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Review of outputs for fire containment tests for buildings in the context of fire safety engineering

Examen des résultats des essais d'endiguement du feu pour les bâtiments, dans le contexte de l'ingénierie de sécurité

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PDF disclaimer

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, 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), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 22898 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 2, *Fire containment*.

Introduction

Fire resistance test methods have been in existence for many decades and they permit various forms of structure to be evaluated and classified for regulatory purposes with respect to their fire containment capabilities, against conditions that reproduce one of the many possible fire scenarios that can exist in practice. Because of the changing use of materials and the design of modern buildings, even this one scenario is becoming less relevant to the performance expected in practice. The criteria of failure used in these standardized tests sometimes reflect pseudo-life risk and sometimes a property risk. More recently, tests have been developed to measure the smoke containment potential of doors at ambient temperatures.

When a fire engineer is designing a structure to resist the spread of fire and the products of combustion in order to satisfy a fire strategy that is responding to actual conditions and known exposure variations, both with respect to the life safety of persons and the limitation of damage to the structure, the output of the standard fire tests are not deemed to be relevant in most situations. This Technical Report reviews the relevance of the standard tests and their outputs for the benefit of committees and working groups developing specifications for structure that can satisfy a functionally derived fire safety strategy.

In considering the effectiveness of the test for life safety purposes, it is solely with respect to the ability of the element to contain the fire to the enclosure/compartment of origin so that people outside of that space, including fire fighters, are not harmed indirectly by the fire or the behaviour of the building. By the time the “flashover” condition exists, it is assumed that the life safety of the persons within the enclosure is no longer a matter of concern because the measures put into the design to ensure escape have achieved their objective.

Once initiated, a fire within an enclosure, during this phase, initially burns in what is known as a “fuel-bed” controlled state. In this condition, in simplistic terms, the rate of combustion (and hence heat release) is controlled by the nature and geometry of the fuel at the seat of the fire. The predominant means of fire spread within the enclosure is by direct flame impingement on other combustible materials or by heat radiation from the flames onto materials positioned very close by. Provided that the hot gases of combustion can vent easily into the open air from the enclosure or compartment (and that the elements of structure forming the compartment’s boundaries are not of a highly insulative nature), then it is conceivable that, for very well ventilated spaces, the fire will continue growing in a fuel-bed controlled state until all combustible material within the enclosure or compartment is either on fire, or has been completely combusted. In large, well ventilated compartments, it has been shown by means of large scale “natural fire” tests that the fire can “leap frog” to adjacent parts of the compartment and that by the time fire reaches combustible materials remote from the original initiation point, the fuel at the initial location has been completely used up. Under such circumstances, the air/gas temperatures within the compartment are likely to be significantly stratified and are unlikely to exceed 500 °C.

In most fire containment applications, however, it is unlikely that there is an adequate supply of air via “natural” ventilation to support a fire in a persistently “fuel bed” controlled state. In these circumstances, the destination of the effluent gases of combustion plays a crucial role in the further development of fire. Once hot effluent gases are being produced by a fire at a rate faster than can be vented from the space, these gases start to collect under the roof or ceiling, thus forming a hot gas layer. As the layer deepens and gets closer to the seat of the fire, the amount of “cold” ambient air drawn into the rising plume becomes less due to the shorter distance available for the plume to entrain the air.

Consequently, the degree to which the smoke products are diluted, and hence cooled, becomes less. This, in turn, increases the temperature of the smoke layer, which also tends to darken due to the increased density of smoke particles. As the magnitude of this temperature approaches 600 °C, the hot smoke layer is radiating significant quantities of heat in its own right and this energy is capable of causing pyrolysis, or even auto-ignition of combustible materials quite remote from the seat of the fire. This phenomenon marks the occurrence of flashover, and, once it occurs, all combustible materials within the enclosure rapidly become involved in the fire.

The fire now enters the post-flashover, or "ventilation" controlled state, which is characterized by turbulent "swirling" flames throughout the entire space in conjunction with large flames from ventilation openings where superheated unburned volatiles escape and burn in the open air. Once a compartment fire is burning in a post-flashover ventilation-controlled state, then temperatures within the compartment are quite likely to be of the order of 1 000 °C.

Whilst the fire-resisting elements of a structure provide a fire containment role during the "fuel-bed" controlled phase, they are primarily designed to provide fire separation with respect to a ventilation-controlled, post-flashover fire phase.

The objective of many fire engineering strategies is to delay or suppress the potential of flashover. This can be achieved by the introduction of suppression measures, e.g. sprinklers (the most common method), smoke exhaust and ventilation, control of contents and/or geometry of the space. Despite such controls, it is naïve to believe that the enclosure boundary, say to a protected stair, or to areas of a different risk category, needs to have no fire-separating abilities. Currently, the fire engineers have no way of determining or measuring the ability of a construction to withstand any condition other than that modelled by the standard fire-resistance test, which could represent an overprovision if the suppression system reliability is high.

As previously stated, it is important to recognize that with the change of lifestyle since the fire-resistance test was developed, there is frequent questioning of the validity of the standard-fire resistance exposure conditions. Few would question the validity of the current conditions for product classification periods, as the experiences of many decades have shown it to be adequate for environments where conventional furnishing materials have been used. Increasingly, though, the validity of the current exposure condition is questioned when using the outputs from a fire-resistance test in a fire-safety engineered strategy. If the rate of heating is increased, the temperature reached could be greater or the pressure could be varied. This Technical Report considers the practicality of changing the exposure conditions, what they should be changed to, and what form the output should take.

Similarly, ISO/TR 5925-1 represents only a limited number of fire scenarios due to the range of pressures and temperatures used in the test. It also measures only the leakage of doorsets, ignoring the leakage of many other forms of construction.

This Technical Report has been prepared to establish how the outputs generated by the tests developed and maintained within ISO/TC92/SC2, i.e. ISO 834 (all parts) test methods, can be modified in due course to support the design codes produced by the working groups of ISO/TC92/SC4, in support of the fire-safety engineering designs of buildings, e.g. ISO 13387, in its various parts.

The Technical Report is of value to the convenors of the working groups developing and maintaining fire containment test procedures. It is also of value in the interim period to fire-safety engineers who wish to understand the limitations of products tested to the SC2-generated test procedures. It is anticipated that further Technical Reports will be prepared giving recommendations to the various working groups as to how their standards, and in particular their criteria, can be improved to reflect the needs of the fire-engineering community.

Review of outputs for fire containment tests for buildings in the context of fire safety engineering

1 Scope

This Technical Report has been prepared in order to review whether the current ISO furnace-based fire resistance testing methods remain appropriate for establishing the performance of elements of structure when exposed to fully developed fire conditions in the context of a fire safety engineered strategy for a building. It identifies whether there is a difference between the data produced and the data required. Where there is, it reviews whether the test methods can be easily adapted to improve either the relevance of the test, or the output data, to make it more suitable for use in fire engineering applications.

This Technical Report reviews the mechanisms and routes of fire spread and identifies the criteria used for these tests to aid simple comparison and compares them with the conditions that can lead to fire spread or a loss of tenability for people in reality.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 834-1:1999, *Fire-resistance tests — Elements of building construction — Part 1: General requirements*

ISO 834-4:2000, *Fire-resistance tests — Elements of building construction — Part 4: Specific requirements for loadbearing vertical separating elements*

ISO 834-5:2000, *Fire-resistance tests — Elements of building construction — Part 5: Specific requirements for loadbearing horizontal separating elements*

ISO 834-6:2000, *Fire-resistance tests — Elements of building construction — Part 6: Specific requirements for beams*

ISO 834-7:2000, *Fire-resistance tests — Elements of building construction — Part 7: Specific requirements for columns*

ISO 834-8:2002, *Fire-resistance tests — Elements of building construction — Part 8: Specific requirements for non-loadbearing vertical separating elements*

ISO 834-9:2003, *Fire-resistance tests — Elements of building construction — Part 9: Specific requirements for non-loadbearing ceiling elements*

ISO 3008:—[1], *Fire-resistance tests — Door and shutter assemblies*

ISO 3009:2003, *Fire-resistance tests — Elements of building construction — Glazed elements*

1) To be published (Revision of ISO 3008:1976)

ISO 5925-1:1981, *Fire tests — Evaluation of performance of smoke control door assemblies — Part 1: Ambient temperature test*

ISO/TR 5925-2:1997, *Fire tests — Smoke control door and shutter assemblies — Part 2: Commentary on test method and test data application*

ISO 6944:1985, *Fire resistance tests — Ventilation ducts*

ISO 10294-1:1996, *Fire resistance tests — Fire dampers for air distribution systems — Part 1: Test method*

3 Executive summary and recommendations

The outputs from standard fire containment and structural fire resistance tests were reviewed and found to be of limited value to the fire safety engineering community when carrying out a performance based fire protection design analysis for a building.

The following revisions are therefore recommended to make the outputs of ISO 834-1 more meaningful in response to the needs of the fire safety/protection engineering community.

a) The deflection and the rate of deflection for beams and floors should be continuously measured and reported without any pre-judgement as to what constitutes failure. No time should be reported as representing failure with respect to load-bearing capacity as this would be defined by the design team or the legislation.

b) In the future, testing furnaces should be made larger. Floor beam/furnaces should be extended to 6 m span and wall/column furnaces should be increased to 4 m height. This allows new elements for which no design code exists, e.g. new materials and new composites, to be investigated more meaningfully.

c) Specimen support frames should be re-designed to permit known levels of restraint and fixity to be applied to specimens, thereby increasing the realism with respect to support conditions.

d) Large-scale testing of homogenous columns and beams should be abandoned in favour of mathematical solutions.

e) The cotton pad should be applied to all constructions whether insulating or non-insulating.

f) In the short term, the 6 mm diameter gap gauge should be modified to facilitate the measurement of labyrinth gaps.

g) The current cotton pad and gap gauges should be replaced by a single quantifiable method of measuring the total heat flux, including flow of heat, either globally (preferred) or locally.

h) The quantified method of evaluating the passage of flames/heat/gases should be able to be used with all elements, including ducts, dampers, glazing, etc.

i) A smoke and hot-gas leakage test apparatus should be developed for all vertical and horizontal separating tests.

j) All temperature data should be recorded continuously and reported as individual time/temperature relationships that should be given along with similar data for the mean and maximum temperatures. No failure time should be recorded.

k) The use of thermocouples should be replaced with an overall heat flux measurement system that can identify the area of max temperature rise.

l) Thermal imaging and associated temperature measurement should be investigated and hopefully introduced for all tests to supplement radiation measurements.

m) Radiation/heat flux measurements should be made and recorded for all separating elements using one or more water-cooled heat-flux meter(s). These measurements should be recorded continuously and included in the report.

n) In the longer term, a full gas-collecting chamber should be developed and installed in the front of all vertical separating elements, and/or over the top of all horizontal separating elements which incorporate continuous heat flux and gas temperature monitoring equipment.

The following revisions are recommended to improve the outputs of ISO/TR 5925-1 and ISO 834-4, ISO 834-5, ISO 834-8 and ISO 834-9 in recognition of the needs of the fire safety/protection engineering community.

a) ISO/TR 5925-1 should be amended to permit the determination of smoke leakage at ambient and medium temperatures of all vertical separating elements, not just doors and even including penetration and linear gap seals.

b) All detachments of material from the unexposed face of the construction should be reported, photographed and where possible a statement as to the hazard that they represent be expressed as part of the report.

The following general revisions are recommended to improve the outputs of all fire containment tests in response to the needs of the fire protection engineering community.

a) All tests should be recorded on high quality electronic medium (i.e. a DVD) that forms part of the report.

b) All aspects of the described construction that have not been quantifiably checked by the laboratory staff should be marked clearly by a symbol in the test report as being accepted “based upon manufacturer’s self-declaration”.

4 Mechanisms of fire spread

4.1 Routes and mechanisms of fire spread

There are many routes, both direct and indirect, by which fire can resist containment and thereby spread to adjacent enclosures, or spaces, with the attendant risk of secondary ignition and fire growth (see Figure 1). Many of these routes have already been identified by ISO TC92/SC4 in ISO TR 13387-6. The figures have been derived from the mechanisms and routes given in ISO TR 13387-6, and have been expanded and developed by the working group responsible both within the fire enclosure and within the adjacent spaces, including its susceptibility to secondary ignition.

The figures illustrate some of the more common routes for potential fire spread and identify the tests designed to control the spread. In many instances, it is also important that designers consider the potential for fire spread between two adjoining enclosures via independent spaces in addition to identifying direct routes. These routes of fire spread often represent a combination of direct spread routes and need to be considered as a series of separate direct spread mechanisms.

Ideally, all of the potential routes for fire spread from the enclosure need to be quantified and the time for fire spread to reach critical conditions should be determined. Any shortfall between this and the “required” time to resist fire spread should be addressed by enhancing the fire and smoke containment capability of the relevant element(s). However, design effort can be reduced in situations where expert judgement can identify those routes most susceptible to the rapid fire and smoke spread. It is important to remember that the determination as to whether or not fire spread takes place is influenced by the local environment.

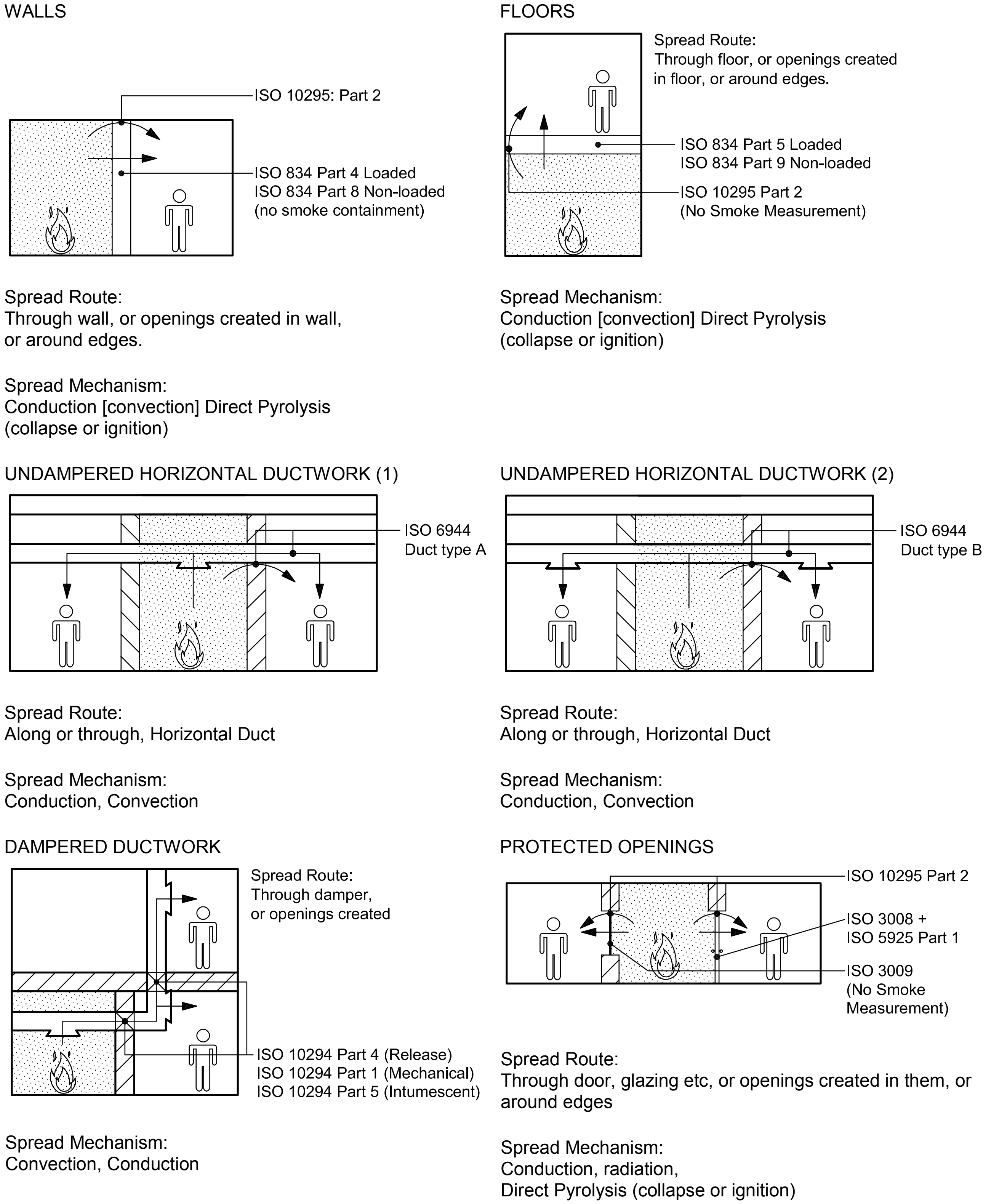
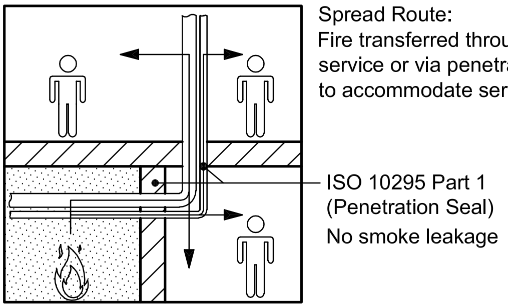


Figure 1 — Routes of fire spread and appropriate standards

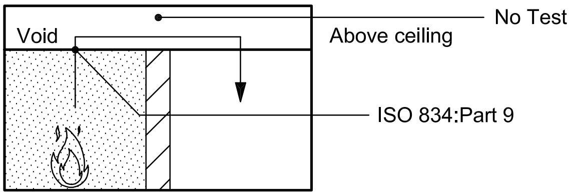
SERVICES (PIPES/CABLES AND SUPPORTS)



Spread Route:
Fire transferred through service or via penetration to accommodate service.

