CRITICAL APPRAISAL OF FIRE TEST METHODS

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DECLARATION

This thesis is the result of research work for the degree of Master of Philosophy undertaken in the Department of Civil Engineering and Building Science, University of Edinburgh.

It is declared that all the work and results in this thesis have been carried out and achieved by the author herself and the thesis has been composed by her under the supervision of Dr. D.D. Drysdale.

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Dedicated to Zaman, Amar and Emir.

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ABSTRACT

A critical analysis of the "reaction-to-fire tests", purported to assess properties, viz. ignitability, heat release and spread of flame is presented.

Two spread of flame tests namely the ISO spread of flame (IMO Version) test and the LIFT spread of flame test have been studied. Experiments were carried out on 7 lining materials using both methods. The parameters "heat for sustained burning" and "critical irradiance for flame spread" are derived from the ISO spread of flame (IMO Version) test and the results are found to be apparatus-dependent. The ignition and flame spread data in the LIFT spread of flame test are derived based on Quintiere's analysis which assumes that the solid under test is thermally thick. The test method allows the derivation of several material properties, viz. critical heat flux for ignition and flame spread, ignition temperature, minimum temperature for flame spread, a rate coefficient and flame heating parameter. The estimation of the critical heat flux for ignition and the flame spread velocity obtained from the flame spread model are crucial as they can influence the determination of the derived parameters. The experimental investigations indicate that the flame spread model is not applicable to materials which char severely, or for materials which melt and shrink upon heating. Improvements in the design of the apparatus in several areas, viz. replacing acetylene with propane as the fuel for the pilot flame, pilot flame and its air supply, sample holder and gas supply are highlighted and recommended for the LIFT spread of flame test if it is to be considered as a reliable tool in providing ignition and flame spread properties. The resulting studies indicate that the LIFT spread of flame test is preferred to the ISO spread of flame (IMO Version) test in evaluating the performance of lining materials in respect of their lateral flame spread in opposed air flow conditions.

CONTENTS

NOMENCLATURE

The definitions of the symbols used in this thesis are listed below. In the few cases where more than one definition has been assigned to a symbol, the meaning will be evident from the context in which it is used.

Roman Characters

b	parameter (in equation 6)
c	specific heat
C	rate coefficient
CO	carbon monoxide
CO_2	carbon dioxide
F(t)	thermal response function
h	heat loss coefficient
h_c	convective heat transfer coefficient
k	thermal conductivity
N	number of time increments
0_2	oxygen
$\dot{q}''_{ig}$	critical heat flux for ignition
$\dot{q}''_s$	critical heat flux for flame spread
$\dot{q}''_e$	external heat flux
$\dot{q}''_f$	heat flux from flame
$\dot{q}''_{bs}$	rate of heat release per unit area from cone calorimeter
$\dot{Q}$	total heat release rate from the large-scale room fire test
t	time
t_{ig}	time to ignition
t*	pre-heat time
t_{fo}	time to flashover in full-scale
T	temperature
T_f	flame temperature
T_∞	ambient and initial temperature
T_s	surface temperature before flame effects
T_{ig}	ignition temperature
$T_{s,min}$	minimum temperature for flame spread
V_f	rate of flame spread
V_g	opposed air flow velocity
y	Distance (Chapter 4)

Greek Characters

α	thermal diffusivity, $k/\rho c$
δ_f	flame heat transfer distance
ΔA	incremental burning area
ε	emissivity
ρ	density
Φ	flame heating parameter
ϕ	configuration factor
σ	Stefan-Boltzmann constant
ξ	$t/t_{ig}^{0.6}(s^{0.4})$

Subscripts

bs	bench-scale
c	convective
ceil	ceiling
e	external
f	flame
fo	flashover
∞	initial
g	properties of the gas phase
ig	ignition
s	spread

List of Abbreviations

ASTM	American Society for Testing and Materials
BS	British Standard
CIB	Conseil Internationale du Batiment
DP	Draft Proposal
EPS	Expanded Polystyrene Foam
HRR	Heat Release Rate
IMO	International Maritime Organisation
ISO	International Standards Organisation
NBS	National Bureau of Standards (Centre for Fire Research) (Gaithersburg, MA, USA)
OSU	Ohio State University

PIR Polyisocyanurate
PVC Polyvinyl chloride

CHAPTER 1
INTRODUCTION

Fire might be characterised as one of man's most important discoveries, it is also one of our most useful tools. From the early days of civilisation until today, we have used it for cooking, heating, generating electricity and to power most forms of transportation. But uncontrolled fire is a danger to life and property.

Over the centuries fire has continually caused injury, loss of life and destruction of property. The appalling losses spur the researchers and inventors to be involved in various extensive and fundamental studies in order to comprehend the complex nature of fire. This leads to the different modules of specialised areas of fire research such as fire protection, fire control and extinction with the objective of reducing the damage caused by fire.

Fire tests which form an essential part of a fire protection and safety philosophy are designed to give an assessment of the hazard, provide guidance in selection of materials to be used in building, a knowledge and prediction of the likely behaviour of the material or the product of the system in actual fire situations.

These tests are normally carried out on a laboratory scale under standardised and reproducible conditions which approximate to one or more aspects of a fire.

Building products and their constituent materials are subjected to standardised fire tests because of the hazards they present to life and property safety in the event of fire. However, it has been emphasised that a fire test itself cannot normally measure fire hazard, nor can the results of a fire test alone guarantee a particular degree of safety. They simply provide information and indicators to assist the determination and control of fire hazards [1].

Even though fire tests have contributed immensely to regulators, specifiers, consumers, manufacturers in their relevant areas of interest, there is still continuous discussion amongst researchers in the European Community, USA, Japan and Australia to improve the various existing test methods available so that international utilisation and application of these tests to real fire situations can be obtained.

It is understandable that action has to be taken to rectify whatever loopholes or criticisms that exist in the available test methods or procedures. However, this can be very troublesome and confusing to countries of the third world like Malaysia where the application of fire technology is still at an early stage.

Only a few years ago considerable efforts were made to put stringent control on fire protection. These included the areas of standardisation, testing and safety for building materials and products in building. Currently, the regulations and provisions relating to fire protection as stipulated in the Uniform Building By-Laws, 1986 are mainly based on the British Standards BS 476. Since Malaysia was once a British colony it is not surprising that Malaysia's regulators absorbed the British Standards wholly even though numerous standards and procedures of equal quality are available from other major countries like USA, Australia, Japan, Germany and Sweden.

However, as Malaysia's economy progresses, especially in the building industry where the number of large complexes and high rise buildings is increasing, problems arise in testing due to various reasons.

There is now widespread use of new materials which are put to use in many ways, such as wall and ceiling coverings, carpeting, in the form of furnishings, roofing and piping. These all increase the fire load and hazards in a building. Therefore these building materials or products need to be tested and evaluated before they can be approved by building officials for use in buildings. Aware of the increasing demand for testing of these materials by manufacturers, the Standards and Industrial Research Institute of Malaysia (SIRIM), which is the testing organisation in Malaysia, has taken the decision to keep pace with these new developments.

Fire tests have been under particularly intensive study by researchers world-wide for the past years for several reasons, one of the most important being the impact of new materials on the long established test methods. New materials exhibit some characteristics not found in traditional building and furnishing materials. The main differences are in the propensities to soften and melt, or to form an insulating char. Also some can be made in a low density form. Subsequently some tests have been modified, some rejected, and new tests developed.

The effect of these revisions lead to some changes in the testing equipment, and some standards that are obsolete. The results of the older, or first generation tests are found to be apparatus-dependent where the results obtained for a particular material can be different even though tested in similar test environments. This inadequacy was clearly illustrated by Emmons [2] when he compared European tests for ranking building materials. The rankings from six tests correlated badly despite being used in different European countries to compare wall lining materials.

Any changes to the test methods is a set-back to the testing body as the existing test apparatus that is available is no longer able to fit to the new standard. To acquire the new testing equipment itself is expensive while at the same time funds are needed to upgrade or purchase other fire testing facilities. There are cases where certain other tests which are obsolete are still used by the testing body until such time when new equipment is available. Therefore it is not surprising that we are far behind in terms of keeping pace with the developments of fire tests in other advanced countries.

Similar problems are faced in the preparation and promulgation of national fire standards. It is recognised that once the tests are adopted in law they become enshrined and very difficult to be altered. There is usually stiff resistance to any change, partly by the users of the test results and partly by the industry. Having acquired familiarity with the interpretation of the results, the users often find it difficult to adjust to changes reflecting a new level of understanding. As for the industry the suggested changes in the test standard may lead to marketing problems because having their products tested is a major investment for them, and as a result they have to include whatever expenditure incurred in testing in the cost of their products. Therefore any new ideas or changes take quite a while for the specifiers, regulators and manufacturers to absorb and this can delay in the revisions of the standards. At least nowadays attempts are made to study other international standards besides British Standards to comprehend the concept of a particular test procedure that can be applied to the local context before it can be adopted to the standard.

There is a great advantage to be gained if all countries accept one test method, or group of test methods. In this way the difficulties of comparing the results of testing to individual national standards would be avoided. The International Standards

Organisation (ISO) is the appropriate body to undertake the task of coordinating this work. Recently, there have been attempts and discussions among researchers within the European Committee for Standardisation (CEN) and ISO to harmonise existing fire tests [3].

The reason for undertaking this study was to make a critical analysis of existing test methods so that a better understanding of the concept and methodology of testing can be gained. If the principles behind each test are known, a more rational decision can be made about the development of future fire testing in Malaysia.

1.1 FIRE DEVELOPMENT

It is often said that no two fires are alike. Researchers working under carefully controlled conditions in the laboratory often have difficulty in producing repeatable fires for experimental purposes. It is a reflection of the complexity of the fire phenomenon, with its fire growth and severity depending upon the interaction of a fire with its environment.

For a typical fire in a compartment, the development of the fire progresses through a number of phases from the initial ignition to the complete involvement of the compartment and its final decay. These can be identified as:

(a) Ignition;
(b) Growth or pre-flashover period;
(c) The fully developed or post-flashover fire; and
(d) Decay.

The different phases of fire are clearly illustrated in figure (1.1). Initially, for a fire to start, a material (fuel) is ignited from an ignition source. The ignition source must contain sufficient energy to raise the fuel to its ignition temperature. Energy can be transferred to the fuel by radiation, convection and conduction. This energy must be transferred to the fuel rapidly enough for the ignition temperature to be achieved.

When an ignition source such as a flame is applied or is adjacent to a material, heat will be transferred to the surface. There are three basic mechanisms of heat transfer involved, namely: conduction, convection and radiation. The exposed surface of the material will become hot. When heat falls on the material some of it is absorbed and

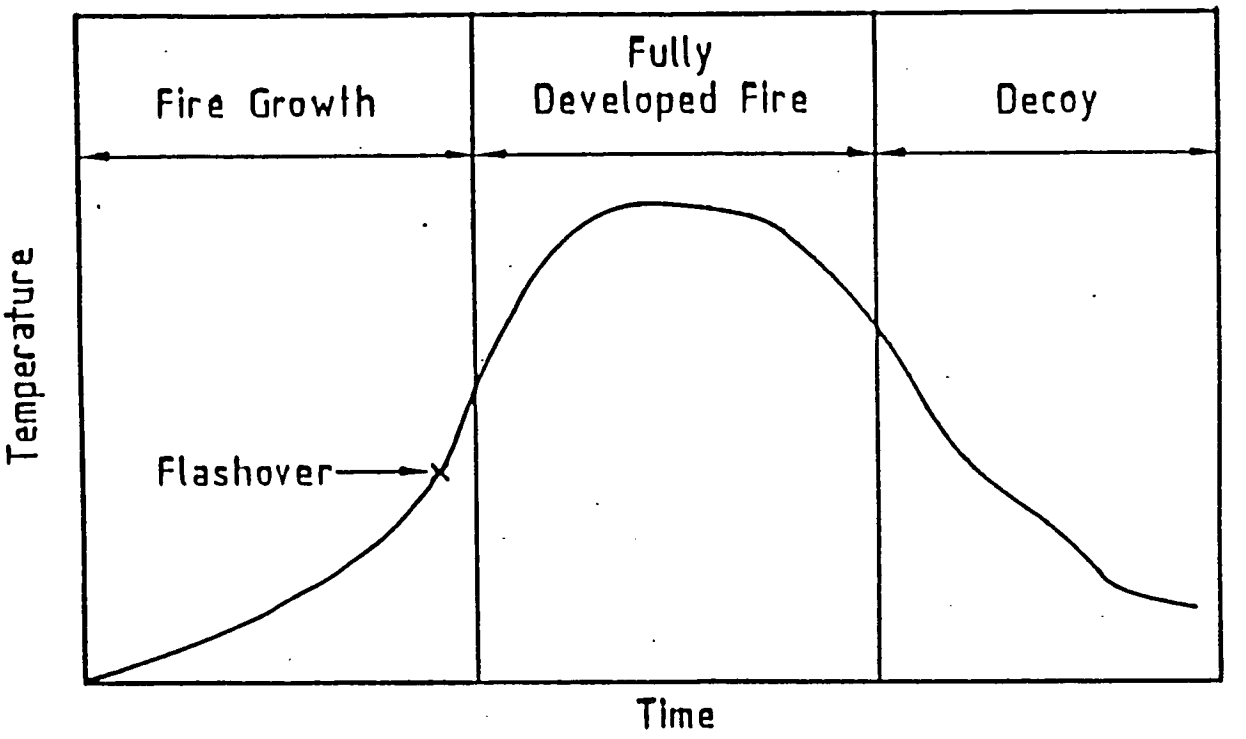


Fig. 1.1

Relationship between temperature and time and stages of a typical uncontrolled fire in a compartment.

conducted into the body of the material. The heat remaining near the surface increases the surface temperature and if the material is a bad conductor the surface warms up more quickly than if it is a good conductor. Also, some of the heat gained by the material will be lost from the heated surface by re-radiation as it becomes hotter, by conduction through the material and by convections. These heat transfer mechanisms are depicted in figure (1.2). It can be said that this balance in heat energy transfer is as important as ignition temperature in determining the ease with which a material can be ignited. Following ignition of materials, combustion takes place and this is controlled by the heat produced on combustion of the initially ignited material.

Once flaming has become established, the heat of combustion released and fed back to uninvolved fuel will promote the growth of the fire (growth period). The rate at which the fire develops increases as heat is liberated, thereby influencing the heat transfer to the surface of burning material. As the materials burn, the flames heat the air above and a convective flow begins forming a rising plume of hot gases. These gases and entrained air accumulate at the ceiling producing a growing hot layer. At this stage, the progress of fire can be influenced by the configuration, physical properties and ventilation of the compartment where the interaction with the compartment boundaries become significant. As soon as the flames reach the ceiling they are deflected horizontally. Here, the principal heat transfer to the surrounding items is by radiation from the hot smoky gases which accumulate under the ceiling. The rate at which the layer deepens depends on the fire size. As the heat intensity in the compartment increases, the surfaces of the materials remote from the site of ignition are heated comparatively quickly to a point at which they decompose. This will increase the rate of flame spread over surfaces and cause spontaneous ignition of these materials. The increasing involvement of additional fuel cause the ceiling flames to increase rapidly, the hot gas layer deepens bringing the flames down closer to the fuel. Subsequently, all of the combustible materials in the compartment become involved and the whole compartment appears to become full of flame.

This transition from a growing to a fully developed fire in a compartment is known as "flashover". Waterman [4] studied the flashover phenomenon in a full-size compartment. From his findings, he concluded that the flashover occurred when the heat flux at floor level was about $20kW/m^2$. Flashover can also be considered to

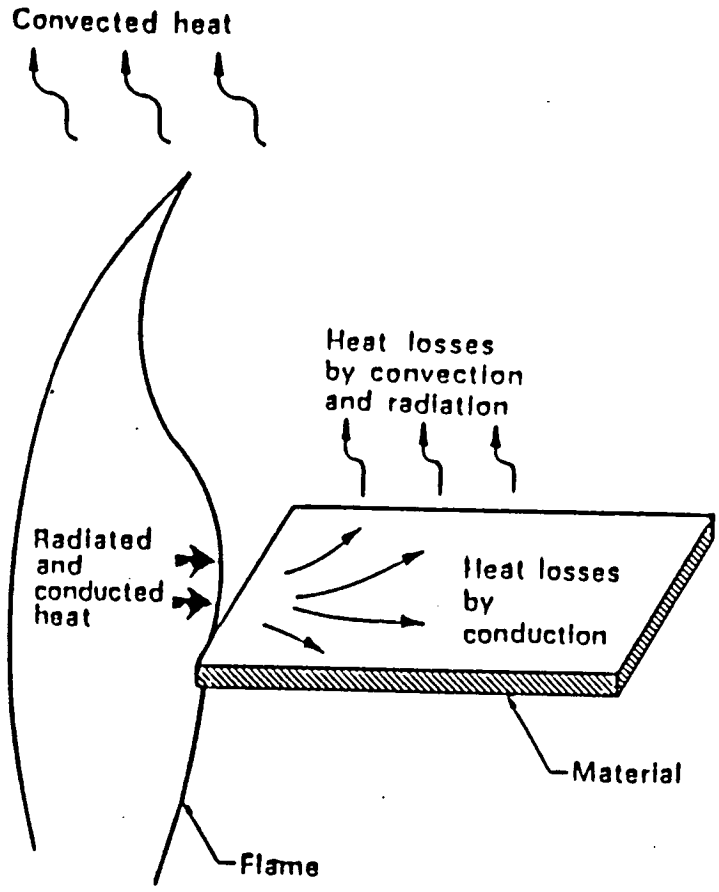


Fig. 1.2

Heat transfer and heat loss mechanism.

occur when the ceiling temperature reaches approximately 600°C as found by Fang [5].

In the subsequent phase of a fully developed fire (also known as the post-flashover fire), the exposed surfaces of all combustible items in the compartment will be burning and the rate of heat release will develop to a maximum, producing high temperatures, possibly as high as 1100°C [6]. At this stage, the fire almost invariably becomes ventilation controlled, the severity depending on the available air supply. Given adequate ventilation the fuel will gradually be consumed by the fire. Further spread of fire is determined by the fire resistance of the surrounding compartment components, which either delay or prevent penetration of fire to neighbouring areas. It is during this period of fully developed fire that building components may fail as a result of high thermal stress in which the failure of a structural component may cause collapse of the building structure [6].

The fire will continue to burn as long as fuel is available. Subsequently, the fire enters the decay phase. Here, the fire will reduce in severity and eventually die down because the fuel is depleted.

1.2 FIRE TESTING

1.2.1 The Relationship between Fire and Fire Tests

A fire test is a procedure designed to assess the response of the material, product, structure or system to one or more aspects of fire. It is of great importance that conditions used to assess these responses are standardised in an appropriate fashion, closely resembling one or more of the phases of fire behaviour. Although it is unlikely that one single test will predict the actual fire performance of the product or structure in a real fire, in certain cases it may be possible to relate the fire performance under a given method to a fire scenario, e.g. a planned representative scale test carried out under known limitations, which is typical of a specific real fire situation [7]. In this way, the validity of the standard procedure and applicability of its results can be established.

Fire tests can be divided into two broad categories:

1) "Reaction-to-fire" test

The test methods that measure the burning and decomposition behaviour of materials and products under conditions typical of the growth stage of fire are commonly known as the "reaction-to-fire tests". These are composed of procedures to assess properties such as:

- ignitability
- spread of flame
- heat release
- smoke obscuration and toxicity.

Generally, these properties of combustible materials determine their performance in fire and their ability to spread flame, their propensity to transfer and extend fire, and their contribution to the development of adverse environments [7].

The scope of this study covers only the "reaction-to-fire" test, discussing most of the above properties except smoke obscuration and toxicity.

2) Fire Resistance Tests

These are test methods that relate to the behaviour of components and structures in the steady stage, or fully developed fire. The methods enable elements of construction such as walls, floors, columns and beams to be assessed according to their ability to retain their stability, resist the passage of flame and hot gases, and provide resistance to heat transmission.

In the United Kingdom, the test procedures for fire resistance are specified in detail in BS476: Part 8 [8], although this standard has recently been revised [9] to give BS476: Part 20 [10], General Principles; part 21 [11], Load Bearing Elements, e.g. walls; Part 22 [12]. Non-Loadbearing Elements, e.g. doors and glazing; Part 23 [13], Components and Part 24 [14], Ventilation Ducts.

In the fire resistance test, an element of construction is subjected to prescribed heating conditions in a furnace according to the standard temperature/time curve (figure 1.3) which is designed to simulate aspects of a real fire.

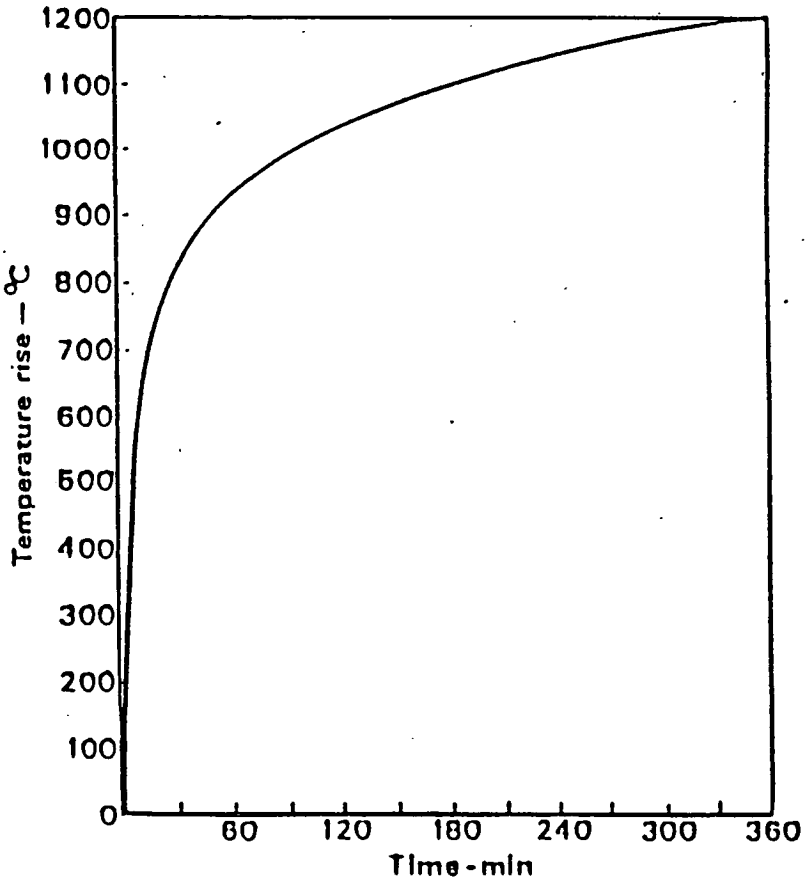


Fig. 1.3

Standard time-temperature curve (BS 476: Part 8: 1972).

Malhotra [17] has commented on the drawbacks of the test procedures outlining the various factors in the tests and their consequences and also factors which may contribute to systematic and random variability. These are listed in tables (1.1) and (1.2) respectively, which indicates where improvements in the procedures are necessary.

The different properties of hazard determined by the "reaction-to-fire" and fire resistance tests are shown in figure (1.4), to illustrate the relationship between the fire phenomena they are designed to assess, and the phases of development of a fire in a compartment.

1.2.2 Historical Background

Fire resistance tests have been used for a long time. The earliest tests had been carried out on an ad hoc basis and testing for fire resistance in the United Kingdom as practised today was formalised in the early 1900's [15].

One of the earliest recorded tests was carried out on a floor by the Associated Architects in London in the 1790's [16]. The British Fire Protection Committee which was formed in 1897 by Edwin O. Sachs did tests following the Cripplegate fire [17]. The committee set up the first fire testing station near Regents Park in 1899 [18]. It was only in 1903 that the International Fire Prevention Congress agreed to establish universal standards of fire resistance, under which tables set down minimum test performances for fire-resisting floors and ceilings, partitions and single doors [18]. The techniques of carrying out fire resistance tests in specially erected furnaces where gas jets created the fire conditions, augmented by the use of wood when extra heating was required, were standardised. Standard fire tests were first laid down in the United Kingdom in 1932 as British Standard BS 476 published by British Standards Institution [19]. Later in 1935, three furnaces (wall, floor and column) were erected at Borehamwood in 1935 to facilitate the testing of various building elements [18].

