour of the specimen is established. These would be done in bench-scale by the use of the ISO 5660 method for heat release rate and either ISO 5660 or ISO 5657 for ignitability.

Flame spread for the opposed-flow configuration also requires information about the flame flux and the flame heating distance for that geometry [27] In the context of ISO bench-scale test methods, this is the role for the ISO 5658 test. Thus, while there are two flame spread modes of concern and while the wind-aided spread is often of dominant concern, there is seen to be a need only for one lateral bench-scale flame spread ISO test, and this test is devoted solely to the opposed-flow mode.

3 Characteristics of flame spread modes

3.1 General

In this clause, the characteristics of different flame spread modes are described and summarized in Table 1. For each of the modes, dominant heat transfer mechanisms are identified. The various modes are distinguished by two criteria: orientation of the fuel surface and direction of the main flow of gases relative to that of flame spread. Only flat fuel surfaces are considered. It is furthermore assumed that the fuel slab is located in a normal gravity environment, i.e., special cases such as flame spread under microgravity conditions (spaceships) are not considered. The analysis is for thick fuels, or else thin fuels in combination with a backing board. Cases where burning may be on two sides simultaneously (e.g. upward flame spread over curtains) are not explicitly included.

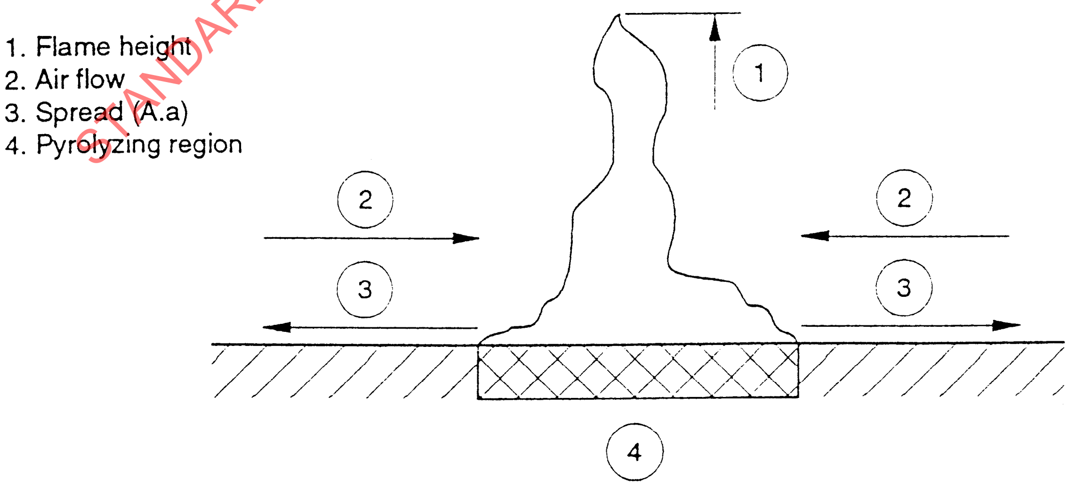


Figure 1 - Flame spread mode A.a (3.1 (a))

Table 1 — Modes of flame spread

Mode reference	Application	Type of flame spread
Aa	Flooring; Horizontal	Opposed-flow
Ab	Flooring; Horizontal	Opposed-flow
Ac	Flooring; Horizontal	Wind-aided
Ba	Walls; Vertical	Wind-aided
Bb	Walls; Vertical	Opposed-flow
Bc	Walls; Vertical	Opposed-flow
Ca	Ceilings; Horizontal	Wind-aided

3.2 Horizontal facing upward

a) Flame spread over a horizontal surface away from a burning area is illustrated in figure 1. The burning area has the characteristics of a pool fire. The air flow rate entrained into the flame is assumed to be reasonably uniform around the perimeter of the fire. Flame spread is against the direction of the entrained air flow, and is therefore of the opposed-flow type. The heat transfer to the non-burning fuel is primarily flame radiation. Only locally, close to the pyrolysis front, is gas phase conduction between the flame foot and the virgin fuel the dominant mode of heat transfer. If the entrained air flow rate is not uniform around the perimeter, the flame tilts in the direction of the dominant flow. As a result, the far field flame radiation to the unburnt fuel is no longer symmetrical. Objects blocking the flow and ventilation openings providing fresh air may have a pronounced effect on the flow field close to the fire.

b) This configuration is identical to that in 3.1 a), except that there is now a forced air flow because of which the flame tilts over in the direction of the flow. This mode is illustrated in figure 2. On the upstream side of the pool fire, flames spread against the air flow. However, the view factor between the flame and the non-burning fuel on this side is now very small. Consequently, the far field flame radiation becomes negligible and the gas phase conduction near the pyrolysis front is the only dominant method of heat transfer. In fact, significant flame heating is only over a very small region near the pyrolysis front (a few mm). Therefore, the spread rate is very slow and opposed-flow flame spread is commonly referred to as creeping spread. For many fuels the heat transfer is insufficient to maintain the spread, at least in absence of external heating (such as in 3.1a). A criterion for creeping spread will be discussed below.

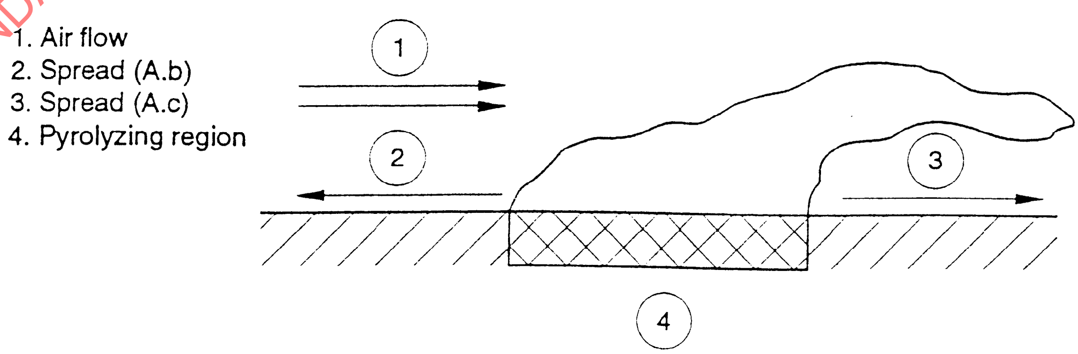


Figure 2 - Flame spread modes A.b and A.c (3.1 b and 3.1 c)

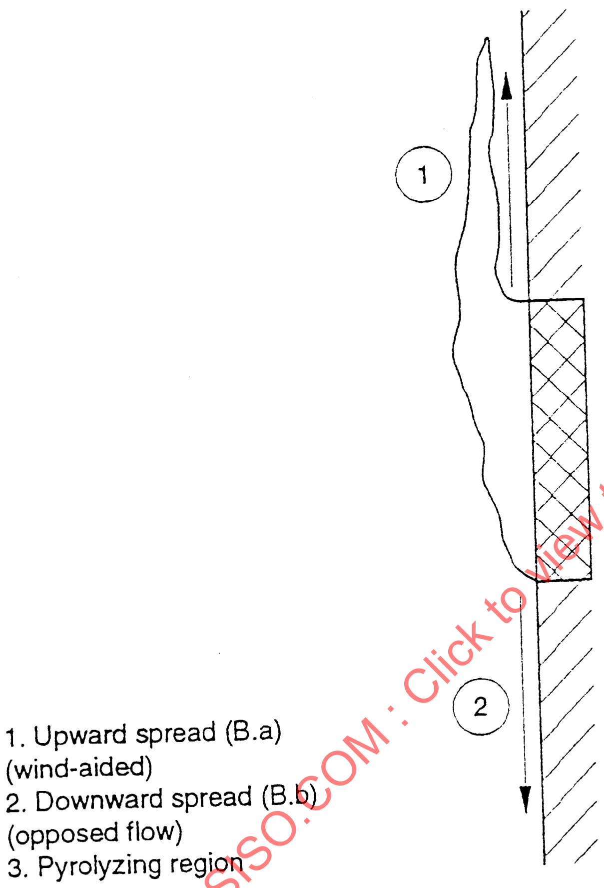


Figure 3 - Flame spread modes B.a and B.b (3.2 a and 3.2 b)