Spread Mechanism:
Complex including radiation, mass transfer, conduction

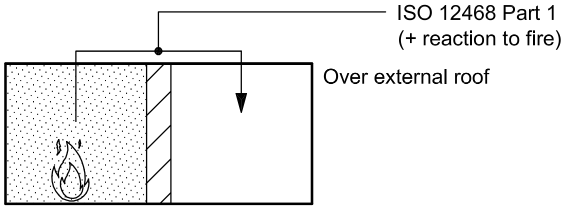
SUSPENDED CEILING VOIDS



Spread Route:
1. Enclosure to Ceiling void
2. Ceiling void to adjacent enclosure

Spread Mechanism:
Complex, including Pyrolysis,
mass transfer and conduction

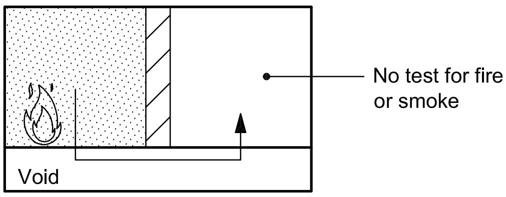
ROOFS



Spread Route:
1. Enclosure to roof
2. Roof to adjacent enclosure

Spread Mechanism:
Pyrolysis, radiation

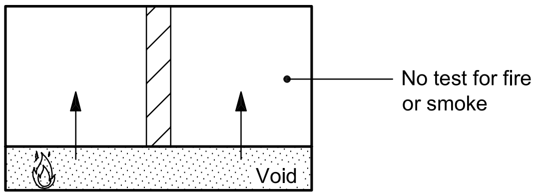
RAISED FLOOR VOIDS (1)



Spread Route:
1. Enclosure to floor void
2. Void to adjacent enclosure

Spread Mechanism:
Complex, including Pyrolysis, mass transfer
conduction and convection

RAISED FLOOR VOIDS (2)

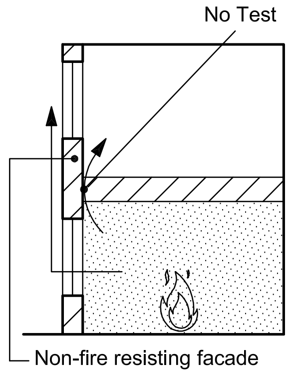


Spread Route:
1. Void to enclosure via floor

Spread Mechanism:
Conduction and convection

Figure 1 — Routes of fire spread and appropriate standards (*continued*)

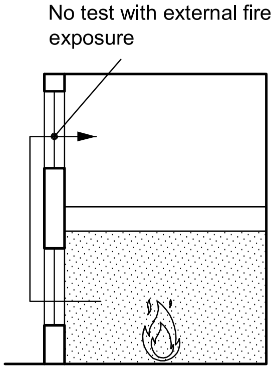
EXTERNAL WALLS/WINDOWS



Spread Route:
1. Enclosure to facade surface
2. Facade to adjacent enclosure

Spread Mechanism:
Complex, including Pyrolysis of surface.

EXTERNAL WINDOWS[a]

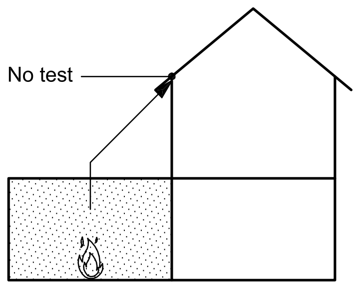


Spread Route:
1. Enclosure to outside
2. Outside to adjacent enclosure

Spread Mechanism:
Collapse, convection, radiation

[a] Can occur horizontally between windows in certain conditions.

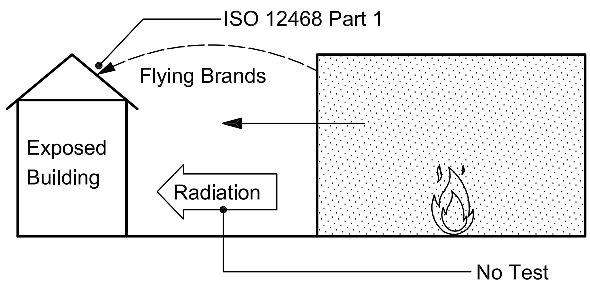
UPPER PARTS OF BUILDINGS



Spread Route:
1. Enclosure to roof outside
2. Roof flames through external envelope eg window

Spread Mechanism:
Pyrolysis (collapse/ignition) convection, radiation

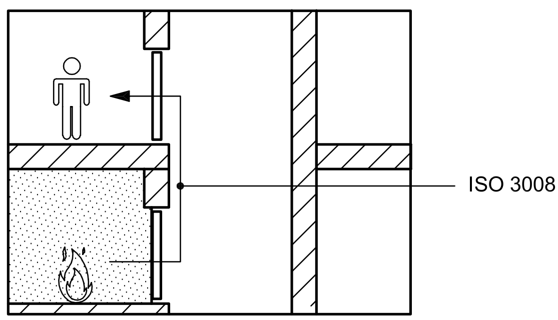
ADJACENT BUILDINGS



Spread Route:
Enclosure to space adjacent to enclosure

Spread Mechanism:
Complex, including radiation, mass transfer

LIFT SHAFT



Spread Route:
1. Enclosure to lift shaft
2. Lift shaft to enclosure

Spread Mechanism:
Convection, conduction

Figure 1 — Routes of fire spread and appropriate standards (*continued*)

4.2 Review of mechanisms leading to secondary fire initiation, fire growth and damage in adjacent areas directly related to the behaviour of the structure

In 4.2 is described, in some detail, the different mechanisms associated with failure of fire separating elements of structure that can be responsible for directly causing secondary fire development in spaces adjacent to the enclosure on fire. In all of the failure mechanisms considered, the effects are most severe when the fire conditions in the enclosure on fire are in a post-flashover, fully developed condition. It is this condition that is replicated in the fire resistance test.

4.2.1 Failure of an element

Complete failure of a separating element or structural member generally has a devastating influence on the conditions prevailing in an adjacent space. However, there are degrees of failure of such elements, all of which influence the tenability of an adjacent enclosure during fire; these are discussed in 4.2.1.1 to 4.2.1.3.

4.2.1.1 Collapse

The collapse of vertical elements has both a direct and an indirect influence on the safety of persons in adjacent spaces. The action of collapse causes large sections of the element, if not the element in total, to “topple” and fall. The direct consequence is that persons in or around the building, including fire-fighters engaged in fire fighting activities close to the perimeter of the building, can be directly hit by the falling structure. Indirectly, the loss of even part of a vital element, as a result of a collapse, allows the uninterrupted flow of combustion gases into the adjacent space leading to an attendant life threat that this represents.

People are not generally alive in the enclosure directly underneath a horizontal separating element, such as a floor, due to the temperatures that need to be reached to cause the collapse. But the people most at risk, and a very serious risk it is, are those persons who are on the element being attacked, either seeking escape, or being unaware of the fire’s presence. The convective heat release also makes conditions above untenable, as well as the obvious risk resulting from these persons falling due to the collapse.

There is an indirect risk to all persons in or around the building as a result of the collapse of a horizontal element, and that is the domino effect.

4.2.1.2 Excessive deformation

The role of deformation of the elements of construction in secondary fire initiation and spread has generally remained unrecognized. Only structural elements are adjudged by maximum deflection criteria and, even then, the degree of distortion permitted is not related to any critical level that could lead to a failure of containment, they are introduced purely as a furnace-protection measure.

The fire tightness (integrity) of an enclosure can be achieved only if the elements are either jointed together in a manner so that

- they cannot physically be separated,
- they cannot bow, or
- they bow in harmony, or else
- the method of jointing is able to accommodate any difference in the direction or magnitude of the bowing between the elements.

Deformation, therefore, leads to an integrity failure and assists in fire and smoke spread if they are not anticipated and accommodated or prevented at the design stage. This aspect has been addressed in an insurance code within the UK [1]. A decision tree incorporated within this guide is included in Annex A of this Technical Report.

Often, the only way that joints between elements can be controlled to maintain integrity is to provide the individual elements with higher levels of applied fire protection than that needed to satisfy any of the standard criteria; i.e., loadbearing capacity, integrity and insulation of the fire resistance test (see Clause 6), which has the effect of restricting deflections.

4.2.1.3 Physical degradation

Fire can exploit the boundary of an enclosure and generate secondary ignition as a result of the barrier physically degrading. Typical of such degradation is the conversion of timber to charcoal, the spalling of concrete, the calcining of gypsum, the exhaustion of intumescent barriers or the consumption of binders and the sintering of fibres in insulating slabs. Generally, these failures manifest themselves as gaps through which flames and hot gases can pass, causing direct secondary ignition (see 4.2.2) or insulation failure, where the unexposed temperature of the element can indirectly generate ignition (see 4.2.4).

However, a number of situations can arise where physical degradation can occur that allows parts of the element to become detached from the barrier and cause indirect ignition. In many cases, the detachment is directly on the unexposed face, but in some cases the problem can originate with materials on the exposed face that can flow or roll under the element and arrive at the unexposed face. There is a greater potential for such happenings on doors where there is a direct and obvious functional gap underneath the specimen. However, gaps can develop under many non-homogenous constructions, permitting a limited transfer of some materials, particularly liquids.

Types of physical degradation that can initiate fire spread on the protected face, but which are not identified as direct failure criteria, include the melting of some forms of plastic, low-melting-point metals, or damping fluids from closure mechanisms. The artificiality of the furnace testing environment often prevents such failure modes from being identified (see Clause 6). Uncontrolled floor covering can be ignited by a number of these mechanisms, but they are identified as a failure of the element against the existing criteria.

4.2.2 Flame penetration

Where through-gaps exist or develop in the barrier resulting from distortion, cracking or burn-through, there is the possibility of flames and hot gases penetrating the barrier. This can manifest itself in a variety of ways from small, candle-like flames to an ignition of the barrier and subsequent rapid spread, depending upon the material from which it is constructed.

Flame penetration can cause secondary fire initiation in two ways:

— by directly igniting combustible products or gases in the protected compartments, or

— by igniting the component materials of the barrier itself (see 4.2.3).

The first mechanism can occur when combustible materials are present within a short distance from the barrier itself, normally closer than 0,05 m (unless there is also significant radiation), or when a combustible gas or vapour mixture is present in the adjacent space. There is a critical amount and rate of application of such heat energy onto the material to initiate ignition and to support combustion. Where combustible gas mixtures and vapours are present, again, possibly being given off by the element itself, then the size of the flame is probably only of secondary importance.

4.2.3 Ignition of the surface of the element

Under test, ignition of the component materials forming the construction is often the cause of integrity failure of the barrier. The nature of the materials used in the manufacture of fire separating elements is such that, when this does occur, it is normally associated with heating the material to a temperature at which spontaneous ignition occurs, particularly if the materials used in the centre of the construction are highly conductive.

Whilst the integrity criteria of sustained flaming permits short-duration, transient flaming (see 6.2), i.e. flames of less than 10 s duration, without being deemed to be the cause of failure, the occurrence of such flames adjacent to linings/facings that are close to their spontaneous ignition temperature inevitably lead to ignition of the surface of the element.

Ignition of the surface of an element is, relative to the ignition of a cotton pad, an event that can have serious consequences in a fire. Even a thin combustible lining has the potential to ignite materials in close proximity to the surface, particularly if they are items of low thermal inertia. It is also likely that materials that do ignite on the unexposed face will become detached, either in part or in whole, and fall burning on the floor. The propensity of the floor covering to ignite, therefore, determines to some extent the magnitude of the hazard that ignition of the surface represents.

Burning on the unexposed face affects the tenability of the protected space in terms of thermal load, smoke production and density and the toxicity of the environment (see 4.3).

4.2.4 Heat transfer into the adjacent space

There are a number of mechanisms by which heat can be transferred into the adjacent space(s) and these are discussed in 4.2.4.1 to 4.2.4.4.

4.2.4.1 Conducted heat

Heat conduction is a feature in all types of material, but mainly represents an issue in solids. The mechanism of heat transfer by conduction is the transmission of energy through kinetic interaction between molecules forming the basic structure of the material. The thermal conductivity of materials varies widely. Metals tend to be good conductors of heat and non-metals, a poor conductor. Amongst the common metals, the best conductors of heat are silver and copper, whilst aluminium has about half the thermal conductivity of copper and iron.

Secondary fire initiation can be caused by heat being conducted through a barrier, which could result in ignition of the surface (see 4.2.3), or via an object, possibly a service or an element of structure, passing through the barrier and coming into contact with combustibles within the adjacent enclosure. The materials most likely to be ignited are timber or wood-based elements, such as joists, flooring or studwork, but electrical insulation to cables and services are also likely to be in contact and have the potential to ignite.

4.2.4.2 Convected heat

Items with a higher temperature than its surroundings, i.e. the air, loses heat to those surroundings by means of convection. Convection is the term used to describe the effect of heating a fluid (liquid or gaseous) transmitting medium, such as air, by conduction and radiation, which moves generally upwards as a result of the change in its density. Convection occurs at the unexposed surface of a fire-separating element as the heat conducted is radiated to the air adjacent to the surface, which increases the temperature of the air. This gives buoyancy to the heated air, which then rises causing a convection current as cooler air is drawn in to replace it.

A non-insulating fire-separating barrier that attains an unexposed face temperature of 600 °C within an area gives a total convected heat output of the order of 55 kW/m^2. Heat output of this magnitude is unlikely to produce non-piloted spontaneous ignition of solid materials due to convection in the short term.

The rise in temperature in an adjacent enclosure as a result of convection can have serious life safety implications (see 4.3.1). The temperature of air in a space 50 m^3 could rise to several hundred degrees Celsius in 5 min to 10 min, depending upon the thermal inertia and insulating nature of the adjacent boundary, which can influence the behaviour of some stored goods.

4.2.4.3 Radiated heat

The exact mechanisms of transfer of heat energy by radiation are extremely complex and rely upon physical properties of materials that often change during the heating-up process. For fire-engineering purposes, the emittance of radiation from most surfaces is treated as having diffuse directional characteristics that are independent of wavelength and temperature. In simple terms, the net heat transfer from a hot body to a cold body as a result of radiation can be considered as being proportional to the difference to the fourth power between the hot body and cold body temperatures. The magnitude of this heat flux is controlled by the relative emissivities of the bodies and also by their relative orientations and geometries (accounted for in calculations by configuration factors).

The emissivity of a surface is a measure of the efficiency with which a surface emits heat, rather than reflects it. A “black body” has an emissivity of 1,0 and reflects none of the heat radiation incident on it. Shiny metallic surfaces, such as stainless steel, on the other hand, have emissivities in the range of 0,05 to 0,2, thus reflecting 80 % to 95 % of heat radiation incident on them. All other steel surfaces discolour rapidly due to oxidation of the surface. Under a given received thermal radiation intensity, the temperature rise exhibited by a shiny metal surface is less than that exhibited by a non-metallic, organic or coated metal surface. Conversely, the magnitude of heat radiation emitted by a shiny metallic surface is less than that emitted by a non-metallic, organic or coated metallic surface at the same temperature.

A combustible surface at ambient temperature, positioned 500 mm from the centre of a rectangular “dull” metallic surface at a temperature of 650 °C, typically receives a radiative heat flux of approximately 25 kW/m^2, which is of a magnitude to cause the non-piloted ignition of cellulosics after a prolonged exposure. For some fire-resisting barriers, the situation is worse due to the use of fire-resisting glass, which is transparent to certain received wavelengths of energy under fire exposure but often becomes thermally “opaque” above a certain temperature. This transparency can raise the incident heat radiation on surfaces remote from the barrier. The received radiation intensity at 500 mm from the centre of a glazed screen is typically of the order of 50 kw/m^2 after 60 min exposure to the standard test for fire resistance. This level of radiative heat flux is sufficient to cause non-piloted ignition of timber in approximately 15 s.

Radiated heat from the fire-separating barrier also warms up the surfaces of any adjacent wall areas, floor areas and structural components that are within the protected environment exposed to the radiated heat flux. Consequently, the air within the protected zone is warmed by convection from these surfaces and, given the volume, geometry, construction and ventilation characteristics of the protected space, this increased heat flux needs to be quantified as part of the overall energy balance, since this can trigger the onset of secondary ignitions.

4.2.4.4 Hot brands

Hot brands are a recognized way by which heat energy is exchanged, particularly in external or wild fires. The mechanism consists of a part of the fuel source, or the building containing the fire source which is itself on fire, and the weight of which is less than that required to resist the upward thrust created by the convection current. In large fires with a high heat release, the plume of combustion gases has such strong upward air currents that it is possible for small items of combustible material to be carried up in the updraft, still burning, and be deposited in the surrounding area once the plume starts to lose its buoyancy.

The mechanism of burnt/decomposed material being taken up in the convection currents does not in itself turn them into brands. These items only become “brands” if they contain sufficient heat energy after they have left the convection current and fallen/landed on combustible materials that they can in themselves cause ignition. Experience suggests that in most cases there needs to be sufficient radiation being received by the surface that the brand has fallen onto for the residual energy to cause it to ignite. Effectively, the brand acts as a pilot light which reduces the temperature needed for an ignition to well below that required if the ignition were non-piloted, i.e., spontaneous.

Ignition by hot brands is a phenomenon normally associated with spread of fire from building to building, rather than from compartment to compartment, although if an internal separating element contains large uninsulated areas, e.g., metal shutters or non-insulating fire glass, then fire development in an adjacent compartment can develop if combustible materials forming part of the construction were to ignite and fall onto combustible furnishings or floor coverings.

Oil-damping fluids in overhead closing devices, whilst not strictly falling under the definition of hot brands, can cause secondary ignition of materials on the unexposed face if they ignite. Plastic ceiling panels, lighting diffusers, or even foamed plastic-cored sandwich panel ceilings adjacent to a fire barrier that is not fully insulating, can result in the dripping or dropping of flaming drips or debris.

4.2.5 Smoke damage

Problems associated with smoke leakage in life safety are discussed in 4.3. Smoke causes damage to property, both the fabric and the contents, if it spreads uncontained throughout the buildings(s) during a fire. The damage generally manifests itself in several ways:

— corrosion;

— contamination;

— odours.

Smoke damage can be as expensive to correct as fire damage itself.

4.2.5.1 Corrosion

The potential for the products of combustion to cause corrosion is directly proportional to the nature of the materials involved in the fire. In the modern structure, it is unlikely that there is a fire that does not involve plastic materials in this day and age. The products of combustion from many plastics will have a pH that is well on the acidic side of neutral and, as such, the smoke condenses on cold surfaces, and if these surfaces are made of untreated metal, then severe attack occurs. Hydrochloric acid condensates are commonly found in, and emitted by, PVC materials and acids as aggressive as this damage coatings and cellulosic material such as paper, card, books, etc.

Electronic equipment is normally destroyed by exposure to gases with a high acid or alkaline content. The modern office, being highly dependent upon electronic data storage and communications, is, therefore, very susceptible to levels of contamination that are likely to be produced from a fairly small fire.

4.2.5.2 Contamination

Unless the construction, or items/components within the structure can be cleaned soon after being exposed to smoke, they become increasingly harder to clean. Should smoke condense onto a surface, the particles adhere to it and, if these items experience an increase in temperature, the particles are baked onto the surface making them almost impossible to remove.

4.2.5.3 Odours

Even if the pH is relatively neutral, smoke consists of particulates that are deposited as the smoke cools, directly contaminating the surfaces. In some cases, e.g. for cellulosic or absorbent materials, this frequently results in staining. Unfortunately, the contamination is not always solely visible, but often leaves a distinct odour that is very difficult to eradicate.