Somewhat similar developments took place in the United States of America. One of the earliest recorded tests was performed on a floor by the Denver Equitable Building in 1890 [17]. Subsequently test furnaces were constructed at Columbia University, the National Bureau of Standards and the Underwriters Laboratories, where building elements were tested for fire resistance [20]. Work at these

Table 1.1: Main Factors in Tests and their Consequences [17]

FACTOR	CONSEQUENCE
A. CONSTRUCTION OF SAMPLES	
1. Site limitation due to equipment	1. Modelling problems
2. Single elements tests	2. Absence of interaction
3. Conditioning - strength - moisture content - wear and tear	3a. Attainment of loadbearing capacity b. Effect of excess moisture c. Representation of service damage
4. Loading - method - constant loads	4a. Response of hydraulic systems b. Unrepresentativeness of constant loads
5. Support and boundary conditions, fixed	5. Lack of simulation of actual conditions
6. Workmanship, high standard	6. Enhancement of performance
B. HEATING	
1. Standard curve	1. Lacks realism, limited application
2. Uniform temperatures	2. Effect of unequal heating ignored
3. Exposure conditions	3. Facades and special conditions omitted
4. Furnace design	4. Lack of specification leads to variability
5. Thermocouple type	5. Does not measure heat transfer
6. Thermocouple location	6. Can be affected by flames
C. PERFORMANCE CRITERIA	
1. Stability, loadbearing elements Non load-bearing elements	1a. Precise collapse point may depend upon the response of loading system b. The precise point of instability difficult to define
2. Integrity - gas leakage through openings - heat transfer	2a. Present system does not have good reproducibility

Table 1.2: Variability in Furnace Tests [17]

A.	SYSTEMATIC VARIABILITY	
(a)	Tolerance on standard temperature curve	
(b)	Tolerance on furnace thermocouple response	
(c)	Location of furnace thermocouples	
(d)	Aging of furnace thermocouples	
(e)	Response of measuring systems	
(f)	Tolerance on the loading system sensitivity	Factors affecting repeatibility and reproducibility
(g)	Variability in ambient conditions (draught etc) and their effect on surface cooling	
(h)	Variability of the cotton pad test	
B.	RANDOM VARIABILITY	
(a)	Inconsistency of samples	
(b)	Variability in moisture conditions	
(c)	Variability in material properties	
(d)	Variability in erection standards	
(e)	Variability due to furnace construction	Factors affecting reproducibility
(f)	Variability due to thermocouple design	
(g)	Method of load application	
(h)	Method of application of cotton pad test	

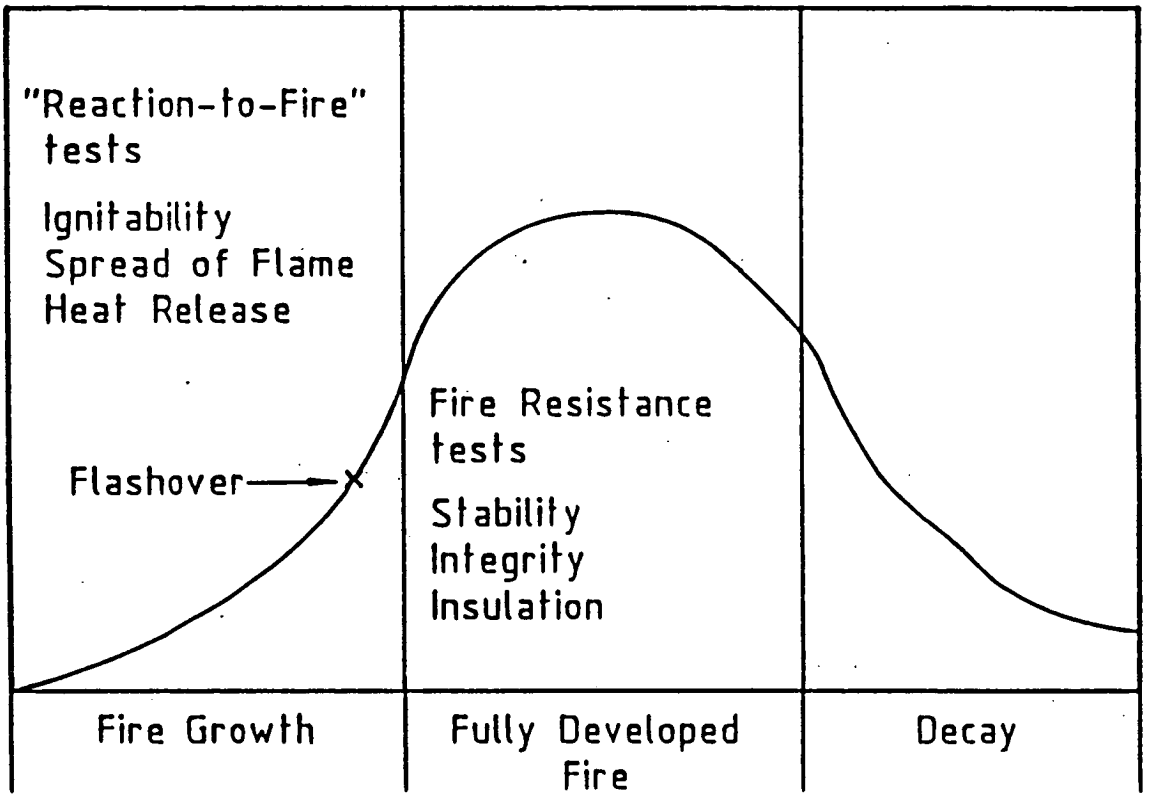


Fig. 1.4

Fire phenomena related to the stages of an uncontrolled fire in the compartment of origin.

laboratories eventually led to the promulgation of ASTM E-119, Fire Tests of Building Construction and Materials [21] in 1918 (then known as C19) [17].

All present fire resistance tests (national and international) involve erection of a portion of a building either within a furnace, as in the case of columns, or as a part of the enclosing walls or top of such a furnace. The structure is loaded if appropriate and oil or gas fires are initiated within the furnace and exposed to a standardised heating regime representative of a fully developed fire. This is controlled and follows a standard time-temperature curve as shown in figure (1.3).

The length of time during which the specimen remains structurally stable and (for walls and floors) without the development of flame penetration or of excessive temperature rise on the unexposed surface is defined as the fire endurance of the specimen.

Considerable progress has been made in the research work to understand and improve the shortcomings of the existing testing procedures as reported in references [22-24]. Refinements have since been made in the testing procedures but no alternatives have yet been proposed [17,20]. Thomas [25] has commented that the problem of standardising the testing of fire resistance is by no means solved although there appears to be a common concept amongst many authorities in many countries. This was largely because variations in the construction of furnaces and in the fuel that is used (some tests use gas, some electricity and some oil) produce differences that are too expensive to remedy.

The earlier fire test development was concerned mainly with minimising the possibility of outbreak of fire and its subsequent spread from building to building (property protection) but attempts were further made in the test development to incorporate the safety of people (life safety).

Another phase of fire test development was a move to embark on research projects studying the compartment fire in view of the increasing use of combustible materials as wall coverings and building components in general. Combustible materials will always burn in a fully developed fire: Thus in estimating the fire hazard it is of concern to make an in-depth study of the early stages of fire up to the point of

flashover (the pre-flashover fire) where the risks can be assessed in order to judge the suitability of materials for use in different types of building occupancy.

This leads to the various enclosure type tests such as the British fire propagation test [26], the Swedish Box test [27], the Dutch Flashover test [28] and other "reaction-to-fire" tests. These tests measure a "reaction-to-fire" - which can be related to ignitability, combustibility, flame spread and heat release. Also with the advent of synthetic materials, simple and easily performed laboratory test methods were needed and developed principally to test properties of plastics and to screen materials during product development or for quality control. This action was necessary because the existing test procedures which had been developed for natural materials such as wood and other cellulose materials no longer provided a satisfactory hazard classification for materials which soften, melt and drip or are of very low density. Examples of such tests are the rate of burning [29]; flammability test using a semi-circular frame [30] and alcohol cup test [31]. These tests are listed under BS 2782 under which the test procedures are specifically designed for thin flexible plastic sheets.

Experiments have been carried out by several researchers for many years in order to augment experience gained in actual fires. These experiments are normally carried out at full-scale and are too expensive to be regarded as a routine tool for testing. There is an obvious need for an evaluation method which will do the job of prediction more effectively. Thus the original 1:1 scale has frequently been reduced to a laboratory scale with rigidly specified procedures which aimed to reproduce some important facets of the initial experiments. This can best be illustrated by the flame spread test being used in the UK as BS 476: Part 7 and the 25 foot tunnel test (ASTM E-84) in the USA. Both tests were developed with the intention of simulating a fire in a corridor in order to ascertain the hazard of fire spreading along a wall or ceiling in a room or a corridor. The difference was that the 25 foot tunnel test more concerned itself with flames hitting a ceiling whilst in the British spread of flame test, the specimen is positioned vertically with the longitudinal axis horizontal to simulate the wall of a corridor while the radiant panel represents a fire at the end of the corridor.

Further developments in fire tests were undertaken when there has been extensive research based on the concept that the rate at which heat is released during burning

is an important criterion for evaluating the fire hazard from a particular material [32]. It is considered to be a significant "characteristic" of room linings and it must also be an important parameter of room contents that could contribute to early fire growth. Babrauskas [33] has given a brief account of the development of several different rate of heat release calorimeters. The earliest calorimeters are operated based on thermal techniques [34-37] but during recent years, new test methods based on an oxygen consumption technique have been developed [33,38]. The latest and popular heat release apparatus is the bench-scale cone calorimeter, developed by Babrauskas [33] which has proved to be a versatile piece of equipment for use in fire testing and research [40-44]. Currently, it is a new proposed ASTM method [45] and work is being carried out internationally to incorporate it as a standard by the International Standards Organisation.

The latest developments involve the use of mathematical/computational modelling in the study of various aspects of fire in rooms or compartments. A computational procedure has been developed to correlate a full-scale room test process and results from the small-scale laboratory tests. Various mathematical models [40-46] have been developed with some degree of success in predicting the likely behaviour in actual fire situations.

Generally, fire test methods have been developed through a lengthy series of experimental studies, revisions and refinements [47]. In the process comparisons have been made between behaviour experienced in accidental fires and the results predicted by the laboratory test.

1.2.3 Current Approaches

The majority of tests used today are accorded various titles, but whatever title they are given, they are all basically tests in which materials are exposed under carefully controlled conditions to a heat source or flame. They often tend to be little more than environmental simulations, an attempt to model on a laboratory scale some aspect of fire behaviour observed in real fires, or large experimental fires. But the tests are small scale due to cost constraints, and have proved to be inadequate in three principal ways: the test results are highly apparatus-dependent; application of the results requires knowledge of the empirical relationship between "real" fire behaviour and performance in the test; and the scaling law is not simple [48].

In recent years there has been a growing concern about the role of fire tests and the data they provide. The credibility of small-scale fire tests in predicting the performance of a product or system in a real fire situation has been under great discussion. Generally, these tests do not give information readily quantifiable for wide application and classification systems are developed, usually on the basis of ranking in a test. The choice of test and the relationship of performance to hazard, still remain arbitrary. The tests are carried out in strictly controlled environments and there is strong interaction between the apparatus and the material under test. The sample size, its physical form, orientation and ignition source can markedly influence the outcome of the test results, hence the ranking order if any changes of these specifications are made.

The tacit classification of small scale fire tests according to the "fire properties" which they are developed to measure, viz. ignitability, surface spread of flame, rate of heat release and propensity to produce smoke and toxic gases, posed another problem to the application and interpretation of test results. None of these is a true material property as can be said for density or thermal conductivity. There is little equivalence or correlatable data produced in the different types of tests mainly because the results are very apparatus-dependent [2]. Thus the results of these tests cannot be correlated to the response of the material in actual (real) fire scenarios.

Considerable progress has been made in the development of the "reaction-to-fire" tests since fire tests came into existence and their numbers have increased significantly. Becker [49] has stated that more than 700 standardised rules for fire testing are used round the world in order to assess fire safety of materials, products and construction elements in different technical fields. The result of this is that there is a growing concern over the confusion caused by the multiplicity of tests of unconfirmed validity.

In view of the shortcomings and also the impact of new materials on the existing test procedures where the traditional method no longer provides appropriate assessment of a material's fire performance, spurred the researchers and test developers at international level to improve these aspects. Work has been carried out to try to establish correlations between full and small-scale tests to evaluate fire behaviour of building materials. The aim of this research was to validate existing laboratory tests and to conceive new ones to identify the hazards introduced by the

use of new materials. Ideally, fire tests should be capable of providing information or data which can be used to predict how a material will react in a real fire scenario. To achieve this, fire dynamics is being applied by researchers and test designers to improve their understanding of the fire problem. In recent years there has been growing support among workers in the fire field of the concept that the introduction of analytic predictive approaches to fire growth (fire growth modelling) is leading to improvements in the testing field. The new generation of fire tests which has appeared over the past decade have been developed with an improved understanding of fire science in which the derived data have an acceptable degree of repeatability and reproducibility and are also able to be applied in relatively simple models to predict fire behaviour.

Below are brief descriptions of some of the tests to exemplify the difference between the old and the new test:

1. Ignitability

The earliest ignitability test available in the United Kingdom is the BS 476: Part 5 [50]. This is a very simple test in which a small gas flame is applied to the face of a vertical specimen, 225mm square, for ten seconds (figure 1.5). If flaming does not continue for more than ten seconds after the flame source is removed, the material is deemed to have "passed" the test. Unfortunately, no data are given on the heat transfer characteristics between the igniting flame and the material under test. The said material might respond differently if exposed to a larger igniting source or radiative flux. Furthermore this test can give misleading results, as most combustible solids which are more than 6mm thick (excluding cellular plastics) are capable of passing this test.

The BS 476: Part 13 [51] or equivalent ISO Ignitability Test [52] is the first of a series of test methods intended to describe precisely the various aspects of reaction to fire of building materials [53]. The test examines the ability of products to become ignited when irradiated from a primary fire in the presence of a means for piloting the ignition. In practice, this might be by flame contact, continuous or intermittent, or by sparks or by burning materials dropping from above.

This test ascertains the time taken for a material to ignite when the surface of the horizontal specimen is subjected to a range of radiant heat fluxes, from 10 to

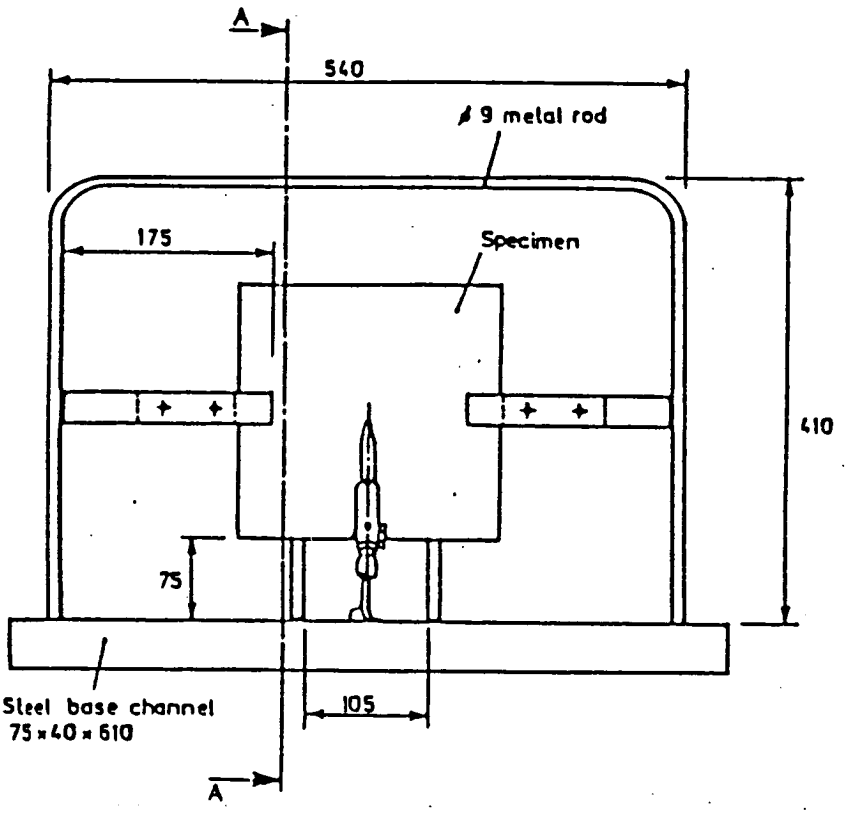


Fig. 1.5

Ignitability test apparatus (BS 476: Part 5).

50kW/m^2 using a conical heater and when there is a pilot flame available to ignite any of the volatile gases given off from the surface. The results can be used to examine the relationship between irradiance and ignition time. By using this relationship, the time to ignition under a different heating regime can be deduced and the limiting radiant heat flux necessary for ignition can be estimated. This test has replaced Part 5. The apparatus is shown in figure (1.6).

Even with the current level of knowledge incorporating the development of this test, the results are still apparatus-dependent; the thermal characteristics of the substrate especially for thin test specimens, the emissivities of the surface of the material being tested and also the spectral distribution of energy from the heater that may vary with temperature can influence the test results [54-55].

2. Combustibility

Two test methods are used in the UK to assess "Limited" or "Non" combustibility. These are BS 476: Part 4 [56] and BS 476: Part 11 [57]. These tests determine whether materials are non-combustible or combustible within the confines of the test.

In part 4, the test is carried out by placing a sample (40mm x 40mm x 50mm height) of the material to be tested in a small calibrated furnace which is maintained at 750^{o}C for 20 minutes after the apparatus has been calibrated. The test apparatus can be seen in figure (1.7). If the extent of decomposition leads to burning of the material or heat evolution causes the temperature to rise more than 50^{o}C then the material is termed combustible. This test has various shortcomings; it is not applicable to composite materials, and it can give misleading results for low density plastics. Some low density plastics could be classified as non-combustible as the material is completely consumed in less than 30 seconds without raising the furnace temperature more than 50^{o}C. On the other hand, this test ensures that normal materials graded as non-combustible have a very low combustible content: it has restricted useful materials which contribute to the attainment of fire safety (e.g. plasterboard). The BS 476: Part 11 [57] or equivalent ISO 1182 was developed as a revision to Part 4 hence the similarity in apparatus and test methodology (figure 1.8a-b). The features which distinguish Part 11 from Part 4 are the specimen is in the form of a cylinder (50mm dia x 75mm long) rather than cube (figure 1.8b), as well as the taking and interpretation of the results. Here limited combustibility is

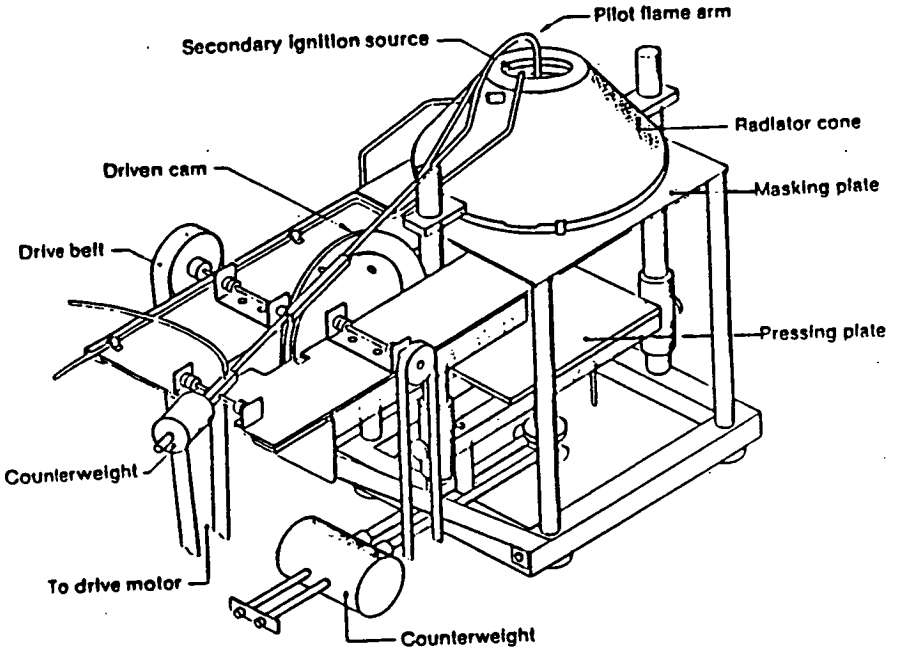


Fig. 1.6 Ignitability test apparatus (BS 476: Part 13).

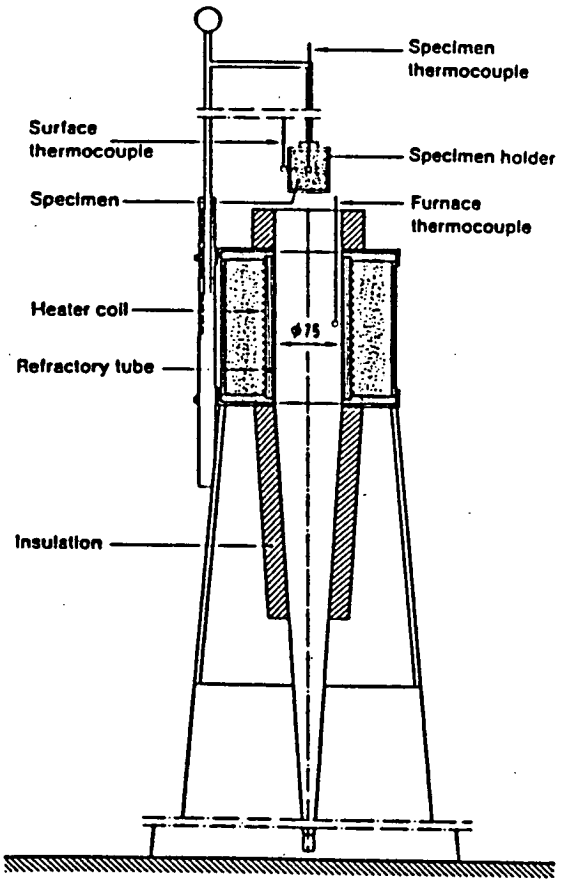


Fig. 1.7
Non-combustibility test apparatus (BS 476: Part 4).

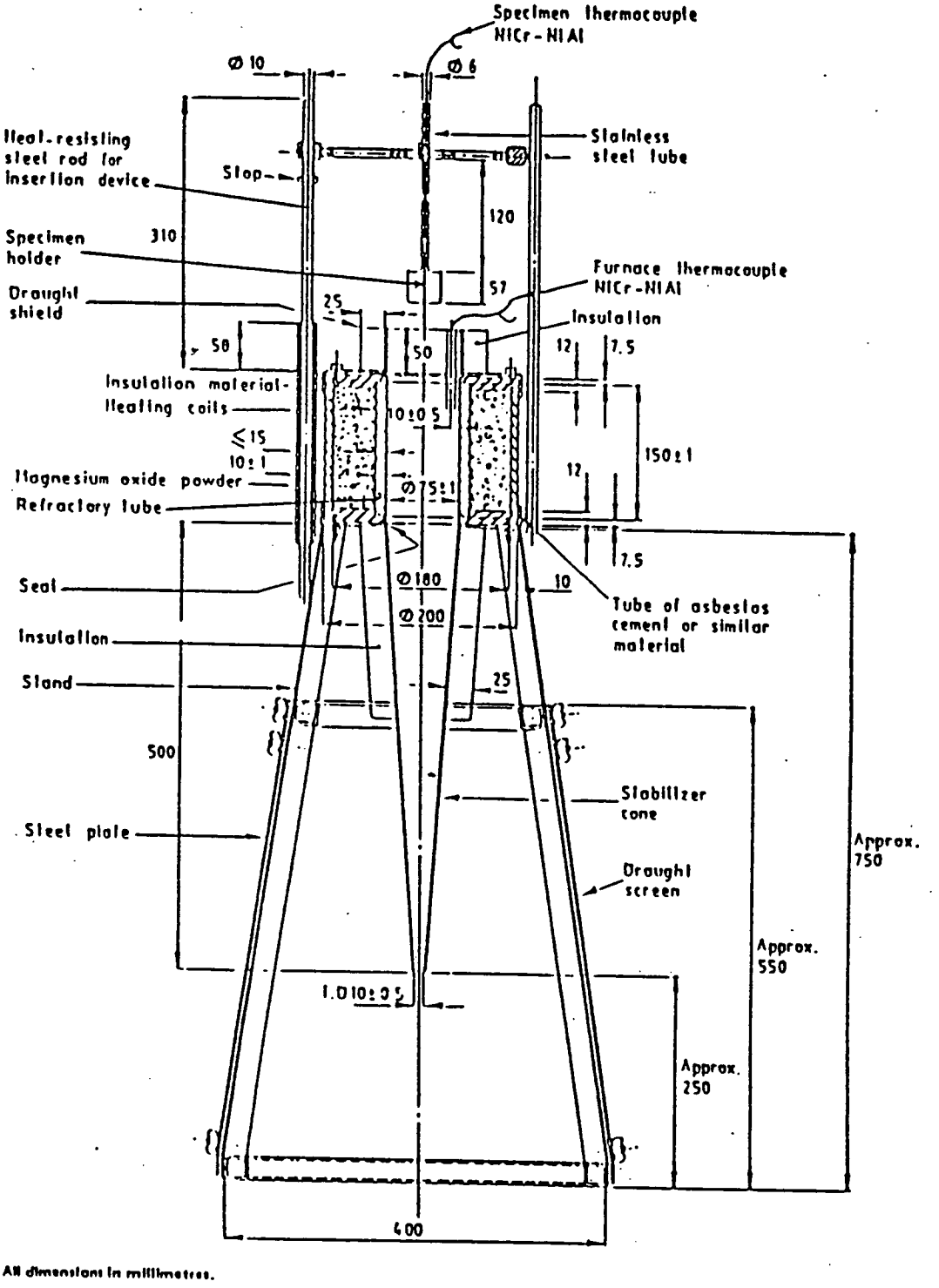


Fig. 1.8a

General arrangement of test apparatus for measuring the heat emission from building materials (BS 476: Part 11: 1982).

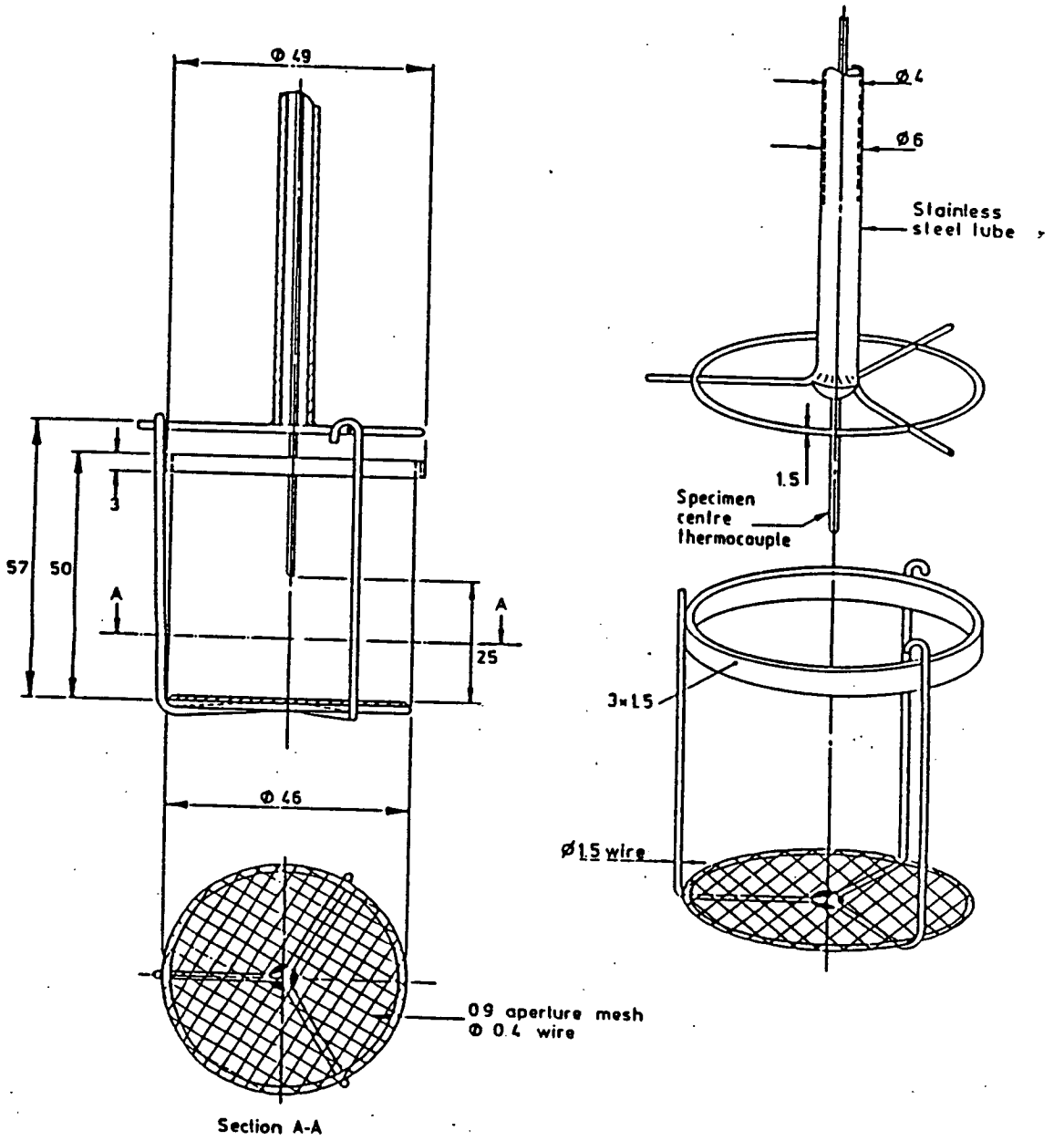


Fig. 1.8b Specimen holder and support (BS 476: Part 11 ; 1982).

defined in terms of duration of flaming and rise in temperature with different criteria being applied for different densities of specimen. This test is unrealistic to some extent as it fails to assess quantitatively the heat emission from building material even though the title stated so.