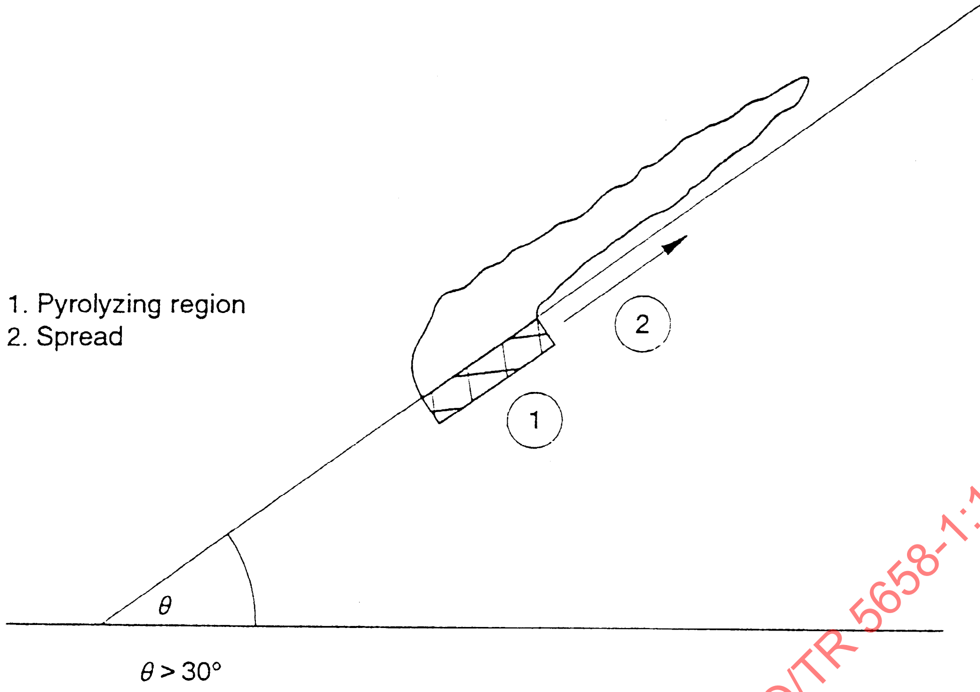


Figure 3a - Flame spread up an inclined plane

c) This mode is illustrated at the downstream side of the flame in figure 2. The fuel area between the pyrolysis front and the flame tip is covered by flames. The heat transfer to this area is primarily by flame radiation and convection. This is a typical example of wind-aided flame spread. There is still gas phase heat conduction near the pyrolysis front, but this mechanism is rather insignificant. Due to the increased view factor, flame radiation in the region between the pyrolysis front and the flame tip is much greater than in mode 3.1a), at least when flames are luminous.

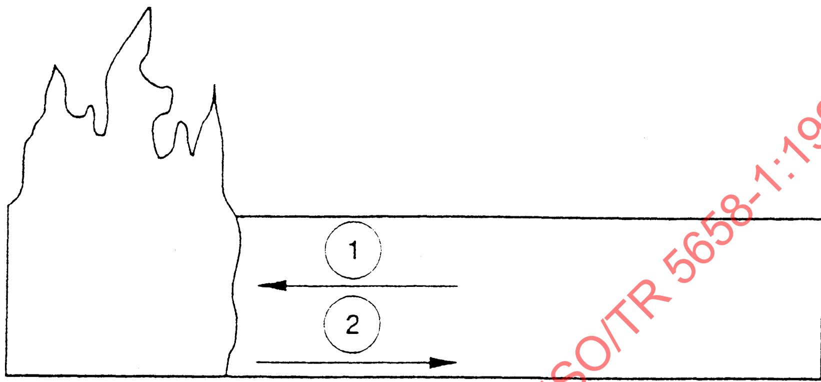
3.3 Vertical or inclined

a) Perhaps the most important flame spread mechanism is that of upward spread over vertical surfaces. This mode is illustrated in figure 3 and is very similar to that of 3.1c). The main difference is that flames cover part of the non-burning fuel ahead of the pyrolysis front due to buoyancy. Wind-aided spread is important because it is by far the fastest flame spread mechanism. Consequently, many bench and intermediate-scale tests used for regulatory purposes evaluate the wind-aided flame spread propensity of a material as a measure of its hazard in fire, for example the ASTM E84 Tunnel Test [3] and the DIN 4102 [2] test.

b) Downward spread from a wall flame is also shown in figure 3. It is a form of opposed flow or creeping spread analogous to 3.1b).

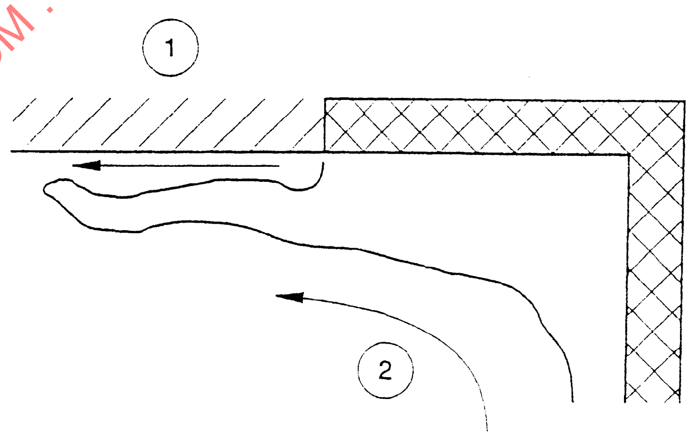
c) Lateral spread is illustrated in figure 4. Heat transfer to the non-burning fuel is primarily gas phase conduction near the pyrolysis front. Consequently this mode is similar to that of 3.1b) and 3.2b).

d) The important flame spread mechanisms over an inclined plane are dependent upon the angle of inclination of a surface and the extent of the pyrolysing region in relation to the width of the combustible surface. For surfaces inclined at angles in excess of around 30 °, flame spread can be represented as illustrated in figure 3a. The flames from the burning fuel are in contact with the fuel surface ahead of the pyrolysing region, producing substantial radiative and convective heat transfer to the fuel. The substantial flame lean is due to the fluid dynamics of the air entrainment process and results in a mode of flame spread similiar to that of upward spread over vertical sufaces, as shown in figure 3. This flame spread process is evaluated in the NT Fire 007 test [41]. This effect is also described in 7.2.5 in relation to sloping corridors.For angles of inclination up to 30 °, the modes of flame spread are represented by combinations of figures 1 (A.a./3.1a) and 2 (A.c/3.1c).