The majority of the bi-products of smouldering combustion, especially in the period just prior to full development of the fire, are in the form of tars and resins, especially when wood is one of the materials that is likely to be burning. These tarry droplets contain much of the particulate matter that is the source of the odour in the fire and inevitably they condense out on the cooler surfaces in the protected space. Being “tarry” in nature, these adhere firmly to these surfaces and resist removal even by washing with water, unless it is in copious quantities, in which case there is likely to be significant water damage in lieu of fire damage.

The smoke odour can persist for intolerable durations both on the contents and the fabric of the building and is best prevented.

4.2.6 Compartmentation general

A fundamental principle of fire protection is to contain the fire to the smallest possible area. For life safety purposes, this should, in all cases, be a time-sufficient process to allow the building occupants to reach a place of safety. For property protection, containment is normally expected to function for the full duration of the fire.

Buildings are normally divided into a number of fire-resisting compartments, which can contain a number of individual rooms. Whilst individual rooms might not necessarily be intended to have fire resistance, they can still, for a limited period, contain the fire.

A problem encountered with existing fire-resistance tests is that measurements of integrity, which are designed to identify a failure to contain the hot gases, are based on a crude measurement of combustion gas leakage, using ignition of a cotton pad to determine if a defined point of "failure" is reached, or to determine if a defined gap size is exceeded. It is, therefore, impossible to directly use the data from fire-resistance tests in any computational simulation of fire spread once a flashover condition is reached at the compartment boundary.

This situation is complicated by having to use two different methods for determining the loss of integrity. The cotton pad evaluates insulated constructions. Uninsulated constructions are tested by using gap gauges. In practice, the development of conditions that can result in secondary ignition, fire growth and damage is the total heat flux received and the level at which it becomes critical is not dependent upon how the criticality is determined in the test. As a consequence of the method of measurement, however, the critical flow of hot combustion gases through, or around, an uninsulating element is much greater and hotter than that from, or around, an insulating element at the time it is deemed to have failed. In terms of the real risk to the protected space, this differentiation between construction forms is irrational.

Some passive fire-protection sealing systems can make a significant contribution to delaying the passage of smoke and hot gases into the next compartment. However, current testing methodology based on furnace testing cannot quantify this potential down-grading of the role of passive fire protection as a barrier for containing smoke.

4.3 Review of secondary indirect mechanisms threatening life safety

The life safety of persons in spaces/buildings adjacent to the one on fire can still be at risk as a result of indirect mechanisms of fire spread. These indirect mechanisms are considered below.

4.3.1 Heat build-up

The temperature of a protected space is likely to rise as a result of conduction and convection from the elements forming the enclosure on fire.

Persons within a space for any length of time can suffer injury solely as a result of heat, or thermal exposure, without being directly exposed to the flames of the fire. Such injuries result either from an increased body temperature, a state known as hyperthermia, or from breathing hot gases. As this is, therefore, critical to life safety, the fire-safety strategy needs to be able to quantify the thermal exposure that persons in the protected space can be subjected to. Information that can help to define the critical temperature of the environment can be found in B.2.

NOTE Additional information is being developed by ISO/TC92/SC4.

4.3.2 Radiation — Skin burn

Radiation from a separating construction can be harmful to the human skin. Exposure to radiant heat can be extremely painful. The human skin can tolerate only a certain level of heat flux for a certain time. The higher the heat flux levels, the shorter the tolerable exposure time. The high heat flux can cause skin burn or even worse, blisters and blackening of the skin. Burn wounds are very difficult to treat as the skin is deeply affected. When large areas of the human body are damaged by skin burn, it becomes more difficult to recover from the injuries. For these reasons, it is important that the fire engineer be able to quantify the tenability of the protected space with respect to this parameter. The life risk associated with radiation is explained in B.3.

NOTE Additional information can be found in publications produced by ISO/TC92/SC4.

4.3.3 Smoke

4.3.3.1 Toxicity

As mentioned above, “hot” air can cause death and serious injury, but the greater risk of death is likely to be as a result of exposure to toxic products within the combustion gases. Many products of combustion have been identified as being toxic, some of them in very small concentrations, but the by-product most likely to cause death and injury is carbon monoxide, CO. This is produced in almost all fire scenarios and is poisonous at fairly low concentration, its effect being accumulative in the body. As it is an odourless gas, people are not even aware of its presence, and it represents the largest risk to persons inside the enclosure of origin during the pre-detection period if the fire has been “smouldering”. However, CO can accumulate in protected spaces if smoke is able to get into them through unsealed gaps. In order to provide a protected space that remains tenable for the period needed, the fire engineer ideally needs to quantify the concentration of toxic gases. Information that can help to define the critical conditions is to be found in B.4.

NOTE Additional information can be found in publications by ISO/TC92/SC3, e.g. ISO/TR 13387-5[4].

4.3.3.2 Obscuration

The risk to life associated with obscuration due to the build-up of smoke is often underestimated. Dense smoke is capable of masking escape signs, even illuminated ones. Of more concern is the effect of causing disorientation, which has the inevitable result of persons not being able to see, and hence interact with common features in the building. Dense smoke has the capability of turning daylight into darkness when the smoke is contained within an enclosure. It has also been demonstrated that people hesitate to enter areas filled with dense smoke, even if it is signed as the designated escape route. Similarly, dense obscuring smoke seriously hampers fire-fighters engaged in search and rescue, or even fire-fighting.

The critical factors that can result in these problems in the space being protected is directly related to

- the density of the smoke in the enclosure of origin,
- the rate of smoke leakage through the boundary element,
- the volume and geometry of the protected space into which the smoke is leaking,
- the level of illumination within the protected space,
- the ventilation rate within the protected space,
- the buoyancy of the smoke leaking into the space,
- the design and construction of the barrier.

4.3.4 Load transfer

A catastrophic failure with respect to loadbearing capacity in a simple structure, i.e. a low-rise, single compartment building, has little indirect influence on the safety of others. A collapse in a high-rise structure or in a multi-compartmented complex structure can have more serious indirect consequences on others, depending on how the structure is constructed. The collapse of any floor beneath the uppermost floors of a high-rise building almost certainly causes a progressive collapse. In low-rise, multi-compartmented buildings, especially those built from panel systems, collapse in any compartment can cause a domino effect with disastrous consequences.

4.3.5 Other indirect mechanisms

Most of the indirect damage from fire exposure, in the form of spalling or falling debris, occurs on the exposed side of a fire barrier and, as it occurs only at very high temperatures, beyond that at which life can be sustained, it has very little consequence with respect to life safety. One exception is possibly with respect to horizontal glass at high level in a mall or atrium where people are escaping in the much cooler air at ground level below. Glass frequently shatters, not as a result of exposure to high temperatures, but when surface temperature differentials develop thermal strains in excess of the strength of the glass. This can occur at fairly modest glass temperatures, certainly where the gas temperature at high level would present no direct threat to persons many metres below. The result is that people below can well be exposed to falling glass, which, depending upon the degree of toughening, can fall as glass "granules" or "shards". Neither is desirable and can induce panic.

Whilst the more serious forms of spalling might not be life threatening for the reasons given above, they can cause such levels of damage to the structure that reinstatement can be much more difficult and hence expensive, or even rendered impossible. Similarly, whilst exposed metal might not cause collapse of the structure, it is likely to be permanently distorted following fire exposure, again requiring expensive refurbishment, even though there might not be any long-term influences on the ability of the structure to carry loads.

Cracking can also have serious implications on the ability of the structure to be reinstated, specifically if it affects

— the fire exposed structure as a result of direct thermal exposure,

— elements in the protected space as a result of being exposed to excessive loads due to thermal expansion from those elements forming,

— the fire compartment.

5 Fire resistance testing — Review of exposure conditions

5.1 Thermal exposure

5.1.1 Standard fire resistance tests

The thermal exposure (time versus temperature heating regime) used in ISO 834-1, is the basis for most national fire resistance procedures, even where a country does not adopt this method unadulterated. The thermal exposure is based on an air temperature measured nominally 100 mm from the fire-exposed face of the element, in either a vertical or a horizontal plane, which is varied with respect to time in accordance with the Equation (1):

$$T = (+)\ 345 \log10\ [8(t - 21) + 1] + 21 \qquad (1)$$

The mathematical relationship exists to help programme the control function, rather than having been derived from any specific predictive fire growth model. The relationship between time and temperature in the manner described by Equation (1) results in a curve with a very steep initial rise in temperature that slows down as time progresses, making a smooth transition into a near steady-state heating relationship. The resultant temperature/time curve is sometimes erroneously referred to as a "cellulosic" curve, but in fact its origins are almost accidental and owe their response much more to the ventilation conditions that exist in small, normally fenestrated enclosures than to the fuel being burned.

The fire test has subsequently been shown to reasonably reflect one of the parametric curves.

It can be seen from this heating curve that throughout the test the furnace environment continues to increase in temperature, albeit at a reducing rate, but at no time does the temperature decline.

On an international level, it can initially be assumed that there would be a high level of harmonization in the results of fire-resistance testing, given that the temperature/time relationship is based upon the same standardized conditions. Unfortunately, this is not the case. Large variations in the design and construction of the furnace chambers, the burner layout and type, and the thermocouples used for monitoring and indeed controlling the furnace-gas temperature all lead to the specimen receiving a variable thermal dose. With respect to furnace control, regrettably, "bead" thermocouples are not designed to measure air temperatures accurately and their response time varies in relation to the wire diameter, the “bead” dimensions and the degree of shielding the bead receives from any support tubes. This means that whilst the standardized exposure conditions are theoretically identical worldwide, there are large variations in furnace-gas temperature at any interval into the test due to variations in the testing equipment.

A recent attempt to harmonize the thermal exposure conditions has originated in Europe. This is the plate thermocouple/thermometer, which evolved in the CEN technical committee TC127. This device, which consists of a folded Inconel[2)] plate backed by an insulation board, has a larger thermal inertia and hence a significantly different time constant from the bead devices currently in use in some countries, the possible exception being the USA which has always used a heavy sheath to support the thermocouple. The principle of the “plate” is to measure the heat flux received by the specimen from all sources, rather than the gas/air temperature traditionally used.

5.1.2 Hydro-carbon fire resistance tests

The above temperature/time curve is primarily designed to nominally replicate the exposure conditions prevailing in a building provided with, possibly, a restricted supply of make-up air, which is subject to fully developed, post-flashover fire conditions. Practitioners have recognized that changes in the fuel and/or the ventilation conditions can result in more or less onerous exposure conditions. The petrochemical industry soon recognized the limitations of the standard curve and a number of “hydrocarbon” fire curves have evolved, all of them fairly similar. These are primarily used for evaluating the resistance to fire of constructions, such as off-shore drilling platforms and “on-shore” petrochemical process stations. The temperature/time relationships are expressed by means of an equation, such as Equation (2) for the hydrocarbon heating curve:

$$\theta_g = 1\,080\,(1 - 0{,}325\,e^{-0{,}167t} - 0{,}675\,e^{-2{,}5t}) + 20 \qquad (2)$$

where

θ_g is the gas temperatures in the fire compartment, in °C;

t is the time, in min.

Building designers and appraisers are actively discouraged in many guidance documents from using hydrocarbon curves for conventional building applications, but this is in the context of prescriptive legislation. The hydrocarbon temperature/time relationship is related more to actual contemporary anticipated exposure conditions than the ISO 834-1 curve.

5.1.3 Alternative exposure tests

An additional fire exposure has evolved from the work of CEN/TC127, namely the “smouldering curve”. This is designed as a conditioning pre-test for certain types of structural steel protection systems prior to exposing them to the standard conditions given in ISO 834-1 or EN 1363-1[9]. The “smouldering” temperature/time relationship is described by Equation (3):

$$T = 154\sqrt[4]{t + 20} \qquad (3)$$

This test has very little validity in practice and is only proposed for use as a product characterization test associated with classifying intumescent-based thin-film coatings. As before, the characteristics of the measuring device, e.g. whether the plate thermocouple or a bead thermocouple is used, affects the gas temperature being experienced by the specimen. It has been observed that the rate of temperature rise generated by this curve is more representative of a post-flashover fire, although the temperatures only rise to a level significantly below those that cause a flashover.

NOTE An external fire-exposure test had been published in ISO 834-2, which has been withdrawn.

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2) Inconel is an example of a suitable product available commercially. This information is given for the convenience of users of this International Standard and does not constitute an endorsement by ISO of this product.

5.1.4 Smoke-control door (and shutter) test

The smoke-control door test totally represents the conditions prevailing in the space immediately adjacent to the room in which fire is developing. There are two exposure conditions, ambient and 200 °C, described in a reasonably well prescribed manner that has more to do with the practicalities of heating the box than with any specific scenario that is being modelled. Once at temperature, the conditions are stabilized and, as in the ambient temperature test, all data are recorded at a constant but elevated temperature.

5.2 Pressure conditions

In ISO 834-1, a positive pressure differential is required to exist between the furnace atmosphere and laboratory atmosphere during the test for establishing the fire resistance of the element, particularly the integrity rating. The pressure in the furnace cannot be set at a standard, constant, even overpressure, but incorporates a pressure gradient, primarily as a result of density changes in the air/gas atmosphere due to the increased gas temperature, which generates buoyancy. Unlike the temperature/time regime, the level of overpressure is designed to mimic reality and the universal adoption of positive pressure differentials is only a recent phenomena.

In ISO 834-1, the pressure differential is stated in two ways.

— A neutral pressure axis is specified to be 500 mm above the bottom of a vertical specimen.

— A pressure differential is specified between the furnace atmosphere and the laboratory of 20 Pa at a position 100 mm from the top of a vertical specimen, or 100 mm below the soffit of a horizontal specimen.

All recommended mean values are given a tolerance of ± 2 Pa.

The stated pressure differential is related to a pressure gradient within the furnace, stated to be 8,6 Pa/m. This gradient is true only at one temperature, normally that which is reached just before the 30 min duration. At all other times, either the position of the neutral pressure axis or the magnitude and position of the maximum pressure differential is a compromise of the stated value.

When establishing the smoke leakage of door and shutter assemblies, leakage measurements are made over a range of pressure differentials (e.g. 10 Pa, 20 Pa, 30 Pa and 50 Pa), at both ambient and medium temperature. National regulations may specify the pressure differential but, as for the temperature conditions, ISO/TR 5925-2 fails to give the rationale that would guide the individual fire engineer to make the correct selection.

When dampers are tested for fire resistance it has a pressure differential of 300 Pa between the duct and the environment, a value that is selected in order to represent an air handling system with the fan left running.

5.3 Specimen size

The majority of fire resistance testing furnaces operate with a capability of testing vertical specimens of overall dimensions 3 m × 3 m and with horizontal specimens of 4 m span × 3 m width. In most cases, the elements are all tested in separate furnaces, although within Europe there are at least three furnaces capable of testing wall/floor combinations.

Whilst being used more for research purposes than for classification testing, there are a number of furnaces capable of evaluating specimens up to 5 m in width and at least one facility that is capable of testing 6 m floors.

5.4 Restraint conditions

For fire resistance testing purposes, the majority of all specimens are housed within a refractory-lined steel restraint frame. As a consequence, the restraint is of a simple nature and is generally unquantifiable. For vertical separating elements, the two vertical edges are treated separately, with one edge being free of restraint and the other edge being fully restrained with respect to in-plane and transverse movement. In the case of load-bearing elements, the top and bottom edges are subject to similar levels of restraint as the fixed side, but when a load is applied the top edge is "pin ended". Few, if any, of the furnaces currently in operation have the ability to measure or monitor the degree of restraint provided by the frames.

Under ISO 834 (all parts) conditions, horizontal constructions are invariably tested in a "simply supported" mode, which is very onerous for the construction. Horizontal frames do offer significant levels of stiffness with respect to lateral loads and it has been possible for research testing to apply some restraint to at least carry out an *encastré* end conditions. Allowance is, however, normally made to accommodate expansion rather than to restrain in-plane movement. When testing horizontal elements, invariably both lateral sides are free of both in-plane and transverse restraint.

It is known that some national fire-resistance tests, e.g. ASTM E119, using the standard exposure conditions, but not fully aligned with ISO 834-1 procedures, support the floors on all four edges.

When testing structural elements in isolation, tested beams are simply supported, invariably with roller support at one end to accommodate expansion.

It can be seen that none of the above forms and magnitudes of restraint is particularly relevant to constructions built *in situ*. Columns are tested with the bottom end fully restrained and with the top end "pin-ended".

It is established that changes are made to the effective length to reflect alternative end conditions.

5.5 Furnace turbulence

Currently, the design of a fire-resistance testing furnace has not been formally standardized. As a consequence, the methods by which the temperature/time relationship is achieved vary in almost every furnace. Both the inner dimensions of the chamber, the number of burners and the position of the burners have been allowed to vary significantly. Similarly, the fuel is not consistent, with both gas and oil being used for such tests. The thermal diffusivity of the furnace lining is also uncontrolled, albeit there is a recommended "target" that the lining should satisfy. There is also no control over the position or size of the exhaust ports. Both pre-mixed and nozzle-mixed burners are used producing even further variations in the nature of the heating regime.

As a consequence of the lack of control over the furnace design parameters, a great deal of variation is observed from furnace to furnace, which, with many constructions, cause differences in the fire-resistance rating achieved. As there is no "norm", the fire-safety practitioner has no awareness as to which rating is the correct rating, even under the nominal standardized conditions, let alone the rating appropriate for the building to which the result is applied. Variations in furnace turbulence are likely to be one of the main reasons for differences in performance, particularly for constructions that are either influenced in their thermal behaviour by air, or possibly erosion, e.g. cellulosic materials and intumescent coatings.

5.6 Atmosphere

Few, if any, furnaces have the ability to control the amount of air in the combustion gases during the test. The general recommendations are to ensure that there is an excess of oxygen when running with a non-combustible material, but as soon as the specimen incorporates any fuel, then this level of free oxygen drops dramatically. The rate of oxygen replenishment varies significantly depending upon the furnace and/or burner design. The amount of free oxygen obviously influences the consumption of cellulosic materials and, therefore, timber constructions burn at different rates dependant upon the availability of free oxygen. However, this influence is not very marked until very low levels of free oxygen are present.

Published research work[8], which utilized a fire-resistance testing furnace, has demonstrated that a modest amount of combustibles brings down the free oxygen to approximately 0,5 %. At this level, the char rate does decrease but only by a small percentage. During this same research programme, methods of enhancing the air supply into the furnace were investigated, but, unless the air could be pre-heated, it was almost impossible to maintain furnace temperature.

This work indicated that low levels of free oxygen are inevitable during most furnace testing.

5.7 Conditioning

5.7.1 Atmospheric conditioning

The condition of the structure, or the materials used in the construction being evaluated, is/are not always characterized adequately, although some national standards and procedures, e.g. those of the USA, are stricter than others. Test standards recommend certain levels of conditioning, i.e. conditioning down to equilibrium with the laboratory atmosphere, but there are inevitably seasonal and laboratory variations. Practitioners recognize that frequently test constructions are only completed just in time for the tests and testing often takes place without full specimen conditioning. Moisture content is measured where practical, but unfortunately encapsulated material, as is the case in many constructions, cannot be measured once the construction is complete.