Although a material can be classified as non-combustible, it can still influence the fire development. Insulating materials, because of their thermal insulation properties stop the passage of heat and necessarily conserve the heat. Materials similar in properties to concrete, normally transmit approximately 20% of heat away from the fire [9]; if this were contained can lead to earlier ignition of any combustible materials present. Hence, fire development would accelerate. Consequently non-combustibility in itself is not a completely reliable guide to distinguishing between safe and unsafe materials.

3. Rate of Heat Release

The basic concept of heat transfer involved in the burning of a material is already explained in section 1.1. As illustrated in figure (1.9), it can be clearly seen that when a material burns (fuel) and if there is enough excess heat generated from the initial combustion reaction and fed back to uninvolved fuel, it will accelerate the combustion process. In a compartment fire, the quantity of available heat from the material burning needs to be considered. The term "compartment fire" is used to describe a fire in a room or similar enclosure within a building [6].

Heat release is a measure of the contribution that a burning material makes to a developing fire. The quantity of heat released from a material and the rate at which this heat is released during burning has a significant influence in determining fire spread. The compartment boundaries retain much of the heat that is released. A high rate of heat release in the compartment will contribute to the increase of temperature. Together with the radiation from the layer of hot gases at the ceiling, the hot gas layer deepens and this depends on the size of the fire to subsequently involved other combustible materials present, and hence accelerates the fire growth.

Various methods of evaluating heat release have been developed where the values of the heat release rate (HRR) are experimentally obtained by either thermal or gas analysis methods.

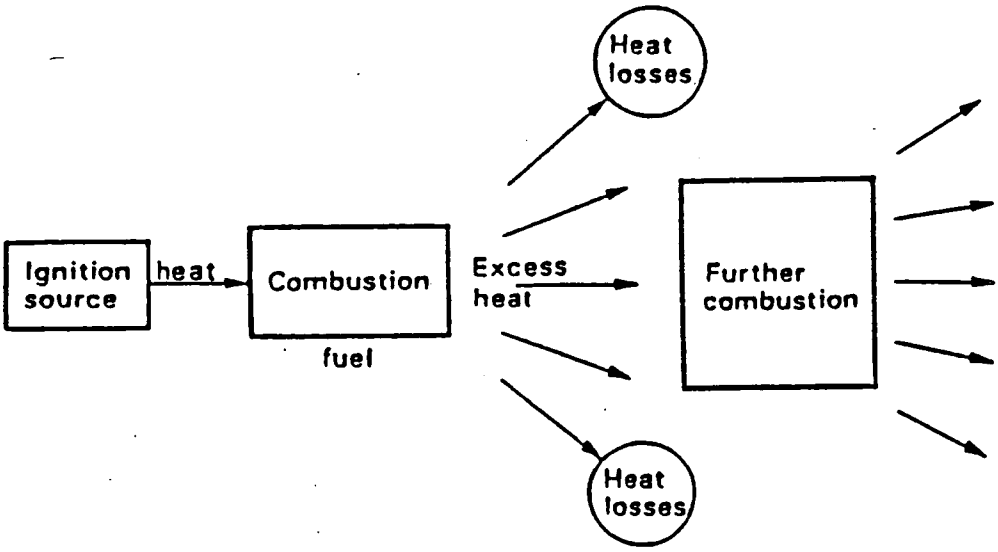


Fig. 1.9 Initial Fire Growth.

At present in the UK, the only standard method available for determining the contribution of materials to fire is BS 476: part 6 [26], which utilises the apparatus commonly known as the Fire Propagation Box. Within the small combustion chamber, the specimen is subjected to strictly defined rate of heating (gas jets are ignited at the start of the test, with the electric heater added after 2.75 minutes) leading to the decomposition and ignition of the combustible constituents. The combustion gases are discharged through a chimney and cowl assembly attached to the top of the combustion chamber. The temperature in the chimney is monitored and the time-temperature curve of the gases obtained from the calibration board is compared with that obtained when one wall of the combustion chamber was lined with the specimen under test. This provides a measure of the heat output from the material, known as the Performance Index. The index is calculated as the sum of three sub-indexes, $I = i_1 + i_2 + i_3$ where sub-index i_1 (0-3 minutes), sub-index i_2 (4-10 minutes) and sub-index i_3 is at the end of the test (12-20 minutes). The individual indices are calculated as follows:

$$i_1 = \sum_{1/2}^{3} \frac{(\theta_m - \theta_c)}{10t}; \qquad i_2 = \sum_{4}^{10} \frac{(\theta_m - \theta_c)}{10t} \quad \text{and}$$

at 1/2 minute intervals — at 1 minute intervals

$$i_3 = \sum_{12}^{20} \frac{(\theta_m - \theta_c)}{10t}$$

at 2 minute intervals

where

θ_m = temperature rise recorded for the material at time t;

θ_c = temperature rise recorded for the non-combustible standard (calibration) at time t;

t = time in minutes from the beginning of the test.

It is worth emphasising that the sub-index i_1 is useful as an indication of the ignitability and flammability of materials. Materials which release heat early in the test are heavily penalised in i_1. Thus it gives some indication that the particular material will contribute to fire propagation at an early stage in fire development.

Hence the Performance Index provides a comparative measure of the contribution a material will make to heat build-up and thus to fire spread within a compartment. The Fire Propagation test apparatus is shown in figures (1.10) and (1.11).

There are some shortcomings related to this test which are worth mentioning. It can be said the test method provides a comparative measurement of rate of heat release. The small rectangular hole at the base of the combustion chamber (figure 1.10) allowed limited access of air so material capable of active combustion may burn in oxygen-deficient conditions. This can provide a lower performance index than justified. Also the concept of calculating the performance index which greatly emphasise the time of occurrence permits certain materials which can ignite only under high intensity exposure conditions to achieve unjustifiably good ratings despite rapid heat being released once ignited. Similarly, a material which ignites rapidly may be heavily weighed against despite the small amount of heat being released. In the case of intumescent materials, care should be taken in carrying out the test since the results can be greatly affected by the build-up of pressure due to swelling which can block the gas ports. Additionally, since the specimen is mounted vertically in an enclosed box, there is also difficulty in testing thermoplastic materials because of their tendency to melt and drip upon heating.

Other different types of heat release rate (HRR) calorimeters have been designed and operated. Table (1.3) [32] displays the various types of HRR calorimeters. They are mostly run by thermal methods and can classify into three groups as reviewed by Tsuchiya [58]:

(1) Methods which involve the determination of a thermal constant for the apparatus developed by ASTM [59] and ISO [60] committees; (2) Substitution methods developed by the Factory Mutual Research Corporation (FM) [34] and the Forest Products Laboratory (FPL) [35]; and (3) constant temperature methods developed by the National Bureau of Standards (NBS) [36] and the Stanford Research Institute (SRI) [61].

In a typical heat release rate calorimeter (HRRC), a sample of material, of known physical and chemical composition, is exposed to a controlled air flow and an external radiant heat flux simultaneously. Once the specimen is ignited, heat is

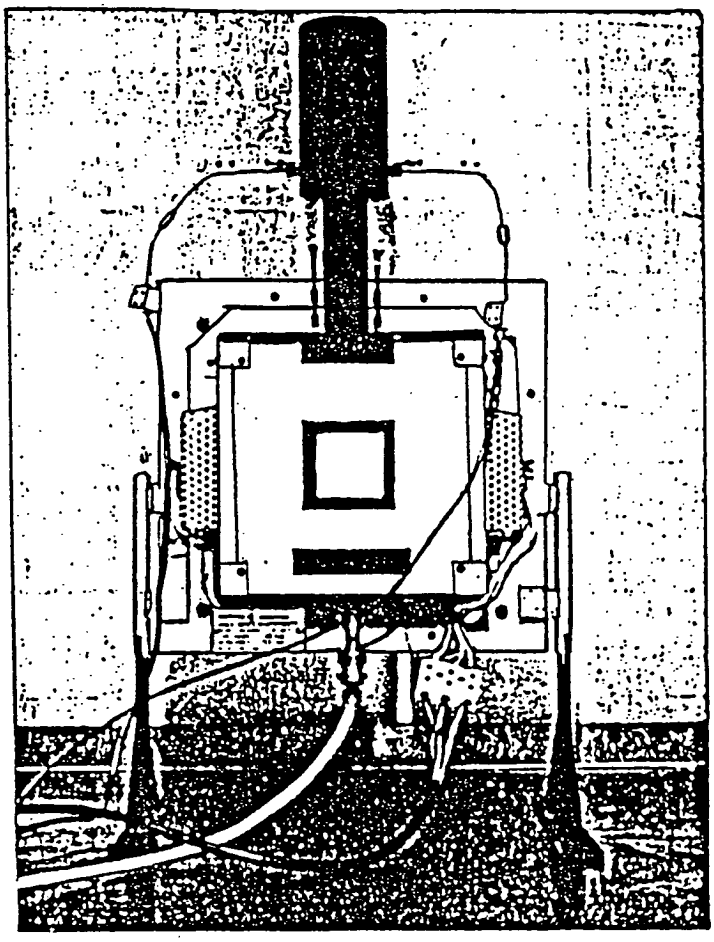


Fig. 1.10
Fire propagation test apparatus (BS 476: Part 6), front view.

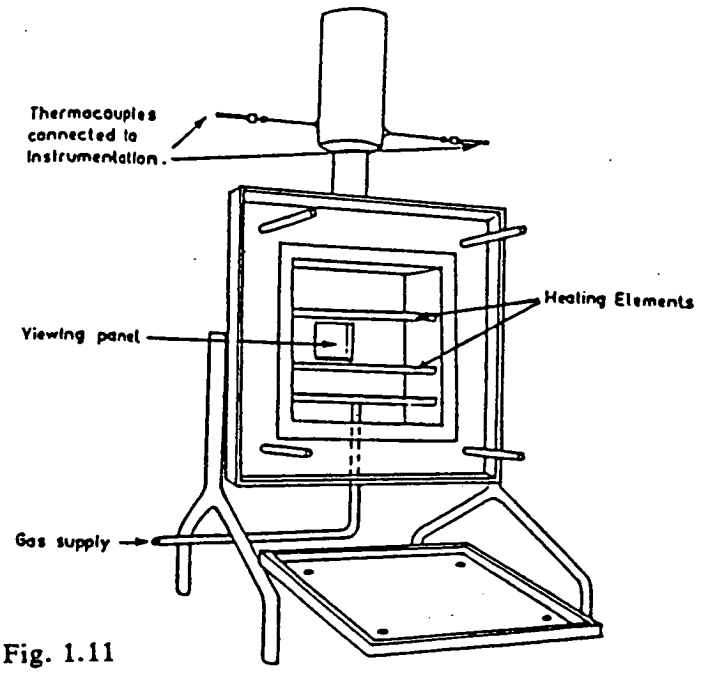


Fig. 1.11

General arrangement of fire propagation test apparatus (BS 476: Part 6).

Table (1.3) Heat Release Rate Calorimeters

Location	Sample Size (cm x cm)	Type	Exposure	
			Source	Intensity (W/cm^2)
FM	122 x 122	Substitution adiabatic equiv. gas flow	Hot combustion gases	t/T curve 0-12
NBS	11.4x15.2	Direct iso-thermal equiv. gas flow	Gas fired radiant panel	1.5-9
OSU	25.4x25.4	Direct adiabatic temperature rise	Electric radiant panel	up to 3.5
SRI	46 x 21	Direct iso-thermal equiv. gas flow	Gas fired radiant panel	1.5-9
FPL	46 x 46	Substitution adiabatic equiv. gas flow	Gas fired panel	Up to 4

released as a function of time. Based on the design of the calorimeters, this released heat may be measured directly or by substitution, by either operating the calorimeter in an isothermal or adiabatic mode. During adiabatic operation of the HRRC, the rate of heat release can be calculated directly from the rate of temperature rise in the products of combustion. In the isothermal mode, the flue gas temperature is monitored by the thermocouples and kept constant by adjusting the energy input to the secondary gas burner in response to the unknown heat release rate. The heat release is then calculated directly from the gas consumption rate. As for the substitution method, the flue gas time-temperature curve is reproduced by burning a gas, e.g. propane to make up the difference between the text and reference (inert) samples. The rate of heat release of the test sample is thus obtained from the rate of consumption of propane during the substitution run.

Generally there are two major problems with these thermal methods. One is the delayed thermal response due to high thermal inertia of the apparatus. The other problem is heat losses to the surroundings. The slow response causes low peak values for the determined HRR of the order of about 60% of the real value [58,62].

Among the HRRC that runs by thermal methods, the Ohio State University (OSU) heat release apparatus, has developed adequate experience [63]. Originally designed by Smith [37] the apparatus was modified to obtain smaller time delay for the thermal response, and also to reduce heat losses through the outer walls. The apparatus also offers the flexibility of different specimen orientations; the vertical and horizontal specimen orientations simulate wall and floor applications, respectively. Briefly, the OSU release rate apparatus [37] employs a chamber 890mm x 410mm x 200mm with pyramidal top section 395mm high connecting to the outlet. The top portion of the apparatus has a double wall design. A radiant heat source, consisting of electric heating elements, is used to generate heat flux to 35kW/m^2. Specimens measuring 150mm x 150mm are tested in the vertical orientation, and specimens of 100mm x 150mm are tested in the horizontal orientation. A radiation reflector is used for horizontally mounted specimens. The total air flow to the apparatus is set at 40 1/s which leaves the apparatus through a rectangular exhaust stack. This high rate of air flow combined with the double wall design minimises the heat retained by the inner walls, resulting in a smaller time delay for the thermal response, and also reduces heat losses through the outer walls [63-64]. The temperature difference between the air entering and the air leaving the

apparatus is measured by a thermopile having 3 hot junctions and 3 cold junctions which are located at the top of the exhaust stack and in the pan at the bottom respectively. The schematic diagram of the OSU release rate apparatus was shown in figure (1.12).

Despite an attempt to yield a better heat release rate using the OSU apparatus problems such as calibration [62] and the baseline of the signal which is unstable due to temperature changes when the tested material is inserted into the apparatus [65] still exist which can be considered as apparatus-dependent. In addition, the OSU apparatus measured only the "convected heat" and could not deal with radiated heat.

In view of the above drawbacks, a new technique for rate of heat release measurement known as oxygen consumption calorimetry, has been introduced. It is based on the principle that, for a given amount of oxygen consumed, there is a constant amount of heat released, nearly independent of the type of material burning [66]. It does not rely on temperature measurement, but rather on measuring combustion product gas flow and oxygen depletion in which the rate of heat release can be calculated. With this technique, problems such as heat loss and delay thermal response that existed in thermal methods can be avoided. Therefore, almost 100% of the heat released can be detected [33,67].

The most important test to have been developed in recent years is the "Cone Calorimeter". It is a bench-scale rate of heat release calorimeter developed by Babrauskas [33] which utilises the oxygen consumption principle in the determination of the HRR. It has been designed not only to minimise apparatus-dependency, but also to be simple to operate and to be capable of higher accuracy than earlier calorimeters. In the UK, this test method is proposed to become the new BS 476: Part 15 [9].

Basically, it can be used to determine the rate of heat release of a material when exposed to thermal irradiance at any orientation between horizontal and vertical. The test apparatus shown in figure (1.13) consists of a truncated cone heater, a hood system with associated ducting and exhaust fan, a specimen holder mounted on a weighing device and instrumentation for gas analysis (O_2, CO_2, CO). A sample (100mm square) of the material to be tested is exposed to heat flux from the cone

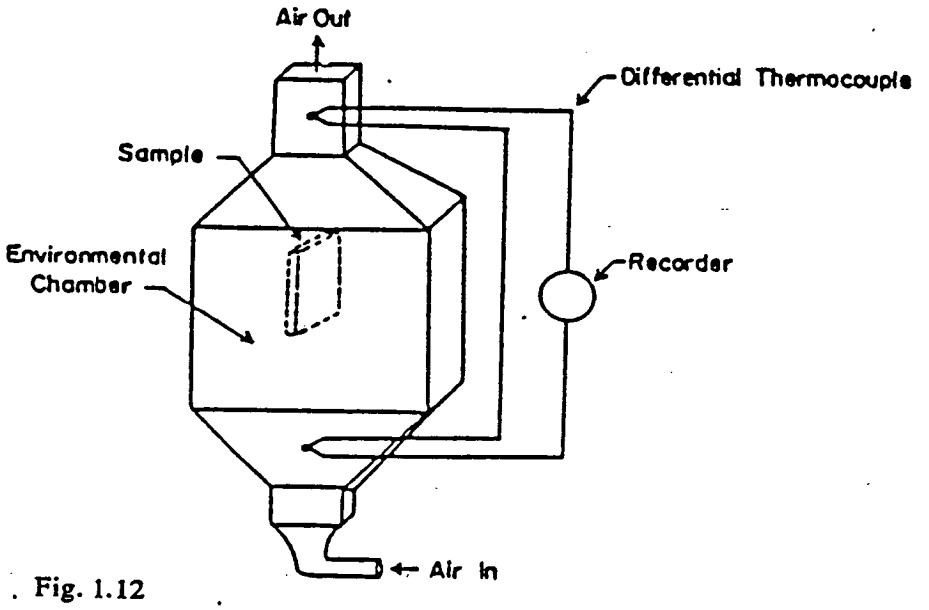


Fig. 1.12

Schematic of OSU rate of heat release apparatus.

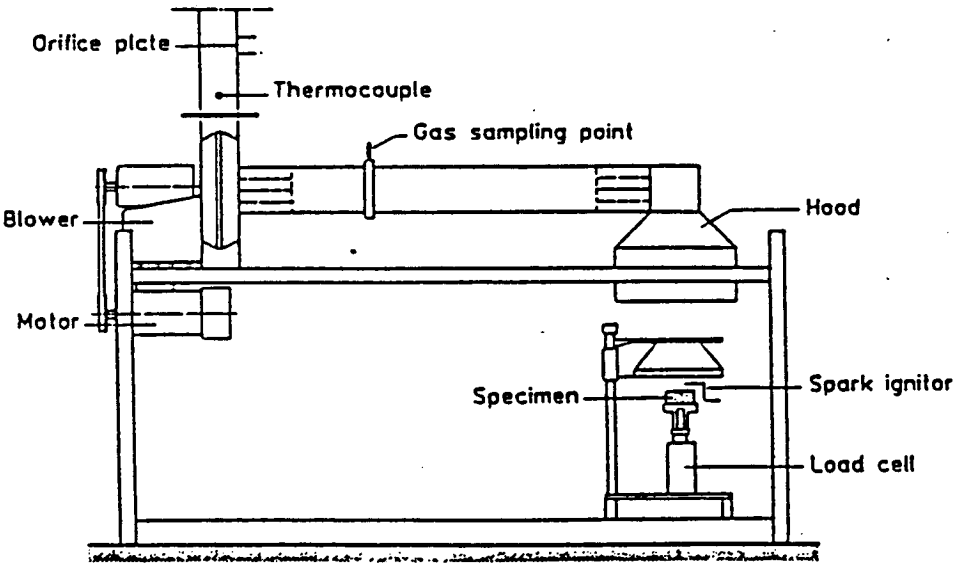


Fig. 1.13

Heat release test apparatus (Cone Calorimeter).

heater which is capable of producing heat fluxes ranging from 10 to 100 kW/m^2. The pyrolysis gases evolved are ignited by a spark plug which is located at 13mm above the centre of a horizontal specimen and approximately 3mm above the face plane of the vertical specimen respectively. The combustion gases are extracted through the exhaust system. Continuous measurements of oxygen concentration and exhaust gas flow rate permit the determination of heat release as a function of time while the mass loss is recorded simultaneously. The time to ignition of a material can also be deduced from the HRR data [39].

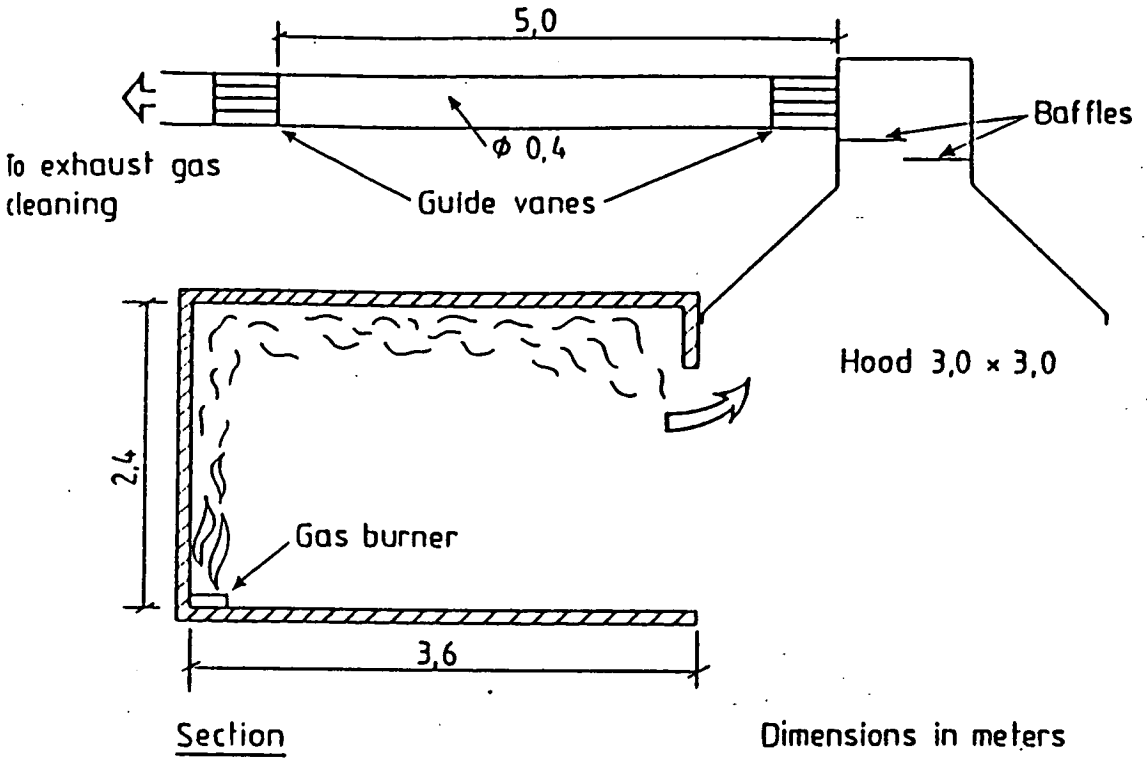
The test is not applicable to products which do not have essentially flat surfaces and that which intumesce badly. Recent work [39] has shown the ultimate goal of complete apparatus-independent of results from this apparatus may never be achieved especially at low heat flux.

Various studies [40-44] have shown that the apparatus has proved to be a versatile piece of equipment. Briefly, these are described below:

(a) Prediction of Corner Wall/Room Fires with the Cone Calorimeter

Corner wall/room test is designed primarily to determine the contribution of wall or ceiling linings to flashover in a room. It is suitable to assess the performance of products which melt, drip, crack or spall etc. where the results from small-scale tests are considered unreliable. The contribution of a specimen to the fire growth within a previously calibrated compartment can then be used to rate material and also to evaluate the validity of existing small-scale tests such as the ignitability test and surface spread of flame test.

The method specified by ISO [68] which is similar to the ASTM version simulates a wall/ceiling fire which starts in a corner of the room, under well ventilated conditions. Figure (1.14) shows the schematic of the Corner wall/room test. The dimensions of the test room are 3.6m long x 2.4m wide x 2.4m high. A doorway opening 2.0m high x 0.8m wide in one end of the wall provides the ventilation. An exhaust hood and duct assembly is located above the doorway outside the room to collect the products of combustion. The primary ignition source is a 170mm x 170mm propane gas burner which is placed at a corner of the room remote from the door and in contact with the lining material. The linings to be tested are mounted as closely as in its actual application on the walls and on the ceiling. The gas burner



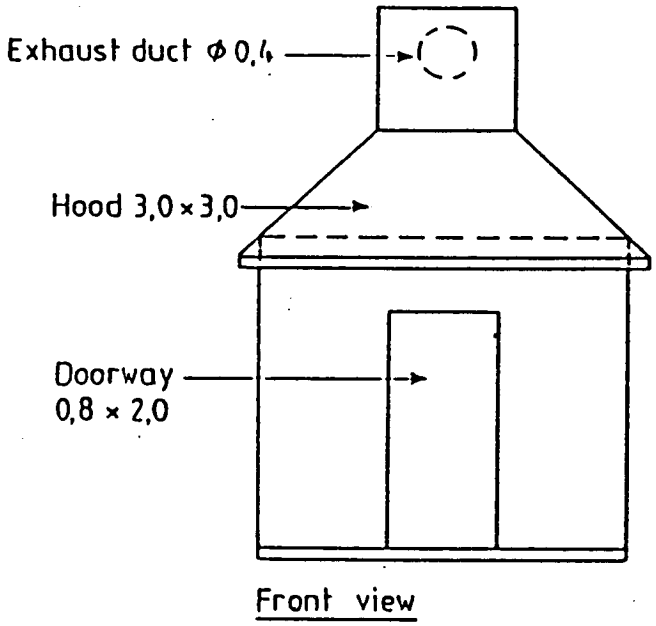


Fig. 1.14 Corner wall/room fire test [69].

can be operated at different output levels according to various fire exposures. For a typical fire exposure for a test for lining material, a heat output of 100kW is used during the first 10 minutes of test. If room flash-over does not occur with 10 minutes, the output of the burner is raised to 300kW for a further 10 minutes.

During the test, the fire spread, fire growth and generation of combustion products in the test room are monitored. In addition, measurements of gas temperatures and thermal irradiances at floor level are recorded. Measurements made in the exhaust duct include gas flow rates, oxygen concentrations, and concentrations of other gases, and optical density of smoke.

Sundstrom [69] carried out a full scale test using the Room/Corner Test (ISO/DP 9705) on 13 types of lining products. He studied the burning rate of these materials up to flash-over where measurements of heat release and productions of smoke and gas species were recorded. Here, flash-over is defined as a burning rate (from gas burner and linings) of 1000kW which coincides with flames emerging out the doorway.

With these results, Sundstrom et al [70] have proposed a classification criteria of lining materials which is based on peak and average rates of heat release and the production of light obscuring smoke. They considered the time elapsed from ignition to achieving the heat release rate at fla-shover could be used for classification.

It is possible to predict the heat release rate of Room/Corner tests based on data from the Cone Calorimeter as suggested by Wickstrom and Goransson [40].

