TECHNICAL REPORT 6585

Published 1979-10-15

ISO Technical Reports are subject to review within three years of publication, with the aim of achieving the agreements necessary for the publication of an International Standard.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION•МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ•ORGANISATION INTERNATIONALE DE NORMALISATION

Fire hazard and the design and use of fire tests

Risque d'incendie et conception et utilisation des essais au feu

Foreword

Technical Report 6585 was drawn up by Technical Committee ISO/TC 92, *Fire tests on building materials, components and structures*, and approved by the majority of its members. It was published in the form of a Technical Report rather than as an International Standard due to the urgent need for an authorative document to widen knowledge about the role of fire testing in the control of fire hazard and about the adequacy and limitations of some fire tests.

However, the whole question of fire tests in relation to fire hazard is one in which considerable controversy still exists and some aspects of this Technical Report were not entirely accepted by all member bodies. For example, some important questions of terminology are unresolved. Nevertheless it is considered to provide a general and much needed overall insight into the main considerations that should be kept in mind when fire tests are being prepared, are being discussed or are being used.

UDC 699.81 : 620.1

Ref. No. ISO/TR 6585-1979 (E)

Descriptors : buildings, design, structural design, fire fighting, burning rate, fire tests.

Price based on 17 pages

Printed in Switzerland

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0 Introduction

Over recent years there has been growing concern about fire testing, both in general and from the viewpoint of international and national standardization, with a view to reducing fire hazard and controlling the materials used in buildings.

It should be noted that the simple phrase "fire test" does not have an agreed usage. For example, the oxygen index test was developed and is used with fire primarily in mind and, even though it may not be regarded by many as properly a fire test, it is sometimes called one. On the other hand, tests for thermal conductivity and diffusivity are not referred to as fire tests, nor were they developed primarily with fire in mind, yet they may well be most relevant to certain fire hazards. For the purpose of this Technical Report, the term "fire test" shall be applied to any test used to provide information relevant to some aspect of the assessment of the behaviour of a material, alone or composite or part of a structural system, in a fire.

Until now, fire performance ratings of materials, products or systems have been based on experience and surmise and this situation is likely to continue for a long period of time. Ultimately, however, a more rational approach to this fundamental problem will be feasible. This Technical Report attempts to introduce some of the avenues open for this purpose.

Fire produces environments which endanger people and valuable property, be it buildings or their contents. These hazardous environments (see clause 7) occur because many materials, especially organic ones, hydrocarbon fuels, wood and many plastics, can be ignited by common energy sources and cause chemical reactions, usually with atmospheric oxygen, to produce heat. The rate of heat production generally becomes more than is needed for ignition and so leads to self sustaining combustion. This in turn can cause the burning zone to spread and to produce temperatures high enough to cause materials to lose strength (such as steel which is normally inert in fires) or to fracture (such as concrete) by inducing stresses when expansion is restrained.

Fires also produce quantities of unburnt liquid and solid residues (soot) which, even when diluted with fresh air, can produce toxic, irritant and corrosive atmospheres and reduce visibility sufficiently to impede escape and cause loss of orientation.

The behaviour of materials in fires is not only to be assessed by exposing them to a source typical of a small ignition source. Some other material may be ignited first and produce strong heat sources capable of igniting materials which a small source would not. The concept "reaction to fire" refers to a range of possibilities according to the conditions. Flammable materials on ceilings may form flaming droplets and spread fire to the floor, a behaviour which depends on the position of the material as well as on the material itself. These few examples illustrate the complex nature of fire behaviour which is characterized by the interaction of materials, design and use.

Were it not that fire can be hazardous, there would be no regulations and few if any fire tests, but it is not the purpose of this Technical Report to differentiate between tests used for regulatory and non-regulatory purposes. It is essential to recognize, however, that there is no *a priori* basis for claiming that a fire test assesses a given hazard. The claim must be justified and may involve more than one test, for example a smoke test and a flame spread together, since the former might use a fixed mass or volume of material and the latter might assess the amount involved in the fire.

The primary purpose of some tests has been directly to control what is manufactured and sold, indirectly to reduce the hazard. It is not obvious that one can replace all such tests by tests based on performance criteria and related directly to hazard.

1 Scope and field of application

This Technical Report gives guidance on the way in which use can best be made of fire tests and briefly discusses certain particular fire characteristics. It should not be considered as providing full guidance on the use of any one test. Each particular test will have its own significance and problems, and more detailed guidance for each test should be sought in the annex to the International Standard for the test concerned.