As a consequence, without a full understanding of the condition of the tested construction, any variation in performance cannot be attributed to moisture content.

5.7.2 Chemical conditioning

A number of construction materials require a certain time to elapse before they reach their maximum strength or hardness. As for moisture content, the condition of cure is rarely adequately characterized at the time of performing the test.

5.7.3 Mechanical conditioning

Whilst most elements of construction are static in use, a number of them are moveable; e.g. dampers, fire-resisting door assemblies. Fire-resistance tests sometimes incorporate an operational test, but the performance of cyclic tests is generally left as a requirement of certification tests. As a consequence, the fire-resistance of such elements is established in the “new” condition.

5.8 Quality of construction

Constructions are invariably evaluated when freshly constructed. There is little evidence of any ageing or wear and tear. Some research testing is carried out, particularly with respect to the historical estate, but the information is not generally available in the public domain.

The method of construction invariably represents near-perfect manufacture if the test is performed solely for classification purposes. Test specimens are frequently constructed with painstaking care and with specially selected materials. Very rarely is sensitivity testing undertaken to establish how variations in the quality of construction influence the fire-resistance rating claimed for the product.

6 Fire resistance testing — Review of the current measurements and criteria

In addition to the exposure conditions, the test criteria in the current ISO test methods for fire-resistance have been identified in Clause 5. These should be more closely examined to ascertain their relevance to the various secondary fire growth mechanisms identified elsewhere in this report. Figure 1, where the direct and indirect routes of fire spread have been identified, also shows the test that is used to establish the fire containment capability of the element/construction.

It is obvious that the failure criteria of these tests have been established by the individual committees responsible for the test and these often bear no relationship to each other, nor to obtaining any particular level of tenability, or damage limitation in the space(s) outside of the enclosure of fire origin. Tables 1 to 3 list the test procedures used for quantifying the ability to prevent fire spread for the various routes given in Figure 1 and identify certain aspects of tests and the inputs and outputs from these tests to facilitate direct and rapid comparison of these criteria. Tables 4 to 6 present a comparison of failure criteria.

It is recognized that various national fire resistance tests draw heavily on the ISO 834 (all parts) procedure, but vary slightly in the details. These differences are not covered in these tables.

Table 1 — Comparison of test conditions for load-bearing elements

Test conditions	**Element and reference** (unless otherwise noted)			
	Load-bearing walls ISO 834-4:2000	**Load-bearing floors ISO 834-5:2000**	**Beams ISO 834-6:2000**	**Columns ISO 834-7:2000**
Furnace temp control				
Measuring device	Plate thermometers	Plate thermometers	Plate thermometers	Plate thermometers
Measurement frequency	Once per minute	Once per minute	Once per minute	Once per minute
Exposure conditions	Std t/T	Std t/T	Std t/T	Std t/T
Test pressure differential				
How measured	Specific pressure probes	Specific pressure probes	Specific pressure probes	Specific pressure probes
Measurement frequency	Continuously or at intervals not exceeding 5 min	Continuously or at intervals not exceeding 5 min	Continuously or at intervals not exceeding 5 min	Continuously or at intervals not exceeding 5 min
Differential pressure	ISO 834-1	ISO 834-1	none	none
N/Axis position	ISO 834-1	ISO 834-1	n/a	n/a
Load application (if appropriate)				
How applied	W, M or H[a]	W, M or H	W, M or H	W, M or H
Load determined	Actual properties, characteristic properties, code or specific use	Actual properties, characteristic properties, code or specific use	Actual properties, characteristic properties, code or specific use	Actual properties, characteristic properties, code or specific use
Support restraint				
Restraint conditions	One free edge	Simply supported, two free edges	Simply supported, two free edges	Rotationally restrained or hinged
Supporting/ associated construction	Supporting construction (when needed)	n/a	n/a	n/a
Restraint forces	Not measured	Not measured	Not measured as standard	Not measured

[a] W, M or H = Dead weights, mechanical or hydraulic, respectively.

Table 2 — Comparison of test conditions for non-load-bearing elements

Test conditions	**Element and reference** (unless otherwise noted)			
	Non-load-bearing wall ISO 834-8:2002	**Ceilings ISO 834-9:2003**	**Doors ISO 3008:—**	**Glazing ISO 3009:2003**
Furnace temp control				
Measuring device	Plate thermometers	Plate thermometers	Plate thermometers	Plate thermometers
Measurement frequency	Once per minute	Once per minute	Once per minute	Once per minute
Exposure conditions	Std t/T	Std t/T	Std t/T	Std t/T
Test pressure differential				
How measured	Specific pressure probes	Specific pressure probes		As per ISO 834-8 (vertical) As per ISO 834-9 (horizontal)
Measurement frequency	Continuously or at intervals not exceeding 5 min	Continuously or at intervals not exceeding 5 min	Continuously or at intervals not exceeding 5 min	Continuously or at intervals not exceeding 5 min
Differential pressure	ISO 834-1	ISO 834-1	ISO 834-1	20 ± 3 Pa (vertical)
N/Axis position	ISO 834-1	ISO 834-1	ISO 834-1	0,6 ± 3 m (vertical)
Load application (if appropriate)				
How applied	n/a	n/a	n/a	n/a
Load determined	n/a	n/a	n/a	n/a
Support Restraint				
Restraint conditions	One free edge	Simply supported, two free edges	Supporting construction fixed edges. Associated free edges?	Vert: 1 free edge Horiz: s/s plus 2 free edges
Supporting/ associated construction	Supporting construction (when needed)	n/a	Standard supporting or associated construction	Supporting or associated construction
Restraint forces	Not measured	Not measured	Not measured	Not measured

Table 3 — Comparison of test conditions for smoke doors and services

Test conditions	Element and reference (unless otherwise noted)		
	Smoke doors **ISO/TR 5925-1:1981** **ISO 5925-2:1997**	**Ducts** **ISO 6944:1985**	**Dampers** **ISO 10294-1:1996**
Furnace temp control			
Measuring device	Bare wire t/c	Bare wire t/c	ISO 834-1
Measurement frequency	Not specified	Once per minute	ISO 834-1
Exposure conditions	20 °C and nom 7°/min to 200 °C	Std t/T	Std t/T
Test pressure differential			
How measured	Suitable instrument	?	Suitable instrument
Measurement frequency	Continuously		Not specified
Differential pressure	10 Pa/20 Pa/50 Pa	20 Pa with lab 300 Pa with duct	Positive over damper and up to 300 Pa to intermittently
N/Axis position	Below specimen	Below specimen	n/a
Load application (if appropriate)			
How applied	n/a	n/a	n/a
Load determined	n/a	n/a	n/a
Support restraint			
Restraint conditions	n/a	Duct expansion restrained	n/a
Supporting/associated construction	Supporting or associated construction	Supporting or associated construction	Standard supporting or associated construction
Restraint forces	Not measured	Optional	Not measured

Table 4 — Comparison of failure criteria for load-bearing elements

Failure criteria	**Element and reference** (unless otherwise noted)			
	Load-bearing walls ISO 834-4:2000	**Load-bearing floors ISO 834-5:2000**	**Beams ISO 834-6:2000**	**Columns ISO 834-7:2000**
Integrity				
Cotton pad	Yes	Yes	n/a	n/a
Flaming	Yes	Yes	n/a	n/a
Gap gauges	Yes	Yes	n/a	n/a
Leakage rate	No	No	n/a	n/a
Others	-	-	-	-
Insulation				
Maximum temp rise	180 °C	180 °C	n/a	n/a
Mean temp rise	140 °C	140 °C	n/a	n/a
Loadbearing capacity				
Maximum temp rise	No	No	?	?
Deflection rate	?	?	?	?
Deflection max.	?	?	?	?
Radiation				
Measured	Yes	No	n/a	n/a
Criteria	No	No	n/a	n/a
Smoke leakage				
Criteria	No	No	n/a	n/a
Observation	Yes	Yes	n/a	n/a
Smoke production				
Criteria	No	No	No	No
Observation	Yes	Yes	No	No

Table 5 — Comparison of failure criteria for non-loadbearing elements

Failure criteria	**Element and reference** (unless otherwise noted)			
	Non-load-bearing wall ISO 834-8:2002	**Ceilings ISO 834-9:2003**	**Doors ISO 3008:—**	**Glazing ISO 3009:2003**
Integrity				
Cotton pad	Yes	Yes	No for uninsulated	No for uninsulated
Flaming	Yes	Yes	Yes	Yes
Gap gauges	Yes	Yes	Yes	Yes
Leakage rate	No	No	No	No
Others	-	-	-	-
Insulation				
Maximum temp rise	180 °C	180 °C	n/a or 180 °C/360 °C	n/a or 180 °C
Mean temp rise	140 °C	140 °C	n/a	n/a
Loadbearing capacity				
Maximum temp rise	n/a	n/a	n/a	n/a
Deflection rate	n/a	n/a	n/a	n/a
Deflection max.	n/a	n/a	n/a	n/a
Radiation				
Measured	Yes	n/a	Yes	Yes
Criteria	No	n/a	No	No
Smoke leakage				
Criteria	No	No	No	No
Observation	Yes	Yes	Yes	Yes
Smoke production				
Criteria	No	No	No	No
Observation	Yes	Yes	Yes	Yes

Table 6 — Comparison of failure criteria for smoke doors and services

Failure criteria	**Element and reference** (unless otherwise noted)		
	Smoke doors ISO/TR 5925-1:1981 ISO 5925-2:1997	**Ducts ISO 6944:1985**	**Dampers ISO 10294-1:1996**
Integrity			
Cotton pad	No	Yes	Yes[a]
Flaming	No	Yes	Yes[a]
Gap gauges	No	No	Yes[a]
Leakage rate	Yes	Not measured	200 °C/360 °C[a]
Others	-	-	-
Insulation			
Maximum temp rise	n/a	180 °C	180 °C[a]
Mean temp rise	n/a	140 °C	140 °C[a]
Loadbearing capacity			
Maximum temp rise	n/a	n/a	n/a
Deflection rate	n/a	n/a	n/a
Deflection max.	n/a	n/a	n/a
Radiation			
Measured	n/a	No	n/a
Criteria	n/a	No	n/a
Smoke leakage			
Criteria	Yes	No	?
Observation	n/a	No	Yes
Smoke production			
Criteria	No	No	No
Observation	No	Yes	Yes

a Dampers are rated E,ES, EI and EIS and not all criteria apply to all types.

The primary test criteria that apply to separating elements are integrity (including collapse) and insulation. These refer to the element's ability to resist the passage of flames and hot gases (to remain "impermeable"), and to restrict heat transmission (by any mechanism) through its structure, respectively. Load-bearing constructions are also monitored for "load bearing capacity" but as this criterion includes "collapse", which is an ultimate state loss of integrity; it is the only aspect that is relevant to the element's separating function. Currently, the test is terminated upon the deflection reaching "critical" deflection levels, or deflection rates. The relevance of these is discussed in 6.1.

Both integrity and insulation are monitored during the fire resistance test, either by observation or by automatic recording equipment. Integrity is monitored wholly by observation, with the assistance of manually applied equipment to indicate pass or failure in a non-qualitative manner. Insulation is monitored using thermocouples, either fixed to the specimen with output continuously recorded, or manually applied and recorded.

6.1 Loadbearing capacity

The criterion of load-bearing capacity is an ultimate-failure state signified by collapse. The fire resistance test procedures set a limit on the amount of, or the rate of, deflection that is taken to the time at which load-bearing capacity is lost, but which, in practice, is a criterion set to protect the furnaces from the damage resulting from a structural collapse. The levels selected, $L^2/400d$ mm or $L^2/9\ 000d$ mm/min (where L is the span of the element and d is the depth of the member/element), are considered to be close to the onset of collapse for horizontal elements and if the test were not to be terminated upon reaching these deflection limits, it is believed that collapse would occur soon after. With simply supported, load-bearing elements, this can be a valid concept, but it might not be true for other end conditions where higher levels of restraint can exist.

It is a limitation of most fire-resistance testing performed for classification purposes that the majority of load-bearing tests are performed simply supported. This is primarily because of the difficulty of providing realistic levels of end restraint within the type of test frames used in testing laboratories. The results achieved by elements constructed from “simple” materials, which are the subject of national design codes, can generally be extrapolated to establish how much better they would be had specific levels of restraint been applied. For composites, or non-code-led materials, however, the safety factor in any result is not known if the evidence generated is established in a simply supported manner and the test is terminated prematurely. For “new” materials and composites, the early termination of the test against some arbitrary level denies the structural or fire-safety engineer any knowledge as to the mode of failure. This is a critical parameter for any designer and understanding the “hot” behaviour is important, and it is ironic that the need to protect furnaces can result in such an important item of knowledge being lost.

The load-bearing failure criterion for vertical elements is even more arbitrary than those used for horizontal elements. In the case of vertical elements, the major axis of deflection is at right angles to the direction of load, unlike horizontal elements where maximum deflection is normally in the same plane as the load direction.

The standard criteria are $C = h/100$ mm or $3h/1\ 000$ mm/min [where C is the contractor (axial) and h is the height of the element], which, like the limit for horizontal elements, is meant to indicate the imminent collapse of the element. There is an additional consideration in setting such limits and that is in recognition of the difficulty of maintaining the application of load over significant distances of travel.

In practice, with conventional materials that do not exhibit high levels of “plastic” deformation, the limits set normally do indicate a near-collapse state. As with horizontal elements, the end conditions are normally pin-ended or with very low levels of restraint.

6.2 Integrity

The determination of the time of integrity failure is, as has been stated above, identified by observation. Laboratory staff monitor the face of the specimen for gaps or fissures that exist, or can have opened up, or for sustained flaming on the specimen’s non-exposed face.

Sustained flaming is defined as being in excess of 10 s. Transient flaming for shorter periods is disregarded as a criterion, albeit it is capable of igniting a cotton pad if the transient flaming occurs during an application of the pad described later. The significance or criticality of any gaps that have opened in the specimen is determined by the use of various types of manually applied equipment, measuring either the gap’s size, or the ability of any hot gases to pass through the gap to possibly ignite combustible material on the unexposed face or otherwise present in its vicinity. Details of the equipment and methods used are given in the Table 7 below:

Table 7 — Comparison of integrity criteria

Failure mode	Equipment	Failure indicated by
Sustained flaming	Monitored by eye, timed using a suitable timing device.	Flaming on the non-exposed face of the specimen adjudged to be continuously alight for > 10 s
“Cotton pad” failure	100 mm square pure fibrous cotton pad, held 25 mm from the specimen by a wire frame.	Ignition (flaming or smouldering) of the pad within up to 30 s of application to the specimen’s non-exposed face **CAUTION — The cotton pad shall not be used on non-insulating areas of specimens where temperatures in the vicinity of its application exceed 300 °C, because of the risk of spontaneous non-piloted ignition.**
Gap failure: 25 mm diameter	25 mm diameter steel rod, mounted on a handle.	The steel rod can be passed through any gaps in the specimen, into the furnace, without using “undue force”.
Gap failure: 6 mm diameter × 150 mm	6 mm diameter steel rod, mounted on a handle.	The steel rod can be passed through any gaps in the specimen, into the furnace, without using “undue force”, and moved a distance of 156 mm (to ensure measurement of 150 mm × 6 mm gap).

One of the most important factors to note from Table 7 is that the cotton pad integrity test shall not be used on constructions that are not designed to provide any insulation (in fire resistance terms), and its use shall be discontinued on all specimens when the temperature in the vicinity of any gaps exceeds 300 °C. After the use of the cotton pad is discontinued, the only modes of failure are through-gaps that are in excess of the permitted dimensions, or by sustained flaming on the unexposed face.

There are a number of areas of uncertainty with respect to the criteria of integrity that are important to address if the leakage method is to be given credibility by the fire engineering community. The reliance on observation to monitor for integrity is of concern. The hot-gas leakage from a furnace test has various levels of luminosity depending on the nature of the fuel and on the specimen being tested. If a furnace is gas fired and is set up to achieve maximum fuel efficiency and if the construction is non-combustible, any gas leakage will have low luminosity and be difficult to detect. Similarly, the visibility of these gases, and hence their ability to be observed, is very dependent upon the ambient lighting levels in the laboratory.

Many gaps require a good view of the specimen, especially when normal to the surface, and, as a consequence, the orientation and access to the specimen influences the ability to observe gaps that should be monitored by the hand-held equipment. There are practical as well as health and safety implications in monitoring horizontal specimens, 4 m × 3 m, for compliance with integrity by means of the cotton pad or the gap gauges, thereby reducing the confidence level in the findings.

The need for gap gauges to pass through the specimen, from the unexposed face to beyond the heated face before failure can be deemed to have occurred, makes the criteria, as measured by this device, fairly irrelevant. Large gaps can exist within or at the perimeter of the construction, but if the gap is of a labyrinth design, it is impossible to pass the gauge through it. As a consequence, high levels of convective gas flow can pass through such a gap, possibly leading to the development of untenable conditions in any enclosure adjacent to the one on fire, but which do not register as an integrity failure under the test.

Because the gap gauge is often used only after the cotton pad has been abandoned due to the surface temperature being in excess of 300 °C, i.e. approaching the short-term spontaneous ignition temperature of cellulose fibres, there is a serious problem of applying the gap gauge due to the heat flux being experienced by the operator. When testing large areas of uninsulated glass and on uninsulated doors and roller shutters, great difficulty is experienced when trying to use the gauges, especially in trying to establish whether the thinner gauge can be moved by more than 150 mm or not.

6.3 Insulation

Insulation performance is monitored by means of thermocouple temperature sensors, comprising a thermocouple wire formed into a measuring junction on the face of a thin, 12 mm diameter copper disc. Some of these thermocouples are fixed to the face of the specimen in pre-determined positions to establish the mean temperature rise, being retained and completely covered by non-combustible insulating pads. Other thermocouples may be fixed in place at the discretion of the testing authority to monitor positions of maximum anticipated temperature rise. Other hand-held thermocouples attached to a portable measuring device are also applied to the surface. Failure is deemed to have occurred when either the mean temperature of the specimen rises in excess of 140 °C above the initial mean surface temperature, or the measured temperature of any point rises more than 180 °C above the initial mean surface temperature.

The mean surface temperature is generally monitored by means of five fixed thermocouples, arranged one at the centre of each quadrant and one at the nominal centre of the specimen. The maximum temperature rise can be monitored by any of the fixed thermocouples or by the portable thermocouple. The application of thermocouples on or near any positions of potential integrity failure or where, during the test, hot gases from the furnace can play upon them, is not permitted; the results should not be taken into account if the thermocouple has been so heated.

If integrity failure occurs before insulation failure, then insulation failure is deemed to have occurred simultaneously with integrity failure.