Here, two assumptions are used in the numerical model that predicts the heat release rate of a product when tested in the standardised full-scale room/corner test. Firstly, it is assumed that the actual flame spread rate depends on the ignition time obtained in the small-scale test.

Secondly, the heat release per unit area in full-scale is assumed to vary with time in the same manner as in the small-scale. Thus, a convenient superposition technique is derived which considers the entire small-scale heat release process. The ignition

time and the heat release rate measured in the Cone Calorimeter test are input to this model.

The theory assumes that the total heat release rate in the test room, $\dot{Q}$, is obtained by summing the contributions from each part of the total burning area. In an incremental form, $\dot{Q}$ at the N time increment is obtained as

$$\dot{Q}^N = \sum_{i=1}^{N} \Delta A^i \, \dot{q}''_{bs}{}^{N-1}$$

where ΔA^i is the incremental burning area growth at the time increment i; and $\dot{q}''_{bs}{}^{N-1}$ is the heat release rate per unit area after (N-1) time increments, as measured in the Cone Calorimeter. In the flame spread theory [6,39], the spread rate is proportional to the inverse of the ignition time, i.e. $(1/t_{ig})$. This suggests that the burning area in general should be a function of time normalised with the ignition time.

Experimental data suggest that the burning area in full-scale can be expressed as a function of $\xi = (t/t_{ig}{}^{0.6})$, where t_{ig} is the time to ignition in the Cone Calorimeter at heat flux of 25kW/m^2. A best-fit expression is obtained as:

$$A(\xi) = \exp(\xi/3) - 2$$

From the above expression, the increments ΔA^i can easily be calculated. Figure (1.15) presents the comparisons between predicted heat release rate histories for various lining materials in the Corner test and actual measured heat release rate histories [71]. It can be seen that they are compatible indicating the success of this correlation.

A similar method developed for the same purpose has also been outlined by Magnusson and Sundstrom [44]. The analysis assumes that the combustible lining material covers ceiling and walls. Their method is more complex and requires more input data such as the derived material characteristics and test room time lag factor to a mathematical expression, essentially describing the full-scale test fire process as an upward flame spread only. They also made comparisons between predicted and measured full-scale heat release rates of seven combustible linings and obtained generally good agreement.

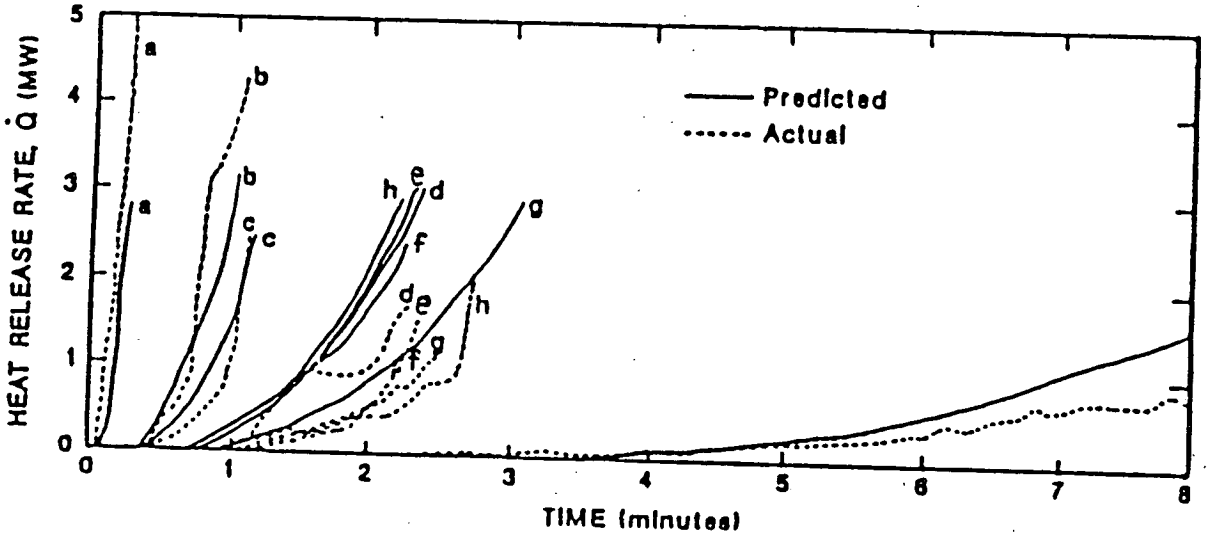


Fig. 1.15

A comparison between predicted heat release rate histories for surface lining materials in corner test (based on bench-scale Cone Calorimeter measurements) and actual measured heat release rate histories. The products are (a) rigid polyurethane foam, (b) textile wall covering on mineral wool, (c) insulating fibreboard, (d) expanded polystyrene, (e) medium-density fibreboard, (f) wood-panel [spruce], (g) paper wall covering on particle board, (h) particle board, (f) melamine-faced particle board. [71]

(b) Prediction of the time to flashover in full-scale test using Cone Calorimeter
Ostman and Nussbaum [42] have developed an empirical relationship in predicting the time to flashover in a full-scale fire test for surface lining materials. The relationship is based on the measurements of rate of heat release obtained in the Cone Calorimeter as well as the time to ignition and the density of the linings.

The empirical formula used is:

$$t_{fo} = a \times \frac{t_{ig} \cdot \sqrt{\rho}}{A} + b$$

where t_{fo} is time to flashover in full-scale, t_{ig} is time to ignition in Cone Calorimeter at 25kW/m^2, A is heat release during peak period at 50kW/m^2, ρ is density, a and b are constant.

This relationship was generally good for the 11 different lining materials which caused flashover in the room fire test as shown in figure (1.16a-b).

(c) Prediction of upholstered furniture fires with the Cone Calorimeter
Babrauskas and Krasny [41] have developed a mathematical model to predict the burning behaviour of upholstered furniture. By using the oxygen consumption principle in the Furniture Calorimeter [72] developed at NBS, the initial data on the full-scale burning rates of furniture are obtained.

The results showed that the important specimen variables were the combustible mass of the specimen, the frame type, the geometric style, and the performance of the fabric/padding composite.

A predictive procedure has been developed, which involves determining the frame type and the geometry from the full-scale article, and also determining its combustible mass by weighing. Then the heat release rate behaviour of the crucial fabric/padding composite is determined by the Cone Calorimeter. The basic correlation derived is in the form:

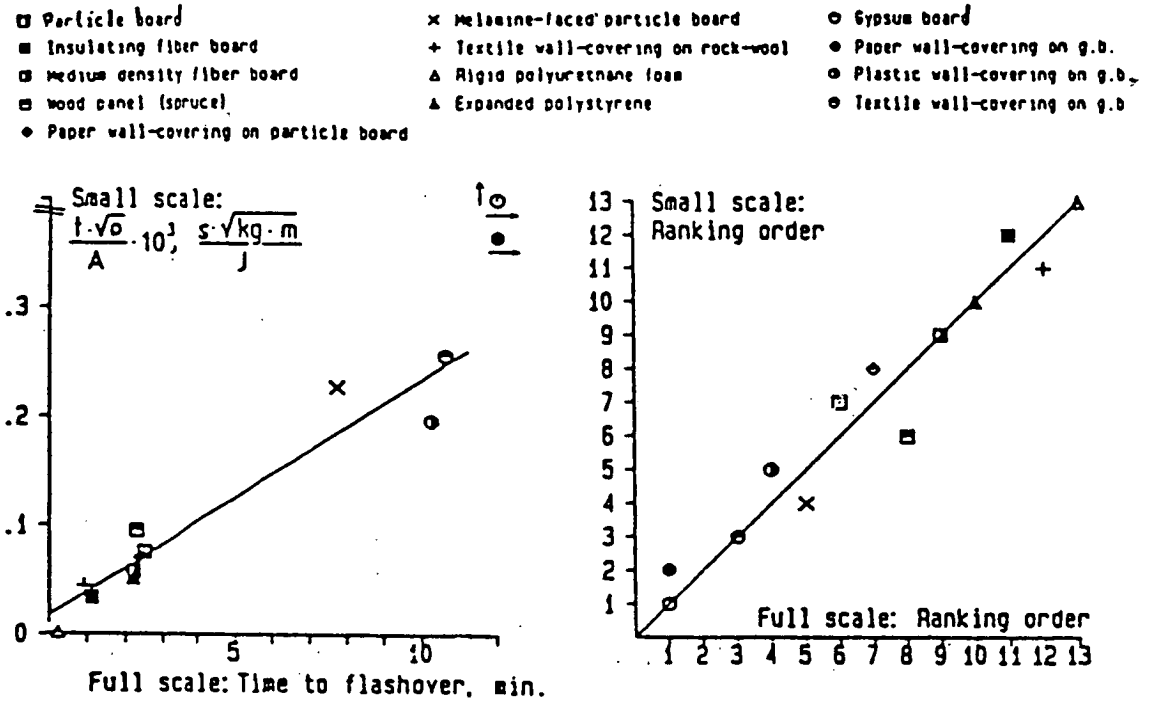


FIGURE 1.16a

The best correlation between a small-scale RHR-parameter and full-scale time to flashover with correlation coefficient 0.963. The standard deviation for the calculated data is $0.023 \cdot 10^{-3}$.

FIGURE 1.16b

Stepwise ranking order of materials according to small-scale and full-scale fire testing at the same conditions as in Figure 1.16a

$$\dot{q}''_{peak} = b\,\dot{q}''_{bs}\,A_{fs}$$

where

$\dot{q}''_{bs}$ = the measured bench-scale value (kW/m^2) for a specified irradiance (a heating flux of 10 to 100 kW/m^2 can be applied to the specimen).

b = a proportionality factor, for the comparison of the full-scale maximum heat release rate and results of the bench-scale test.

A_{fs} = the total exposed surface area of the full-scale item.

For a real furniture burning, the total area, A_{fs}, may be difficult to measure as the frame, style used in the construction may have an effect or contributing to the rate of heat release. It was found from the initial study [73] that rate of heat release could be expressed in terms of three factors; one depending upon the mass, one on the frame type, the third on the construction style.

Thus, the model to determine $\dot{q}''_{fs}$, the peak full-scale rate of heat release is given as:

$\dot{q}''_{fs}$ = b(q''_{bs})(mass factor)(frame factor)(style factor)

Consequently, from further tests gives the final equation as:

$\dot{q}''_{fs}$ =0.63(q''_{bs})(mass factor)(frame factor)(style factor)

where

$\dot{q}''_{fs}$ = estimated rate of heat release peak (kW) in full-scale; the proportionality factor b is equal to 0.63m^2/kg,

$\dot{q}''_{bs}$ = rate of heat release (kW/m^2) in bench-scale test, under specified conditions

mass factor = combustible mass, in kg

frame factor = 1.66 for noncombustible
0.58 for melting plastic
0.30 for wood
0.18 for charring plastic

style factor = 1.0 for plain, primarily rectilinear construction

1.5 for ornate, convolute shapes and intermediate values for intermediate shapes.

The results for different types of upholstered furniture obtained in this study showed good correlation as depicted in figure (1.17).

In view of the above, the Cone Calorimeter is presently a new proposed ASTM standard [45] and undergoing development work to incorporate it as an established standard by the ISO.

4. SPREAD OF FLAME

A measure of the spread of flame across the surface of a material, gives an indication of the flammability of the material and its ability to spread the fire and thus endanger life [9]. There are many flammability tests that have been developed to evaluate or assess the potential hazard of flame spread on interior finish materials and products, particularly wall and ceiling applications.

Some of the common flame spread tests with distinct modes of flame spread are BS476: Part 7 [74], ISO/DP 5658 [75-77] and ASTM [E162-83] [78]. These tests are examples of the opposed flow flame spread. The concurrent or flow assisted flame spread is typified by the ASTM [E84-84] [79]. The descriptions of these tests will be discussed in detail in chapter 2 emphasising more on the ISO/DP 5658 - ISO Surface spread of flame test [IMO Version] [76] and Surface spread of flame by LIFT method [77]. It is known that flame spread is related very closely to the ignition process where the leading edge of the advancing flame front acts as both the source of heat and pilot [80]. Heat is transferred ahead of the flame to the unaffected fuel, thereby raising it to the firepoint condition. Moreover the rate of flame spread is increased if the surface of the material is exposed to a radiant heat flux [81]. Therefore in the building context the flame spread is influenced both by ignition and by effect of radiation which may impinge on the material. This forms the basic principle behind the developments of these tests where measurements of flame-spread distance are taken commonly based on the progression of the flame front as a function of time.

Generally these tests [74-75,78-79] are used to assess the potential hazard of materials by providing ranking or classification of flame spread characteristics. The

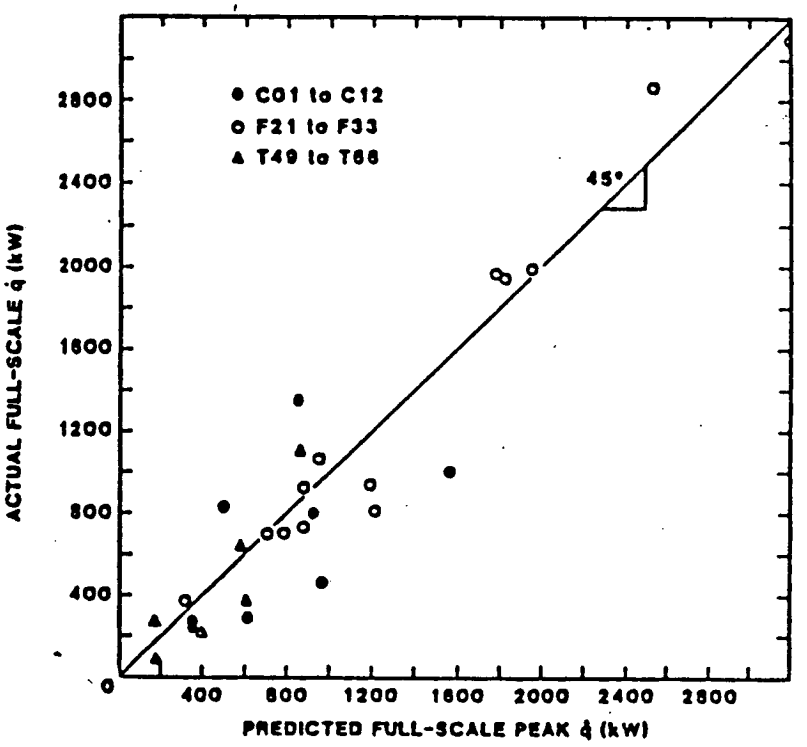


Fig. 1.17

A comparison between the prediction of peak full-scale rate of heat release for upholstered chairs (based on bench-scale Cone Calorimeter measurements) and actual measured peak full-scale values [71].

flame spread characteristics of materials are expressed either as numbers/index [78-79] or class/grade [74,79]. They provide information or guidance to assist the determination and control of fire hazards particularly to how an interior wall or ceiling material is likely to behave. This is relatively important where the selection of materials for the interior linings of buildings is of upmost consideration, it affects not only the safety of the occupants but also the safety of the property. But there are drawbacks in that the results are characteristics of the test procedure and can be greatly affected by factors such as sample configuration particularly the magnitude of the heat transfer modes involved.

However work is still in progress within the International Standards Organisation to improve the flame spread test [77] where attempts have been made to interpret this test from first principles. Quintiere [82] has analysed the ISO Surface Spread of Flame Apparatus [77] and developed a mathematical model from which relevant material properties such as thermal inertia, ignition temperature, the minimum heat fluxes necessary for the material to ignite and flame to spread can be inferred.

CHAPTER 2
SPREAD OF FLAME TESTS

2.1 INTRODUCTION

The spread of fire from a compartment within a building can pose a serious threat to the rest of the building once a fire has been initiated. Within an enclosure, the rate at which a fire will develop will depend on how rapidly flame can spread from the point of ignition to involve an increasingly large area of combustible material. Therefore, it is important to consider flame spread over combustible materials as a basic component of fire growth where the rate of flame spread is of direct relevance to the safety of the occupants, because it determines the time available for escape.

The rate of spread over a combustible solid is influenced by its physical properties as well as its chemical composition. Friedman [83] has listed the various factors which are known to be significant in determining the rate of spread. It is indicated that the flame spread velocity is affected by the following parameters:

* **Physical and geometrical parameters including:**
  - orientation of surface
  - direction of propagation
  - thickness of specimen
  - specimen size
  - thermal capacity and thermal conductivity
  - specimen density
  - initial fuel temperature
  - environmental pressures
  - flow velocity of environment
  - external radiant flux
  - humidity

* **Chemical parameters including:**
  - composition of fuel
  - composition of atmosphere
  - presence of retardants

The use of combustible linings for walls or ceilings in a compartment can have an effect upon the rate of fire growth during the early stages of a fire. In a compartment, ignition of lining material as the first material involved in a fire is very infrequent as has been found by Ferris [84] based on his experiments on series of fires in a room. Contents of rooms, furnishings or waste materials are more likely to be ignited and lead to involvement of wall lining materials. Similarly, study of the pre-flashover fire carried out by the Fire Commission (W14) of the Conseil Internationale du Batiment (CIB) showed that the flammability of the lining materials affected growth to flashover only to a minor extent. Flashover may be said to have taken place when the whole volume of a room is engulfed by the flame: this occurs after a ceiling temperature of 600°C has been reached. Fires often develop slowly, but when flammable interior linings are involved early in the fire, they tend to speed up the development so that flashover is reached more rapidly depending on the location of the ignition source. This is particularly so if a combustible lining becomes involved as a result of an ignition source in the corner. According to Bruce [85] the lining materials do not significantly get involved in fire until flashover has occurred if the ignition source is in the centre of the compartment.

If the lining materials have good thermal insulation properties, they can affect the development of fire by conserving heat, allowing rapid rise of temperature in the fire compartment leading to earlier ignition of any combustibles present. Hinkley and Wraight [86] have studied the contribution of flames under a combustible ceiling lining and found that a combustible ceiling could increase the heat flux by more than twice that of an incombustible ceiling. This was further discussed by Thomas [87], who stated that the time to heat up and ignite a combustible material is directly proportional to its thermal inertia ($k\rho c$). Hence, low density linings will tend to heat up quickly and ignite quickly.

Recognition of the potential for rapid flame spread and the contribution made by flammable lining materials has resulted in the development of various flame spread tests internationally, reflecting the need for interior finish tests. In the United Kingdom, a test for surface spread of flame was first introduced in 1945.

2.2 FLAME SPREAD TESTS

Although the concept of flame spread is relatively simple, the real situation is not. Consequently, it is not an easy task to develop a standard test to evaluate the flame spread hazard of linings in actual situations. Presently, there are three established small scale tests that are in widespread use: these will be described here.

2.2.1 ASTM E84-81 Test for Surface Burning Characteristics of Building Materials

This test [79], developed by Steiner in the early 1940's, was predicated on measuring the hazard resulting from fire propagating up a wall or along a ceiling in a room or corridor.

The ASTM E-84 tunnel test requires a specimen of 7.62m by 0.496m, mounted face down so as to form the roof of a tunnel 7.62m long by 0.445m wide by 0.305m depth. The fire source consists of two gas burners which direct a gas flame upwards on to one end against the surface of the test specimen. The igniting flame extends 1.65m from the end of the combustion chamber. A diagram of the 25-foot tunnel is shown in figure (2.1). Measurements are made of the speed of flame travel, the density of smoke and the temperature of the outgoing gases. The performance of the material is compared with the behaviour of the standard materials, asbestos-cement board and select-grade red oak flooring and subsequently a "flame spread classification" (FSC) is calculated from an empirical formula.

There are various shortcomings concerning this test method. The apparatus is too large and expensive to be acquired by many fire testing laboratories. The need for a 25-foot specimen is already contributing to the high cost of running the experiment from the economic point of view if just to accommodate the assessing of the flame spread rate. However, Steiner [88] did issue a statement when discussing the development of the Tunnel Test regarding the size of the specimen.

He stated:
"In the development of this test, the size of the specimen was aimed at the minimum which would reproduce actual behaviour of surfaces under fire exposure conditions, which requires that the test surface be given the opportunity to develop conditions contributing to flame spread, such as distortion and separation of joints and to delamination. The larger the area, within limits, the more realistic is the behaviour created by the fire exposure."

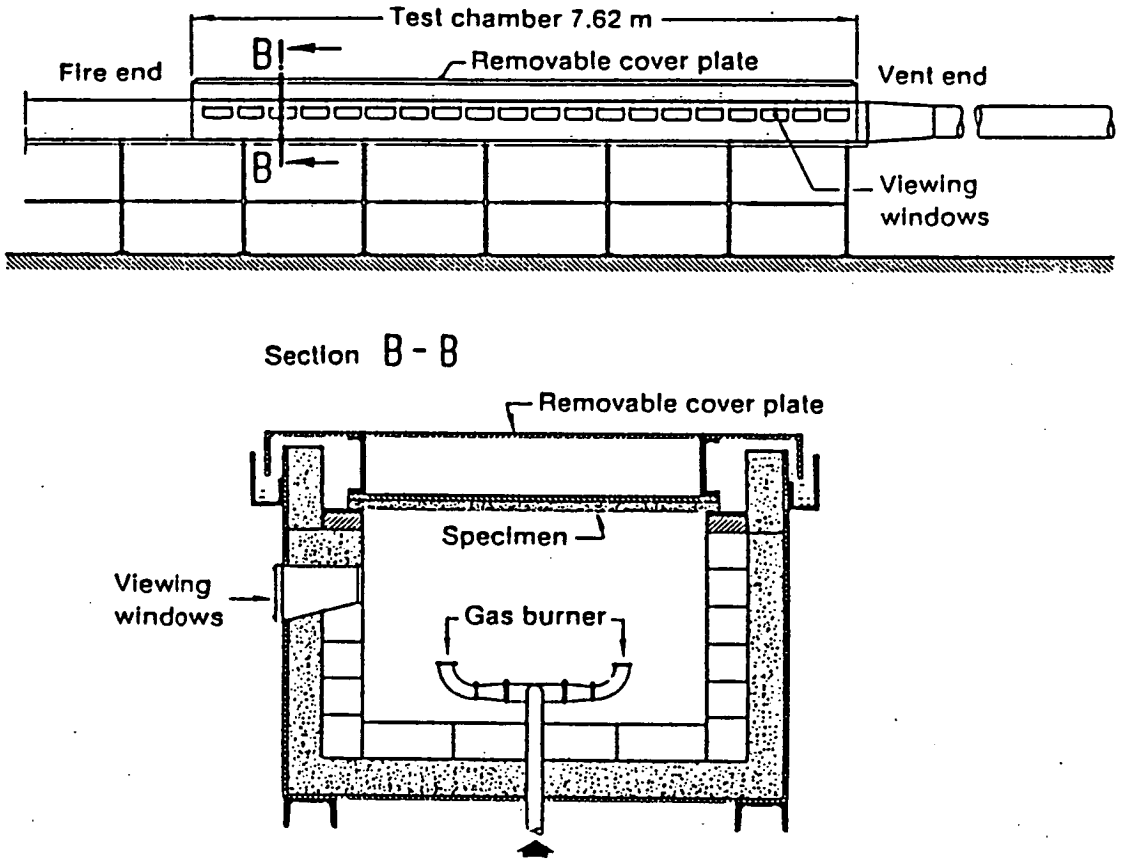


Fig. 2.1 25 Ft. Steiner Tunnel (ASTM E84-81).

Additionally, this test method does not give a satisfactory flame spread rating for synthetic polymeric materials. Originally, this test was developed to compare wood and wood products but it has proved to be inadequate when subjected to test foamed synthetic materials such as low density polyurethane, polystyrene, and other types of thermoplastics which tend to soften, melt and drip in the vicinity of the impinging gas flame. With the ceiling-mounted sample configuration, polystyrene foam melts, drips and collects in small puddles continuing to burn on the tunnel floor [32]. This prevents flame spread down the tunnel and consequently a low flame spread rating is given.

Similarly, for low density polyurethane foam, only a thin surface layer of foam is heated by the hot gases, pyrolysing and charring the surface. If this char layer becomes thick enough before the arrival of the burning front, the supply of pyrolysis gases becomes sufficiently exhausted that the flames are extinguished and this influences the flame spread rating.

The performance of a material in the 25-foot tunnel can be influenced by the chemical and physical properties of the material and the way the material is used in practical structures. Since the radiant flux in the tunnel is low, whereas in a fire it is high, the tunnel test results can be misleading. Materials such as polystyrene and polyurethane foam having low flame spread rating given by this test will burn in a very hazardous manner in actual fire whereas the test indicates that they should not.

Some work has been carried out by several researchers in correlating the test results with large scale tests. For example, Christian and Waterman [89] carried out tests where a corridor was employed to evaluate the meaning of the ASTM E-84 flame spread classification with materials on the wall and ceiling. The fire was originated in a room adjacent to the corridor and the time required to burn the length of the corridor with various linings was observed. It was concluded that:

"It is clear that placement of the materials in the order of ascending tunnel test flame spread ratings does not quite place them in the order of increasing flame spread rate or decreasing time in the full-scale corridor."

Fang [90] studied lining materials exposed to a corner ignition source in the large scale corner test. He used flashover as the criterion which is related to an upper gas

temperature of roughly 600°C. He found that flashover occurred for wall materials having flame spread classification (FSC) > 180.

Similar experiments were conducted at Underwriters Laboratories [91] by Castino and co-workers to investigate the flashover characteristics of rooms where the walls and ceiling were lined with cellular plastics and other materials having the E-84 flame spread classification. In the report, based on the criterion whether the room reached flashover conditions, it was noted that the flame spread classification of materials obtained in the standard 25-foot tunnel test are comparable to the performance of those materials conducted in corridor, corner and vertical wall full-scale building geometry tests. But when the time to flashover is employed as the criterion for hazard, there appeared to be poor correlation between the time to flashover and the flame spread classification - some low density foam boards with a flame spread classification of less than 25 caused flashover in the room, whereas others with a comparable flame spread classification did not.

Despite considerable discussion regarding the cost and validity of the ASTM E-84 tunnel test in the evaluation of flame spread, the ratings resulting from this method have widespread use and remains the most extensive source of information on the relative fire hazard characteristic of lining materials in North America. Full-scale studies of fire propagation in corridors by the Illinois Institute of Technology Research Institute (IITRI) [89] and National Research Council of Canada [92] have provided evidence to substantiate this opinion. The 25-foot tunnel test has been the most influential and commonly cited criterion used in the United States and Canada to certify the fire safety of construction materials, including cellular plastics [93].

2.2.2 ASTM E162-78 Test for Surface Flammability of Materials Using a Radiant Heat Energy Source

The ASTM E162 radiant panel test [78] was developed by the National Bureau of Standards in the late 1950's with the specific objective of providing a relatively simple and reproducible method for measuring the surface flammability of materials.

The apparatus for the ASTM E162-78 surface flammability test is shown in figures (2.2 and 2.3).