The relevance of fire tests should be seen as providing information to assess fire hazard, and thereby safety, rather than the reverse. This view corresponds to emphasizing the caution necessary in interpreting test performance.

In relating tests to hazards, it is necessary to identify and quantify the various components of fire environments so that the extent to which a test simulates any aspect of a fire can be stated. Procedures are needed by which a correlation between tests and "real" fires can be established through research on experimental simulations of "real" fires.

These questions are briefly discussed, through mainly in connection with the growth of fire in buildings. It is suggested, for example, that the distinction between tests which purport to relate to hazard and those which do not lies not in the tests themselves but in the claims made for them and the presence or absence of objective evidence supporting such claims.

2 The control of fire hazard

A person must have confidence in the safety of those places into which he may have to go. Such confidence or feeling of safety is partly a matter of likelihood that a fire will not occur and partly that if one does, one will not suffer. Whilst objective economic criteria may be possible for expenditure on safety as an investment or as an alternative to investment, it is doubtful if one can be devised for the subjective maintenance of confidence or to express consumer preferences which are culturally and socially dependent.

It must be emphasized that testing is only part of the process by which danger from fire is limited and by which hazards are controlled. It is sufficient to mention codes of practice, legal prohibitions, the roles of inspection and education, to realize that testing and the specification of performance requirements are but part of the control process.

Figure 1 illustrates schematically how fire hazards result from activities, some of which are the consequence of the development of new materials and new designs. New developments in fire standards and codes arise not only from the recognition of hazards but from new social habits and from new materials, some of which replace existing materials, whilst others permit new types of activities and therefore introduce new kinds of hazard. Figure 2 amplifies the "analysis and research" shown in figure 1. A "verification" feedback is shown from "control" to "hazard" in figure 1.

Unless there is some way of checking whether the controls have influence on the occurrence or severity of fires, there is little effective meaning to the elaborate discussion of what particular type of control is applicable or to its existence. Some administrative device is required in order to check whether the introduction of any control has an influence on the occurrence and severity of fires and the minimum requirement is the collection and analysis of data.

3 Fire hazard

3.1 The major problem in any discussion of the significance of test data lies in their relation and relevance to fire hazard. Danger can arise from fire because there is too high a probability that a fire may start or because there is too high a probability that, once started, its dangerous consequences cannot be mitigated. Measures to reduce the former are fire prevention, those to reduce the latter are fire protection and they include, *inter alia*, the provision of escape routes and fire-fighting equipment.

It may be necessary to distinguish formally between the likelihood of a fire occurring and the likelihood of a particular consequence once the fire has started. The former is largely the province of ignitability (in so far as tests are involved) and the latter of other tests (or ignitability tests of higher severity). The two probabilities are, to some extent, dependent on different factors and so statistically might be regarded as independent. Such independence has considerable implications for probabilistic design criteria but in so far as both probabilities are dependent on a common factor, for example bad management, the value of distinguishing between the two is lessened. Nevertheless, it is important to recognize that some tests are concerned only with the risk of initiation and others solely with the consequences of fire starting. Provisionally one might distinguish between these components of "hazard" by referring separately to "risk of initiation" and "consequential hazard". A third element is of course the degree of exposure of the property or people to the fire. Higher standards might be appropriate if more people were likely to be present at any one time.

3.2 It is assumed that a hazard has been recognized and is described in terms of some fire situation. It may, of course, be identified by statistical reports of real incidents, by the study of some puzzling incident, or it may be identified *a priori* (it does not take research to confirm that smoking near dip tanks of flammable liquids could be dangerous). Once a hazard is publicly recognized then the appropriate authorities can examine a particular situation and ask whether or not the elimination of that hazard requires a change in design or a change of procedure, or change of material. If the latter, one can then devise a routine test to compare one material, or product, with another fulfilling the same purpose.

3.3 Alternatively a manufacturer may be making a product which has many uses. It can therefore be involved in several fire situations, some of which may have a recognized hazard and some not. Enquiries then start from the point of view of the material or product, and the various hazards to which it may be exposed, or to which it may contribute, need to be identified.