As stated earlier, pre-selection of the measuring point is one of the major areas of uncertainty when considering unexposed face temperature measurements. It can be easy to identify obvious “thermal bridges” and to fix thermocouples in these positions. However, where the construction is more homogenous, but where variation can occur, e.g. mineral fibre, then there is an element of luck as to whether the hottest parts of the unexposed face are measured or not. This is not providing the level of confidence that a fire engineering practitioner needs.

The accuracy of the reading depends upon surface contact between the copper disc and the specimen surface. Even on a nominally “smooth” surface, this is going to be variable and on a rough surface the measurements are very unreliable. Whilst the disc is retained by the pad and the method of fixing the pad varies among pins, staples, adhesives, etc., all of these can locally influence the temperature of the surface being measured.

Variations in contact quality, pressure, surface irregularities and operator skills can make any measurements made by means of the roving thermocouple highly unreliable. Very rarely does the roving thermocouple provide a steady reading and there is invariably a “lag” between readings made with the device and those made with the fixed thermocouples.

6.4 Radiation

The measurement of the radiant heat flux emanating from the face of non-insulating (or partially insulating) constructions is a criterion of failure in the national codes and legislation in some countries.

Radiant heat flux tends to be measured by means of restricted view “radiometers”, normally water-cooled, restricted-view heat-flux meters. These are set up with their angle of view circumscribing the area of the test specimen and their output is normally continuously recorded.

Observations of the general behaviour of the specimen during the test, measurements of the distortion of non-load-bearing test specimen, and measurement of the temperature within the specimen interior, are some of the more common examples of such additional data.

Such instruments generally exhibit poor reproducibility due to

— overheating,

— discolouration of the monitoring surface,

— misalignment in-service,

— damage,

— their need to be frequently re-calibrated if their output is to be relied upon.

It is necessary for the heat-flux meters to be water-cooled in order for them to be able to give repeatable and reproducible readings. If the water supply is interrupted, or the flow drops significantly, then very significant errors in measured values result. Discolouration reduces the efficiency of the receiving surface. Misalignment changes the geometry of the receiving surface, relative to the specimen, which reduces the output.

Another problem is whether the view-restricting shield is itself cooled. This means that, although the figures given in test reports may be used to approximate the amount of heat radiation given off by a specimen, the procedures and equipment need further refining if they are to be used with confidence in any fire engineering analysis.

6.5 (Hot gas) leakage

Currently ISO 834-1 does not include any leakage criteria. There is, therefore, no control over the leakage of gases until they become hot enough and flow sufficiently to ignite the cotton pad, which forms the basis of the integrity criterion. Even then, if the unexposed face temperature is in excess of 300 °C, then the cotton-pad test is not used because of the possibility of it spontaneously igniting as a result of radiation. Therefore, on non-insulating constructions, the flow of even hotter gases can be tolerated as long as the deflection is not excessive, e.g. so as to allow a metal rod to be passed through the specimen. There is, therefore, currently no failure in respect of the passage of hot smoke and combustion gases.

6.6 Other data collected

In addition to the criteria described in 6.1 to 6.5, other information is collected during the test. Whilst these additional data have no direct bearing upon the specimens' "rating" in terms of integrity or insulation failure, it is presented as ancillary information for use in assessments and/or extended application reports and may be used, in an ad-hoc way, in support of a fire-engineering-generated safety case.

Visual observations of the behaviour of a specimen are made by the laboratory staff. These may include comments on the deflection/distortion of the specimen, behaviour of individual components, the amounts of smoke produced, discolouration of surfaces and other indicators of pending integrity or insulation failure. These observations are subjective and extremely operator-dependent. The quality, frequency and relevance of such observations are very variable.

Photos forming part of the report should be presented as .jpeg- or .tiff-formatted files and the report containing such pictures should be in .pdf format before being issued to a wider audience.

6.6.1 Deformation

For non-load-bearing constructions, distortion measurements are often not mandatory and the points of measurement vary from laboratory to laboratory, if they are performed at all. The measurements are taken in a variety of ways, ranging from the attachment of taut wires connected to transducers, to measurements taken by eye against a fixed datum. It is important to select fixed measurement positions with experience of the known distortion of similar constructions. Generally, the more measurements that can be accurately taken the better. Manual measurements permit the collection of data from many points but at fairly long intervals, whilst the deflection transducers provide continuous data but tend only to be used at a few pre-determined points on the specimen.

A further problem associated with manual distortion measurement is that measurements can only be made whilst the safety of the person doing the measurement is not compromised (by radiant heat or due to imminent collapse of the specimen). With non-insulating constructions, measurements can normally be taken manually (by suitably protected personnel) for up to 30 min on non-insulating steel doors, or 10 min on constructions with large areas of non-insulating glass. The limit normally corresponds to a radiant heat flux of about 5 kW/m^2 at a distance of 1 000 mm from the specimen.

6.6.2 Boundary conditions (thermal actions)

There are no attempts to quantify the levels of restraints to expansion provided on the fixed edges, apart from an instruction with respect to vertical separating elements to have one edge unrestrained, and, in the case of horizontal separating elements, for the two long edges to be unsupported (both in order to maximize the field of application of the test result). There are certainly no criteria with respect to the maximum restraint on the forces generated at the edges by the construction being tested, either within the plane of the specimen or normal to it. Whilst there is no recommendation to test horizontal elements simply supported because it represents a worst case test condition, the use of simply supported end conditions is the “norm”.

As a consequence, in routine fire-resistance testing, nothing is learnt with respect to the forces generated at the ends or edges of constructions due to thermal action or, more importantly, the strength required from the surrounding supporting construction to resist them in a real fire.

6.6.3 Significant changes to the specimen

There is a general instruction to record all significant events that occur to a specimen during a test and to report them. Unfortunately, what constitutes a recordable event is qualitative and, therefore, there is no consistent policy with respect to what is significant. As the observations are subjective in nature, generally laboratory accreditation bodies prefer that such non-quantifiable matters are not reported or kept to an absolute minimum. Sponsors of tests are equally not supportive of statements being included in a report that are not directly related to one of the failure criteria or recommended measurements. Events that happen on the hot, exposed face are frequently not reported despite their potential importance in any post test analysis. Generally, monitoring is restricted to the unexposed face behaviour.

6.6.4 Residual load-bearing capacity

The ISO 834 (all parts) test procedure does not require any determination of the residual strength of the element that has been tested. This situation exists in order to encourage testing being continued until complete failure of the element has been achieved. By taking the element to this end-point, the designer gains knowledge of the most likely mode of failure, which could, and should, form part of the report. To the responsible designer, such knowledge is invaluable. It is normal to apply a safety factor to the duration for which the criteria was met, which could pre-empt the onset of failure, but care should be exercised in this approach as the test is not designed to directly imitate reality.

In some countries, national test methods based upon ISO 834 (all parts), e.g. the hose stream in the USA (ASTM E119), do continue to have some form of residual strength test, albeit the strength is not quantified. What is known is that the specimen was strong enough to resist the specified pressurized jet of water in the direction it was applied.

6.7 Pre-test and post-test measurements and observations

The degree of specimen characterization, and hence the level and accuracy of the information on the construction that is reported is quite variable. There is no consistent way that such information is reported, leading to further discrepancies in reproducibility and the establishment of the field of application. Such information is vital to those bodies drawing up the field of application of the test results and standard methods of reporting should be developed.

Rarely is there a post-test analysis of the state of the construction, again because, unless it is carried out in a consistent manner, it can result in subjectivity and differences between testing authorities.

7 Comparison between exposure conditions used in the test and conditions likely to prevail in a real fire and recommendations for changes to the test procedures

7.1 Thermal exposure

The defined furnace thermal exposure outlined in 5.1.1 does not claim to reflect any current particular exposure conditions, albeit the exposure conditions currently used are primarily historic and can have, when first drawn up, reflected more accurately the conditions that might have prevailed in dwelling houses at that time. Certainly changes in life style, furnishing materials and build forms, mean that it is now definitely less representative of a typical “modern” fire scenario.

Almost all of current understanding of how various forms of constructions perform under fully developed fire exposure is based upon the temperature/time exposure conditions as given in ISO 834 (all parts). It is frequently stated that the test has only one purpose and that is to “rank” constructions/materials against each other under “identical” conditions that allow easy comparison. The fact that the failure times recorded bear no relationship to the anticipated failure duration in practice is not thought to be a matter for the test but more of an issue with respect to the durations assigned to various perceived risks in national building codes that call upon the test as a method of justifying the construction/materials to be used.

It is important to question whether code officials know how to set times in legislation that are “adequate” when the link between the standard thermal exposure and real fire exposure conditions is not known. There is a general recognition that contemporary fires are hotter than the standard exposure, assuming no lack of oxygen, and they probably have a greater rate of temperature rise than that currently used in the test. In the modern world, many of the materials that are used in construction are temperature-sensitive, and the continued use of an exposure condition that could be several hundred degrees cooler than those that are likely to be experienced in a real fire can be questionable.

As stated in 5.1.1, the standard time/temperature exposure relationship used in fire-resistance testings shows a continuously rising temperature with respect to time with no discontinuities in the increase in temperature. In “real” fires, the heating rate is commonly interrupted as a result of a shortfall in air supply. This can often cause a fire to self-extinguish or at least to stay in a ventilation-controlled state, but often the temperature in the enclosure can stop rising or even decline until there is a fresh input of oxygen, at which time the temperature rises rapidly again towards flashover. This change in temperature is of little consequence to traditional forms of construction, but interrupted heating can induce cracking, fracture or spalling in a range of contemporary materials, such as some fire-protection boards and many glasses. The use of continuously increasing thermal exposure needs to be questioned for all applications.

ISO 834-1 introduced a new form of thermocouple for measuring the furnace temperature in 5.1.1. This has had two major effects.

- The actual gas temperatures within the furnace are much higher than was previously reported with the original sheathed or beaded thermocouples due to the thermal inertia of the measuring device. This effect is predominant during the first 20 min of the fire test, but subsequently the two measurements converge so that after 35 min the differences are minor.
- The measuring of time/temperature conditions has been changed significantly, meaning that all previous historical data are no longer comparable with that produced to the latest version.

The loss of historical data on the way elements of construction perform was always a major consideration when considering revisions of the fire curve to reproduce more meaningful exposure conditions.

It should be noted that respective national standards have often used thermocouple devices different from those specified in the existing ISO 834 (all parts). As a consequence, all had different thermal inertias and gas temperatures were never truly comparable on a country to country basis, unless the test had been fully instrumented in accordance with ISO 834-1. Fire engineers have become aware of the different levels of performance registered in national tests and some of this might well be due to the measuring devices or the method of support.

NOTE If a change in the thermal exposure conditions is contemplated, then this is a suitable time before an enormous store of data is generated using the new plate thermometer.

An alternative time/temperature curve, frequently referred to as the hydrocarbon curve and referenced in EN 1363-2[10], has been developed for the petrochemical industry (see 5.1.2).

NOTE This was originally given in ISO 834:1975, which has been withdrawn.

The hydrocarbon curve differs from the standard curve in two ways.

a) The rate of temperature rise at the start of the test is greater and reaches higher temperatures quicker.

b) The maximum temperature reached during a one-hour test is significantly higher than in the standard test.

The hydrocarbon time/temperature curve can reflect more accurately the temperatures that are likely to be reached in a fuel-bed-limited fire when modern materials are involved and adequate ventilation rates are available. The rise in temperature, however, is unique to that which is experienced as a result of the ignition of liquid-petroleum-based products and therefore such a rate of temperature rise can be seen to be unrepresentative of a contemporary building fire, except in a special situation. It is up to the fire engineer who felt that the hydrocarbon test was more valid to justify the choice in the fire strategy.

Potentially, another factor is that fire-protection products are sometimes exposed to a significant thermal shock and the furnace curve might not adequately model this. Even with the hydrocarbon curve, higher temperatures can still be reached in a shorter time in practice. In other fire scenarios, the compartment temperature can be much slower to reach elevated temperatures than that described by the standard furnace curve. Again, some fire-protection products might not work if exposed to a slow rate of thermal exposure. Currently, the test has no way of comparing the influence of the rate of heating.

It is important to recognize that the growing use of sprinklers means that many fires continue with a suppressed output. Whilst sprinklers can put out fires that start and remain small, the primary function of a sprinkler is to reduce the maximum heat output to an estimated 2,5 Mw output. This means that elements of construction, particularly ceilings, are subjected to elevated temperatures for a significant duration, over even a sprinkler-controlled fire. With conventional building materials, exposure to these conditions is unlikely to lead to any significant deterioration in their performances. Some of the more modern forms of construction, such as intumescent-based penetration seals, intumescent-laminated glasses, intumescent-coated fire protection, composite panels, aluminium constructions, and some modern forms of resin-based plastic, can suffer significant damage at these elevated temperatures. Currently, there is no suitable time/temperature exposure condition that would allow the fire-safety engineering practitioner to obtain a measure of the deterioration in performance under these intermediate exposure conditions.

Similarly, many fires in practice are contained in their heat output due to a lack of ventilation, and once more the temperatures potentially reach up to nominally 600 °C and remain there for the duration of the fire. The fire engineer currently has to use the fire-resistance test exposure for these elements, but where there is a lack of fenestration, it could be unduly onerous on the material specification.

A new “smouldering curve” has been introduced (see 5.1.3).

NOTE This alternative procedure was originally given in ISO 834:1975, which has been withdrawn.

For product characterization purposes, this procedure is used selectively, being applied to some products and not others. It is a pre-conditioning test that has more of a relationship with “reaction-to-fire” conditions than it has to fully developed fire behaviour, not even with the slower rate of rise to flashover. The shape of the curve is even wrong in the context of reaction-to-fire, following, as it does, a typically exponential relationship. It has no perceived use in the fire-engineering context, and because of its selective use and the wrong time/temperature relationship, even its use in product characterization should be subject to review.

For evaluating smoke leakage, the use of ambient temperature and 200 °C can be correct in the context of a real fire exposure for the door assemblies in some specific locations and with respect to certain fire scenarios. Currently, the fire engineer can look to the commentary document ISO 5925-2 for guidance as to which of these exposure conditions is applicable to a design application, but as it is currently drafted, there is little justification for these temperatures. The 200 °C temperature is not in line with temperatures given for evaluating other products used for smoke control/management in European Standards [e.g. EN 12101 (all parts)].

It is obvious to the fire engineer that elements forming part of the façade of the building probably experience exposure to high temperature conditions due to

— flame impingement from broken windows below, or

— fire exposure from external fire sources, e.g. adjacent buildings, vehicles or stored materials.

The ISO 834 (all parts) test procedure does not include a standardized external fire exposure test, even for elements being heated by the plume from windows below the one in question, as a result of the same fire within the building.

The need to model the decay period of the fire can also usefully be debated with a cooling down cycle being closely specified.

7.1.1 Summary of the thermal exposure issues

A summary of the issues that it is important to consider further with respect to the thermal exposure conditions if the test is to be more meaningful to the fire-engineering community are the following.

a) Should the existing temperature/time relationship be modified to reflect modern compartment fires?

b) If so, should the maximum temperature and/or rate of heating be increased?

c) Should there be more than one heating condition available for evaluating products for fire engineering use, reflecting different heating rates, maximum temperature, etc., thereby giving exposure grading?

d) Should the current hydrocarbon test conditions be more widely used and endorsed for building use, and can it be one of the grades of exposure in c)?

e) Should there be an exposure condition that reflects the heating output of a sprinkler suppressed fire, i.e. nominally 2,5 Mw, and/or an oxygen-controlled fire scenario?

f) Should an interruption in the heating conditions be introduced to reflect the commonly experienced oxygen shortage?

g) With respect to the smoke control door and shutter test procedure, should ISO 5925-2 provide a greater justification for the temperatures used, or should the temperatures be reviewed in the context of typical smoke control strategies?

h) Should there be a standardized external exposure temperature/time regime?

i) Should the decay period be controlled and form part of the test?

7.1.2 Recommended changes to the test procedure

The test methods described in ISO 834 (all parts) should be modified as follows:

a) short-term:

Before too many products have been tested using the new plate thermometer, the thermal exposure conditions should be modified to model real fire more accurately.

b) medium-term:

There are no medium-term measures.

c) long-term:

There are no long-term measures.

7.2 Pressure differentials

The pressure differential between the exposed and unexposed faces of the tested construction is one of the most onerous aspects of the fire resistance test. It can be seen from 5.2 that the current pressure differential between the furnace and non-furnace sides of a floor is from 20 Pa measured 100 mm below the soffits and in a wall to 18 Pa measured near the top of the furnace. A neutral pressure axis exists when testing vertical elements at a nominal height of 500 mm from notional floor level. This condition is quite specific but there is poor correlation between this value and any particular fire scenario. The main effect that this pressure differential has on the fire resistance is that it is forcing furnace-temperature gases through any gap or crack that exists or develops within the element, which, in the case of the separating elements, can increase cavity temperatures and unexposed face lining temperatures significantly.

Field testing, where buildings have been set on fire in a controlled manner, tends to indicate that the pressure differentials in a real fire, particularly within compartments that represent dwelling houses, are less than that used in the furnace. This can, in part, be due to the fact that a higher neutral axis exists in such compartments than exists in the furnace. One of the major components of this pressure is the buoyancy created by the reduced density of the heated gases. At gas temperatures of approximately 800 °C, the pressure gradient per unit height due to this effect is 8,6 Pa/m. This equates to a time duration of approximately 30 min. As the gas temperature rises, so the buoyancy effect also increases. In practice, therefore, the differential pressure between the exposed and unexposed face of the elements is a product of the height above the neutral pressure axis and the temperature of the fire gases at that time. From this, is can be seen that there is no universally accepted pressure differential for all situations and durations.

Increasingly within modern buildings, there can be some artificially induced pressures as part of the smoke management system. In order to keep escape routes, particularly protected stairways, free from smoke, pressurization is now frequently used. This ensures that any element forming the boundary of such a staircase is subjected to a positive pressure on the unexposed face that prevents heat and hot gases from exploiting any joint. Such pressurization systems frequently use pressures in the region of 50 Pa, which is significantly higher than the induced positive differential used in the test. This means that elements bounding these spaces have a “net” negative pressure in the region of 30 Pa. This is a very different situation from that reproduced in the fire test, and it is likely that the actual fire-resistance duration under these conditions for some elements is longer than the fire test indicates.

As an alternative to pressurization of the adjacent space, there are a number of smoke-controlled systems that de-pressurize the fire-exposed face as a result of fan extract systems. One of the primary objectives of a smoke-extract system is to induce cool air, which helps to dilute the fire/smoke plume and reduces the temperature of the gases. This process normally operates in the pre-flashover conditions and because the fan is unlikely to withstand gas temperatures representative of a fully developed fire for more than a few minutes, this influence on the fully developed fire pressure differentials is, therefore, likely to be brief.