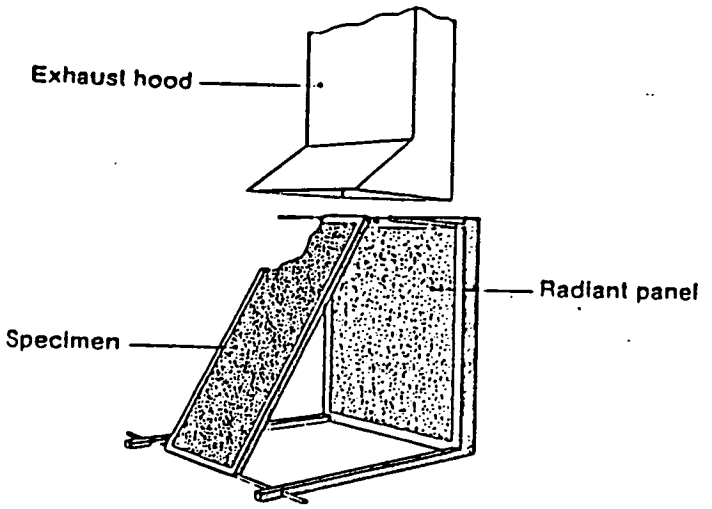


Fig. 2.2

Surface flammability test apparatus (ASTM E162-78).

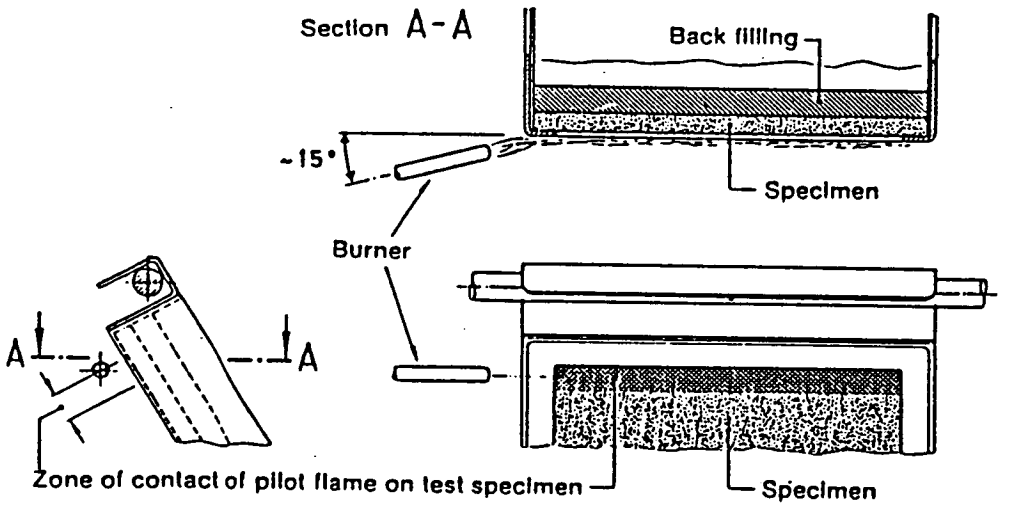


Fig. 2.3

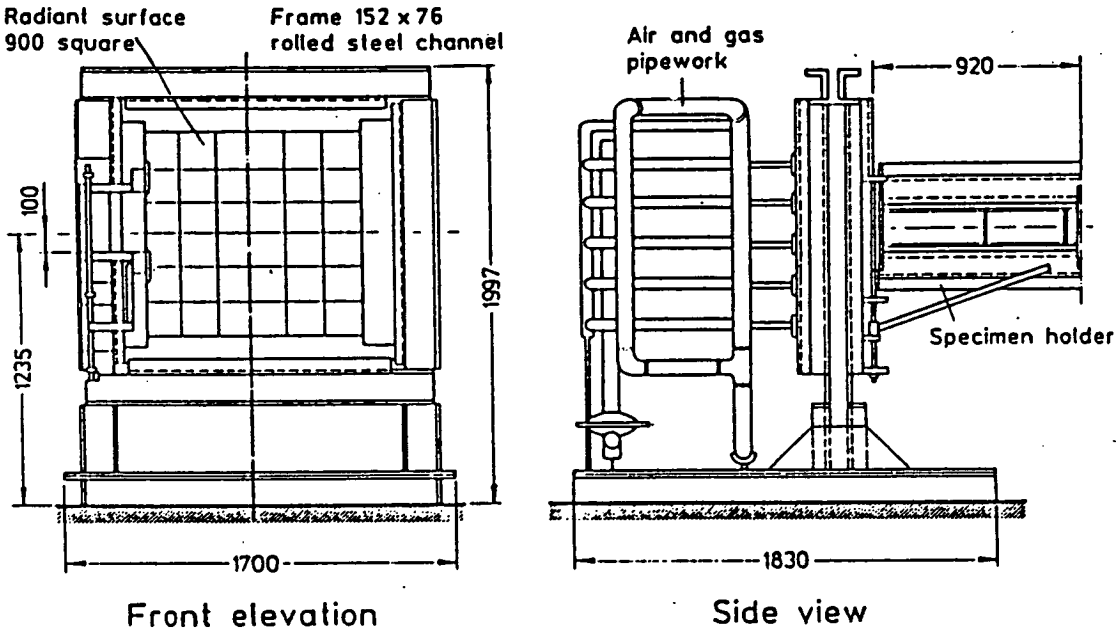
Position of pilot burner in relation to test apparatus of ASTM E162-78 .

This method employs a radiant heat source consisting of a 305mm x 457mm vertically mounted porous refractory panel maintained at 670±4°C (1238±7°K). A specimen measuring 152mm x 457mm is supported in front of it with the longer dimension inclined 30 degrees from the vertical. A pilot burner ignites the top of the specimen, 122mm away from the radiant panel, so that the flame progresses downward along the underside exposed to the radiant panel. The factor derived from the rate of progress of the flame front (ignition properties) and another relating to the rate of heat liberation by the material under test are combined to provide a flame spread index. Provision is also made for measuring the smoke evolved during tests. Similarly this method does not give satisfactory FSI for synthetic polymeric materials. Considering the classification of materials using this test method corresponds to that obtained with ASTM E-84 it can be widely used for research and quality control purposes during manufacture of building finish materials.

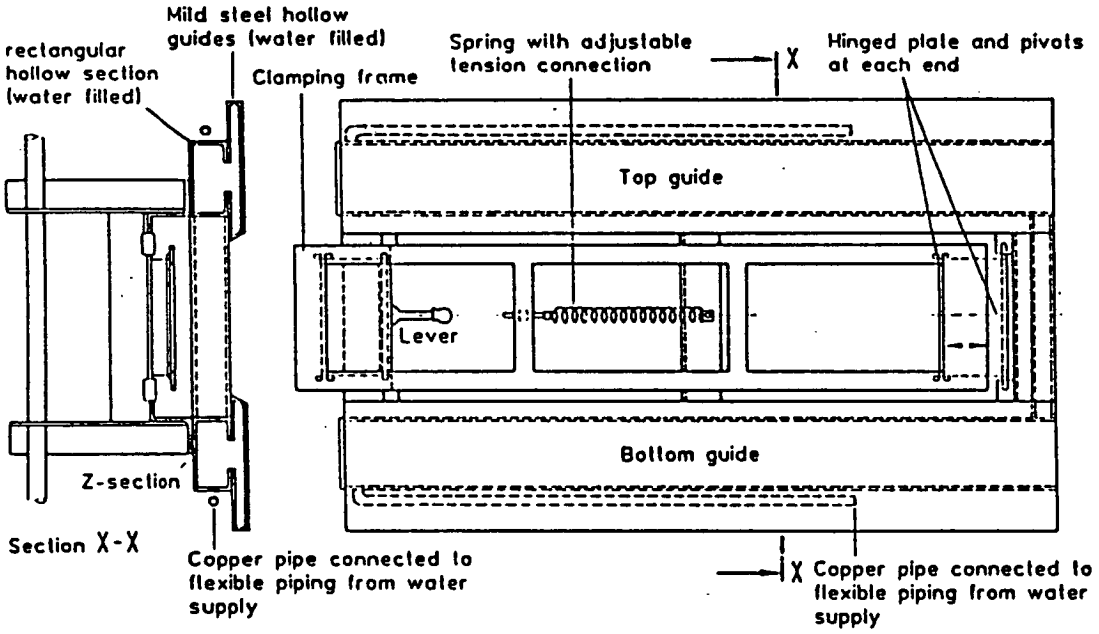
2.2.3 BS476: Part 7 - Surface Spread of Flame Test for Materials

This test [74] which is referred to in the Building Regulations in Great Britain was developed at the beginning of the 1940's to simulate a fire in a corridor. The specimen is positioned vertically with the longitudinal axis horizontal to simulate the wall of a corridor, while the radiant panel represents a fire at the end of the corridor.

The test apparatus (figure 2.4) comprises a gas-fired radiant furnace panel 850mm square operating at 800°C with two hinged wings mounted centrally on the sides of the panel. These wings are capable of taking samples measuring 885mm x 270mm. The sample is fixed to a non-combustible backing so that one face is exposed to radiant heat from the panel. The face of the board is vertical and its long axis is horizontal and at right angles to the radiant panel so that the intensity of heat falling on it varies from the maximum at the end nearer the radiator (37kW/m^2) to a minimum at the remote end (5kW/m^2). The furnace panel is controlled to give a specified temperature gradient along the specimen. Immediately the specimen is exposed to radiation at the start of the test, a vertical luminous gas pilot flame is applied to the surface of the material at its hot end for one minute. If the specimen ignites, the spread of flame away from the pilot source along the specimen is monitored. The distance the flame has spread is recorded at the end of 1.5 minutes and measurements of spread are continued up to a total time of 10 minutes, unless the flame has reached the far end of the specimen in less than 10 minutes. The



General arrangement of the apparatus



Specimen holder

Fig. 2.4

BS 476: Part 7: 1987 spread of flame test apparatus.

material is then classified as Class 1, 2, 3 or 4 according to Table (2.1) and Figure (2.5). Class 1 materials have the lowest rate of flame spread and class 4 have the highest.

It has been recognised that there are problems encountered when testing some thermoplastic products because of their tendency to melt and fall away from the specimen holder in advance of the flame front. When the specimen melts and slumps, it exposes the edges and this can cause rapid spread. However, the introduction of the water-cooled specimen holder and samples being held by a clamping arrangement such that the edges of the sample are covered, tends to offset this difficulty [9]. It is not only intended to improve the ability of the method to assess the performance of thermoplastics but also to reduce the influence of edge burning.

Additionally, the test measures only the contribution to fire spread over the surface of the material. Being an 'open' type test, most of the heat of combustion is lost into the atmosphere and no significant contribution is made by the heat evolved from the test material during its combustion towards its further decomposition as is likely to occur in an actual fire. Considering a fire in a room, once ignition has been established, its early stage of growth involved spread away from the ignition source initially via the material first ignited. Furthermore the rate of growth will be particularly rapid if vertical surfaces become involved as flame spread is most rapid in the vertically upward direction. In the flame spread mechanism it is essential that the fire must be producing more heat than was necessary in promoting the initial combustion reaction. Thus the quantity of heat output from the material burning, the rate at which heat can be released and fed back to the fuel is vital in contributing to fire spread, hence fire development. Consequently, the test provides an incomplete measure of the effect that a given material is likely to have on the growth of fire in a room.

It is also interesting to note that the maximum exposure of radiant intensity (approximately $37kW/m^2$) was not severe enough or sensitive enough to indicate the fire risks of materials capable of rapid rates of heat release which are protected by facings just able to resist maximum furnace exposure. Therefore, to sub-divide the Class 1 category further the materials are subjected to BS476: Part 6 "Fire

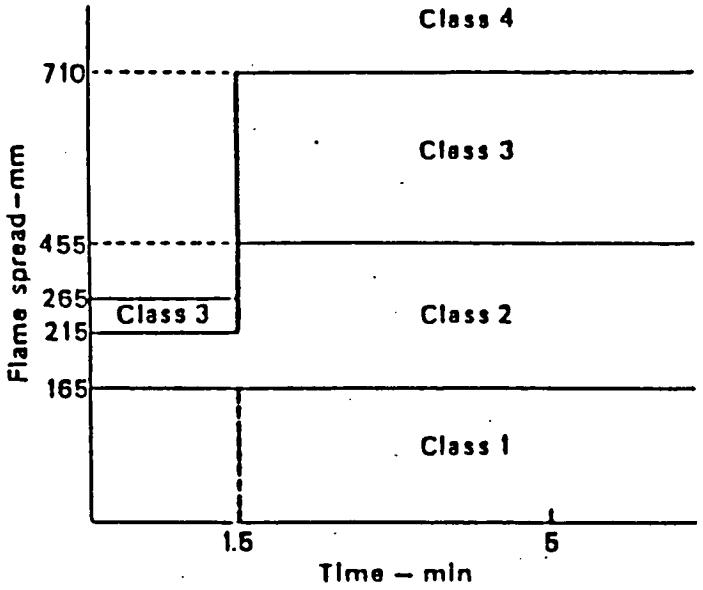


Fig. 2.5

Spread of flame classification for BS 476: Part 7.

Table 2.1 Spread of flame classification for BS 476: Part 7.

Classification	Flame spread at 1.5 min		Final flame spread	
	Limit [mm]	Tolerance for one specimen [mm]	Limit [mm]	Tolerance for one specimen [mm]
Class 1	165	25	165	25
Class 2	215	25	455	45
Class 3	265	25	710	75
Class 4	Exceeding class 3 limits			

Propagation Test" [26] and those that meet the stringent requirements of this test are designated Class 0.

Walker [94] has criticised the use of the BS 476: Part 7 procedure for walls on the basis that although the orientation of specimen is correct, flame spread is measured horizontally, whereas in many, if not all cases, flame spread in practice is vertical on a wall. As in this case, it is interesting to note that the test method is specifically designed to measure the lateral spread on wall and not for the vertical spread. So this criticism seems unjustified as this test did give classification/ranking of lining materials to some extent which is useful to the Building Regulator.

Hird and Fischl [95] conducted a series of tests on wall linings at the Joint Fire Research Organisation using a 12 x 18 x 9 ft high room. They compared their results with BS 476 and came to the following conclusion:

"The highest classification of the surface spread of flame test includes boards with a wide range of performance, and where they are to be used for linings for both walls and ceilings of compartments containing an appreciable amount of combustible material, the surface spread of flame classification is not sufficient indication of the fire hazard".

However, when the ranking produced from the Fire Propagation Test BS 476: Part 6 was applied to the full-scale and small-scale rooms behaviour, the results are comparable.

In general, the tests described above are designed to simulate the fire hazard scenario based upon the background experience that the test designers were able to bring to the specific problems. Additionally these tests are employed to assess the potential hazard of lining materials by providing ranking of classification of flame spread characteristics according to their performance. The test results are expressed in terms of some observations or measurements which are arbitrary and have limited application. In these tests physical form and orientation of the material are specified and the fire environment is strictly controlled. By changing these specifications such as the specimen geometry, size, thickness and particularly the magnitude of the heat transfer modes involved can have profound influence on the ranking order or the relative flame spread characteristics of various materials. As a consequence, results from one test do not necessarily agree with one another where tests which purport to

measure the same "property" can place a set of selected materials in widely different ranking orders. Therefore, it cannot be assumed that the classification of flame spread characteristics of a particular material will be the same in other situations. Discrepancies in the ranking of products by propagation propensity according to the results of various tests have been demonstrated by Emmons [2].

Additionally, several researchers [2,96-98] have commented that the results of flame spread tests are solely dependent on the test procedure and do not reflect the complex influence on the performance of materials of factors extrinsic to the specimen. This is soundly supported by several investigators [89-91] in their studies of correlating the flame spread ranking obtained from these tests in their large-scale room tests.

Though the test measures some aspect of flammability such as ignition, flame spread or energy release, the results are limited in their use since no attempt is made to relate them to material properties or to theories of ignition, spread or combustion. Hence, mathematical models are needed in order to elucidate the appropriate material properties for these phenomena. Furthermore, it is desirable that when combined with theory, these properties can be used over a wide range of fire conditions for predicting material ignition and flame spread behaviour.

Various mathematical modelling of flame spread using a radiant panel has been undertaken by several researchers [99-102]. From these studies, it was realised that radiation has such a marked influence on the rate of flame spread.

For example, Fernandez-Pello [103] showed that an imposed radiant heat flux will cause an increase in the rate of flame spread, primarily by preheating the fuel ahead of the flame front. Kashiwagi [101] in his 2-D steady state experiments on horizontal flame spread on carpets with external radiation has found that flame size and spread rate is increased significantly by increasing external radiation.

A series of flame spread tests on various plastics, hardboard, fibreboard, particle board and some specimens of fir, balsa and spruce, using the radiant panel flame spread apparatus in E162, were done by Robertson [102] and Gross et al [100]. They correlated their data using physical and thermal properties of the materials. Quintiere [104] and Quintiere et al [105] conducted similar tests on various

materials where lateral flame spread rate on vertical surfaces and time for piloted ignition were measured under externally imposed radiant flux. Here Quintiere [104] has developed a simplified theoretical flame spread model to correlate his experimental data.

Kashiwagi [101], Fernandez-Pello [103] and Quintiere [104] have found that the response of a surface to the imposed flux is not instantaneous. There were transient heating effects which must be considered if the flame begins to spread over the surface before thermal equilibrium has been reached.

In view of the need for better spread of flame tests, development work is still being carried out in the ISO [76-77] to devise spread of flame tests that are not only able to differentiate adequately between different building materials but also to assess the hazard of the materials in actual fire situations based on its properties derived from the tests. Presently, in the building field ISO Committee TC92 is developing its own spread of flame test which has already been published as a preliminary draft proposal under the number 5658 namely known as Surface Spread of Flame Test (ISO/DP 5658 - IMO Version) [76] and Surface Spread of Flame Test (LIFT Method) [77].

This led to the present work undertaken where experimental studies of lining materials were carried out at the Warrington Fire Research Centre in Cheshire. This project is in collaboration with the International Standard of Organisation ISO/TC92/SC1/WG3 where the results are used in the preparation of an International Standard for Assessing Spread of Flame. The ultimate goal of the project is to study the effectiveness of each of the ISO and LIFT methods of Spread of Flame. Areas to improve the design of apparatus and its applicability need to be highlighted so that a better and preferred method of assessing flame spread can be ascertained which can give results on the performance of materials which are relevant to real fire situations.

CHAPTER 3
ISO/LIFT METHODS OF ASSESSING SPREAD OF FLAME

3.1 Surface Spread of Flame Test (ISO/DP 5658 - old ISO version)

ISO/TC 92 has drawn up a first spread of flame test [75] which was published as a preliminary draft proposal. The basic principles of the apparatus are similar to those adopted in the UK (BS 476: Part 7) in that a specimen is mounted in front of a radiant panel and the flame spread is measured. It differs from the BS 476: Part 7 test apparatus in that the radiant panel is smaller and provision is made for various orientations of the specimen. The test [75] enables materials to be tested in horizontal (floor and ceiling) and vertical (wall) orientations. Figure (3.1) shows the spread of flame test apparatus: the configuration of the specimen and the radiant panel are clearly illustrated in figures (3.2a and 3.2b). Briefly the test specifications are summarised in table (3.1).

In the test proposal, no reference to classifications is given but the following are recorded:

(a) The time to ignition of the specimen.

(b) The time the flame-front along a centre line of the specimen passes each of the marks 100, 150, 200mm etc. until the maximum distance has been obtained and the time to extinction if the end of the specimen is not reached are recorded.

There are problems experienced with this apparatus. Some of which are related to the relatively poor life of the specified radiant panel when operated at the normal condition of temperature and heat radiation [94]. Round robins claimed that the test method does not differentiate adequately between different building materials [106].

The International Maritime Organisation (IMO) is also drafting a test procedure for surface flammability of bulkhead, ceiling and deck finish materials [107]. Attempts are being made within ISO to standardise a single spread of flame test not only for ISO but which could also be adopted in IMO regulations for marine engineering [106].

3.2 Surface Spread of Flame Test (ISO 5658 - IMO Version)

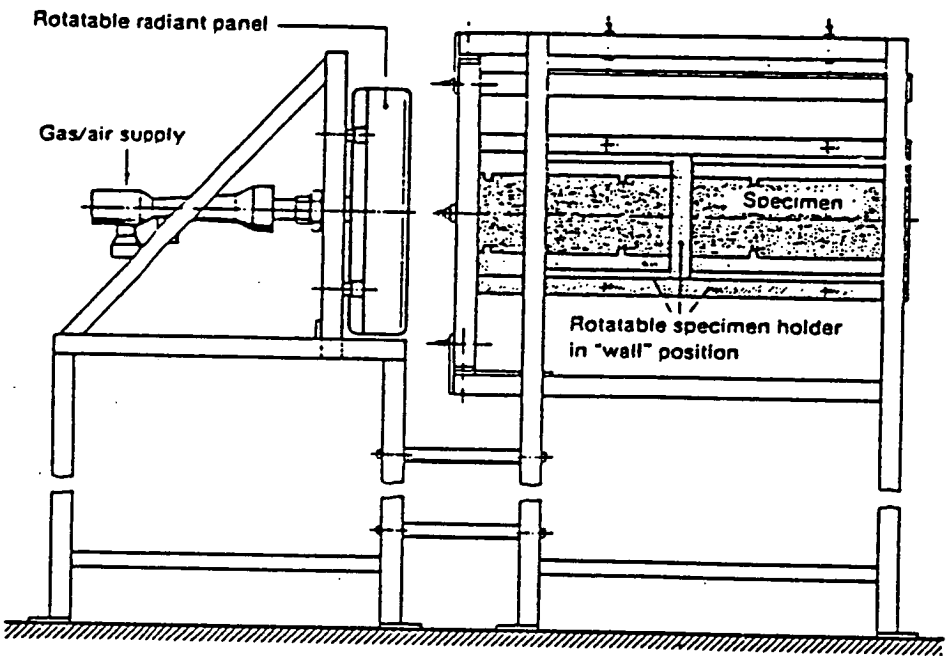


Fig. 3.1

Side view of ISO spread of flame test apparatus (old version).

Table 3.1 ISO/DP 5658 spread of flame test specifications (old version).

Specimens	800 mm × 155 mm × ≤ 40 mm, three specimens for each orientation (wall, floor, ceiling)
Specimen position	end of exposed area nearest radiator at a distance of 100 mm – wall: 450 mm side of radiant panel horizontal, specimen vertical, long (800 mm) horizontal side at 45° to radiant panel – floor: 450 mm side of radiant panel vertical, specimen horizontal and located centrally in the plane of the bottom of the radiant panel, long (800 mm) side at 90° to radiant panel – ceiling: 450 mm side of radiant panel vertical, specimen horizontal and located centrally in the plane of the top of the radiant panel, long (800 mm) side at 90° to radiant panel
Ignition sources	– vertical variable propane radiant panel 300 mm × 450 mm, radiation intensity 6.2 W/cm², surface temperature 750 °C – variable propane pilot flame, length 80 mm, impinges on specimen 20 mm from edge nearest to radiator
Test duration	test terminated when flame front extinguished or reaches end of specimen
Conclusions	the maximum distance in mm of flame travel and the time to extinction if the end of the specimen is not reached are recorded

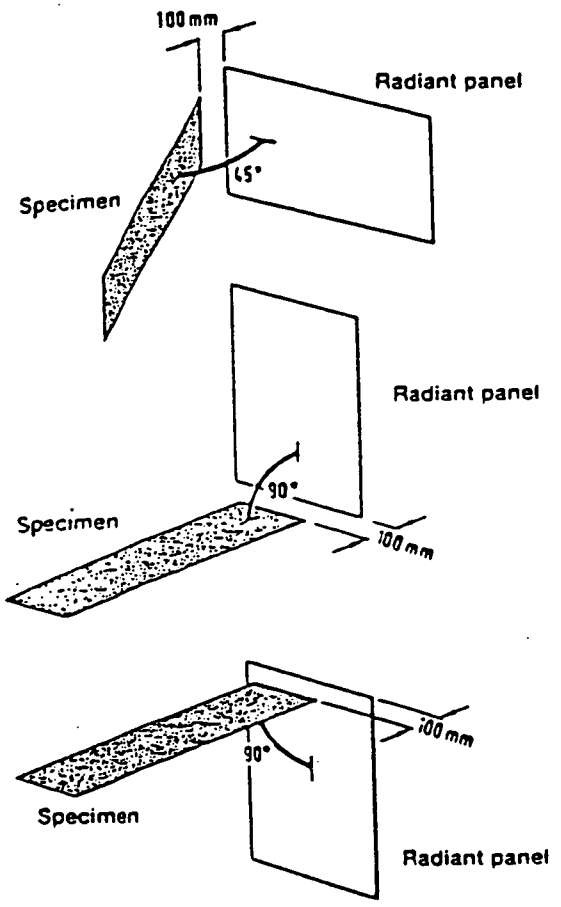


Fig. 3.2a

Orientations of specimen and radiant panel in ISO spread of flame test apparatus

Top: wall position,
Centre: floor position
Bottom: ceiling position

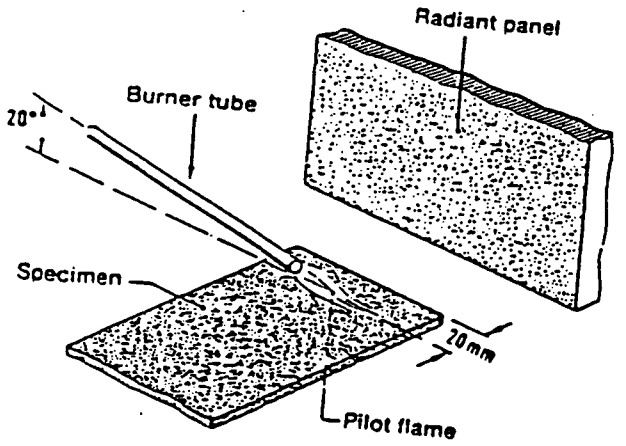


Fig. 3.2b

Position of pilot flame in ISO spread of flame test apparatus (old version).

Based upon the IMO test method, ISO has developed a test procedure for measuring the lateral spread of flame along the surface of a specimen orientated in the vertical orientation [76].

The schematic arrangement of the test apparatus is shown in figure (3.3). The detailed layout and description of the complete apparatus is available in draft proposal DP5658 ISO/TC 92/SC1/WG3 N128.

The IMO version of spread of flame test differs from the old ISO version in the use of a different radiant panel, a different specimen holder and a different angle between specimen and radiant panel (15^{o} instead of 45^{o}, refer figure 3.4). This results in a fundamentally different irradiance profile.

Prior to the commencement of the test, calibration of the apparatus has to be carried out. Using a water cooled heat flux meter (Medtherm) mounted in the calibration board, the irradiance measured at each position must correspond to values shown in table (3.2). The irradiance measured at 50 and 350mm positions must match the appropriate values in table (3.2) as accurately as possible, within $\pm 1\%$. For the other six positions, the irradiances measured should be within $\pm 5\%$ of the values given in the table. The values of irradiance against distance were plotted and a smooth curve drawn through the points to give the irradiance as a function of distance along the sample. An example of this irradiance profile is illustrated in figure (3.5).