1. Air flow
2. Lateral spread (B.c)

Figure 4 - Flame spread mode B.c (4.2 c)



1. Ceiling spread (C.a)
2. Main flow of gases

Figure 5 - Flame spread mode C.a (3.3)

3.4 Horizontal facing downward

Ceiling spread is shown in figure 5; a similar mechanism applies to the underside of wide ventilation ducts. Buoyancy and the main flow of gases result in a wind-aided type of spread similar to 3.1c) and 3.2a).

4 History of surface spread of flame tests

Different spread of flame tests have been developed in several countries and for different applications.

These tests are different concerning specimen size, specimen orientation (sometimes depending from the type of application a material is designed for), heat and ignition source applied to the specimen as well as criteria for acceptance.

Table 2 shows the most important "spread of flame tests" used all over the world.

Table 2 — National spread of flame tests

Test	Specimen Orientation	Direction of Flame Spread	Specimen Size (mm)	Heat flux Density from .....to (kW/m2)	Ignition source	Criteria	Principal countries of use
ASTM E 162 [5]	Inclined (face down)	Downward	150 × 460		Horizontal gas flame, applied to upper end	Flame spread Heat evolved Smoke	USA
ASTM E 648 [4]	Horizontal (face up)	Horizontal	250 × 1050	11................1	Horizontal gas flame, applied to the hot end	Critical flux for spread	USA, Germany
BS 476-7 [1]	Vertical	Lateral	885 × 265	33................5	Vertical gas flame, applied to the hot end	Extent and velocity of spread after 1,5 min and 10 min.	GB, Belgium
NEN 3883 [6]	Vertical	Lateral	1000 × 230	37 0	Vertical gas flame, applied to the hot end	Flame spread after 1,5 and 10 minutes	Netherlands
CSE/RF3/77 [7]	Vertical (wall position) Horiz. (floor position) Horiz. (ceiling position)	Lateral Horizontal Horizontal	800 × 155	16.................0 30.................1 12.................0	Gas flame, applied to the hot end	Critical flux for spread of flame	Italy
NFP 92-506 [8]	Vertical	Lateral	400 × 95		Vertical gas flame, applied to the hot end	Velocity and extent of spread	France
DIN 4102-15 [2]	Vertical (4 opposed specimens)	Vertical	190 × 1000	30.... ....0 + influence of opposed burning material	Gas flame at lower end of specimen (pilot and radiation)	Flame spread after 10 minutes	Germany
IMO Resolution A 653 (16) (a) ASTM E 1317-90 [10]	Vertical	Lateral	155 × 800	50................15	Vertical gas flame, applied to the hot end	Heat for sustained burning (HSB) Critical flux at extinguishment (CIE)	For ships in different countries
ASTM E84 [3]	Horizontal (face down)	Horizontal	510 × 7320	35 0	Horizontal gas flame, applied to one end of spcimen, with heat output of 5,3 MJ/min.	Flame spread Smoke	USA, Canada
NT Fire 002 [39]	Vertical	Vertical	800 × 300	35 0	Gas flame, applied to lower end of specimen	Ignitability Flame spread	Scandinavia, Austria

5 Small-scale tests

5.1 Method given in ISO 5658-2 [31]

ISO 5658-2 has been derived from a surface spread of flame test developed by the International Maritime Organization (IMO): Recommendation on Fire Test Procedures for Surface Flammability of Bulkhead, Deck and Ceiling Finish Materials: IMO Resolution A.653(16) [9].

The purpose of the test method in IMO was to provide a method of classifying surface finish materials used on board ships relating their characteristics of surface flame spread.

The development has concentrated on lateral flame spread over a vertical orientated specimen, because:

a) there was a draft of an ISO spread of flame test which utilized lateral flame spread;

b) reference was made to British Standard BS 476-7 [1];

c) heat release measurement on the IMO test method is only possible in a vertical specimen position.

During the first stage of the round robin test in IMO, it was found difficult for some laboratories to obtain a strictly specified heating condition because of the variety of the fuel (methane, propane, electric, etc.).

However, it was also found that if test results were described as multiplication of flame spread time at a place on the specimen and irradiance at this position, the results showed a good agreement among laboratories even if there was some variance in the ability of laboratories to obtain identical heating gradients.

Due to the above reason, this parameter was introduced for classifying materials. The level of the classification on flame spread was developed in conjunction with BS 476-7.

'Heat for sustained burning (HSB)' and 'Critical irradiance at extinguishment (CIE)' are used in the IMO spread of flame test as parameters to describe degree of lateral flame spread on the surface of materials. The decision on the use of these parameters was a consequence of experimental studies on the test method and consideration to the parameters of a similar test method (BS 476-7).

BS 476-7 specifies the heating condition of the specimen by incident heat flux. Then, flame spread distance at 1,5 min from the beginning of the test and maximum flame spread distance within 10 min are used for categorizing the specimen in one of the four classes. During the discussion in IMO, it was assumed that incident heat flux along the lateral direction of the specimen was a more direct explanation of the heating condition than lateral distance, and that incident irradiance at the maximum flame spread position (CIE) could be used, instead of maximum flame spread distance, as a parameter which indicated capability of flame spread.

In IMO, it is assumed that flame spread at 1,5 min was an explanation of the flame spread speed, and that multiplication of incident heat flux and time of flame spread to the position (HSB) can be used as a parameter of flame spread speed. Some experimental studies have indicated that even if the heat flux condition is different, in some limited degree almost the same CIE and HSB could be obtained.

Results of some experimental studies and first round robin tests on the test method have demonstrated that logarithm plotting of flame spread time to positions along the specimen against incident heat flux on these positions gives a unique linear line for the specimen, and the slope is nearly -1; (see ref. [34], figure 6). This means that multiplication of incident heat flux and flame spread time can be a material unique value.

Taking into account a comparison test, results between BS 476-7 and IMO spread of flame test [29,37] pass/fail criteria for the IMO test were developed using CIE and HSB.

5.2 Method given in ISO/TR 5658-3 [32]

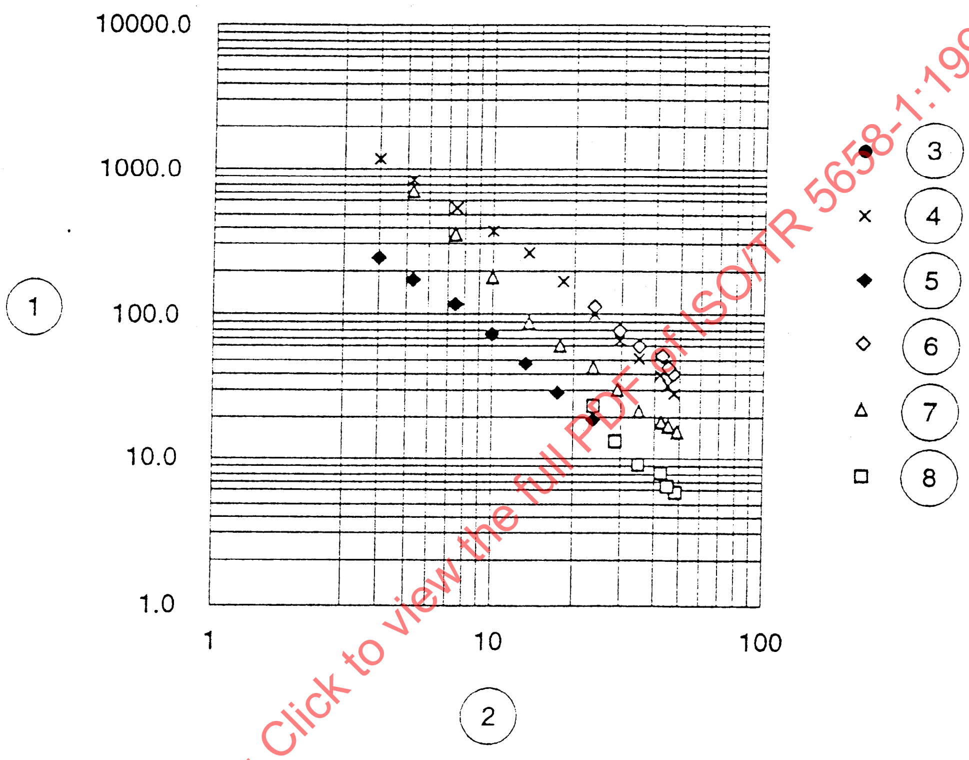
The continuing development of ISO 5658 is based on the LIFT procedure for determining ignition and lateral flame spread, which has been standardized in U.S.A. as ASTM E1321-90 [11].