The top end of the current range of pressures used in the evaluation of the smoke-tightness of door and shutter assemblies could relate to the overpressure used to produce a pressurized escape stair, but it is important to establish the leakage for both directions of exposure for such doors. There is no obvious reason why the other pressure differentials (i.e. 10 Pa, 20 Pa, 30 Pa, etc.) are used and to what fire scenario they are related.

The use of a 300 Pa pressure for evaluating dampers is many magnitudes greater than that for the wall or floor through which the duct passes, and it is important that the fire engineer understands the reasons for this. Similarly, the pressure differential used for dampers is different from that used for the wall/floor and it is important that this be taken into account.

The positive pressure in the furnace is not, however, appropriate for testing elements that are subjected to external fire exposure, nor is it representative of fires in compartments where the roof has been encouraged to collapse or burn through in order to produce venting. Under both of these specific conditions, the use of positive furnace pressures is inappropriate and likely to result in pessimistic fire resistance ratings.

It would be rare for a real fire to take place under absolutely still air conditions. As a consequence, most fires, during the course of the event, are subjected to dynamic wind loadings. These can have a positive or a negative effect on the internal pressures within the building. These dynamic pressures are capable of producing pulses that can cause pressure changes in fire-fighting staircases that can cause doors to come open temporarily. This influence is not reproduced in any of the fire-door fire-testing procedures.

7.2.1 Summary of the pressure differential issues

The issues that are important to consider further with respect to the pressure differential conditions if the test is to be more meaningful to the fire engineering community are the following.

a) Should the pressure differential currently being used be lowered or increased to reflect the average condition?

b) Should the test be able to adopt a graded range of temperature differentials to reflect the fire scenario being modelled?

c) Should external exposed elements be evaluated without a pressure differential?

d) Should the pressure differentials used to evaluate smoke control doors be aligned with the smoke control methods draft and be rationalized?

e) Should the pressure be cycled or pulsed to reflect the dynamic conditions likely to be experienced in practice?

f) Should the relationship between pressures in room fire scenarios, ductwork and dampers be harmonized and variations explained clearly in a suitable guidance document?

7.2.2 Recommended changes to the test procedure

The test methods described in ISO 834-4, ISO 834-5, ISO 834-6, ISO 834-7, ISO 3008 and ISO 3009 should be modified as follows.

a) short-term:

The furnace pressure differential for vertical furnaces should be increased to 28 ± 2 Pa at a height of 3 m and for horizontal elements the pressure 100 mm below the soffit of the element should be increased to 25 ± 2 Pa.

(Reason: In order to generate the smoke leakage/total heat flux measurements recommended in Clause 8, a full over-pressure results in more repeatable measurements and the difference between 20 Pa and 30 Pa is very small compared to the difference between − 5 Pa and + 5 Pa.)

b) medium-term:

It is important that the pressure differentials used in the testing of other assemblies, e.g. ducts, be rationalized to ensure a scientific relationship between the conditions in ducts and the conditions imposed upon solid separating elements.

7.3 Specimen size

The size of elements tested, 3 m × 3 m for walls and 3 m × 4 m for floors only mimic reality for the very smallest of domestic dwellings. For this reason, all fire-resistance tests should be reviewed to establish whether the field of application of the result applies to the construction at the installed size.

The wall test is designed to accommodate longer lengths of installed wall by having one edge free from restraint, which is meant to simulate a longer length of wall. Similarly, floors are normally tested with two free edges to simulate a greater width of specimen transverse to the span. This approach means that ISO 834-1 produces an unrestricted direct application of these elements in the indicated directions. In practice, many walls are over 3 m in height, except possibly in domestic housing; but in almost every application, the span is greater than 4 m. The height and width, therefore, invariably require extrapolation to establish what the performance will be in the end-use conditions.

Floors are tested in a simply supported mode that is deemed to be a worst-case scenario; this, again, allows extrapolation to take place a little more easily, albeit in reality there is always a significant amount of restraint and can require additional re-calculation of the bending moments and shear forces to the revised size. One of the major problems associated with extending this span and/or height is the fact that the mode of failure can change significantly between the mode of failure experienced in the test and the mode of failure that occurs in a real situation. It is never possible to design furnaces that can test constructions at full size. Some increase in the size of the test specimen can, however, induce more realistic modes of failure, which aids in the extrapolation process, but does not necessarily make the results instantaneously acceptable for use at larger sizes. However, any change in size, without addressing quantification of the restraint conditions, is probably fairly meaningless.

It should be noted that some guidance on extrapolating the results of fire resistance tests is to be found in ISO/TR 12470.

7.3.1 Summary of the specimen size issues

The issues relating to specimen size are few and simple, but the implications of implementing them are costly and fundamental. The main issues are the following.

a) Should the specimen size be increased in any new furnace test facility and, if so, up to any size, or up to an internationally agreed-upon new maximum size?

b) Should furnaces that are used for initial-type tests be kept at the existing maximum size, but should various countries have a furnace that can accommodate larger test specimens for the development of extrapolation/extended application rules?

7.3.2 Recommended changes to the test procedure

See 8.1.2 for recommended changes in furnace size.

7.4 Boundary conditions (load actions)

The test procedure utilizes only simple restraint conditions for all elements as listed below:

a) beams;

b) floors/roofs;

c) load-bearing walls;

d) partitions;

e) ceiling membranes.

A number of test facilities do enable specific restraint to be applied on some edges of the test specimen, but this is rarely applied during standard testing. Buildings are, however, complex structures and the levels of restraint are complex and very variable and are hardly ever simply supported or pin-ended in practice. Figure A.5 shows how the restraint increases as the complexity of the structure increases and it can be seen how relatively unrealistic the simple restraint conditions are, if a true evaluation of the fire resistance is to be evaluated. It should also be recognized that the restraint condition invariably modified as a result of the increase in temperature in the element itself. This makes simple application of the results of the fire tests to real buildings quite difficult.

There has been a number of notable experiments that have addressed the issue of restraint conditions in real structures, rather than the individual elements. Many of these are supported by detailed reports. The most important of these are References [1] and [2].

Non-load-bearing vertical elements are tested with one fixed edge and one free edge as standard, but no measurements are made to quantify the fixity on the fixed edge. Again, this suggests a more onerous situation, but it prevents the designer from quantifying the high or lower levels of fixity as exist in practice.

Under the general heading of boundary conditions and associated restraint, a fire engineer should consider that the individual elements invariably are all connected to each other to form a construction. Standard fire-resistance testing only considers individual elements in isolation and, therefore, the interaction between elements is not normally modelled. As a result, little information is available to enable the integrity of wall/floor, wall/wall constructions to be evaluated. Reference to Figure A.5 shows the complexity of the real fire behaviour relative to the tests currently undertaken. An ability to test elements in context with each other helps to reproduce the real restraint conditions that exists on the side, albeit with the larger elements, there is inevitably a higher level of stress to be resisted in practice.

Fundamental problems with fire-resistance tests are that they are normally restricted to a single element of construction. It is important to test the interaction between two elements of construction to ensure that a reduction in fire resistance performance does not occur.

7.4.1 Summary of boundary condition issues

It can be seen from 5.6 and derived from Figure A.5 that restraint of the specimen is addressed fairly pessimistically by testing most elements under minimal levels of restraint. Whilst this can be deemed safe, it can lead to serious levels of over-design if the actual restraint that occurs in practice, which is invariably higher, is ignored. The following are to be reconsidered if the tests are to be of greater value to the fire engineer.

a) Should the general use of simply supported elements continue?

b) Should the restraint applied to the edges or ends through which the load is reacted have measured and monitorable levels of restraint?

c) Should both vertical and horizontal non-load-bearing elements have one free edge, or both have two free edges?

d) Should the testing of walls in conjunction with adjacent walls or floors be more encouraged in future design of laboratory test facilities where actual proposed fixing systems can be evaluated on a rational basis?

7.4.2 Recommended changes to the test procedure

See 8.1.2 for recommended changes in the specimen boundary conditions.

7.5 Furnace turbulence

It has been identified in 5.5 that the velocities of gases in a test furnace are not controlled. In real fires, there is great variety in the range of turbulence levels that are experienced. There is likely to be one major difference and that is, in a furnace, the air is delivered to the heating device(s)/burners in whatever quantities are required for good combustion. In a fire, the fuel (furnishings, etc.) are ignited as a result of the temperature increasing to a critical level. Once ignited, these items draw sufficient oxygen/air into the adjacent area to continue the burning process. The speed at which the air enters the combustion zone almost certainly depends upon physical features of the room/property, such as

— the height of the space,

— the potential rate of heat release of the fuel that is burning,

— the area of ventilation forming the source of make-up air,

— "stack effects" due to the height of buildings adjacent to the one under consideration,

— active smoke management systems,

— fire brigade activities.

From 5.6, it can be seen that the main change of turbulence in test furnaces is likely to be as a result of

— nature of the burners used in the furnace, i.e. nozzle-mix or diffusion,

— distribution and number of burners,

— flue extract arrangements and positions (including chimney height),

— the fuel.

The probability of a construction performing in a similar manner in a fire or in a fire test is likely to be more adversely affected by differences between the levels of turbulence than almost any other characteristic of the test, especially for materials or protection systems that are easily eroded. Fire engineers can have little or no confidence in the use of fire-resisting constructions that are shown to produce high levels of variation in the result.

7.5.1 Summary of furnace turbulence issues

If confidence is to be placed in the output of the fire resistance tests by fire engineers, then reproducibility should be improved. As furnace turbulence is one of the items that has a greater influence on certain materials and systems than any other, then consideration should be given to the following.

a) Should all burners be of the same type and design?

b) Should the number and distribution of burners be similar?

c) Should the fuel be standardized?

d) Should standard exhaust-port positions be identified?

e) Should furnace gas-flow baffles be introduced to even out the flow?

More research may be needed to establish typical gas velocities in real fire scenarios if these are to be modelled more realistically.

7.5.2 Recommended changes to the test procedure

The test methods described in ISO 834-4, ISO 834-8, ISO 3008 and ISO 3009 should be modified as follows:

a) short-term:

   There are no short-term measures.

b) medium-term:

   Vertical furnaces should be fitted with a stainless steel permeable heat-diffusing screen, such as a stainless steel "chain mail" curtain 250 mm in from the exposed face of the furnace for the purpose of creating constant turbulence levels.

   NOTE This is a new concept that needs research to demonstrate its effectiveness.

c) long-term

   Develop and fit a diffusing screen beneath horizontal elements.

7.6 Furnace atmosphere

Both real fires and furnace tests run with virtually no free oxygen. It is unlikely that any difference between the two conditions is significant with respect to changing the value of the output to fire engineers.

The only output that can be affected by high levels of excess oxygen is the charring rate of combustibles, but research work has shown that an excess of 12 % O_2 is required before the rate is seriously affected, and this is unlikely to be found in enclosed compartment fires. After failure of a roof, the O_2 level can rise, although there is little documented evidence of this.

7.6.1 Summary of furnace atmosphere issues

Research suggests that there are no serious influences on the test output as a result of furnace atmosphere variations. As a consequence, no change in the test conditions for fire resistance tests is proposed.

7.7 Conditioning

The moisture content (m.c.) and the state of cure of time-dependent materials are likely to affect the result of a fire test. For homogenous (concrete) construction, it is possible to correct the result obtained from the test for different m.c. values This correction method is mentioned in ASTM E119. No such correction factor can be easily applied to other materials or to composites. Despite the importance of these factors, it is unlikely that testing at a fixed m.c. or after a pre-conceived duration, as the influence of each has different effects on different materials. The principle of measuring the m.c. condition of the element or reporting the curing time immediately before the test is probably acceptable.

7.7.1 Summary of conditioning issues

No real change in the procedures and on reporting is recommended, except for the statement requiring the report to highlight these characteristics. Should the report, where possible, include guidance on where greater information can be found and include correction factors if these are known?

7.8 Quality of tested construction

Fire tests are rarely repeated to establish the effect that a change in one of the construction parameters can have on the result, despite the importance of some of them. It is unrealistic to expect any particular manufacturer to carry out a wide range of variations on his construction, as this would complicate the certification process when the product is used in prescriptive legislation. Attention can be drawn to the fact that there is virtually no sensitivity testing of furnace test outputs.

7.8.1 Summary of the quality of construction issues

Whilst this is a potentially vast subject in respect to the influence that the quality of the specimen can have on the result, it does not lend itself to a change in the normal test procedures. The following should be considered, however:

Should the reports of fire-resistance tests carry the statement: “There has been no sensitivity testing of this result to establish which of the parameters is most critical to the result, and what the influence a change of quality in that parameter would be. The effect of a reduction in quality should feature in an extended application analysis, which can require additional testing.”?

8 Comparison between data measured in the test and data required by the fire engineer and recommendations for changes in the test procedure(s)

It can be seen from Tables 4 to 6, where the criteria of failure for the ISO “containment” tests are compared, that the criteria of failure can vary for various elements and, more worryingly, for components forming part of the same barrier. In most tests, there is only one failure level for each of the important criteria, e.g. load-bearing capacity, integrity, insulation. This inhibits any potential to develop a grading system to reflect different hazard levels. In practice, the risk to people and property within the “protected space” varies as a function of the environment of the space, its occupancy and its size.

The main concern of the fire engineer is the tenability of the protected space to persons, i.e. the time when the conditions that ensure life safety are exceeded. This time varies in relation to the nature of that space, i.e. size, ventilation, boundary characteristics, and as a consequence, there are no fixed criteria that apply universally to the elements separating the various types of spaces from the fire. Similarly, the tolerance of the population in that space varies depending upon their awareness, capacity to respond, mobility, etc.

Such variations lend themselves to having graded levels of protection, a system currently denied by the use of fixed single levels of safety for each of the criteria applied to the important characteristics that have been identified as being critical to life safety and which have subsequently been turned into performance criteria.

8.1 Behaviour of the load-bearing structure in fire safety engineering

Current fire-testing procedures monitor lateral deflection in horizontal and vertical separating elements and in beams, but not in engulfed columns due to procedural difficulties. Only in the case of floors and beams is there a failure criteria based upon lateral deflection. In the case of walls, both load-bearing and non-load-bearing, the lateral deflection is only monitored and recorded, and not used as a pass/fail criterion. Columns are monitored for vertical displacement, which is used to indicate the onset of structural failure, mainly to permit the test to be terminated before equipment-damaging deflections are reached; but these are not selected with life safety or property protection limits. Having stated that lateral (vertical) deflection of beams and floors are used as a criterion of failure, they do not represent a particular fire safety case, or even an acceptable degree of property protection. Instead, they are used in a manner similar to the vertical displacement criteria for columns, i.e. to permit termination of the heating period to prevent furnace/equipment damage as a result of collapse of the element.

This satisfies the hazards-to-life considerations created by the collapse of the structure under consideration to those people in or around the building (see 4.2.1.1), as the construction would not be expected to collapse in practice as it did not collapse in test, as long as the failure mode is the same for the tested size as it is in practice. With the current limits on furnace size, this can represent a problem and trial calculations can be needed to confirm this, albeit the bigger the section tested, the more inappropriate the current test-furnace sizes.

The absolute criteria do not altogether address the implication of excessive deformation (see 4.2.1.2). Obviously, at some stage in the future, the deformation can induce gaps in separating elements that cause a loss of integrity and be measured and failed accordingly. However, as smoke leakage is not a failure criterion, purely a test observation, it can allow constructions to pass that have been severely compromised in their ability to maintain tenable conditions on the protected face as a result of smoke leakage. Nor, unfortunately, is the impact of the levels of distortion on the integrity of these dimensional junctions, e.g. wall/wall, wall/floor joints, known, due to the inability to evaluate them. Movements of the magnitude permitted in the floor/beam test are likely to seriously compromise the fire-containment capability of even fire-tested constructions if they are permitted to happen. This can be damaging to life-safety objectives, especially if a door or glazed aperture in a wall is unable to perform as proposed due to excessive distortion of the supporting construction; but in a property-protection role, deflection of the maximum amount permitted by the test can be catastrophic.

Dampers, ductwork, penetration seals, linear gap seals, doors (and to a lesser extent roller shutter doors), cavity barriers and glazing are generally dependent on the separating elements remaining reasonably planar during the fire.

The test method is used in an adapted form to evaluate the performance of protection systems, especially for steelwork. In this case, full-sized specimens are tested only to establish “stickability”, i.e. the ability of the protection system to withstand excessive deflections, the basic behaviour of the protection system being established solely on the basis of temperature measurements, normally on smaller sections. These measurements are used to predict the effect of different thicknesses of protection, different section sizes and, where possible, alternative durations using a variety of interpolation-extrapolation techniques. As unprotected steel has a poor fire resistance, the test is used more for the purpose of evaluating protection systems than primary materials.

Currently, whilst an element can satisfy the load-bearing capacity criteria, no attempt is made to determine the residual strength of the construction. In some national standards, a pass/fail impact test is used (i.e. the “hose stream”), but this fails to provide the fire engineer with any quantification of the residual strength.

Ideally, the fire engineer would like the specimen loaded, whilst hot, until it collapses, once it has passed the pre-determined classification duration, as this gives actual residual strength and identifies the mode of failure. It is recognized, however, that this can be difficult to accommodate in conventional furnaces.

8.1.1 Summary of load-bearing issues

It can be seen that collapse of constructions is a criterion currently in use and one would anticipate a reasonable correlation between the test and real fire behaviour, as long as the mode of failure is reproduced. When one considers the impact that furnace size and boundary conditions have (see 7.3), it is unlikely that there is much of a correlation between the modes of failure in the test and in reality. If temperature measurements on small-scale specimens can be reliably used to evaluate a protection system (except for the stickability test), it is important to question whether a large-scale furnace test is required for testing homogeneous structural members, or separating elements. The use of large-scale specimens for evaluating “stickability” is also questioned, as there is a certain lack of repeatability in such a test, which is better evaluated by applying protection to constructions where distortion can be imposed at will in a known and reproducible way.

The “stickability” of fire protection systems should be considered in use, particularly with respect to structures where movement is expected during the working life.

In considering the issues that limit the use of the results for the purpose of a fire-engineered solution, the following should be considered.

a) Should the current fixed distortion criteria for beams and floors be abandoned in favour of a “graded” distortion criterion, e.g. time to 50 mm, 100 mm, 200 mm, etc.?

b) Should the size of furnaces be increased to ensure that the mode of failure is correctly reproduced, even for larger/deeper sections, especially if the recommendations in 7.4.1 d) were to be implemented?

c) Should the method of fixing/restraining the ends of load-bearing elements, especially floors, be improved to reflect real life conditions?

d) Could the beam and column test procedures be abandoned and replaced by mathematical models supported by material tests, smaller-scale controlled deflection tests and laboratory tests designed to evaluate any mechanical/thermal interactions between materials forming a composite?

e) Could “smoke” leakage criteria, or measurements be added to the separating wall and/or floor test procedures?

f) Should residual strength tests be introduced?