The experimental work in this test procedure was done as described below. A test specimen, 800mm long and 155mm wide is placed in a vertical position adjacent to a gas-fired radiant panel where it is exposed to a defined field of irradiance in which the irradiance decreased uniformly along the length of the specimen. A pilot flame is sited close to, but not in contact with, the hotter end of the specimen to initiate flaming by igniting the volatile gases evolved from the surface (fig 3.6).

Three specimens were tested for each type of the seven lining materials. All the specimens were conditioned at $23 \pm 2^{o}C$ and a relative humidity of $50 \pm 5\%$. For easy visual observations of the spreading of the flame front, a reference line was made by drawing a line centrally along the length of each specimen. Vertical lines at 50mm intervals were also drawn across the surface (figure 3.7) along the whole

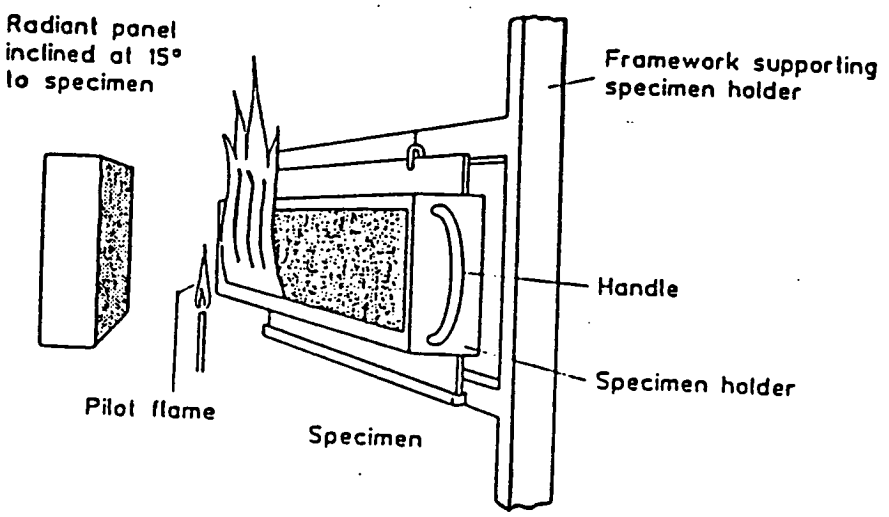


Fig. 3.3

Apparatus for ISO surface spread of flame test (IMO version).

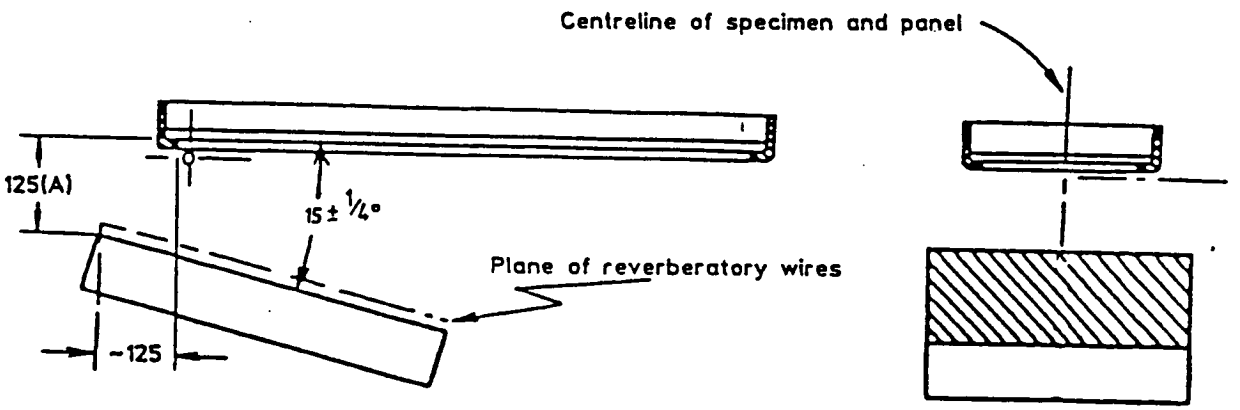


Fig. 3.4

Specimen-Panel arrangement for ISO spread of flame test apparatus (IMO version).

Table 3.2 Calibration of Flux to the Specimen

Typical flux incident on the specimen and specimen positions at which the calibration measurements are to be made. The flux at 50 and 350 mm positions should be matched. Calibration data at other positions should agree with typical values within ±5 %.

Distance from exposed end of the specimen	Typical flux levels at the specimen	Calibration position to be used
0 mm	49.5 KW/m^2	
50	50.5	50.5 kW/m^2
100	49.5	
150	47.1	X
200	43.1	
250	37.8	X
300	30.9	
350	23.9	23.9
400	18.2	
450	13.2	X
500	9.2	
550	6.2	X
600	4.3	
650	3.1	X
700	2.2	
750	1.5	X

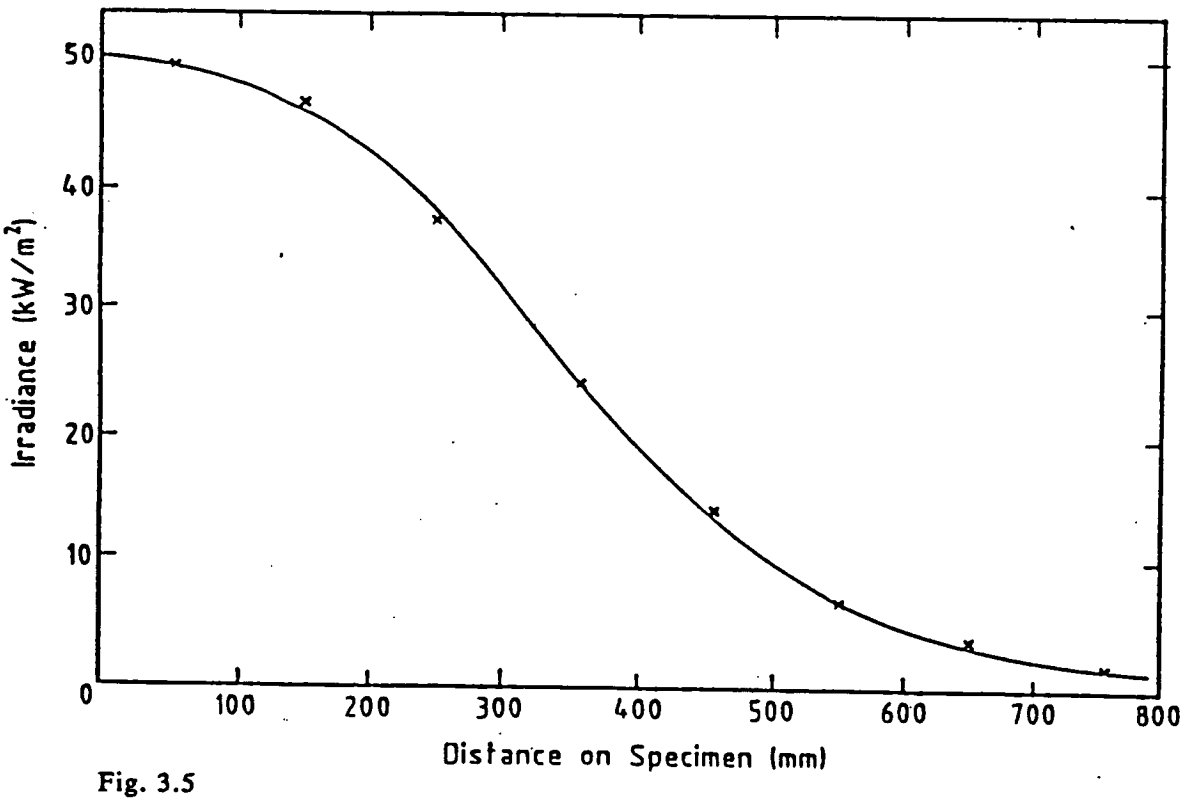


Fig. 3.5

Irradiance profile for ISO spread of flame test apparatus (IMO version).

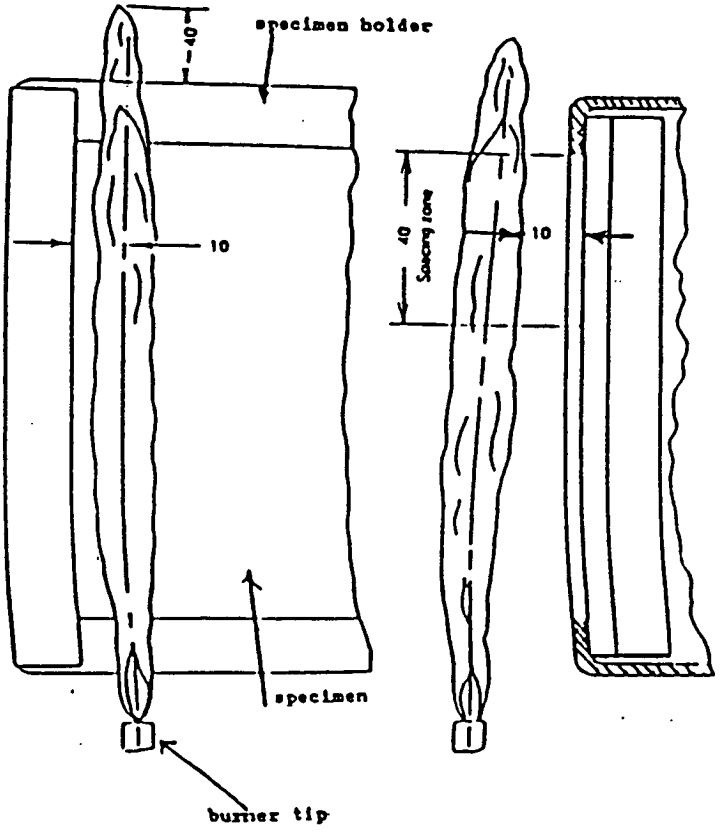


Fig. 3.6

Position of pilot flame in ISO spread of flame test apparatus (IMO version).

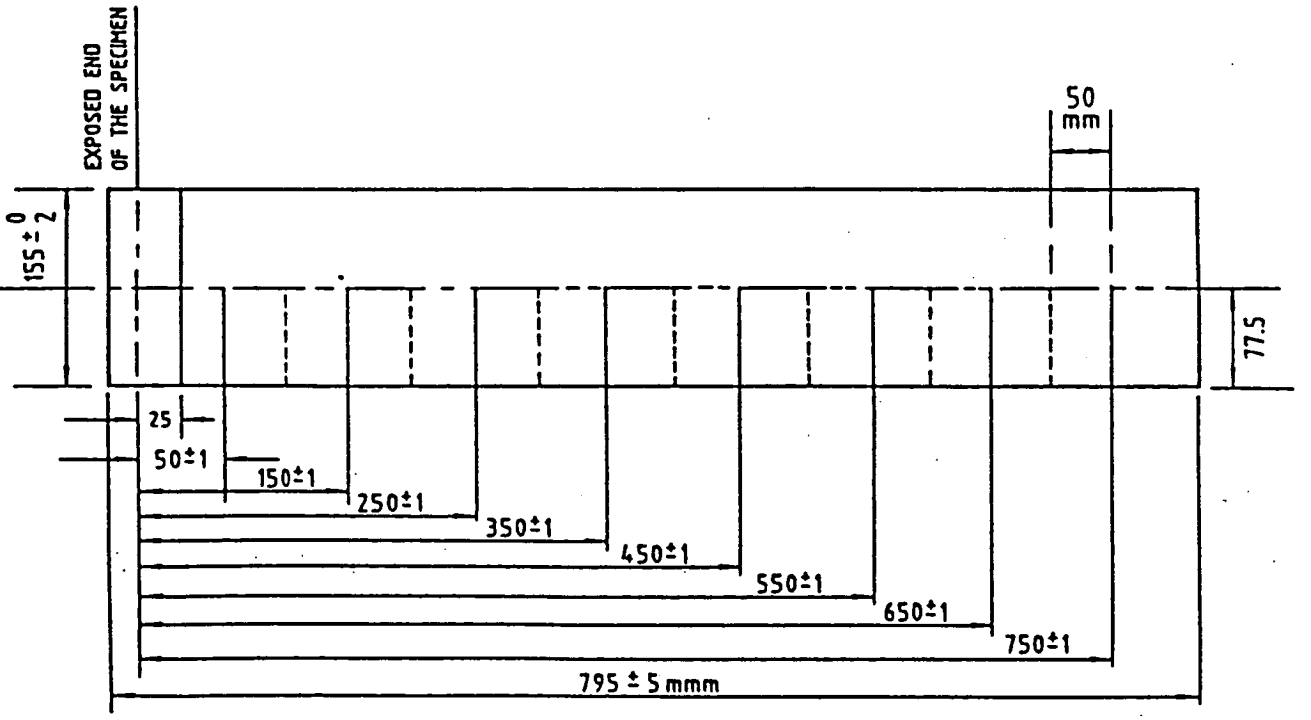


Fig. 3.7

Vertical lines at 50mm interval on sample surface.

length of the specimen. Before the test, the edges and the rear faces of the specimen were wrapped with aluminium foil allowing a width of about 10mm of foil to overlap evenly over the edges of the front face of the specimen.

Upon insertion of the specimen, following ignition, if a flame front develops, its lateral progress is assessed visually in relation to distance markers and expressed as a function of time. Also, the time to flame initiation, the time to flame front extinguishment and the maximum distance of flame travel are recorded.

The test is continued for a minimum period of 10 minutes and until 6 minutes after all flaming has ceased, or when the flame front reaches the end of the specimen. General behaviour of the specimen, e.g. charring, glowing, production of flaming droplets, etc., is recorded.

The fire characteristics derived from the experimental results are the "heat for sustained burning" and the critical irradiance for flame spread. The "heat for sustained burning" is defined as the product of time from the start of the exposure of a specimen to the arrival of the flame front at one of the marked distance and the irradiance corresponding to that distance measured on a calibration board. The critical irradiance for flame spread is taken as the value of the irradiance at the surface of a specimen at the point along its centreline where the flame ceases to advance (and may subsequently go out).

3.3 Surface Spread of Flame Test (ISO/DP 5658 - LIFT Method)

The LIFT surface spread of flame test [77] is one of the new generation of test methods developed within ISO where the experimental data are used to correlate with the ignition and flame spread models [108].

In search of correlation parameters for the radiant panel flame spread apparatus, Quintiere [104] developed a simplified flame spread model in which transient one dimensional conduction is considered in the solid phase and forward heat transfer to the surface from the flame is assumed constant over a certain width (approx. 1mm) [109]. He carried out a detailed mathematical analysis of transient flame spread with external radiant heating following similar analyses by Rockett [110] in analysing vertical downward spread as in ASTM E-162 and his own studies of horizontal spread on floor covering materials as in ASTM E-648 [111]. In his analysis, the experimental results on the lateral flame spread and time for piloted ignition under

an externally imposed radiant flux using the ISO/IMO Surface Spread of Flame Apparatus [112] developed at the National Bureau of Standards were analysed with a theoretical model. His approach is more towards determining important fire parameters rather than identifying flame spread mechanisms has been done by de Ris [99], Fernandez-Pello and Williams [113], or Frey and Tien [114]. He introduced his analysis in the LIFT method. By correlating experimental data with theoretical analysis for a particular ignition or flame spread process in the test method, material properties which provide information about the flame spread characteristics of materials can be obtained. In particular, these properties include minimum surface flux and temperature for ignition, effective material thermal inertia values ($k\rho c$) and a flame heating parameter (Φ) pertinent to lateral flame spread. The detailed theoretical analysis used in the LIFT method is discussed in the next section.

Comprehensive studies on various materials have been carried out by Quintiere et al. This is clearly illustrated by Tables (3.3) and (3.4) which displayed the ignition and flame spread characteristics as well its flame spread properties respectively.

3.3.1 Theoretical

Basically two theoretical models are involved in the LIFT flame spread test which yield the relevant material flammability parameters that include minimum exposure level for ignition, thermal inertia values and flame spread properties. The experimental data are correlated using the Ignition and Flame Spread Theory.

Ignition Theory

In existing radiant ignition tests [39,52,116], the time to piloted ignition (t_{ig}) is determined by igniting the pyrolysis gases from the sample after exposure to a specified irradiance from the radiant panel. Even though there is a difference in the location of the pilot flame and type of fuel used, there is a common understanding on the assumptions involved in piloted ignition.

Initially, it is assumed that the most common organic solids ($k/\rho c \simeq 0(10^{-7})m^2/s$ in applications of construction can be treated as a semi-infinite solid since the depth of heating for conditions of piloted ignition is 2 to 5mm. A wall or a slab of thickness L can be assumed to be semi-infinite provided that $L > 2\sqrt{(\alpha t)}$ where $\alpha = k/\rho c$ is the thermal diffusivity of the material and t is the duration of heating.

Table 3.3: Ignition and flame spread characteristics under constant irradiance conditions[e] [108]

Material	$\dot{q}''_{o,s}$ (W/cm^2)	C $(s/mm)^{1/2}$ (cm^2/W)	$\dot{q}''_{o,ig}$[a] (W/cm^2)	$\dot{q}''_{o,ig}$[b] (W/cm^2)	b ($s^{-1/2}$)	t_{ig} (s)
Plywood, plain 0.635cm	0.4	1.8	1.2	1.6	0.07	190
Plywood, plain 1.27cm	0.3	1.5	1.4	1.6	0.07	225
Plywood, FR 1.27cm	...[c]	...[c]	...[c]	4.4	0.10	110
Hardboard, 6.35mm	0.4	5.8	1.0	1.0	0.03	1190
Hardboard, 3.175mm	0.1	2.2	1.3	1.4	0.05	420
Hardboard, (S159M)	0.1	1.8	1.5	...[d]	...[d]	...[d]
Hardboard, gloss paint 3.4mm	1.1	4.1	1.8	1.7	0.05	468
Hardboard, nitrocellulose paint	0.4	2.0	2.1	1.7	0.06	306
Particle board, 1.27cm stock	0.9	3.2	1.7	1.8	0.05	312
Douglas Fir particle board, 1.27cm	0.6	2.0	1.7	1.6	0.05	395
Chipboard (S118M)	0.4	2.2	1.6	...[d]	...[d]	...[d]
Wood panel (S178M)	0.4	1.1	1.6	...[d]	...[d]	...[d]
Fibre Insulation Board	0.6	3.4	1.4	1.4	0.07	205
Fibreboard, low density (S119M)	0.1	1.3	1.2	...[d]	...[d]	...[d]
Polyisocyanurate, 5.08cm	0.9	0.4	1.7	2.1	0.36	8
Polystyrene, 5.08cm	...[c]	...[c]	...[c]	4.6	0.14	53
Polyurethane (S353M)	0.2	1.0	0.9	...[d]	...[d]	...[d]
Polycarbonate 1.52mm	2.2	1.5	3.0	3.0	0.06	260
Foam, rigid 2.54cm	0.6	0.6	2.0	2.0	0.32	100
Foam, flexible 2.54cm	0.2	1.2	1.2	1.6	0.09	132
PMMA Type G, 1.27cm	0.1	2.0	1.6	1.5	0.05	456
PMMA Polycast, 1.59cm	0.3	3.4	1.0	0.9	0.04	462
Carpet #1 (wool, stock)	2.1	1.5	2.5	2.3	0.18	32
Carpet #2 (wool, untreated)	1.2	1.2	1.6	2.0	0.11	83
Carpet #2 (wool, treated)	1.4	3.2	1.6	2.2	0.12	72
Carpet (nylon/wool blend)	0.8	1.7	1.8	1.8	0.06	248
Carpet (acrylic)	0.4	1.8	1.1	1.0	0.06	250

Note: GPR = glass-reinforced polyester, FR = fire-retardant treatment

[a]From spread data

[b]From ignition data

[c]Flame spread was not measurable

[d]Data were not taken

[e]Values are only significant to two places.

Table 3.3 continued.

Material	$\dot{q}''_{o,s}$ (W/cm^2)	C $(s/mm)^{1/2}$ (cm^2/W)	$\dot{q}''_{o,ig}{}^{a}$ (W/cm^2)	$\dot{q}''_{o,ig}{}^{b}$ (W/cm^2)	b ($s^{-1/2}$)	t_{ig} (s)
Gypsum board, common 1.27cm	1.9	0.9	3.5	3.5	0.11	87
Gypsum board, FR 1.27cm	1.0	1.1	2.1	2.8	0.10	95
Gypsum board, wall paper (S142M)	0.7	5.8	1.0	1.8	0.07	208
Afincral wool, textile paper (S160M)	0.2	1.2	1.7	...[a]	...[a]	...[a]
Asphalt shingle	0.3	2.7	1.6	1.5	0.06	306
Fibreglass shingle	1.8	1.5	2.7	2.1	0.08	161
GRP. 2.24mm	0.1	1.3	2.0	1.6	0.09	132
GRP, 1.14mm	1.4	2.9	1.6	1.7	0.06	279
Aircraft panel epoxy fibrelite	...[c]	...[c]	...[c]	2.8	0.13	57

Note: GPR = glass-reinforced polyester, FR = fire-retardant treatment

[a]From spread data

[b]From ignition data

[c]Flame spread was not measurable

[d]Data were not taken

[e]Values are only significant to two places.

Table 3.4 Flame spread properties[c] [108]

Material	T_{ig}, °C	$k\rho c$ $(kW/m^2K)^2s$	$\dot{q}''^2$ $(kW)^2/m^3$	$T_s$mins °C	$\dot{q}''^2/k\rho c$, mK^2/s
PMMA polycast, 1.59mm	278	0.73	5.45	120	8
Polyurethane, S353M	280	...[b]	...[b]	105	82
Hardboard, 6.35mm	298	1.87	4.51	170	2
Carpet (acrylic)	300	0.42	9.92	165	24
Fibreboard, low density (S119M)	230	...[b]	...[b]	90	42
Fibre insulation board	355	0.46	2.25	210	5
Hardboard 3.175mm	365	0.88	10.97	40	12
Hardboard (S159M)	372	...[b]	...[b]	80	18
PMMA Type G, 1.27cm	378	1.02	14.43	90	14
Asphalt Shingle	378	0.70	5.38	140	8
Douglas Fir Particle Board, 1.27cm	382	0.94	12.75	210	14
Wood panel (S178M)	385	...[b]	...[b]	155	43
Plywood, plain, 1.27cm	390	0.54	12.91	120	24
Chipboard (S118M)	390	...[b]	...[b]	180	11
Plywood, plain, 0.635cm	390	0.46	7.49	170	16
Foam, flexible, 2.54cm	390	0.32	11.70	120	37
GRP, 2.24mm	390	0.32	9.97	80	31
Mineral wool, textile paper (S160M)	400	...[b]	...[b]	105	34
Hardboard (gloss paint) 3.4mm	400	1.22	3.58	320	3
Hardboard (nitrocellulose paint)	400	0.79	9.81	180	12
GRP, 1.14mm	400	0.72	4.21	365	6
Particle board, 1.27cm stock	412	0.93	4.27	275	5
Gypsum board, wall paper (S142M)	412	0.57	0.79	240	1
Carpet (nylon/wool blend)	412	0.68	11.12	265	16
Carpet #2 (wool, untreated)	435	0.25	7.32	335	30
Foam rigid, 2.54cm	435	0.03	4.09	215	141
Polyisocyanurate, 5.08cm	445	0.02	4.94	275	201
Fibreglass shingle	445	0.50	9.08	415	18
Carpet #2 (wool, treated)	455	0.24	0.89	365	4
Carpet #1 (wool, stock)	465	0.11	1.83	450	17
Aircraft panel epoxy fibrerite	505	0.24	...[a]	505	...[a]
Gypsum board, FR 1.27cm	510	0.40	9.25	300	23
Polycarbonate, 1.52mm	528	1.16	14.74	455	13
Gypsum board, common 1.27mm	565	0.45	14.44	425	32
Plywood FR (1.27cm)	620	0.76	...[a]	620	...[a]
Polystyrene (5.08cm)	630	0.38	...[a]	630	...[a]

Note: GPR = glass-reinforced polyester

[a]Flame spread was note measurable

[b]Data were not taken

[c]Values are only significant to two places.

The depth of the heated layer is of the order $(\alpha t)^{1/2}$ [6]. Here, the thermal inertia (which is the product of thermal conductivity (k), density (ρ) and heat capacity (c)) of the solid determines the rate of response [6] of its surface to an imposed heat flux and also in the time constant of heating materials [100,120,130]. It was found that the higher the value of $k\rho c$, the longer it takes for the surface temperature of a solid to approach the temperature of a fluid stream it is placed in.

For a solid having a thickness that is greater than 50mm, it can be considered thermally thick ($2\sqrt{(\alpha t)} < 50$mm for the heating times involved. Thus increasing the thickness further would not change the ignition times [117-118].

The irradiance at the surface of thick, cellular materials which melt and recede on heating, such as expanded polystyrene foam (EPS), will be less than specified when the material has melted back on to the baseboard. In addition, the surface will be further from pilot flame than in the original configuration. Consequently for materials which are not thermally thick at the time of ignition, the nature of the backing material or substrate can influence the measured value of the ignition time. Particularly, materials with a high thermal conductivity, increasing the thermal conductivity of the substrate increases the "heat sink" effect and may delay ignition of the exposed surface.

Finally, it is assumed that piloted ignition occurs when a (material dependent) surface temperature reaches a crticial temperature T_{ig}. From figure (3.8) which displayed the scenario for piloted ignition, T_{ig} is the lowest temperature at which ignition of the pyrolysis gases gives rise to sustained burning at the surface. There is known to be some experimental evidence to support this assumption [108,119]. Therefore, it is important that for a well designed radiant ignition apparatus, the location of the pilot ignitor is located in the stream of high concentration of fuel vapours where the lower flammability limit is expected to first be reached after the specimen begins its pyrolysis.