3.4 With the former approach, beginning with hazard, each material or product is submitted to one and the same test or set of tests, corresponding to the hazard situation, whereas, beginning with material or design, different types of tests for different situations are required. It can be argued that some, if not all, quality assurance tests are relevant (or are intended to be relevant) to ignition when the material is the one first ignited from a small source, and if certain materials and products, for example electrical equipment and clothing, are exposed only in certain hazardous situations in which there is no inter-changeability with other materials or products, there are good reasons why tests might differ.

3.5 If different materials or products are used where they may be subjected to a common ignition source, one must test them in the same way, using a suitable source of ignition.

However, to consider the contribution of the given material to a fire started by some other material, the behaviour of the material has to be examined in the context of the kind of fire in which it could become involved so that it may be necessary to test it in a situation simulating a fire in, say, a corridor or a fire in an aeroplane. These arguments necessarily imply that there may be a necessity to test materials or products in more than one fire environment.

3.6 The choice and the definition of such environments is not necessarily a simple matter. It is usually accepted that fully developed fires are simulated in the fire resistance test. So far as a structural failure is concerned, it has the sanction of tradition but this is possibly not the best representation of such a fire for all the hazards with which, say, the fire brigade is concerned. Indeed, fire brigades and architects may well have different subjective concepts of what a fire is, and testing must become objective to overcome many of the reservations held by one or other interested parties.

3.7 Two approaches have been considered, but there is a third. The two described ought to simulate some aspect of fire hazard, for example the ignition of a chair by a cigarette or the exposure of a wall to a fully developed fire, or a stage in the development of a fire. In the third approach sufficient understanding is assumed of the nature of fire and fire behaviour and the way in which materials contribute to fire development, to use test data from selected environments to make predictions for others. Such predictions may be by means of theory or experience.

3.8 The tests which are being studied and developed clearly simulate some hazards. The test for ignitability is simulating a very conventional risk even in a simplified form and the spread of flame test is the latest in the long development of such tests.

Although the tests are not directly measuring basic physical and chemical properties of a material, it is desirable to reduce as far as possible the dependence of what is measured on the apparatus itself, if one is seeking to obtain data having general use. Thus the time to spread flame under defined and reproducible thermal flux is a quantity which research can hope to relate to more basic properties.

It follows that some compromise may be required at the present time between a close simulation of a particular hazard (necessitating tests for each hazard) and idealization of the exposure to permit interpretation and generalization.

3.9 A method of using the data from these simplified situations is needed to assess the hazard in a more complicated situation and it is this problem i.e. the assessment of hazard from data obtained from ignitability, spread of flame, the rate of heat release, and other tests, that must now be considered. Some of the arguments can be extended to other tests.

4 The assessment of hazard by tests

4.1 In general terms, one has to assess the relevance of any tests or test to some given hazard. If the hazard is well recognized and can readily be simulated, for example the ignition of a mattress by a cigarette, it is sensible to base the test directly on that hazard itself, but where this is not possible, or is temporarily not practicable, we have to correlate the tests with the hazard in some way. Fires are fortunately rare events; about 10 % of building fires in the UK are started by smoking materials, but only 1 in 10^8 cigarettes are associated with a fire so that the hazardous situation needs to be well defined before experiments are productive.

In consequence, the experimental study of risk raises problems different from those in the experimental study of consequential hazard.

4.2 One way or another some situation is presumed and experiments are undertaken to simulate fires in this situation (see figure 2). If the problem is one of risk of fires starting, an attempt may be made to simulate the ignition situation or the equipment failure by a test leading to it and to conduct many repeat tests, the results of which are to be analysed statistically. If the more complex consequential hazard is being examined, one can, as an example, describe a procedure in terms of a fire in a room (see figure 3). Various measurements can be made : measurements (M) of the temperature, gas concentrations, time, collapse of ceiling, ignition of walls, etc., can be taken for a variety of different materials, for example different lining materials (L), and different carpets (C), etc. i.e. various measurements M_1, M_2, M_3, etc. can be made for various combinations of L and C, etc. Some assessment must then be made of the relationship between hazard of injury or death and any one or more of the various measurements — threshold danger levels for example, can be set for temperature or gas concentration or ignition time. It should be recognized that this step is, at present, almost exclusively qualitative because, although it is known that life cannot be supported below some concentration of oxygen or above some gas temperature, translation of these thresholds into risk is quite a different matter. It is presumed, however, that various criteria can be fixed for M_1, M_2, etc., but it has to be recognized that there may be a need to change these in light of experience.