8.1.2 Recommended changes to the test procedures

The test methods described in ISO 834-4, ISO 834-5, ISO 834-6 and ISO 834-7 should be modified as follows.

a) short-term:

Both the deflection and the rate of deflection for beams and floors should be continuously measured and reported without any pre-judgement as to what constitutes failure. Termination of the test can take place at a pre-agreed deflection limit, or rate of deflection limit, the reason for which should be reported. No time should be reported as representing failure with respect to load-bearing capacity as this would be defined by the design team or the legislation.

b) medium-term:

1) For materials for which no design codes exist that allows scaling up, e.g. new materials and new composites, then floor beam/furnaces should be extended to 6 m span and wall/column furnaces should be increased to 4 m height.

2) Specimen support frames should be re-designed to permit known levels of restraint and fixity to be applied, to allow tests to be carried out with greater realism in the support conditions.

3) Large-scale testing of homogenous columns and beams should be abandoned in favour of mathematical solutions.

4) Smoke-leakage test procedures should be available for all vertical separating element tests that can be carried out coincidental with the fire resistance test.

c) long-term:

Smoke-leakage test apparatus should be available for all horizontal separating element tests that can be carried out simultaneously with the fire resistance test.

The use of a residual strength test is not recommended, especially if the element has to be moved to a position where it can be tested, as this does not reflect reality. The hot or recovered strength of the materials and joint methods used in the construction should form part of the report, which might need quantifying on parts of the specimen.

8.2 Leakage of fire into protected space

The phenomenon of ignition of the unexposed face is a general criterion of failure, as is the appearance of visible flames egressing out of any hole or gap in the face of the element. This is undoubtedly an accurate and reliable method of ascertaining that fire has pervaded the protected space. However, in the case of separating elements, prior to either of these events occurring, it is normal to monitor “integrity”, which is an indication that the flow of hot gases/fire is reaching critical levels. This monitoring is carried out by means of

— prescribed cotton fibre pad in a holder to keep it away from the surface, and

— gap gauges which have to totally penetrate the specimen.

The cotton pad is not used when there is a danger of it being ignited by the radiation emitted from the specimen.

Oven-dry, cotton fibre represents one of most easily ignited materials, especially when held very close to the gap from which the hot gases are emanating. It can be seen that a criterion based on a material with such a low potential ignition temperature does mean that it is modelling a very high risk. Whilst it is possible for the element to be protecting spaces that have a high potential for ignition of the contents and the furnishings, it is not the norm. As a consequence, from a fire-safety engineering point of view, the ignition of a cotton pad can be seen to be unduly cautious.

A fire engineer would ideally like to quantify the flow of heat in terms of the gas temperature and the volume flow. Whilst there are no such instruments currently available within a fire testing tool kit, it is possible that such instruments could be available from other industries or could be adapted, and, if so, should be used in lieu of those currently used.

The current procedure for the use of gap gauges, where they have to penetrate the gap to the extent that they pass through the specimen into the heated zone, is, in fire engineering terms, a meaningless criterion. For the sake of classification purposes, the method can be retained, but the integrity of non-insulating constructions should preferably be quantified. It is important to consider whether it is correct to abandon the use of the cotton pad for uninsulated constructions, because ignition of the cotton pad should represent failure of the element due to excessive heat flux regardless of whether it is by convection or radiation.

In practice, it is the total heat flux that ingresses into the protected space that defines the limit of tenability. Measuring the “criticality” of the flow in a questionable manner, in a few selected positions, or checking the size of gaps is not a measure of life safety, nor a property threat.

Using even higher levels of air/gas flow through a damper has even less of a correlation with tenable conditions than does the cotton pad or the gap gauge and should be questioned as providing a similar level of protection as the methods used for plane elements.

8.2.1 Summary of integrity issues

If the fire engineer is to obtain more meaningful and quantifiable information with respect to when fire-spread into the protected space becomes untenable to life, or puts property at risk, consideration should be given to the following.

a) Should the cotton pad be replaced by a device with a greater potential to quantify the flow?

b) Until such instruments become available, should the same method of measurement apply to insulated and uninsulated constructions, as they have similar objectives?

c) Should local measurements be replaced by a “global” method of measuring heat flux (see 8.4)?

d) The integrity criteria for all elements should be reviewed and harmonized to ensure equal levels of fire protection regardless of the element.

8.2.2 Recommended changes to the test procedures

The test method described in ISO 834-4, ISO 834-5, ISO 834-8, ISO 834-9, and ISO 3008 and ISO 3009 should be modified as follows.

a) short-term:

   1) The cotton pad should be applied to all constructions whether insulating or non-insulating.

   2) The 6 mm diameter gap gauge should be modified by the addition of a 20 mm extension at right angles so that as the rod is “twisted” the gauge can establish whether a gap of similar dimensions exists in the plane at right angles to the outer gap. If it can be twisted, it is assumed that a through gap exists throughout the edge and an integrity failure is deemed to have occurred, even if the gauge cannot penetrate right through.

b) medium-term:

   1) The current cotton pad and gap gauges should be replaced by a single quantifiable method of measuring the total heat flux, either globally (preferred) or locally.

   2) The quantified method of evaluating the passage of flames/heat/gases should be able to be used with all elements, including ducts, dampers, glazing, etc.

c) long-term:

   Smoke and hot-gas leakage test apparatus should be available for all vertical and horizontal separating tests, as in 8.1.2.

8.3 Temperature rise on the unexposed face

Currently, the test monitors the temperature of the unexposed face of the specimen for both mean and maximum temperature rise and these data tend to be recorded up to and beyond failure. The failure criteria themselves are fairly important to a fire engineer as there is no direct correlation with a particular risk scenario.

It is recognized that at all times the unexposed face temperatures are directly related to the exposure conditions of the ISO 834 (all parts) standard heating conditions. Whilst the temperature on the unexposed face is what creates the risk, the important value to record is probably the temperature drop across the specimen under dynamic heating conditions, as the time/temperature regime, in practice, is almost certainly going to be different. The temperature drop across the specimen is not the same at more or less rapid heating rates, but it gives an idea as to what magnitude of temperature can be expected on the unexposed face if the hot-face temperatures vary significantly from the standard heating conditions.

The use of a temperature drop in lieu of a temperature rise does not require different instrumentation, just a different way of presenting the findings.

Again, whilst ISO 834 (all parts) does not restrict it, and indeed in many cases actively supports it, greater monitoring of internal temperature is of great value to fire engineers who can make use of temperature profile information for a wide variety of predictions.

8.3.1 Summary of insulation issues

It can be seen that the data measured are of direct value to a fire engineer, albeit the temperatures measured only relate to a specific heating regime, as given in ISO 834 (all parts). As a consequence, no particular changes to the measurement procedures are proposed.

Due to the way the data are used, it is recommended that they be presented in a modified manner that can make the information of greater value to the engineer who needs to compile unexposed face temperatures for elements exposed to a “parametric fire” condition.

8.3.2 Recommended changes to the test procedures

The test method described in ISO 834 (all parts) that measures the unexposed face temperature should be modified as follows.

a) short-term

   No failure time should be recorded. All temperature data should be recorded continuously and reported as individual time/temperature relationships, which should be given along with similar data for the mean and maximum temperatures.

b) medium-term

   The use of thermocouples should be replaced with an overall heat-flux measurement system as is discussed in 8.4.2.

8.4 Heat flux received in the protected space

From 4.2.4, it can be seen that there are a number of heat-transfer mechanisms that result in the temperature rising in the protected space, such that it can lead to untenability for humans or cause property damage. These are conduction (measured by the thermocouples), convection (partially measured by the cotton pad) and radiation (measured by radiometers). Of these measures, radiation from uninsulated elements is the primary cause of temperature rise in their protected space.

The received radiation can be measured by a radiometer and recorded, albeit if the measuring instrument is not fitted with a window it also measures the convective component from all surfaces below the height of the instrument that have been warmed up by the radiant heat flux. Recordings of the radiation/heat flux are valuable to the fire engineer.

The next most important mechanism for heating up the protected space is by convection, which is significant for a non-insulated specimen. Currently, this mechanism is not measured, as most of the convective gases flowing up the unexposed face of the element are mixed with the laboratory air and eventually get exhausted to atmosphere without ever being measured. This can be a large component of the total heat transfer into the protected space and be of great interest to a fire engineer. It can be possible, with accurate temperature measurements and a knowledge of the heat transfer coefficients, to calculate this influence, but the thermocouples used to establish the unexposed face temperature are not readily suited to measuring high temperatures and if the element is not claiming insulation, e.g. some fire glasses, steel roller shutters, etc., then temperatures are not measured.

Measuring the total heat flux from the element is probably easier than computerizing it, although if there is only one standard heating curve in use the data will be fairly limited. ISO 3008 and ISO 3009 introduced a “canopy” over the top of door tests and glazing tests, solely for the reason of gathering data against which the fire safety community could assign failure criteria that correlated with the cotton pad test, gap gauges and unexposed face temperature criteria. Due to the non-mandatory nature of ISO tests in member countries, information from these countries could be particularly valuable.

Even with this canopy, it is necessary to acknowledge that there is a significant spill of convective gases and not all of the heat flux is measured.

8.4.1 Summary of radiation issues

It can be seen that, whilst radiation is measured, it does not represent the total heat flux received in the protected space. If more information is to be provided to the fire engineer, then the following should be considered.

a) Should improved methods of measuring unexposed face temperatures, especially on uninsulating construction be introduced?

b) Should thermal imaging be introduced that can scan the complete surface of the unexposed face remotely?

c) Should the canopy used for doors and glazing be developed for vertical and horizontal elements in order to obtain a measurement of total heat flux from unexposed face?

d) Should a full gas-collecting chamber be developed for fitting to the unexposed face in order to capture the complete convective flow, both from the specimen and from a surface heated by radiation?

8.4.2 Recommended changes to the test procedure

The test method described in ISO 834-4, ISO 834-5, ISO 834-8, ISO 834-9, ISO 3008 and ISO 3009 should be modified as follows.

a) short-term:

   1) Thermal imaging and associated temperature measurement should be introduced for all tests to supplement radiation measurements.

   2) Radiation/heat flux measurements should be made and recorded for all separating elements using a water-cooled heat-flux meter. These measurements shall be recorded continuously in the report.

b) medium-term:

   A full gas-collecting chamber that incorporates continuous heat flux and gas temperature monitoring is to be developed and installed in the front of all vertical separating elements.

c) long-term:

   1) A full gas-collecting canopy as in 8.4.2 b) is to be developed and installed on top of all horizontal separating elements.

   2) A gas-collecting chamber as in 8.4.2 b) is to be developed and installed around all ductwork and associated extract grilles.

8.5 Smoke leakage into the protected space

The importance of smoke as a life-safety hazard has been discussed in 4.3.3 and as property protection risk in 4.2.5. It is probably the single most life-threatening and property-damaging aspect of fire and yet the standard fire-resistance test fails to measure smoke leakage and/or smoke production.

Of the related tests, ISO has only one designated smoke leakage test, ISO 5925-1, which is restricted to door and (roller) shutter assemblies, and this is restricted to measuring leakage at ambient temperature (and at 200 °C). This measures only leakage, using air as the medium, and does not evaluate the influence of particulate matter and aerosols on the leakage rate. The test certainly does not measure smoke production.

("Smoke-tight" dampers are evaluated by the damper fire resistance test purely by assigning the category to dampers that demonstrate lower leakage levels than the standard fire damper.)

Research work in Australia showed how a corridor built onto the front of a wall furnace can generate some valuable information relating to smoke logging, but without controlled joints between the corridor and the furnace, repeatability is questionable. The data generated could be more repeatable if a special chamber were affixed to the unexposed face of the specimen, not just for doorsets as in ISO 5925 (all parts), but for partitions, glazing, suspended ceilings, etc.

NOTE ISO TC/92/SC2/WG3 was involved in the development of a smoke chamber during the early 1980s following research work carried out in Finland, where an "Oksanen" box and a "Loikanen" box were trialled. The work was abandoned partly due to funding problems and partly due to technical problems associated with thermal feedback.

It is anomalous that probably the main causes of life loss and property damage do not have adequate methods of measurement or criteria.

8.5.1 Summary of smoke leakage issues

If the fire engineer is to be provided with information on leakage rates of smoke and/or smoke development, the following changes to the test methods need to be considered.

a) Should all fire-resistance tests be carried out with some form of gas-collecting box in order to monitor both leakage and smoke production?

b) Should ISO 5925-1 be extended in scope to cover all elements?

NOTE If the heat-flux collecting box, as recommended in 8.4.1 were to be adopted, then this could also carry out the function of a smoke leakage measuring chamber.

8.5.2 Recommended changes to the test procedure

The test methods described in ISO 5925-1 and ISO 834-4, 834-5, 834-8 and 834-9 should be modified as follows:

a) short-term:

   The test for smoke leakage of doors, ISO 5925-1, should be amended to permit the determination of smoke leakage at ambient and medium temperatures of all vertical separating elements, including penetration and linear gap seals.

b) medium-term:

   A method of measuring the smoke leakage at ambient and medium temperatures should be available for evaluating the smoke leakage through permeable, composite flooring systems, including penetration sealing systems.

c) long-term:

A full gas collecting box and/or canopy, as described in 8.6.1, should be in place for measuring total smoke and heat leakage transmission during fire resistance testing conforming to ISO 834-4, ISO 834-5, ISO 834-8 and ISO 834-9.

8.6 Other life safety and property protection consideration

Of the mechanisms identified in 4.2 and 4.3, most of them are covered in the analysis given above. Only burning brands have not been covered. It is not unknown for the hot material to fall from the unexposed face of vertical elements, but there is currently no attempt to quantify the risk that they represent with respect to ignition of material in the protected space. Most laboratories report such phenomena, but the information would remain within the test report and not be known to the specifier.

8.6.1 Summary of other measurements and observation issues

Unanticipated events and significant changes in the behaviour of the specimen are important to a fire engineer for some product applications. For this to be transmitted to the fire engineer, the following should be considered: should certain key observations form part of the expression of the result?

8.6.2 Recommended changes to the test procedure

The test methods described in all parts of ISO 834 should be modified as follows:

a) short-term:

In the short term, all detachments of material from the unexposed face of the construction should be reported, photographed and, where possible, the hazard that they represent should be quantified as part of the report.

b) medium-/long-term:

All tests should be recorded on a high-quality electronic medium (i.e. a DVD), which forms part of the report.

8.7 Ensuring the construction

It has been recognized that the quality of the construction and the installation is vital to achieving the performance. Whilst not requiring a change in the test procedure, it is vital that the specimen is fully characterized, as this is the only way the construction on site can be audited. The fire engineer needs to know which items of the construction were checked by the testing authority and which were reported on the basis of manufacturer's declaration.

8.7.1 Summary of characterisation issues

If the fire engineer is to be able to audit the on-site construction, it is of importance to know what aspects of the construction have been determined and what aspects have been taken on trust, and as such, the following should be considered: all aspects of the described construction that have not been checked by the laboratory staff should be marked clearly by a symbol in the test report as being accepted "based upon manufacturer's self-declaration".

9 Conclusions

It can be seen from the report that the current fire-resistance test method, whilst being a reasonable method of comparing the behaviour of products under nominally fully developed fire exposure conditions, offers little to the fire engineering community. The criteria of failure in the various tests have not been selected with a particular safety case or degree of property protection in mind, and hence there is no correlation among the criteria used in various test methods. It is recommended that an overview of the criteria be undertaken by TC92/SC2 to establish whether some harmonization of these criteria with life safety can occur. This should be undertaken in conjunction with TC92/SC4 and involve TC92/SC2/WG2.

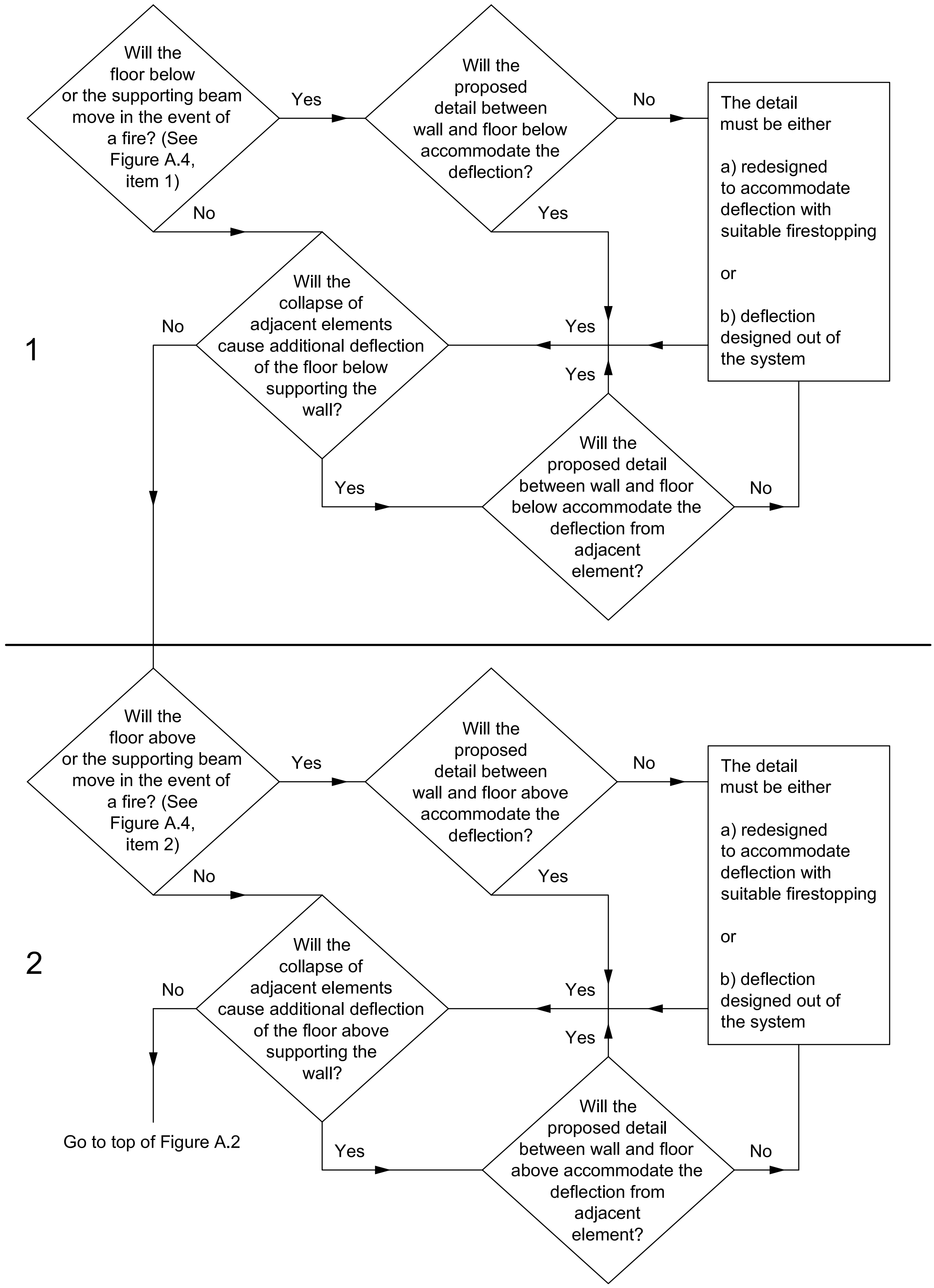
The report shows that the fire-engineering community would benefit from changes made to the test methods and the method by which the results are reported. The convenor of each working group should be allocated the task of reviewing whether some of the suggestions for change are feasible.