Based on these two assumptions, Quintiere developed the ignition theory in th LIFT method [77]. In this piloted ignition test, a sample of the material to be tested is suddenly exposed to a fixed irradiance $\dot{q}''_e$ from a radiant panel. At some time after the start of exposure pyrolysis gases from the sample will ignite at the pilot flame which is located in the plume (refer figure 3.9) above the sample. Shortly, thereafter, the flame attaches to the surface indicating successful ignition. Tests are

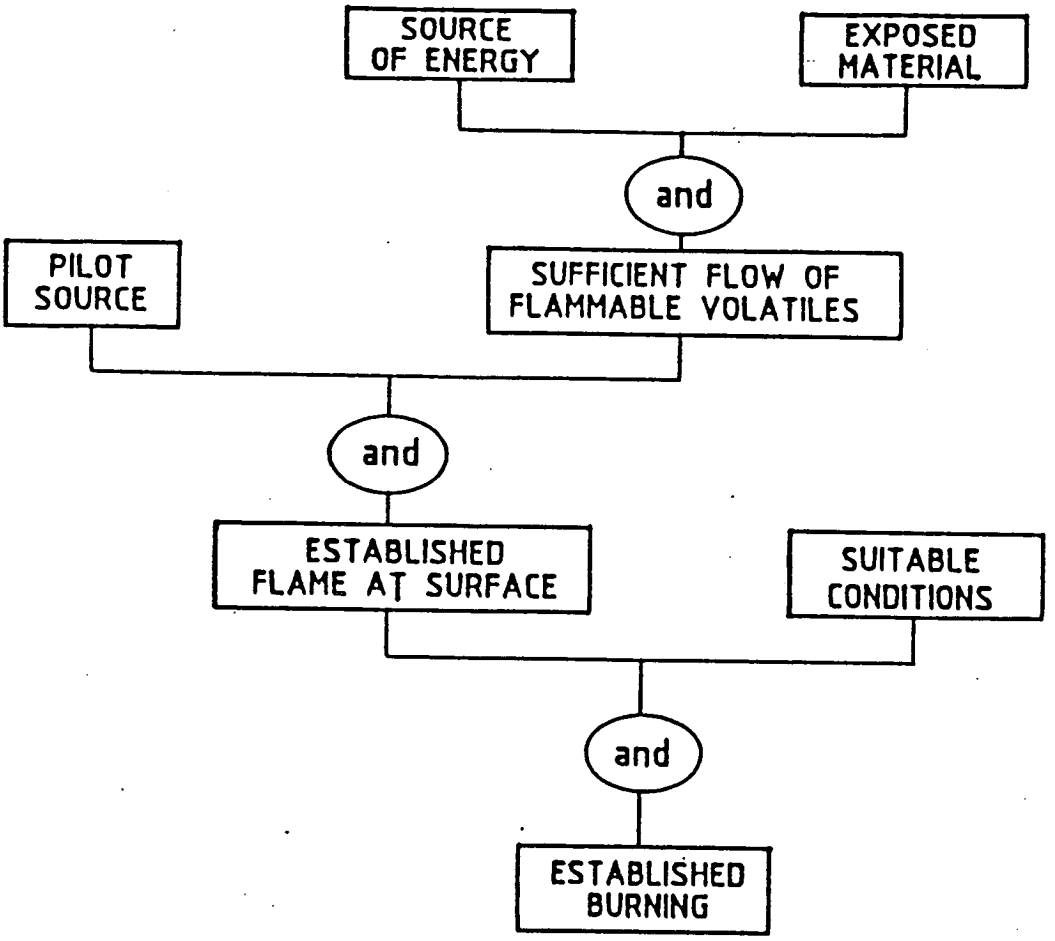


Fig. 3.8 The scenario for piloted ignition [55].

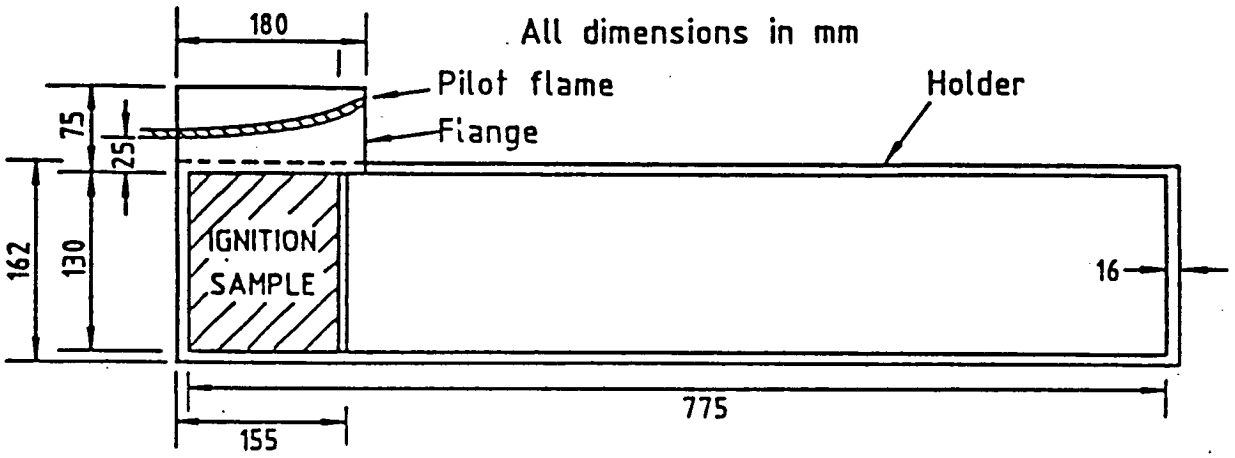


Fig. 3.9

Pilot flame configuration for LIFT spread of flame test apparatus.

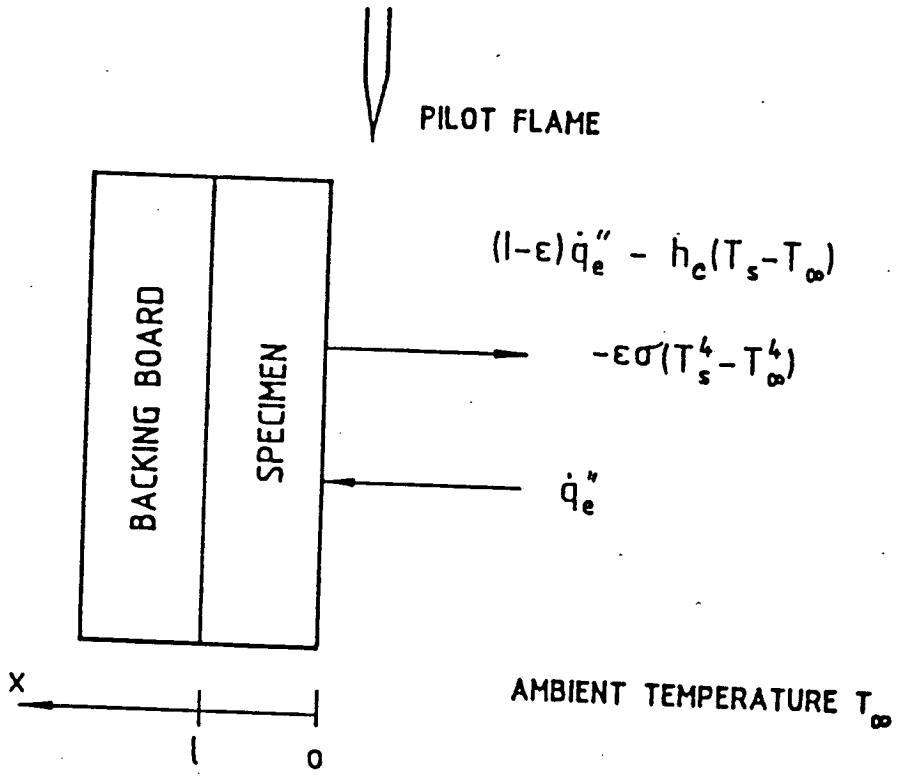


Fig. 3.10 Ignition mathematical model.

repeated at various irradiance in the range of 10 to 70 kW/m^2. A schematic of the test arrangement with some information relevant to the mathematical model is shown in figure (3,10).

Applying the one dimensional conduction theory, mathematically the ignition model is posed below. The symbols used are explained in the nomenclature at the beginning of the text.

The governing equation is given as:

$$\frac{\delta T}{\delta t} = \frac{k}{\rho c}\frac{\delta^2 T}{\delta x^2} \qquad (1)$$

By imposing the boundary conditions of $T(x,0) = T$ and $-k(\delta T/\delta x) = \dot{q}''_e - h(T_s - T_\infty)$, where h is the heat loss coefficient inclusive of radiative and convective effects, the equation is solved to yield the surface temperature for $x = 0$:

$$T_s - T_\infty = \frac{\dot{q}''_e}{h}\left[1 - \exp(\tau)\,\mathrm{erfc}\,(\sqrt{\tau}\right] \qquad (2)$$

where $$\tau = \frac{h^2 t}{k\rho c}$$

Theoretically the critical irradiance or the minimum flux for piloted ignition q''_{ig} is defined as the irradiance which results in ignition at $t \to \infty$ when conductive losses into the material will be zero and heat losses (convective and radiative) from the surface are equal to the incident irradiance:

Thus,

$$\dot{q}''_{ig} = h(T_{ig} - T_\infty) \qquad (3)$$

Therefore putting $t = t_{ig}$ and $T_s = T_{ig}$ and inserting eqn (3) into (2) will give:

$$\frac{\dot{q}''_{ig}}{\dot{q}''_{e}} = [1 - \exp(\tau_{ig}) \operatorname{erfc} \sqrt{\tau_{ig}}] \qquad (4)$$

Here the critical flux for ignition $\dot{q}''_{ig}$ is determined from experimental data where the time to ignition (t_{ig}) is measured at various levels of external flux ($\dot{q}''_{e}$). By bracketing the fluxes for ignition/no ignition, the minimum flux for ignition is determined. Also by plotting the results of the reciprocal of the ignition time ($1/t_{ig}$) as a function of external flux gives a linear relationship where it is assumed that there are no heat losses, especially at high fluxes.

Accordingly, the ignition temperature (T_{ig}) can be determined from the ignition test data. Here the ignition temperature represents the surface temperature required to produce a flammable mixture at the flammability limit. Note that this temperature is not measured directly as has been done by Thomson [55]. She determined surface temperature at ignition directly for six common thermoplastics. Fine thermocouples were attached to the exposed face of the horizontal sample and the surface temperature at ignition was recorded.

In the LIFT method, the surface temperature is predicted from theory. This is shown in figure (3.11) which compares the theoretical result for surface temperature as a function of external radiant heat flux with measured surface temperature for three materials. Low density aircraft panel and wood particle board are tested in vertical orientation in the flame spread test apparatus where h_c was determined to be $15 W/m^2K$ under conditions of natural convection [108]. Using calcium silicate with a blackened surface as an idealized material and assuming $\varepsilon = 1$ and $h_c = 15 W/m^2K$ provides a good overall fit to the idealised data. It is assumed that this curve can be used to infer surface temperature for a material under long-time heating conditions. Thus from the experimental determination of $\dot{q}''_{ig}$, T_{ig} can be found from the above curve. Subsequently a heat loss coefficient (h) which is inclusive of both radiative and convective effects can be derived from eqn (3).

The eqn (4) is solved empirically by using a function F(t) which is a time dependent factor to account for non-equilibrium conditions [104]. F(t) will depend upon h and the thermal inertia of the sample which are assumed to be independent of time.

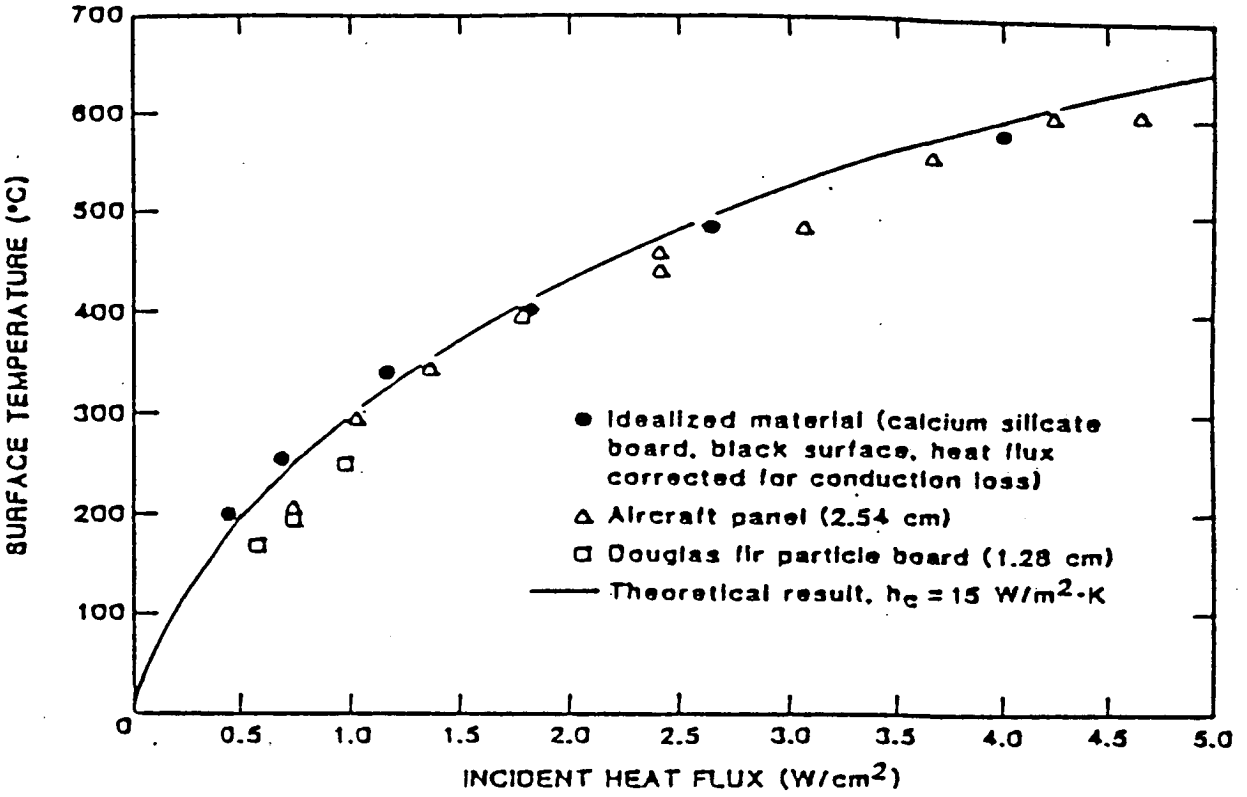


Fig. 3.11

Equilibrium surface temperatures as a function of external radiant heating in the test apparatus.

From conduction theory (120):

when t is small, $F(t) = \dfrac{2h\sqrt{t}}{\sqrt{(\pi k\rho c)}}$

when t is large, $F(t) = 1$

Quintiere empirically determined that:

$$F(t) = \frac{\dot{q}''_{ig}}{\dot{q}''_{e}} = \begin{bmatrix} b\sqrt{t}, & t \leq t^* \\ 1, & t \geq t^* \end{bmatrix} \qquad (5)$$

where t^* is the preheating for the material to reach equilibrium or steady state.

Consequently the thermal properties, $k\rho c$, of the material can be derived.

Thus for $t \leq t^*$:

$$k\rho c = \frac{4h^2}{\pi b} \qquad (6)$$

where b can be derived from experimental data, therefore $k\rho c$ can be calculated.

The parameters b and t^* can be found by plotting the values of the flux ratio $(\dot{q}''_{ig}/\dot{q}''_{e})$ versus the square root of the ignition time $\sqrt{(t)}$ where the slope of the linear region of the graphs was considered to be representative of b. As for t^*, it is given by the interception of the correlation line with the unity value of the flux ratio [$F(t) = 1$]. This value (pre-heat time) gives one a working measure of the time needed for an externally heated sample of the given material to come to thermal equilibrium with an external flux and will be used in the lateral flame spread tests.

Even though the predicted correlation yields the two effective parameters, $k\rho c$ and T_{ig} for a material, these values are not considered as the exact properties of the said material. It must be emphasised that the results obtained from this correlation are characteristic of the apparatus where configuration, the effect of heat losses from the back of the sample and the backing board contribute significantly. Thus the results will be different in other configurations and set-up.

Flame Spread Theory

The basis of the theoretical model for flame spreading into an opposed ambient flow used by Quintiere is displayed in figure (3.12).

The model illustrated that the flame is spreading over the surface in the x direction. The solid is considered thermally thick and its initial temperature and that of the ambient is constant at T_∞. It was assumed that the solid is inert with negligible pyrolysis before ignition. The heat flux from the flame $\dot{q}''_f$ acts over a distance of δf ahead of the advancing flame front and the surface ahead of the flame is also heated by the imposed radiant flux $\dot{q}''_e$. Since heat transfer is involved due to flame and external fluxes at the flame front x_f there is a conduction problem. Therefore in this model, the study considered a fixed position x_f and that there is a one-dimensional conduction through the solid.

Several other simplifying assumptions were employed to enable the equations to be solved including the following:

(1) The heat flux from the flame $\dot{q}''_f$ is constant and uniform over the distance δ_f.

(2) Conduction of heat through the solid is 1-dimensional in the direction normal to the surface; i.e. no forward heat conduction in the solid.

(3) The surface heat loss is represented by the equation; $h(T_s - T_\infty)$ where h is an effective heat transfer coefficient that includes both radiative and convective components.

(4) The flame moves forward when the unburnt fuel reaches an "ignition temperature". That is the surface temperature at the flame front must be equal to the ignition temperature T_{ig}.

(5) The flame spread velocity $V_f = dx_f/dt$ is constant over the time that it takes for the flame front to traverse the distance δ_f.

From the derivation, Quintiere has shown that the flame spread velocity is given as:

$$V_f^{-1/2} = \left[\frac{(\pi k \rho c)^{1/2}}{2(h\delta_f)^{1/2} q''_f} \right] \left[h(T_{ig} - T_\infty) - q''_e \right] \qquad (7)$$

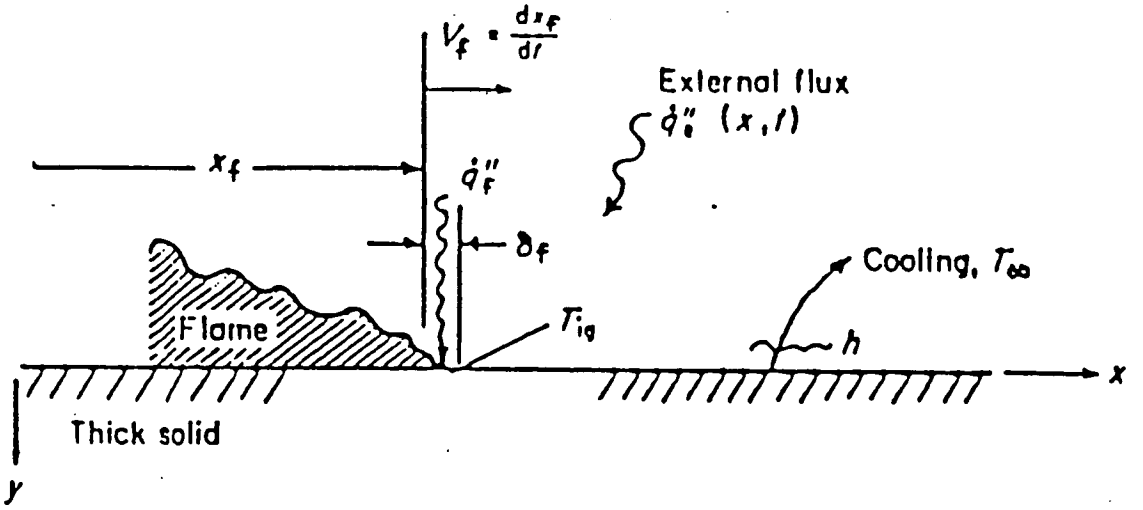


Fig. 3.12 Flame spread model. [82]

where $\dot{q}''_f$ is the heat flux from the flame to the surface across a distance δ_f, $\dot{q}''_e$ is the externally imposed heat flux, T_∞ is the initial temperature and h is an effective surface heat transfer coefficient.

Eqn (7) represents the steady state or maximum flame spread under thermal equilibrium or when the surface temperature has nearly reached its steady value due to radiant heating q''_e. This equation can be rewritten:

$$V_f^{-1/2} = C(\dot{q}''_{ig} - \dot{q}''_e) \qquad (8)$$

where C is referred to as a "rate coefficient" and $\dot{q}''_{ig}$ is the critical heat flux necessary for pilot ignition.

The rate coefficient,

$$C = \frac{(\pi k \rho c)^{1/2}}{2(h\delta_f)^{1/2}\dot{q}''_f}$$

and the critical flux for ignition, $\dot{q}''_{ig} = h(T_{ig} - T_\infty)$

These two parameters can be considered as the basic properties of the material that should have universality with respect to flame spread. From the experimental data, these two parameters can be determined through the relationship as displayed in figure (3.13).

In this form, it was found that $V_f^{-1/2}$ was a linear function of $\dot{q}''_e$ over the range from $\dot{q}''_e = \dot{q}''_s$ (the minimum flux necessary to permit flame spread) to $\dot{q}''_e = \dot{q}''_{ig}$ (the minimum flux for ignition). Here $\dot{q}''_s$ is the value of q''_e at the asymptote whilst the critical heat flux, $\dot{q}''_{ig}$ is taken as the value of $\dot{q}''_e$ at the intercept on the abscissa respectively. The rate coefficient is equivalent to the slope in this relationship.

The formula derived by de Ris [99] is also used to analyse and generalise the flame spread data. Here the flame spread velocity is given as:

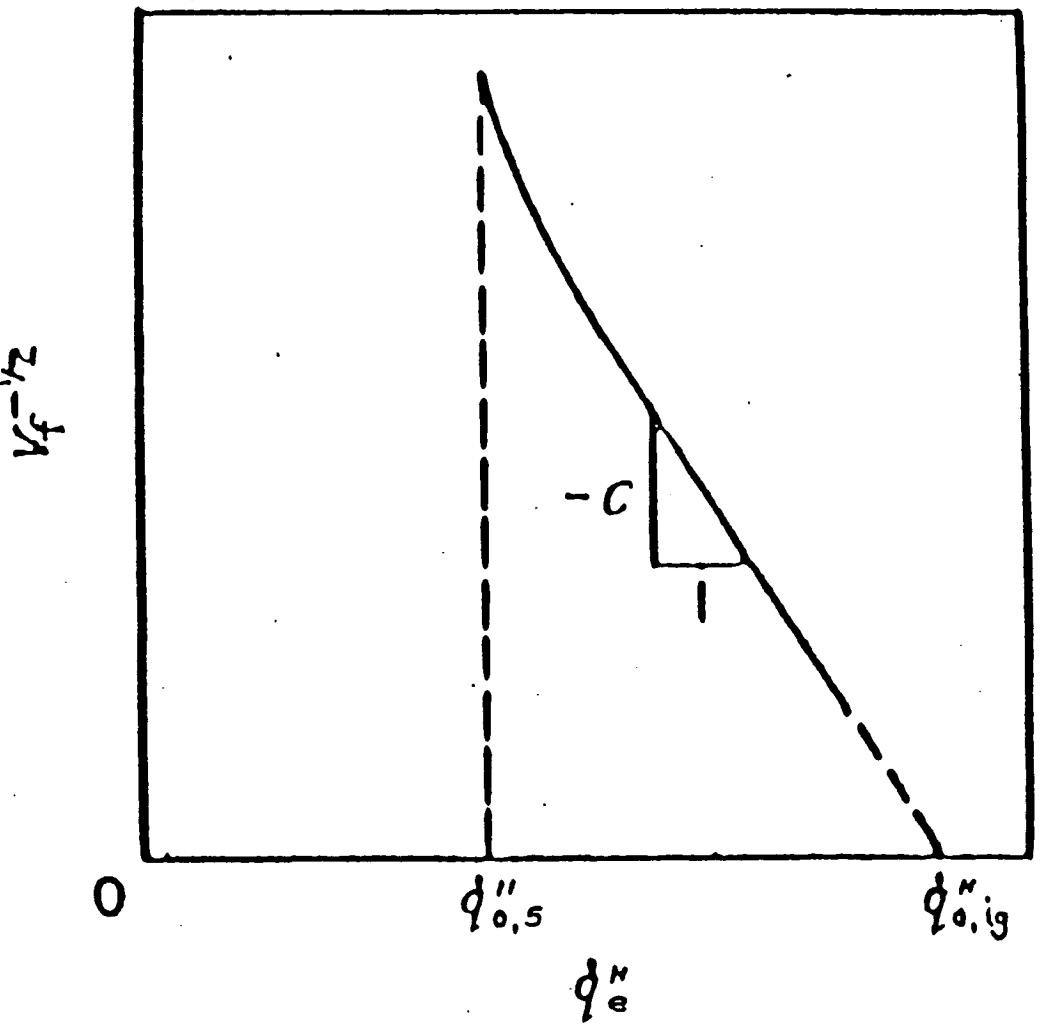


Fig. 3.13

Relationship between flame spread velocity and external flux in LIFT spread of flame test.

$$V_f = V_g \frac{(k\rho c)_g}{k\rho c} \left[\frac{T_f - T_{ig}}{T_{ig} - T_s} \right]^2 \quad (9)$$

where V_g is the opposed air flow velocity, T_f is the flame temperature and the subscript g denotes the properties of the gas phase.

Since there is a problem in determining the flame temperature for a a complex material experiencing opposed flow flame spread, the data can ultimately be correlated by the relationship:

$$V_f = \frac{\Phi}{k\rho c(T_{ig} - T_s)^2} \quad (10)$$

where Φ is a new material flame spread "property" which is termed the flame heating parameter. This value represents the available flame energy for spread.

Equation (10) then forms the basis for analysing the experimental data. With the assumptions of that conduction is only in y direction and the temperature rise due to external heating is given by:

$$T_s - T_\infty = \frac{\dot{q}''_e}{h} F(t)$$

Eqn (10) can be expressed as

$$V_f^{-1/2} = C[\dot{q}''_{ig} - \dot{q}''_e(x).F(t)] \quad (11)$$

where C is a constant related to Φ

Thus,

$$\Phi = \frac{4}{\pi} /(Cb)^2 \quad (12)$$

To obtain values of the individual parameters the velocity is determined by a three point running least square fit on the distance and time obtained from the

experiment. The function F(t) is applied to $\dot{q}''_e$ at the corresponding flame position and elapsed time from the initiation of heating. By plotting these results as $V_f^{-1/2}$ against $\dot{q}''_e$ F(t), both C, the slope and $\dot{q}''_{ig}$, the intercept can be found.

3.3.2 Experimental Procedure

A schematic of the arrangement of the flame spread apparatus is depicted in figure (3,14).

The apparatus was developed by Robertson [112] and comprises a gas-fired (air-natural gas) radiant panel and a framed sample holder assembly to hold a vertically oriented sample. The radiant panel is also vertical, but inclined at an angle of 15^o to the sample support frame so as to yield an incident heat flux distribution along the centreline of the sample. By varying the fuel-air flow rate to the radiant panel, the incident heat flux at 50mm could be varied from 15 to 70kW/m^2. The heat flux at increasing distances along the surface of the sample is measured and a normalised heat flux distribution calculated to be used as a calibration reference in subsequent flame spread measurements. A typical normalised irradiance over the sample is illustrated in figure (3.15).

The pilot flame configuration for the apparatus is displayed in figure (3.9).

A 75mm x 180mm steel flange was attached to the top of the sample holder at the hottest end to enable the boundary layer containing the volatile gases and the induced air flow to be maintained above the sample. The acetylene-air pilot flame was positioned about 25mm from the top of the sample and 5mm from the extension steel flange. This arrangement ensured a sustained pilot flame since it is located in the boundary layer.

3.3.2.1 Sample Preparation

All the samples for ignition and flame spread tests were conditioned to a constant mass at a temperature of 23 ± 2^oC and a relative humidity of $50\pm5\%$. The edges and the rear faces of the sample were wrapped with aluminium foil allowing a width of about 10mm of foil to overlap evenly the edges of the front face of the sample. This was to prevent the release of volatiles from these surfaces. The samples were backed up by a calcium silicate board and secured to the sample holder frame by means of a restraining steel bar tightened with screws at both ends of the holder.