4.3 For each type of lining and carpet, etc., a second set of numerical values can be obtained, some of which are the results of existing or proposed fire tests. There are also data pertaining to basic properties of each material, such as calorific value, thermal conductivity, k, density and specific heat capacity, c, as well as a mass transfer B number, oxygen index, etc. We then require an examination of the multi-variate correlation between the various values of M and this set of numerical values. Such an analysis could tell us which of the various numerical values are significant and which are the most significant — the most primitive form of this activity is to correlate one given measure from a test with one experimental property. For example, the results of the US E162 test with the thermal inertia of $k\varrho c_p$ or of the British Standard fire propagation test provide a numerical index, the components of the index being weighted to give the simplest meaningful correlation to flashover time. Even this kind of exercise must be conducted over as wide a range of materials as is likely to be tested; few fire tests have been correlated with reality even at this primitive level.

4.4 Although the above procedure is a pragmatic approach which can establish a correlation, a rational use of data from standard tests in a functional design requires an understanding of the physical realities expressed by the test result. To this end, an analytical model of the dynamics of the test process is necessary. As a corollary to this, if a test is measuring something which can be quantitatively defined in physical or chemical terms, it ought to be possible to predict test results for certain simple, idealized situations, for example a homogeneous flat material. Such exercises are commonly performed in research, and success allows one to better understand what the test really does and the extent to which the results are apparatus dependent.

Concurrently with the evolution of the theoretical analysis of testing methods, the last few years have seen rapid progress in the capacity to describe mathematically radiant and convective energy transport from large scale turbulent flames and the influence of this energy transport on burning and fire spread.

With the main features of the analytical model thus assumed, and with material characteristics determined from the standard tests, comparison between theory and a specified full scale test should make possible the validation of model structures as well as identification of undetermined parameters. Techniques to be used for this purpose have been developed within the field of automatic control to identify a variety of industrial chemical and physical processes.

When, for a given simplified geometrical full-scale situation, the process dynamics have been identified, deterministic sensitivity studies may be performed to ascertain the influence of the properties of the test material on the fire spread and fire product generation processes. Finally, going from the deterministic phase to a recognition of the stochastic nature of many state variables, reliability studies may be made, taking into account uncertainties in ignition processes, material properties, analytical modelling and environmental conditions. The results could have the form of time and space-dependent probability density curves of fire products. More realistically, a distribution-free, first order linear analysis would provide the first and second moments of the maximum values of the corresponding quantities. Coupled with definitions of the limits of human tolerance and escape facilities, the fire hazard may be evaluated. This may in turn lead to a consistent definition of the integrated concept of a "reaction to fire" index for the given situation.

To reach this stage of development will take a considerable number of years. Research is required on :

a) the applicability, to the tests being developed, of available analytical thermophysical mathematical models regarding fire product generation;

b) systematic identification studies of model structures and parameters (such as basic and derived material properties);

c) studies to identify those full-scale fire situations where at least the gross features of the process dynamics are known, and by use of model validation and parameter determination techniques to evaluate quantitatively the fire performance of the tested material;

d) procedures to translate fire performance results into a fire hazard assessment.

4.5 The above separate arguments suggest that one or more research programmes are required so that one can find the proper weightings to be attached to the results of separate tests before assessing a hazard. If this is not possible in the short term, what instead can be done ?

The short answer is that the assessment must be completed by an appeal to experience or to surmise. In some way or another, by a committee or by research, materials or products can be placed in an "acceptable" order of rank and test results weighted for whatever hazard is involved. Such "acceptable" orders can be revised pragmatically or as a result of analysis or research. It is essential that as wide a range as possible of materials be included.

In view of the variability of fire behaviour, i.e. its sensitivity to factors (some of which are not controlled, for example extent of door opening, arrangement of furnishings), such experimental studies must include sensitivity tests. All too often research teams have reached contradictory conclusions because they have had to presuppose different standardized conditions.

4.6 It should be emphasized that poor performance or failure in a test gives grounds for a presumption of hazard. The converse is not necessarily true; good performance does not equally provide a presumption of safety. One might contemplate defining safety by the effectiveness of measures to limit fire hazard. Such a definition would be consistent with the view that the role of fire tests is more in connection with assessing fire hazard and not safety from hazard.