This fire test response standard determines material properties related to piloted ignition of a vertically oriented specimen under a constant and uniform heat flux and to lateral flame spread on a vertical surface due to an externally applied radiant-heat flux.

The results of this test method provide a minimum surface flux and temperature necessary for ignition and for lateral spread, an effective material thermal inertia value, and a flame-heating parameter pertinent to lateral flame spread.

The results of this test method can be used to predict the time to ignition, and the velocity, of lateral flame spread on a vertical surface under a specified external flux. This analysis can be done using the equations in, for example, references [11] and [15], that govern the ignition and flame-spread processes and which have been used to correlate the data.

The analysis may be used to rank material performance by some set of criteria [14] applied to the correlation, or the analysis may be employed in fire growth models to develop a more rational and complete hazard assessment for wall materials.



1. Flame spread time (s)
2. Incident heat flux (kW/m^2)
3. Chip board
4. Hard wood fiber board
5. Soft wood fiber board
6. Melamine formaldehyde laminate
7. Acrylic carpet
8. Wool carpet

Figure 6 - Relationship between heat flux and flame spread time in ISO 5658-2 and IMO tests

5.3 Method given in ISO 9239-1 [35]

This International Standard was initiated by ISO/TC 38/SC 19, *Textile floor coverings*, and was progressed to DIS in 1988. In 1992, ISO/TC 92/SC 1 conducted a ballot for a new work item on flame spread over all types of floor coverings. This work item was well supported and the development of flame spread tests for floor coverings, including both textiles and non-textiles and taking into account the last improvement described in ASTM E 648, was begun by ISO/TC 92/SC 1 in 1993.

ISO 9239 provides a simple method by which horizontal surface spread of flame on a horizontal specimen can be determined for comparative purposes. This method is particularly useful for research, development and quality control purposes.

This International Standard describes a method of test for measuring the wind-opposed flame spread behaviour (mode A.a) of horizontally mounted floor covering systems exposed to a radiant heat gradient in a test chamber when ignited with a pilot flame. The imposed radiant flux simulates the thermal radiation levels likely to impinge on the floor of a corridor whose upper surfaces are heated by flames or hot gases or both, during the early stages of a developing fire in an adjacent room or compartment under wind-opposed flame spread conditions.

This test method is applicable to all types of floor coverings such as textile carpets, cork, wood, rubber and plastic coverings.

The test is intended for regulatory purposes, specifications, or development and research.

This test method consists of mounting conditioned specimens in a well defined field of radiant heat flux from 11 kW/m^2 to 1 kW/m^2 and measuring the rate of spread of flame and the position of flame extinguishment.

A test specimen (1050 mm long by 230 mm wide) is placed in a horizontal position below a gas-fired radiant panel inclined at 30° and a pilot flame is applied to the hotter end of the specimen.

Following ignition, any flame front which develops is noted and a record is made of the progression of the flame front horizontally along the length of the specimen in terms of the time it takes to travel to various distances.

The results are expressed in terms of flame spread distance versus time and their derived radiant fluxes at X minutes (RF-X) as well as the critical heat flux at extinguishment (CRF) and the average heat for sustained burning (HSB). The derivations for these last two parameters are made by a similar procedure to ISO 5658-2.

The test may be terminated after 30 min since burning behaviour may not be significant for fire hazard assessment purposes after this point of time.

Further flame spread test developments are in progress to recognise the following additional requirements of fire growth involving floor coverings :

a) Ventilation controlled test conditions to simulate wind-aided flame spread (mode A.c).

b) Higher irradiances to the floor covering specimen to simulate the heat flux conditions existing at floor level in developed fires; these conditions may require exposing specimens to irradiances of 25 kW/m^2.

6 Intermediate-scale tests

6.1 Corner tests

A full-scale corner test is a widely recognised configuration for conducting large-scale fire test evaluations for demonstrating the flame spread potential and the material damage characteristics of insulated walls and ceilings. A corner provides a critical surface geometry for evaluating the fire behaviour of material surfaces since it results in a combined heat flux from the conductive, convective and radiative response of any material burning in the corner. Large-scale corner tests are, however, expensive to conduct. A scaled-down screening test which exhibits good reproducibility and good correlation is therefore useful for predicting the results of full-scale corner testing. A variety of small corner tests have been judged to meet these criteria but none has yet been internationally standardized. In particular, specimen assembly dimensions and testing times are convenient so that if necessary, several tests may be conducted daily.

Corner tests are particularly useful for measuring wind-aided flame spread on the tops of the walls and over the ceiling (mode C.a). They are also able to observe opposed-flow flame spread (mode B.c) laterally and downwards over the walls for more flammable linings.

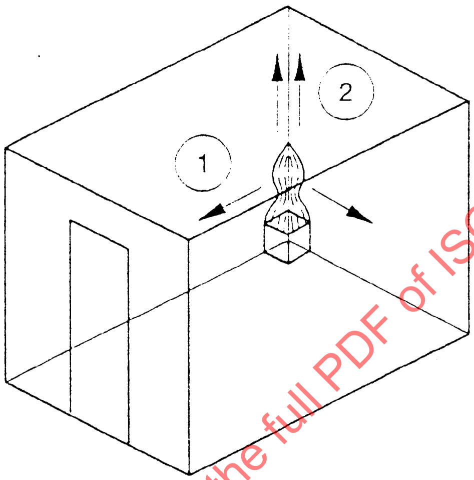
7 Large-scale tests

7.1 Room/corner test (ISO 9705) [13]

ISO 9705 describes a full-scale room fire test method to evaluate the performance of lining materials in a room/corner scenario. The test room has a height and width of 2,44 m, and a depth of 3,66 m. There is an open doorway of 0,76 m wide by 2,03 m high in the front wall. All walls (except the front wall) and/or ceiling are lined with the test material. A gas burner ignition source is placed in one of the rear corners of the compartment. The main measurements are time to flashover, heat release rate and smoke obscuration in the exhaust duct.

Corner fires are more severe than wall fires due to the radiative heat exchange between the two burning walls. For this reason, corner tests have been preferred in the evaluation of pre-flashover fire performance of wall linings. However, the physical phenomena controlling fire growth in corner and wall scenarios are very similar, if not identical. Therefore, the description of fire growth in a corner test given below is also applicable to wall fires. The important physical phenomena can be identified on the basis of visual observations of and experience with full-scale tests. Fire size is primarily determined by the spread of flames over the walls i.e. the increase in surface area of material involved:

a) At the start of a test, the ignition burner is lit. A diffusion flame develops and is in contact with the walls. For burner sizes and power levels commonly used in room/corner tests, the flame is turbulent. Figure 7 is a 3-D view of the room in this stage of a corner test.