In some cases, it has been shown that improved instrumentation could significantly improve the quality of the data that forms the output of the test procedures. Often this can be introduced whilst maintaining the use of an International Standard for product-comparison purposes. It has been identified that many of the fire-resistance measuring devices are very crude and cross fertilization with other technologies is recommended as a way of determining whether superior methods of measurement can be sourced from elsewhere.

One of the working group papers deals with the subject of uncertainty of measurement in fire-resistance testing. It is suggested that this be used by the individual working groups to ascertain how much the uncertainty of measurement can be improved. A fire engineer will find it difficult to endorse results that have such low levels of reproducibility and repeatability as the current ISO-834 (all parts) based fire-testing procedures.

Annex A
(informative)

Decision tree for evaluating the compatibility of elements in respect of maintaining the fire tightness of the compartment

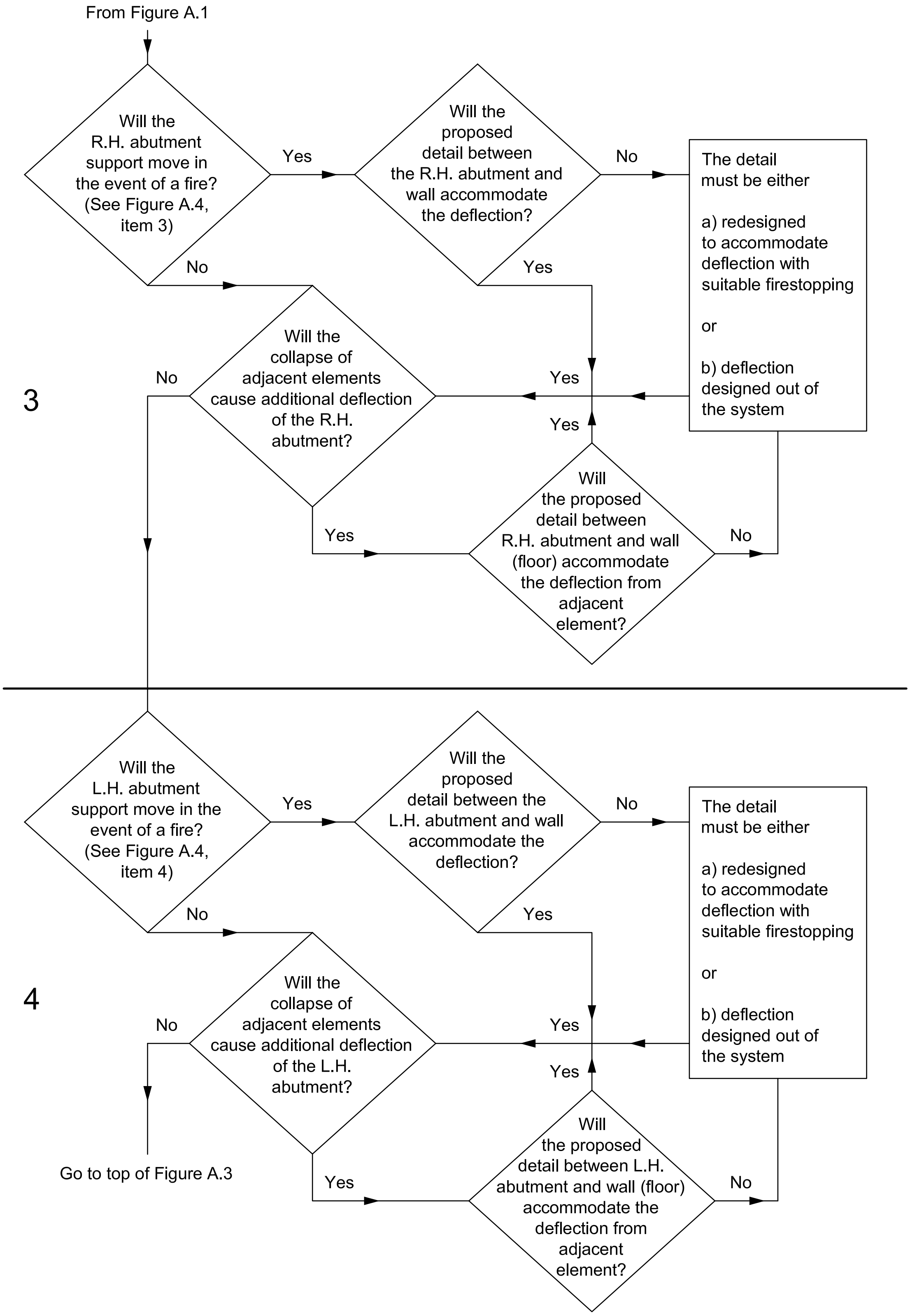


Key

1 floor below

2 floor above

Figure A.1 — Decision tree for establishing the acceptability of a compartment wall — Reference section (Adapted from Reference [1])



Key

3 R.H. abutment

4 L.H. abutment

Figure A.2 — Decision tree for establishing the acceptability of a compartment wall — Reference section (Adapted from Reference [1])

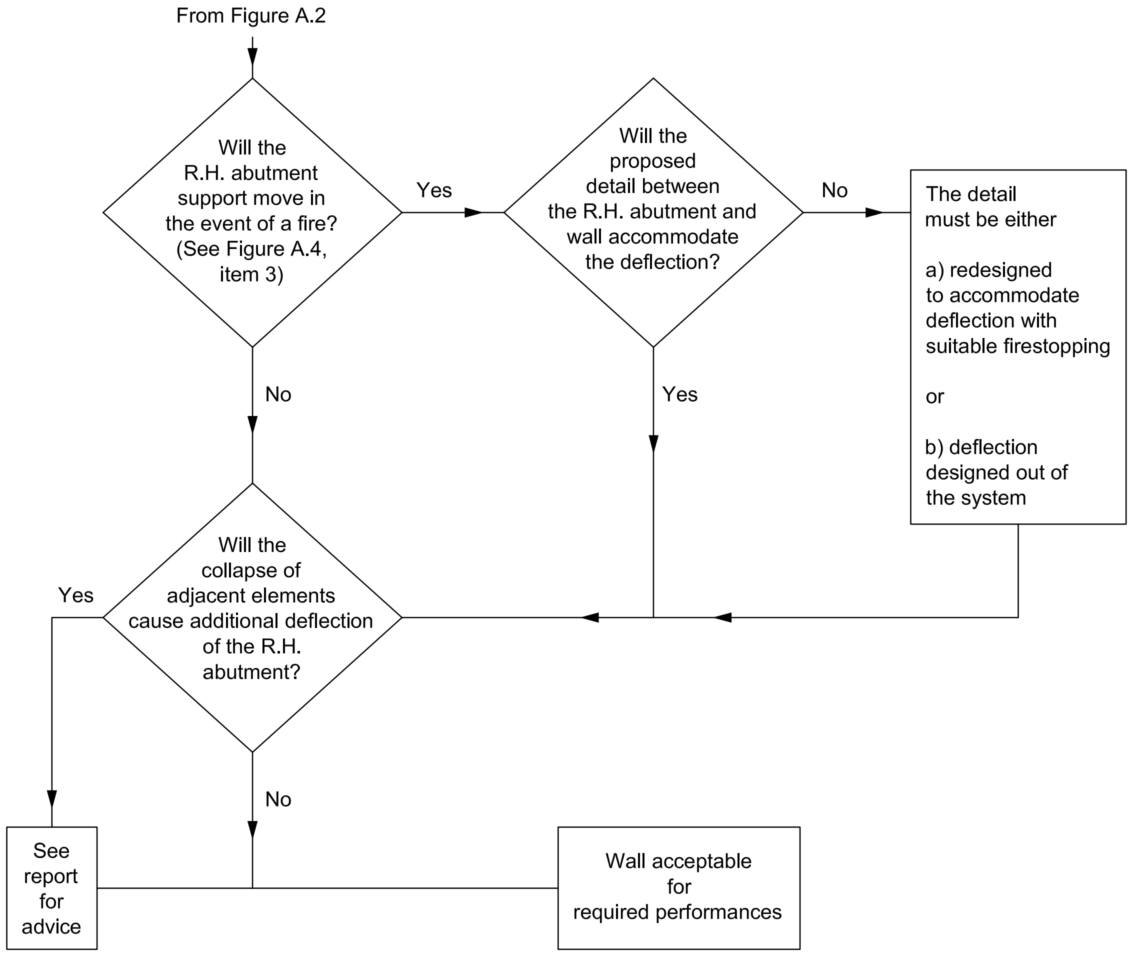
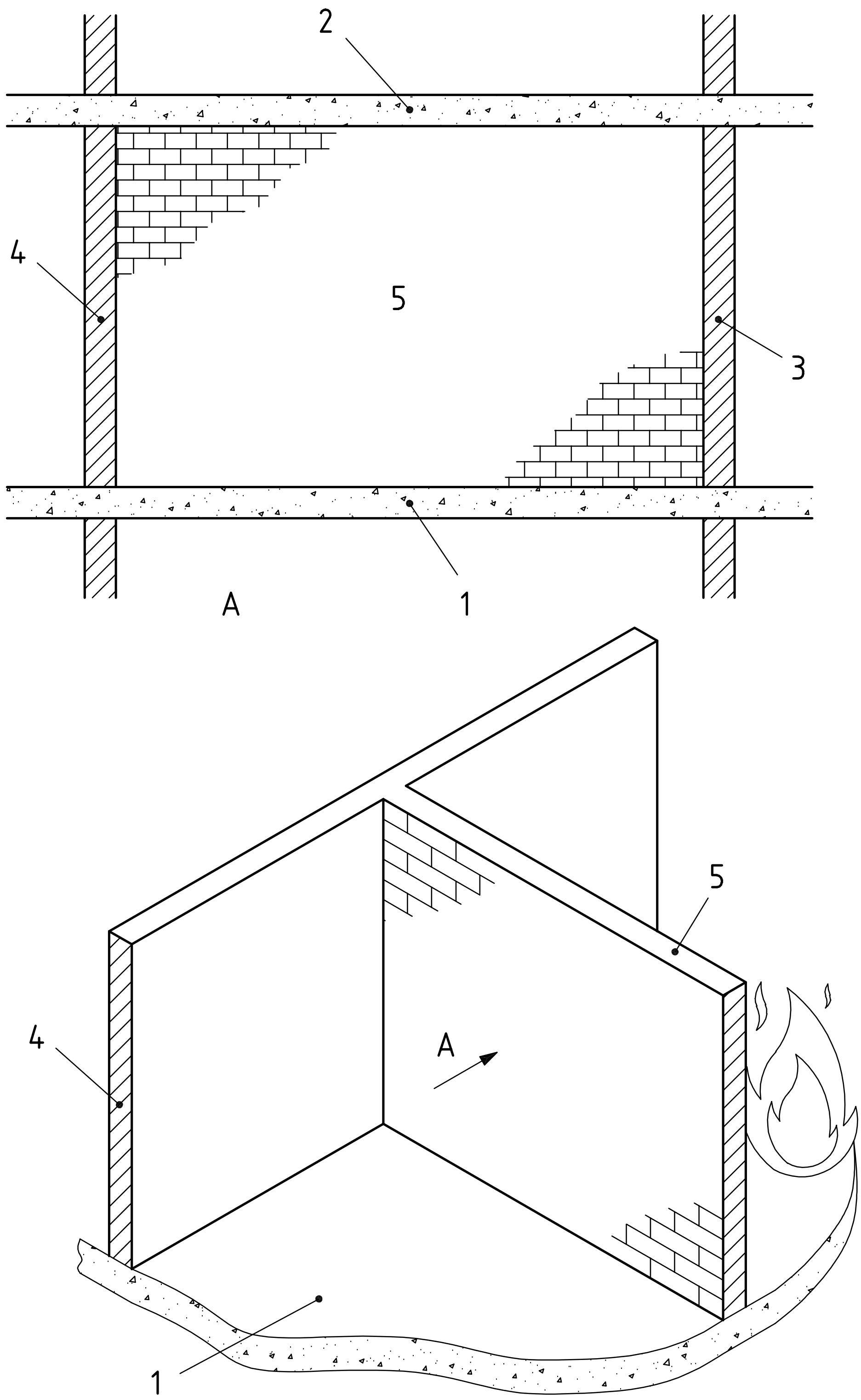


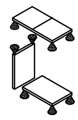
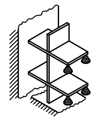
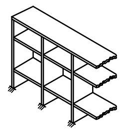
Figure A.3 — Decision tree for establishing the acceptability of a compartment wall — Reference section 8 (Adapted from Reference [1])



Key

1 floor below
2 floor above
3 R.H. abutment
4 L.H. abutment
5 compartment wall

Figure A.4 — Key to decision tree shown in Figures A.1 to A.3

Analysis of thermal response	Analysis of mechanical response					
	Standard tests	Experimental tests	Expert assessment	Engineering calculations		
				 Single element	 Sub-frame	 Entire structure
Standard curves	✓ (R,E,I)[a]	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✗
Experimental curves	✗	✓	✗	✓	✓	✓ (R,I)[b]
Time equivalent	✓	✗	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✗
Predicted maximum temperature	✗	✗	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✗
Predicted temperature curves	✗	✗	✗	✓	✓	✓ (R,I)[b]

[a] R is the load bearing capacity criterion; I is insulation criterion; E is the integrity criterion.

[b] R is the load bearing capacity criterion; I is insulation criterion; E, the integrity criterion, is difficult to determine by calculation.

Figure A.5 — Exposure/Restraint matrix

Annex B
(informative)

Background information on factors that affect life safety

B.1 General

The information included in this annex is for guidance to those persons considering changes to the testing standards. The information given herein is not definitive and those persons wishing to quote values in the context of a fire-safety strategy are advised to research other International Standards, especially those produced by other sub-committees of TC92, e.g. SC1, SC3 and SC4.

B.2 Exposure to heat

Hyperthermia is normally induced by reasonably long periods of exposure in a “hot” enclosure. The humidity of the air influences the time taken for hyperthermia to be induced; high-humidity air (100 % relative humidity) induces the state at a lower temperature than low-humidity air (normally dry). Research workers have identified that temperatures of less than 90 °C in saturated air can bring about dangerous increases in body temperature, whereas in dry air, temperatures in excess of 120 °C are generally needed.

The body normally operates in a range between 37 °C and 39 °C, the higher temperature normally being associated with exertion. However, when the body temperature is raised by the environment to more than 40 °C, reduced consciousness is experienced, and at temperatures as low as 42,5 °C, there is a serious risk of death.

The skin experiences burns following exposure to high temperatures, regardless of whether it experiences the increased temperature as a result of radiation (see 4.3.2), conduction (due to coming into contact with a hot surface), or by convection from the ambient surrounding.

Burns are not only experienced by a person's outer skin; the respiratory track is severely damaged, possibly resulting in death, as a result of breathing air at temperatures of little over 120 °C.

Clothing can protect the skin from direct burns as a result of exposure to hot gases but unfortunately it also prevents evaporation, nature’s way of losing heat, which can induce hyperthermia earlier.

B.3 Exposure to radiation

A person who suffers from burn wounds is not ill immediately after the fire experience. Although the skin looks blistered and blackened in some areas, and although the condition is very painful, the patient can normally breathe and the vital processes for life are not affected in the early stages of burn wounds. It is normally a day after the burn that the body becomes critically affected, especially when there are large areas of skin damaged by heat radiation. The skin starts to produce a poison. This poison spreads throughout the body and affects organs that are vital for the life functions. Moreover, the pain is terrifying and trauma normally sets in with inevitable results. Exposure to radiant heat can be extremely painful. The human skin can only tolerate a certain level of heat flux for a certain time. The higher the heat flux levels, the shorter the tolerable exposure time as is illustrated in Table B.1.

Table B.1 — Effects of radiation on life safety

Heat flux kW/m^2	**Effects or phenomena of the heat flux** **Exposure in seconds before intolerable pain**
1,0	Maximum for indefinite tolerable exposure for humans
2,0	50
3,0	30
4,0	17
5,0	12
6,0	9
7,0	7,5
8,0	6
9,0	5
10,0	4,5
10,5	4
11,0	3,5
12,0	3
13,0	2,5

The above values relate to a sudden exposure to that particular level of radiative heat flux and do not take into account any cumulative effects of exposure to varying levels of heat radiation intensity.

B.4 Toxic smoke

Whilst CO is readily identified as a toxin, carbon dioxide (CO_2) is also produced in large quantities, and whilst not being as progressive as CO, it has the ability to act as an asphyxiate (i.e. precludes oxygen), which can in itself be fatal. More importantly, it is in itself toxic at high concentrations. Such products are readily given off by burning cellulosic materials. It is the growing use of polymeric materials (plastics) that is causing the greatest concern as they produce potentially highly toxic gases. The most frequently quoted toxic product of combustion is hydrogen cyanide, which is extremely toxic and can induce death at low concentrations. This is not a primary product of combustion and requires secondary combustion to produce it.

Of more concern to researchers is the production of trace elements that can have a physiological effect on the body causing disorientation and confusion. Many of these are hard to identify and even harder to predict. There has also been a great deal of concern about dioxins and super toxins, products of combustion given off by a range of fairly common products, e.g. PVC, fluoropolymers. As an example, fluoropolymers can give off type 1 (normal) toxic products, or type 2 (super toxic) products[1]. Type 1 products are 10 times more toxic than the products of combustion from cellulosic materials, whereas type 2 products are 1 000 times more toxic. However, type 2 products, whilst being highly toxic, decay rapidly and have an extremely short life. They also need critical conditions and high temperatures between 450 °C and 650 °C to be produced and, therefore, are more likely to cause death and injury to those within the area of fire origin, rather than to affect those people within protected spaces.

Whilst not strictly falling under the definition of “toxic”, many of the combustion gases are very acid (or very alkaline) causing immense discomfort and often resulting in impaired vision. This can have a major influence on the ability of people to leave a protected space rapidly, causing their time of exposure to the other, more toxic gases, to be increased making them even more vulnerable to injury.

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