4.7 Quantitative differences between the performances of a material or product in two tests that purport to assess the same fire characteristic (and therefore which should have no qualitative differences) have probably much less physical significance compared with differences between, on the one hand, real fires as a class and, on the other, tests which simulate them. Even if they are not trivial, it will be difficult to demonstrate the differences in any verification procedure. Such differences that do exist between tests may however be very important for good reproducibility and other properties required for approved tests. They may also be important commercially for defining acceptable performance near border lines.

4.8 A test, or group of tests, which provides, in the manner described in 4.3, some quantitative measure of fire behaviour may still be used in an arbitrary manner in some general grading system, be it a "points" scheme or a simpler classification system based on experience, codified inductively. A requirement in drawing up such schemes should be the inclusion of some rational means of exploiting the results of "verification" to ensure that the scheme is "self-adjusting" or "adaptive" with time.

4.9 In some tests, more than one measurement is taken, for example ignition time, time for a flame to spread a certain distance, the height of flames. Whether the amount of information is thereby increased depends on the extent to which they are uncorrelated with each other.

They are more likely to be correlated if all are measured under the same exposure conditions and the degree of correlation will vary between types of material. If there is too great an interdependence, the resulting extra information may be more likely to confuse than to clarify.

4.10 It should be clear from the above that there may in principle be certain hazards or, more precisely, some important or critical component of a hazard which can be assessed by one test. This is more likely the closer the test reproduces the hazardous situation. It should be equally clear that no one test alone can assess the "hazards" from a particular material or product. Indeed it is doubtful what meaning can be attributed to this phrase if no particular hazardous situation is implicit and it is safer to recognize that even a full-scale test cannot fully simulate a "real" fire.

5 Types of fire test

Broadly speaking, without attempting to make rigorous definitions several types of fire test may be distinguished. All are designed to assess some characteristic of the behaviour of a material or system in a fire from its response on exposure to some simulated aspect of a fire environment and it would seem possible to classify these tests in two ways.

The first way distinguishes two main types of test : those conducted to assess the response of the whole system in a way intended to be realistic and representative of some fire conditions, and those designed to measure a property which can be used quantitatively in design calculation, hazard analysis, theoretical models, etc. An example of the former, which would include fire exposure tests, would be the exposure of a mattress to a cigarette, and of the latter, sometimes called basic property and combustion characteristics tests, examples would be a smoke production test, giving measurements of opacity, and the oxygen index test.

Another independent way of classifying tests is based on a "post hoc" examination of the relevance and relationship of the results obtained to actual behaviour in a particular fire. A test may be found to be relevant to some hazard and not others and for that hazard it could be included in a quantitative system of data for hazard assessment. Until it is found to be relevant to some hazard, it is better referred to by some neutral title with a disclaimer as to its relevance to fire hazard. A test found to be relevant to a hazard can also be described by reference to that hazard, but since it is doubtful if any test is relevant to all hazards the limitations on its relevance must be clearly stated.

Figure 4 summarizes the above. Some tests may be in a different row according to how they are used. A spread of flame test may be used to simulate fire spread on a roof or may be used to measure $k\rho c$ of a material. The procedure described in 4.2 and 4.3 can make use of any data. Whether it is from one kind of test or another is immaterial. The significance of the classification is to emphasize :

a) the desirability of having tests relevant to several hazards, where possible;

b) the various ways of using test results not all of which relate directly to hazard;

c) the need to establish the relationship with hazard. Additional knowledge (statistics or research) is necessary for this. It is not sufficient to intend to provide a relationship with hazard, it must be confirmed.

6 The "reaction to fire" tests

6.1 General

Although some of the previous discussion has had a general implication, it is useful to consider specifically some of the tests whose scope is the initiation and development of fire, in particular fire in enclosures. This involves the use of tests to assess :

a) combustibility;

b) ignitability;

c) spread of flame;

d) heat release (composite materials).

The reaction to fire of combustible materials determines their involvement in fire and their ability to spread flame, their propensity to transfer and extend fire, and their contribution to the production of adverse environments, of which here consideration need only be given to the thermal environment.

Smoke production and toxicity tests (which might be classed as reaction to fire tests) are not discussed although it is necessary to remember that, as commonly conceived, these tests cannot be used alone to assess the smoke or toxic hazard. The reason lies in the use of a particular size of sample, whereas the amount of material becoming involved in a fire is dependent on its flame spread characteristics. These are but two of the many examples of the interrelation of test performances in hazard assessments.