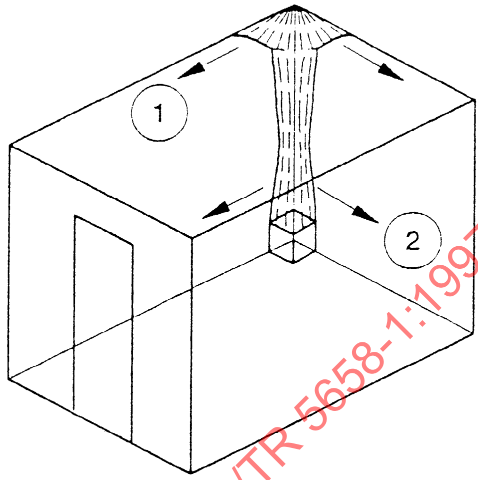


1. Lateral spread (opposed-flow)
2. Upward spread (wind-aided)

Figure 7 - 3-D view of a corner fire in an early stage

b) The wall material in contact with the flame and plume is heated. The heat flux to the wall is a function of location. It is the highest in the flame region, and decreases sharply in the plume region. At a certain time, part of the material in contact with the flame ignites. At ignition, the total flow of fuel gases suddenly increases. This results in a higher flame and an increase in heat flux to parts of the wall above what is ignited. As the critical conditions for ignition are reached at locations above the burning zone, the flame works its way towards the ceiling. This phenomenon is referred to as upward spread. It is in the same direction as the main flow of gases, i.e. wind-aided (mode B.a).

c) After the flame has reached the ceiling, it turns into a ceiling jet flame. Just as for upward spread, the flame travel rate is the highest in the direction of the main flow of gases, i.e. along the interface between the ceiling and walls or over the ceiling itself, if it is combustible. Wind-aided flame spread also continues over a combustible ceiling (mode C.a).



1. Wall/ceiling spread (wind-aided)
2. Lateral spread (opposed flow)

Figure 8 - 3-D view after flames reach the ceiling

d) While the flame spreads upward as described in b), it also spreads laterally as shown in figure 8. However, this opposed-flow spread rate (mode B.c) is much slower than in the case of upward spread for two reasons:

1) Lateral flame spread is opposite in direction to the main flow of air entrained into the flame and plume; and

2) The heat flux to regions ahead (in the direction of flame spread) of the flame front is much smaller for lateral spread as the flame does not cover that region. However, this heat flux is very important in a small region near the flame foot.

e) As flames spread along the wall/ceiling interface, eventually they reach another corner. In tests where the ceiling is lined, it is very likely flashover occurs before this happens. With a non-combustible ceiling, flames also spread downward before flashover as shown in figure 9. The downward spread phenomenon has much in common with lateral spread as described in d). Flames are not exactly travelling in a direction against the entrained flow of gases. However, due to buoyancy, flames do not cover the region ahead of the flame front just as for lateral spread. Experimental observations indicate that downward spread becomes very significant shortly before flashover. This is because at that time heat flux to the ceiling and upper part of the walls increases dramatically, thus significantly enhancing this mode of flame spread.

From the description above, it is clear that both wind-aided and opposed-flow flame spread characteristics of a material (modes C.a and B.b) are important factors for its performance in ISO 9705 [13].

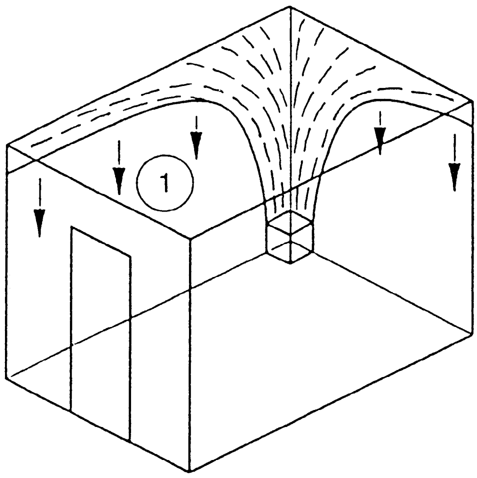


Figure 9 - 3-D view shortly before flashover

A key parameter output from the surface spread of flame test ISO/TR 5658-3 is the flame spread parameter ϕ. The usefulness of ϕ could be much enhanced if it was shown to be accurate for predicting large-scale lateral or downward flame spread over linings. Some work on this type of validation has been done, for example, Karlsson [28] has developed the following expression for the ISO 9705 test:

$$t_{fo} = a(k\rho c)^{b_1} \phi^{b_2} T_{ig}^{b_3} (\dot{Q}''_{max})^{b_4} \lambda^{b_5} \qquad (1)$$

where

t_{fo}	= time to flash-over in ISO 9705
a and b_a	= constant and exponentials respectively
$k\rho c$	= thermal inertia
ϕ	= flame spread parameter
T_{ig}	= ignition temperature
$\dot{Q}''_{max}$	= maximum heat release rate from ISO 5660-1
λ	= decay coefficient from HRR curve from ISO 5660-1

The exponent of λ will depend on specimen configuration in the actual fire test. Karlsson used a value of -0,37. For products where there is no flash-over during the test, equation (1) could be adapted to predict maximum rate of heat release instead of time to flash-over using other exponents and constants.

NOTE - ϕ Karlsson is not equal to ϕ LIFT; ϕ Karlsson = $\dfrac{\phi\ LIFT}{k\rho c}$

The importance of the flame spread parameter is less compared to the heat release rate, HRR. Therefore attempts have been made to only use ignition time and HRR as measured in ISO 5660-1 under constant external heat flux. Kokkala has shown that the following expression is valid for a large range of products:

$$t_{fo} = a I_Q^{n_1} I_{ig}^{n_2} \tag{2}$$

where

t_{fo} = time to flash-over
a and n_n = constant and exponentials respectively
I_Q = heat release index from ISO 5660-1 [12]
I_{ig} = ignitability index

NOTE - The above correlations depend on the specific conditions selected for ISO 5660-1.

7.2 Room-corridor scenarios

7.2.1 General

The description of fire growth for any particular scenario will include a combination of some flame spread mechanisms. Differences observed in real fire behaviour for the same material in different scenarios result from the gas phase behaviour which determines the thermal environment to which the materials are exposed. In this context, the flame spread mechanisms contributing to fire growth in three different room-corridor scenarios will not be discussed.

In each case, the room doorway opens into the corridor and once flashover has occurred in the room, it becomes the ignition source for the corridor. The corridor is open at one or both ends. The rate of fire growth in the corridor will be dependent on the location of the lining materials for which there are a number of options. The most important of these include:

1) Combustible wall lining;

2) Combustible ceiling lining;

3) Combustible wall and ceiling linings;

4) Combustible floor lining;

5) Combustible wall, ceiling and floor lining.

Fire growth will result from flame spread along the ceiling lining as well as downwards and laterally over the wall linings. The most severe rate of fire growth is likely to occur when the ceiling is lined in addition to the walls and floor. Flames on the ceiling will produce enhanced radiative heat transfer to the other vertical and horizontal surfaces. Clearly, the dimensions of the corridor will influence this process. The following scenarios assume that both the ceiling and the walls have combustible linings.