Strictly, one should also include a test for the rate of heat release of a small piece of a single material. This could, in principle, be used to define as "non-combustible" a material having a rate of heat release within certain limitations, but would also give an assessment of a degree of combustibility.

A brief discussion of each of the above properties and the associated test in the context of fires developing in an enclosure (see figure 3) is given below.

Ignitability and surface spread of flame are two properties readily affected by the passage of time. Accidental damage to a surface, deliberate if occasional painting, and natural ageing, can alter these properties, and its relevance to such tests in a system of continuing control needs consideration outside the scope of this Technical Report.

6.2 Combustibility

Although tests of combustibility are now described as non-combustibility tests, it is thought better here to refer directly to what the test tells us. "Failure" in a combustibility test tells us the material is combustible; "passing" does not tell us that the material is non-combustible, only that it is non-combustible in so far as this is defined by the test[1].

A second reason for using this term is in line with the argument of 4.6. A term referred to relates to the "hazard" — not the uncertain criterion for uncertain safety.

At first sight, it might seem that materials that release no heat in fires could be used without restriction. It is true that, by definition, they do not contribute directly to fire development as they provide no fuel. However, they could less obviously contribute to the development of fire by retarding the loss of energy, because their insulating properties affect fire behaviour. This effect is important only if there are large enclosing areas of the material, for example as wall linings, and if the value of the transient thermal effect, mainly controlled by the product of thermal conductivity, k, density, ϱ, and specific heat capacity, c, is lower than is conventional.

Similar arguments apply to the use of inert materials over large areas, but which have reflecting surfaces. These problems are not solved by an assessment of the degree of combustibility. It has been estimated that roughly one quarter of the heat produced in a conventional, fully developed fire is transmitted into walls, ceiling and floor, having thermal properties similar to that of normal concrete. A roughly similar proportion is lost from an "open" fire by radiation. If the fully developed fire is one controlled by the fuel, i.e. heat release is not limited by a restricted air flow, the inert walls with a reflecting surface may be said to be contributing roughly 20 % of the heat release. In practice, the reflectivity applies only to the radiation transfer, not to the convection transfer, and the fire would damage the reflecting surface to the point at which the effects would be considerably lessened, and in general the contribution of an inert material by virtue of its thermal insulation is usually neglected. However, the necessary conservation of heat by the expected future improvement of insulation standards may inevitably bring about more fires or more severe fires as a result of this effect.

Tests which measure the heat release of materials having a low calorific value, for example the potential heat test used in the USA, allow one to add the calorific content of the material to that of the room contents but this is less a problem of fire growth than one of fire severity. The rate of heat release has a more complex significance which will be discussed later.

6.3 Ignitability

Two ignition properties are distinguished (see figure 5). Under any given imposed flux of heat there are two kinds of response :

a) the material does not ignite;

b) the material ignites after a delay (ignition time).

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[1] ISO 1182 does not identify inert materials, but only materials having less than some combustible content or releasing heat more slowly than some given rate.

For the second class there is a quantitative measure of ignition time. On the other hand, for any combustible material there is likely to be a threshold flux for ignition in the absence of a pilot flame, and a different, lower threshold[1] for ignition in the presence of such a flame. Again, if the flux is above either threshold, there is a corresponding ignition time. Ignitability is best thought of as a complex of responses, some negative, to a range of imposed thermal fluxes.

A knowledge of the expected thermal environment is therefore essential to specifying the conditions to be used in an ignitability test. Clearly a low level of imposed flux or a zero level with a pilot flame, could be used to assess the hazard from an accidental ignition source, and the risk of the material becoming the material first ignited. Ignition response under a high level of imposed flux is a measure of the possibility that the material can contribute significantly by becoming a path for fire to spread along. Thus, if a wall can be ignited easily in the early stages of a fire, the fire may spread to the upper part of a room and to the ceiling where it has the possibility of interacting with fire on the floor and accelerating the development of fire to flashover. On the other hand, fire may readily spread to the ceiling because of the existence of high stacks of fuel or tall furniture, and in this situation the extra path via the walls may be much less significant.

There are certain hazards for which it may be appropriate to use a varying intensity of radiation in ignitability testing. Normally a constant flux is imposed. When a material may be exposed for a long time to a thermal flux insufficient to ignite it, it may be heated through its bulk so that when finally exposed to a higher thermal flux it behaves in a different way from the way it would without preheating. This is primarily of importance for composites which may have combustible materials behind an incombustible surface or which could delaminate and expose otherwise protected surfaces and adhesives. A typical example of a fire situation of this kind would be the leakage of hot smoke from a doorway into a corridor over a long period of time, followed by the burning through of the door and the impinging of flames onto the ceiling.

6.4 Spread of flame

Spread of flame tests are of various types and the simplest is designed to measure the rate of flame or fire spread along a thin sample of material unaided by any source of heat other than that initiating the fire. Such tests are sometimes called rate of burning tests but this phrase is better used to imply that the mass loss or heat production is measured. The basis of many spread of flame tests for building materials is that flames may spread over a surface only if there is supporting heating, so that if the supporting flame varies along a surface, the final distance of spread is a measure of this limit. It has often been argued that the critical level of supporting flux has some similarity with the threshold for ignition with the pilot flame, and that prior to reaching this limiting position the rate of spread is related to the ignition delay when exposure is above the ignition threshold, and so is a measure of the rate of growth of fire on an extended surface, see figure 6. In this way, one test is capable in principle of providing information for which a series of ignitability tests would need to be made at different levels of imposed radiation.

There is, however, an important difference between the two types of test. In certain orientations, the convective and radiant heat from flames to a surface augment the supporting radiation so that the spread of the flame is influenced partly by the flame itself. This fact has sometimes been used as a reason for using the "spread of flame" test in orientations in which feedback does not occur or is minimized, so that the exposure is well defined. However, because predictions concerning heat transfer from flames are difficult and at present not practical for real material systems, a spread of flame test can give information not obtainable from an ignitability test, particularly in those orientations that favour feedback from the flame. It is not possible to vary exposure history so easily in the spread of flame test as in the ignitability test.

6.5 Heat release

The feedback discussed in 6.4, in connection with the spread of flame, is local from the flame to the nearby unburnt fuel. It does not include any contribution from the heat produced by the combustion of the test material as do the many varieties of enclosure tests. It is because this heat affects the total environment in an enclosure (see figure 3) that the property of heat release has to be measured. The conditions under which this is performed must be related to the conditions of exposure in the hazard concerned. Since the effect of the combustion products is cumulative in an enclosure and affects the response and contribution of all other materials, one might expect the relevance of ignitability, spread of flame, and heat release tests to the speed of development of a fire in an enclosure containing only the one kind of fuel to increase in that order, i.e. the order of increased provision in the tests for the assessment of feedback. To the extent that feedback or part of it is retained in addition to the imposed heating, the tests are also progressively more severe but justification of any *a priori* judgement of relevance, be it analytic or subjective, must be confirmed by experiment.

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1) There are many factors including area of exposure which affect the threshold. The level of flux and the presence or absence of a pilot flame are the main ones.

7 Environment modelling

7.1 General

In the preceding clause, reference was briefly made to some of the relationships between properties measured in established types of tests and fire behaviour. This subject needs much further study but one can now begin to consider how the conditions to be imposed in tests are to be evaluated other than pragmatically by reference to detailed data, where such exists, on hazard.

Whether or not a test simulates a particular fire environment with the intention of assessing the hazard directly, for example the use of a cigarette to test a mattress, the information obtained from a test must relate to some fire condition and some rôle that the material or product plays in that fire environment, for example the property of thermal conductivity is relevant both to many ignition and to many fire resistance situations. The material or product in question is itself in an environment concerned with its normal function, its connection with other materials and components fulfilling some design purpose and it may well be under load and all of these can be affected by the fire. The immediate purpose of this clause is to catalogue the factors that must be included in any consideration when defining a fire environment. The main categories are shown in the table with examples.

7.2 Thermal environment

The thermal environment is the particular feature of a fire test, whether it purports to simulate a real fire or to simulate it in an idealized way by standardizing the conditions for measurement of, for example, heat transfer and thermal expansion. It can be seen in figure 3 how the imposition of a given environment onto a combustible material will produce heat which will itself alter the thermal environment.

If one has to identify one characteristic only for the prescription of a thermal environment, then that will be the heat flux onto the surface of the object being tested. This, with the main exception of self-heating in storage, has usually more significance as the factor determining the response of the object than has the definition of some surrounding temperature. The external heat flux will, in general, comprise the components of convection and radiation. The response of the material will depend largely on the total heat flux, but for certain situations the separation into components of radiation and convection must be contemplated because the distinction between convective and radiant heating can sometimes be important, for example when the reflectivity of the heated surface is high, but since such a reflectivity is itself affected by the deposition of soot in a fire it is clear that complex interactions occur and must be considered in fire testing.