7.2.2 Scenario A

For the first scenario illustrated in figure 10 ((i) and (ii)), it is probable that a fire will become ventilation controlled at a relatively early stage of corridor involvement because the room would become involved first. The design of the corridor in relation to the room will influence the initial spread of flame into the corridor.

The general behaviour responsible for fire spread along either corridor will be similar with the airflow entering the room through the corridor. This results in an inflow of cooler air along the lower regions of the corridor and an outflow of hot combustion products along the upper regions of the corridor. After ignition with burning on the wall and ceiling linings, flame spread along the ceiling lining will be wind-aided (mode C.a) and rapid, with flame radiation and convection being the dominant modes of energy transfer. Flame spread along the wall lining below the ceiling layer, will generally be opposed flow lateral and downward spread (modes B.b and B.c). This is obviously slower and only proceeds under the influence of radiation from the flames and hot gases below the ceiling.

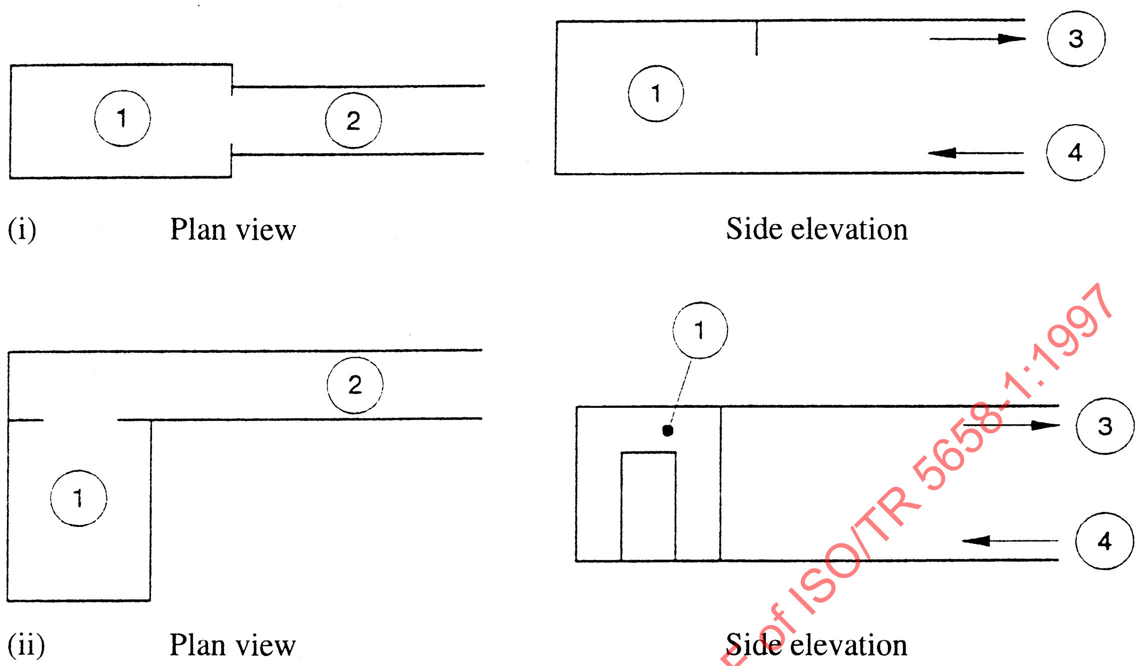
7.2.3 Scenario B

Room-corridor scenario B is illustrated in figure 11. An additional ventilation opening has been included in the wall of the room, opposite the doorway. The significance of this vent depends entirely on its dimensions and position. If it is below some critical size, the flame spread behaviour might be expected to be similar to that described for scenario A. However, provided that it is located at floor level and is large enough to more than meet the requirement for the air supply to the room fire, then a situation may be created where the flow of gases along the corridor occurs in only one direction. This could result in a scenario similar to scenario C with wind-aided flame spread across all linings. Downward flame spread on vertical wall linings will always be opposed flow due to the buoyancy effects of fires.

7.2.4 Scenario C

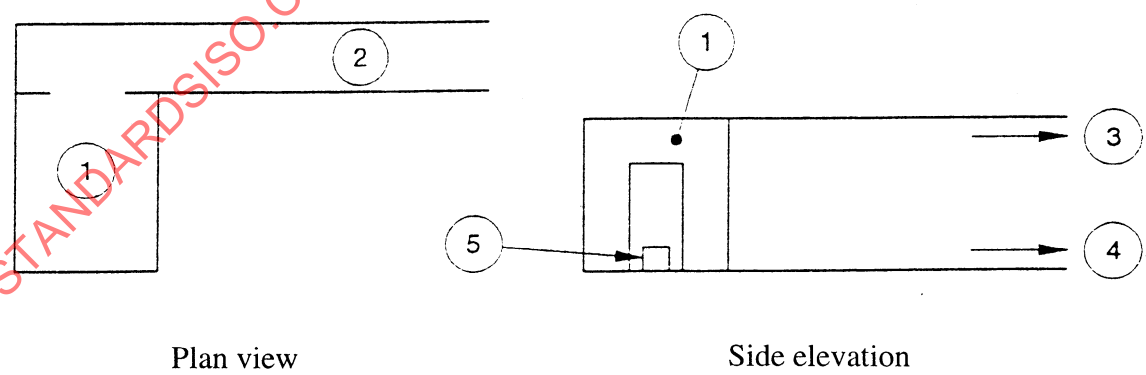
In scenario C illustrated in figure 12, the corridor is open at both ends and force ventilated, resulting in an initial air velocity through the corridor. The effect of the additional air velocity due to forced ventilation will be to lengthen the flames under the ceiling. This will increase the area of fuel exposed to flame radiation and convection and will tend to accelerate the rate of flame spread.

The mechanism of flame spread over a floor lining will depend on the magnitude of the air velocity produced by forced ventilation. If the forced velocity is less than some critical value, air may be entrained into the fire from the opposing direction. This will occur at a low level, so flame spread over a floor lining will be opposed flow and will make only a minor contribution to fire growth (figure 12 (i)). However, if the forced velocity is greater than the critical value, the overall flow will be uni-directional and the flame spread over the floor lining will be wind-aided. In this instance, a floor lining could make a more major contribution to fire growth through its involvement (figure 12 (ii)).