A second aspect of the thermal environment is the presence or absence of a flame. If flammable vapours can be produced by the heating of a material and if the ignition of these affects fire behaviour as, for example, in an ignitability test or in a spread of flame test, then clearly provision must be made for the presence of such a flame. The difference between a general heating level in a thermal environment and a concentrated ignition flame may alternatively be regarded as a combination of thermal and spatial factors. Initial temperature or a quasi-steady temperature produced as a result of pre-heating is of considerable importance for the time scale of the response and for particular materials that suffer damage at low temperature.

7.3 Spatial relationships

Environments may be uniform around an object, for example a column, but there may be a variation in the heating of a floor from fire below or from fire above, or a wall lining may be exposed to heat from one side only. Thin materials are more easily ignited on an edge or corner than by exposure of a flat surface to an igniting flame. In a given thermal environment the orientation of a flat surface introduces considerable qualitative and quantitative variations in its response to fire. Objects in the path of a fire are rarely heated uniformly and, once ignition has occurred in one part, flame will tend to spread according to the distribution of the heat flux on at least part of the remainder of the object.

7.4 Atmospheric environment

The role of the surrounding gases in creating a thermal environment is largely covered by the definition of the convective components of the thermal flux. The oxygen concentration in the gases surrounding a heated object may have significant effects on the onset of ignition. It will also affect the character of any flame that can be supported in this atmosphere and so affect the thermal feedback to the burning material. In addition it will affect the nature of the combustion products (i.e. smoke, toxic gases) and thus it will affect the surrounding atmosphere.

7.5 Mechanical load

The expansion of a loadbearing structural element can induce loads on itself and on other parts of a structure and in theory the expansion of gases can do so as well. It is, after all, this which causes the buoyancy that moves the hot gases and drives the circulation and requires a pressure to overcome smoke penetration onto escape routes and in extreme cases, results in explosion. Changes in thermal properties at high temperatures can, depending on the load, hasten the loss of protection of steel by spalling and hasten collapse which, apart from being an undesirable outcome of a fire, is a means of spreading the fire to new fuel and new spaces.

7.6 Interaction effects and variations in time

Pursuing further the details of these environmental categories is outside the scope of this Technical Report and is best associated with a particular hazard. We should, however, note that any one may be a function of time and there can be complex transient multiple interactions between them as mentioned above (see figure 7).

Complications from transient effects can arise from the simplest of conditions since the extent or depth of heating after exposure depends on the thermal properties of a material. This, for example, can induce a variation in the induced thermal forces or the delamination of laminates of different thicknesses (see 6.3). The course of a fire can vary with the order in which various effects occur. Under certain exposures some materials melt away from the surface before igniting, or fall from a ceiling onto a floor and if remaining alight drastically influence the development of the fire.

Most fire tests do not deliberately vary the thermal environment with time other than those variations imposed by the thermal time constants of the apparatus. In fire resistance tests this variation has itself been standardized into a standard temperature/time curve which is representative, in general, of fully-developed fires prior to decay. The British Standard fire propagation test begins with one level of heating and then after three minutes imposes another.

Varying the transient character of the improved environment can be a source of variation in test performance, but in view of the variable nature of fire, it would seem essential for a test not to be too sensitive to whatever variations are incorporated in it.

At worst a catalogue such as that given in the table and figure 7 provides a check list for the examination of a test.

8 Conclusion

However the development of fire tests is initiated, one cannot proceed properly without recognition and definition of hazard. On the basis of these, one needs criteria to relate behaviour in real situations with behaviour in simulated ones and to compare one or both of these with the behaviour in idealized test situations. Outlines of a pragmatic procedure and of a long term research approach for doing this have been discussed and the first task in the application of tests relevant to defined idealized conditions, other than those of the test, in the adequate description of the various conditions to which a material or product may be subjected in a fire. For this, a catalogue or check list of environmental conditions needs to be developed, to which this Technical Report gives an introduction. Hazards, similarly, will involve some of these conditions and the process of definition and its formalization will itself play an important role in the development of more rational test procedures. These will need definitions of fire environments in the context of an understanding of fire behaviour. An outline of this has been given for fire growth in an enclosure. For further elaboration it will be necessary to have particular hazards in mind.