1. Room fire
2. Corridor
3. Flame spread
4. Air

Figure 10 - Room-corridor, scenario A



1. Room fire
2. Corridor
3. Flame spread
4. Air
5. Vent

Figure 11 - Room-corridor, scenario B

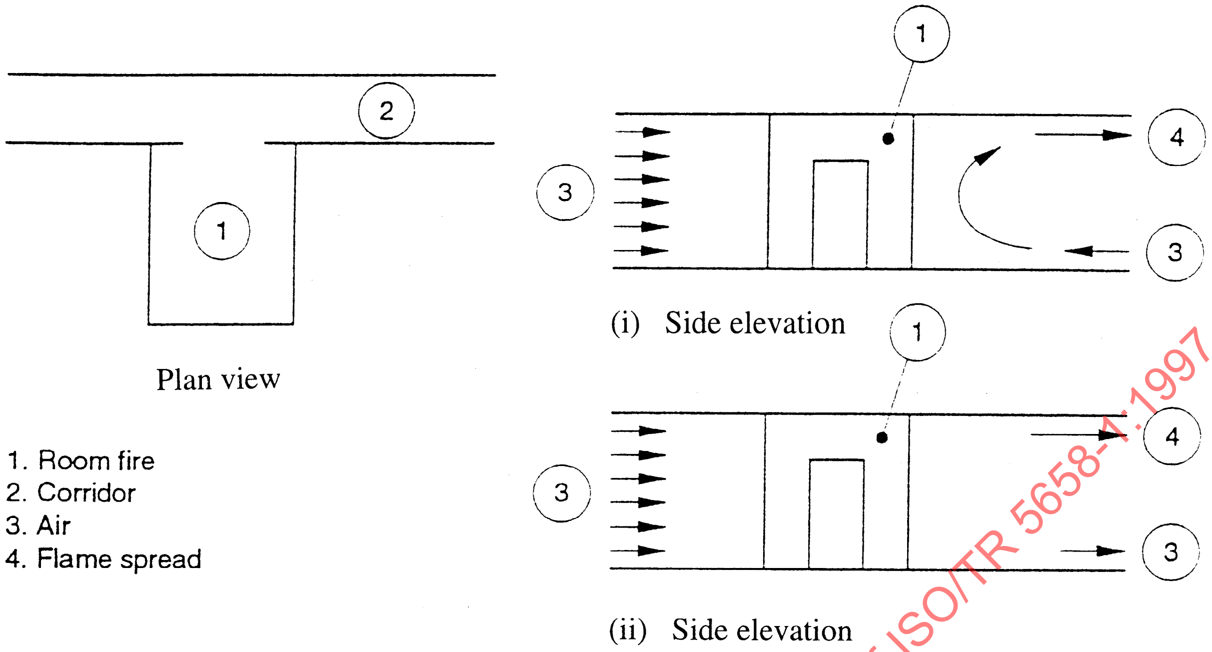


Figure 12 - Room corridor, scenario C

7.2.5 Scenario D

An additional scenario of a sloping corridor open at both ends and without forced ventilation, e.g. escalator shaft, will be considered. The entrainment of air into a fire occurring across the full width of the base of an inclined corridor is restricted, which results in the flame leaning up the incline. The angle of lean depends on the inclination of the corridor base [16, 17] leading to flame attachment at some critical angle of inclination (greater than 30° from the horizontal). As the flame lean increases, flame radiation to the corridor base becomes greater, producing a potential for very rapid wind-aided flame spread. This specific problem is approximately two-dimensional. However, if the fire does not extend across the full width of the base or the ends of the corridor (one or both) are closed, the problem is no longer two-dimensional and is obviously more complex.

7.2.6 Applicability of test-data for room-corridor scenarios

Since both opposed flow and wind-aided flame spread contribute to fire growth in the room corridor scenarios considered, it may be necessary for both mechanisms to be addressed in a robust assessment of spread of flame. Data applicable to both of these mechanisms are unlikely to come from a single bench scale test. The LIFT method [14] in conjunction with the cone calorimeter [12] may be capable of providing a solution.

Using the cone calorimeter, it may be possible to derive data applicable to wind-aided flame spread since that degradation process is primarily driven by flame radiation, in addition to background radiation from the walls, hot gas layer etc. However it is not clear that the cone calorimeter can provide data relevant to opposed flow flame spread. This is simply because gas phase conduction at the flame leading edge, in addition to imposed radiation, is crucial. Two very different energy transfer mechanisms are dominant in each case and any attempt to predict opposed flow flame spread that neglects gas phase conduction must be treated with caution.

Finally, consideration should be given to the thermal exposure and ventilation conditions in bench scale tests, in particular ISO 5658 and the cone calorimeter. The test conditions should attempt to simulate real fire exposures so that reliable spread of flame classifications may be produced. It is not yet clear how this may be achieved for the range of conditions typical of real fires.

7.3 Large-scale vertical flame spread tests

7.3.1 Upward flame spread along a vertical combustible surface (mode B.a) is a key process governing the transition from the local combustion of an ignition source to the full involvement of an enclosure by fire, especially in an enclosure with a high ceiling compared with the wall widths. A similar wind-aided spread process occurs in large-scale tests on external facades [38]. Flames spreading upwards over the external surface or within the cavity of a combustible facade assembly govern the occurrence of self-sustained fire remote from the influence of the ignition source (such as a flashed-over room or a fire in a rubbish skip against the external wall) which causes localised combustion. The resulting flames can spread vertically upwards on the exterior wall surface of tall buildings or within the cavity.

Preheating of unburnt surface beyond the pyrolysis front during upward flame spread along a flat wall is primarily dependent on the heat flux normal to the surface from the wall fire and external radiation. Determination of the wall flame heat transfer by heat release rate suggests that upward flame spread can be predicted from the heat release rate and the ignitability of the specimen assuming one directional thermal conduction within the specimen [18, 19, 20, 21, 22]. However, grooves or roughness on the surface would make the heating and pyrolysis of the surface rather complicated through the increase of the surface exposed to the heating, establishment of two- or three-dimensional thermal conduction within the specimen, and radiation between heated elements of the surface. A large-scale test is necessary on the upward flame spread at least for the following purposes:

1) validation of upward flame spread models based on the bench-scale ignitability and heat release rate tests;

2) evaluation of upward flame spread over an uneven vertical combustible surface or over assemblies of building materials.

7.3.2 Prenormative research in large-scale vertical flame spread tests is continuing and no method has yet been developed into an International Standard [36]. However, it is considered to be valuable to provide information here on the BRI experimental procedure developed in Japan during 1990-93.

An arrangement for large-scale vertical flame spread tests is shown in figure 13 [23]. A water-cooled copper sidewall is located on each side of the specimen to keep the flame spread one-dimensional. The radiant panel is used as the source of external radiation to the specimen. Measurements are made on heat release rate using the oxygen consumption method, its convective fraction using thermocouples at the entrance of the duct, temperature of surface/backsurface of the specimen, and surface heat flux. Weight loss can be measured with load cells beneath the specimen table. Measurement of flame height, x_f, local extinction etc. can be made visually on a videotape [18, 19, 23] or by radiation measurement [24]. The specimen is ignited with a line burner generating a uniform flame at the bottom of the specimen surface.

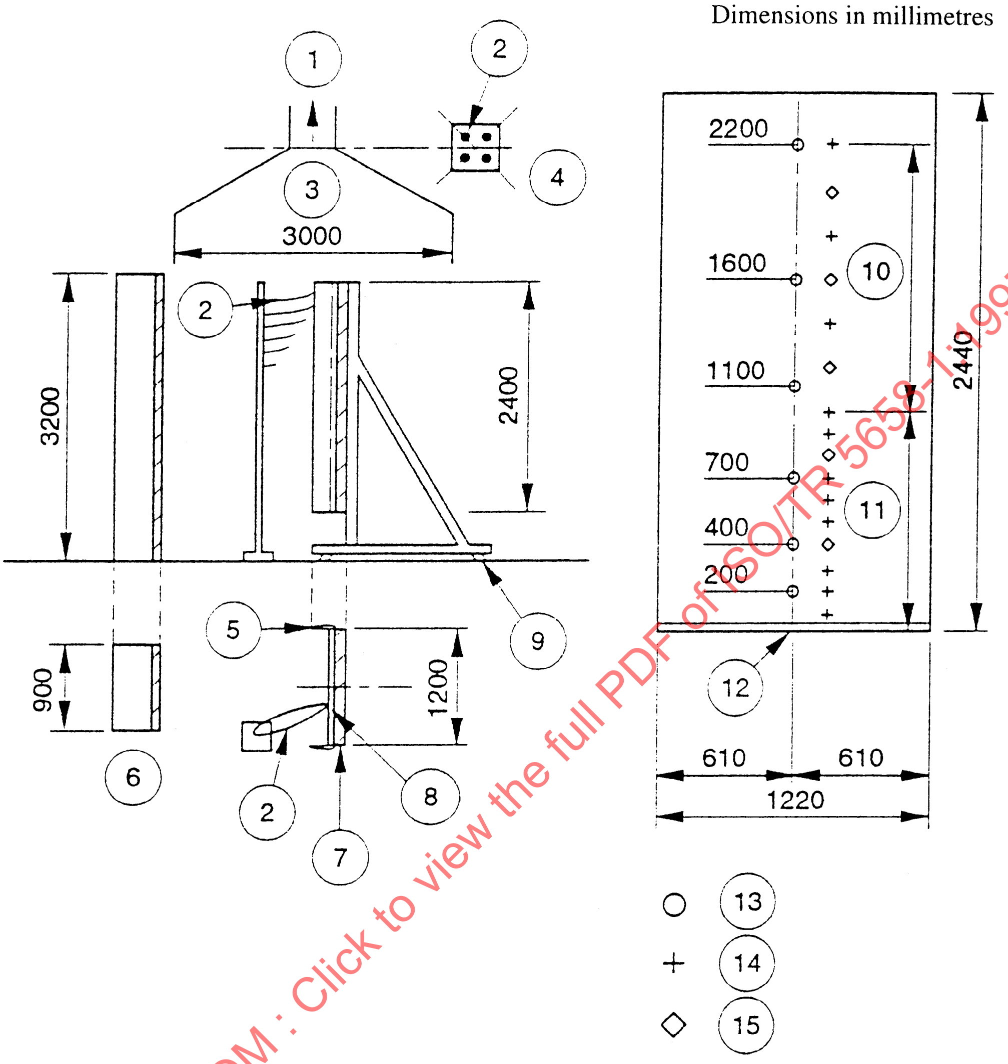
Unlike opposed-flow flame spread, it is usually difficult to observe the location of the pyrolysis front, x_p, visually in a wind-aided flame spread test since a wall flame may cover the unburnt surface beyond the pyrolysis front. For a noncharring material such as PMMA, the beginning of a plateau in the time-history of surface temperature at nearly the pyrolysis temperature indicates the arrival of the pyrolysis front at that height [18]. For a charring material, surface temperature tends to rise even after the pyrolysis has started at that height due to the char formation; however experiments have shown that the surface temperature at the beginning of a plateau in the time-history of surface heat flux at the same height is close to the ignition temperature and the beginning of the heat flux plateau nearly indicates the arrival of the front of the zone contributing fuel to the wall flame at that heat (figure 14) [23]. Change of the colour of the surface starts earlier than the beginning of the heat flux plateau. Development of wall fire may stop at some height. This maximum height of pyrolysis front, x_{poff}, is worth measuring for the evaluation of fire safety related to upward flame spread.

7.4 Flame spread in ducts and concealed spaces

Flame spread in ducts (horizontal or vertical) and concealed spaces (ceiling voids or floor spaces) can pose a serious problem. The geometry of this type of space is usually such that at least 2 of the bounding surfaces are in close proximity to each other which tends to result in high interactive radiative heat feedback between surfaces. These spaces may also contain a high density of fuel in the form of cables or piping. In such geometries, the spread of flame could be very rapid with a mechanism similar to that described in B.a/3.2a. The spread of flame over combustible surfaces (linings or services) in such confined spaces may be ventilation controlled. However, the generation of combustible volatiles that ignite when vented into a larger space remote from the initial fire still pose a significant problem but which is now one of fire spread rather than flame spead.

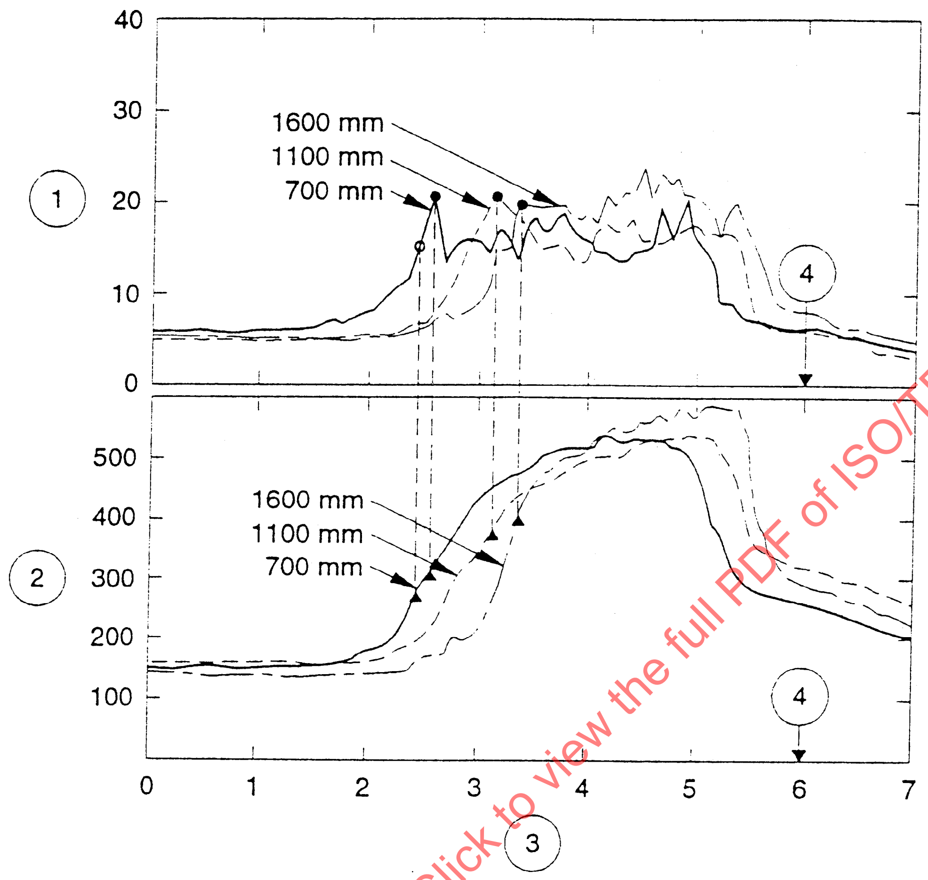
The Schlyter Test [39,40] was developed to evaluate the flame spread over materials in vertical ducts.

Dimensions in millimetres



1. Gas analysis
2. Thermocouples
3. Hood
4. Duct section
5. Side wall (100 mm long)
6. Radiant panel
7. Insulation (25 mm thick)
8. Specimen
9. Load cell
10. 200 mm Intervals
11. 100 mm Intervals
12. Ignition source
13. Heat flux gauge
14. Surface temperature
15. Backsurface temperature

Figure 13 - Experimental arrangement and specimen for large scale vertical flame spread test (BRI)



1. Heat flux (kW/m²)
2. Surface temperature (°C)
3. Time from ignition (minutes)
4. Burner off

Figure 14 - Time histories of surface heat flux and surface temperature during an upward flame spread test at three positions

8 Flame spread within assemblies of building products

Figures 15 and 16 may assist schematically to explain some flame spread effects which may occur within composites or assemblies of building products. If a thermoplastic substrate is present (e.g. some expanded foams), a cavity may be created behind the facing after exposure to heat, and this may provide an additional route for flame spread.