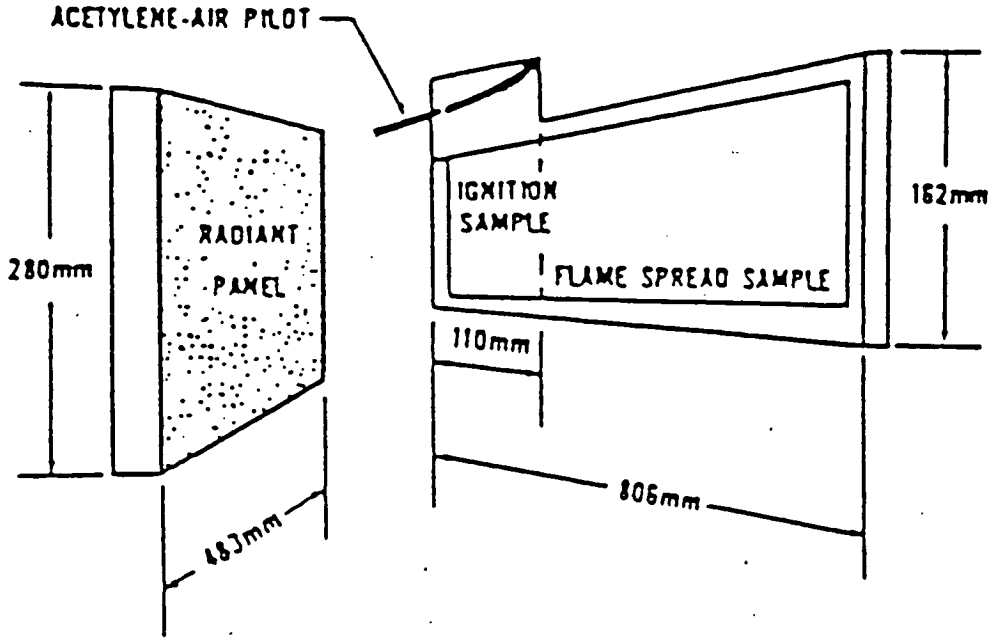


Fig. 3.14 Schematic of LIFT spread of flame test apparatus.

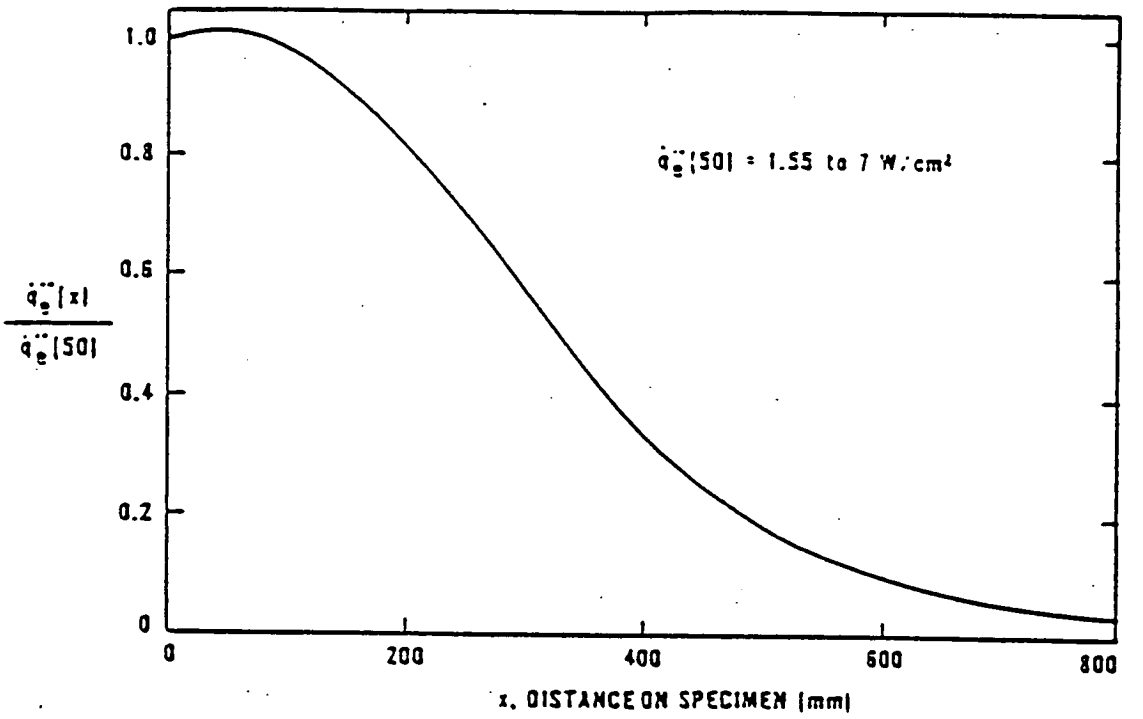


Fig.3.15

Normalised irradiance over the sample in LIFT spread of flame test.

3.3.2.2 Ignition Test

Ignition tests were carried out on 7 different wall lining materials as listed in table (4,2).

A sample size of 155mm x 155mm was used for each ignition test. The sample was mounted over the 0 to 155mm region as shown in figure (3.9). In each experiment the radiant panel was allowed to reach its equilibrium or stable condition before the sample assembly was placed in position using fixed guide rails. Initially the incident heat flux ($\dot{q}''_e$) was set and measured at the 50mm position. The pilot flame was lit. It should give a light blue conical flame extending length-wise along the contiguous steel flange at the top of the sample holder (figure 3.9).

Upon stabilising, the dummy board for flux measurement was removed and within seconds the sample assembly was manually mounted in place. Some time after the start of exposure, volatile gases evolved from the sample ignited at the pilot flame. Shortly thereafter, the flame attached to the surface indicating piloted ignition. In some cases, oscillatory flame or flashing was sometimes observed. Sustained ignition was noted and its time recorded when continuous combustion was visible at the centre of the sample. Ignition times were determined using a stop-watch. The experiments were repeated and data were recorded for a series of decreasing or increasing heat fluxes until a flux at which no ignition or ignition occurs respectively has been identified. The minimum flux for ignition ($\dot{q}''_{ig}$) was determined by bracketing the fluxes for ignition/no ignition.

From the value of the minimum heat flux for ignition, the surface ignition temperature (T_{ig}), effective thermal inertia ($k\rho c$) and heat transfer coefficient at ignition (h) can be determined.

3.3.2.3 Flame Spread Test

Flame spread tests were done on five of the wall lining materials. The test was not carried out on PVC faced plasterboard because no ignition was recorded up to a heat flux of 59kW/m^2. As for sample of A1 foil faced on PIR, ignition was only noted at the imposed heat flux of 60kW/m^2. Since there was a difficulty of setting up the radiant heat flux to go up higher than 60kW/m^2 due to insufficient gas pressure, it was not feasible to execute the flame spread test on these materials. The flame spread test was initiated by setting the external heat flux at the 50mm position slightly greater (about 5-10kW/m^2) than the minimum heat flux for ignition $\dot{q}''_{ig}$.

The sample size required was 155mm x 800mm. Each material was tested three times. To get a good timing of the flame spreading along the surface of the sample, vertical reference lines were marked at 25mm intervals along the length of the sample (figure 3.16).

Once the external heat flux (q''_e) was set and stabilised, the calibration board was removed and the sample assembly was inserted in place. Using a stop-watch, the timing was immediately activated and the sample was allowed to undergo a sufficiently long heating time (preheat) before igniting the pilot flame. This preheat time was obtained from the ignition test results. The pilot flame was in the same configuration as in the ignition test (figure 3.9). Exceptionally the Phenolic GRP sample was not ignited by this method and the sample was ignited by locating the pilot flame at the bottom surface of the sample.

Following sample ignition, the flame propagated in the direction of decreasing external flux. It was observed that the flame front was not vertical, but curved. The arrival times of the flame front progressing along the horizontal centreline of the sample at 25mm increments were noted and recorded. The results were analysed and computed to obtain the flame spread velocity and subsequently other parameters such as rate coefficient (C), the minimum heat flux for flame spread (q''_s), the surface temperature to sustain flame spread (T_s) and finally, the flame heating parameter (Φ).

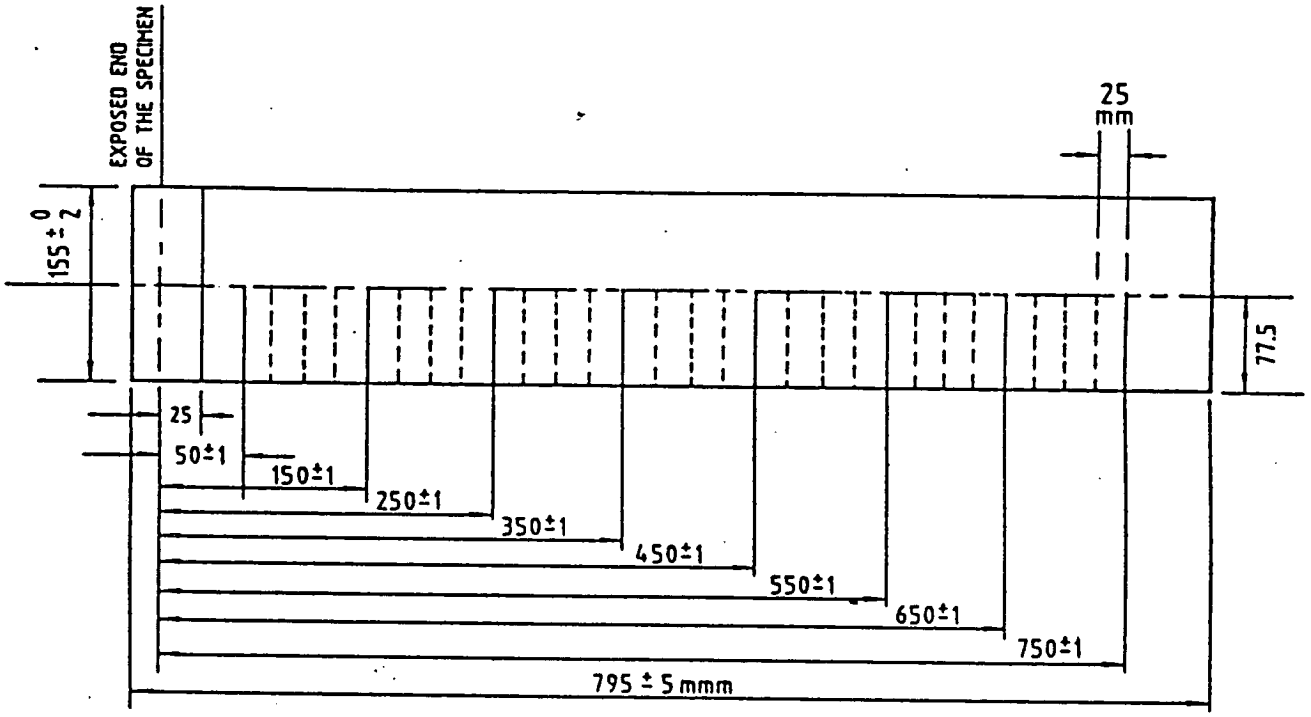


Fig. 3.16

Vertical lines at 25mm intervals on sample surface.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 ISO/DP 5658 - Surface Spread of Flame Test (IMO Version)

Surface spread of flame tests were carried out on the 7 materials. The results obtained are tabulated in table 4.1 which shows the values of the heat for sustained burning and the critical irradiance for flame spread for the individual samples. Three tests were performed for each material.

It is generally clear from the results that the higher the value of the heat necessary for sustained burning, the higher the value of critical irradiance for flame spread. This is noted for PVC faced plasterboard having 75.3MJ/m^3 of heat needed for sustained burning and 50kW/m^2 for the critical irradiance for flame spread. In this test, the pilot flame was lit prior to the insertion of the sample and the sample was exposed to the heat flux from the radiant panel (ranging from 50kW/m^2 at the hot end to 1.5kW/m^2 at the cooler end). It was observed that the PVC faced Plasterboard took 142 seconds to ignite and flame spread occurred with only one of the three samples tested, although this was not considered significant as it spread only over a distance of 35mm. As defined by Ohlemiller et al [121] an organised flame spread process is one in which heat transfer from the flames in the ignited region of the sample causes a smooth movement of the flame towards regions of the sample that are cooler by virtue of their receiving a lower incident heat flux from the radiant panel. There appeared to be ignition at the other two samples and the surface scorched and blackened but extinction occurred before there was any flame spread. This is typical of PVC as its thermal decomposition product, hydrogen chloride is a very effective combustion inhibitor and tends to extinguish a developing flame.

It is known that foamed polymers with low thermal inertia ($k\rho c$) can be ignited quickly as the surface temperature rises rapidly when exposed to a heat flux. But this is not necessarily so as indicated by the sample of Al foil faced PIR having a density of 41kg/m^3. Not only did it require about 15MJ/m^2 of heat to support burning but it also gave a critical irradiance of 49.5kW/m^2 for flame to spread. The sample surface experienced scorching and swelling ahead of the flame front due to the imposed heat flux. The aluminium foil split open, emitting volatiles and ignition did occur at about 9 seconds. The flame ceased to spread with the aluminium foil protecting the surface beyond 60mm. The aluminium foil which covers the

Table 4.1: Parameters deduced from the ISO Flame Spread Test

Material	Density* (kg/m^3)	Heat for Sustained Burning (MJ/m^2)	Critical Irradiance for Flame Spread (kW/m^2)
Fire Retardant Plywood, 4mm	510(a)	2.8	13.3
Birchfaced Plywood, 9mm	654(b)	2.2	4.3
PMMA, 3mm	1192(c)	2.6	-(e)
PVC faced Plasterboard, 9.5mm	935	75.3	49.9(f)
Al. foil faced PIR foam, 30mm	40	15.0	49.5
Phenolic GRP, 4mm	1109	14.0	38.2
EPS pm Calcium Silicate Board, 46mm	262(d)	7.8	18.6

(*) Average from 3 samples.
(a) Standard Deviation 6%
(b) Standard Deviation 2%.
(c) Standard Deviation 5%.
(d) 40mm expanded polystyrene foam cemented to 6mm calcium silicate board with a cement adhesive.
(e) No flame extinguishment, flame continued to spread until end of sample.
(f) Based on one sample. No flame spread on the other two samples.

Polyisocyanurate (PIR) foam, affects the surface emissivity and absorptivity and consequently makes it difficult for the rapid flame spread.

When the graph of spread rate (mm/s) against irradiance was plotted for Fire Retardant Plywood, Birchfaced Plywood and PMMA as depicted in figure (4.1-4.3) it was generally observed that there appeared a similar trend for most of the materials tested. The flame spread data for the respective samples are shown in Appendix A. The graphs clearly show that initially the flame spread velocity increases as the distance increasing up to 250mm (corresponding to 37kW/m^2) due to the surface temperature not being at equilibrium and gradually reducing to a slower pace as the heat flux decreases. Figure (4.4) shows an example of the plot of the flame front position against time for Birchfaced Plywood where the pattern of the flame spread can be clearly seen. The samples ignited before the surface achieved equilibrium, and therefore a slower rate of flame spread, but as the distance increased, the samples reached a quasi-steady state equilibrium (took 60 s) and the flame spread is rapid up to 250mm. At lower heat fluxes where the heat losses are greater, the rate of flame spread is decreased. The reduction in forward heat transfer and a decrease in formation of volatile gases appears responsible for the cessation of flame spread.

Figure 4.3 shows data obtained on 3 samples of PMMA. It was generally observed that the flame spread velocity was not consistent especially in the region of irradiance 50-25kW/m^2 although the samples are from the same batch. At the lower heat fluxes (<25kW/m^2), eventually the flame spread at a steady pace until the end of the sample. Upon insertion of the sample to the imposed heat flux, bubbling occurred and volatile gases are seen to emit from the surface. The sample ignited at about 5 seconds and flamed vigorously. The flame front of the propagating flame is not vertical. Initially in the heat flux ranging from 50-48kW/m^2 the sample behaved thermally thick particularly up to 100mm where the sample is still cool and held the sample in place. At the propagating flame front, the sample buckled and this changed the rear boundary condition that possibly accounted for the erratic flame spread pattern in the region of 50-25 kW/m^2. After passing the 350mm where by this time the sample had achieved equilibrium, the flame continued to spread until the end of the sample. From here it can be deduced that for PMMA, the flame can spread along its surface without the influence of external heat flux as confirmed by a test done in the laboratory which will discussed in a later section.

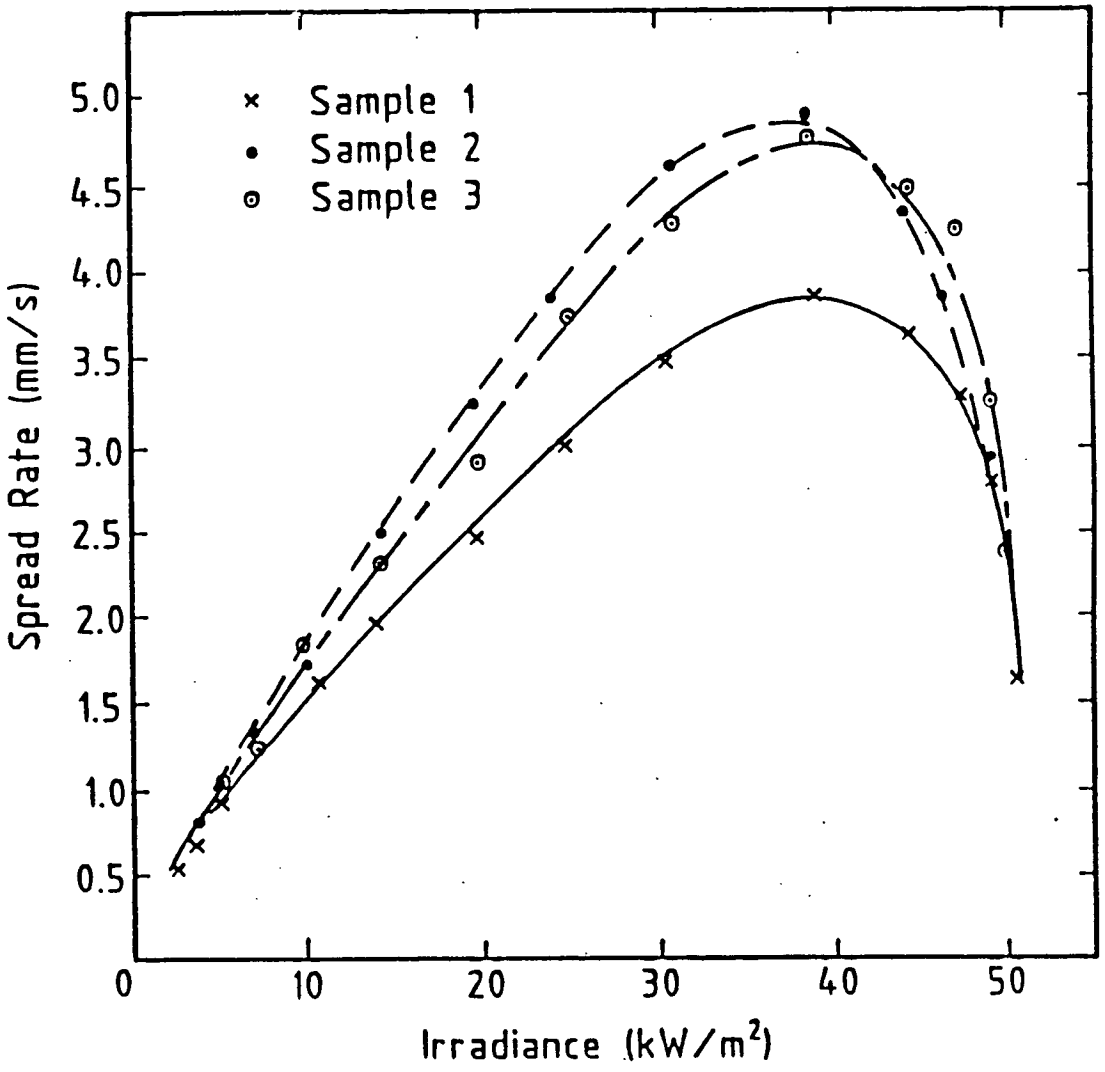


Fig. 4.1

The graph of spread rate versus irradiance for Birchfaced Plywood (ISO spread of flame test).

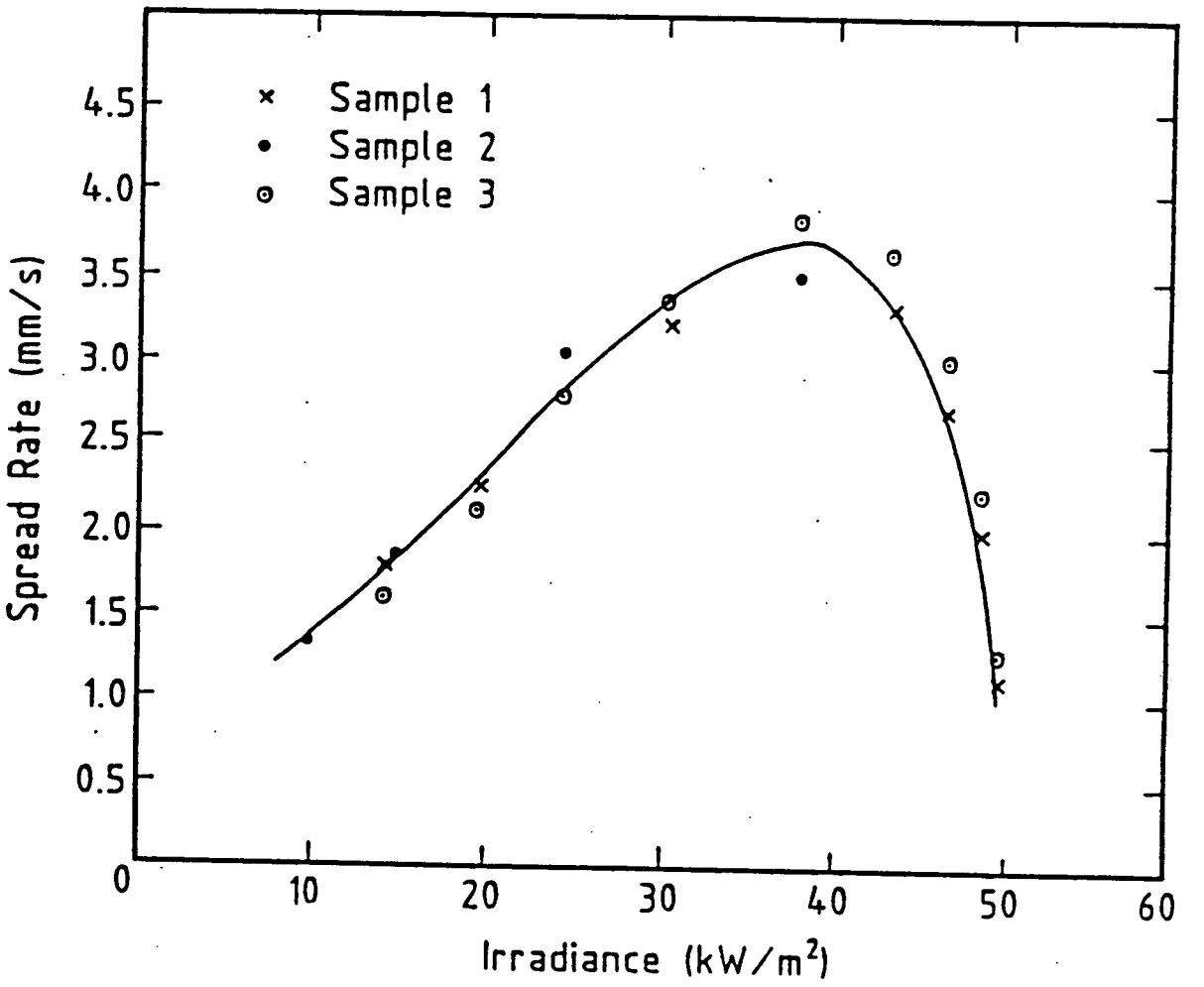


Fig. 4.2

The graph of spread rate versus irradiance for Fire Retardant Plywood (ISO spread of flame test).

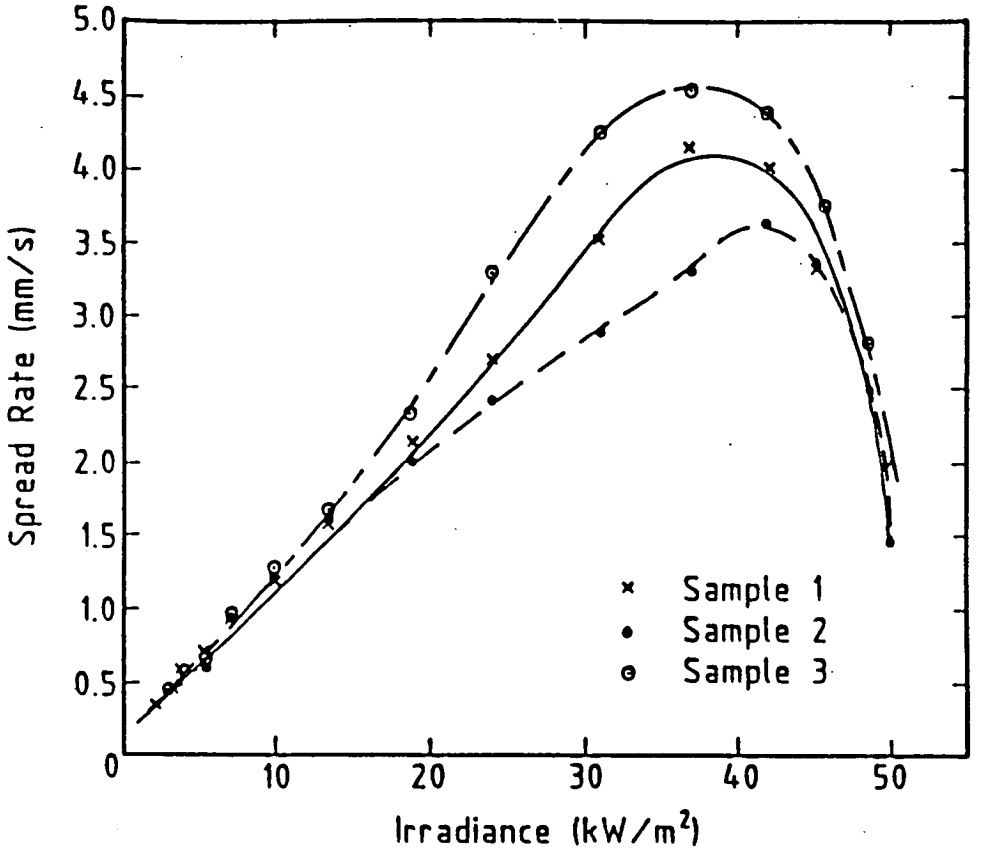


Fig. 4.3

The graph of spread rate versus irradiance for PMMA (ISO spread of flame test).

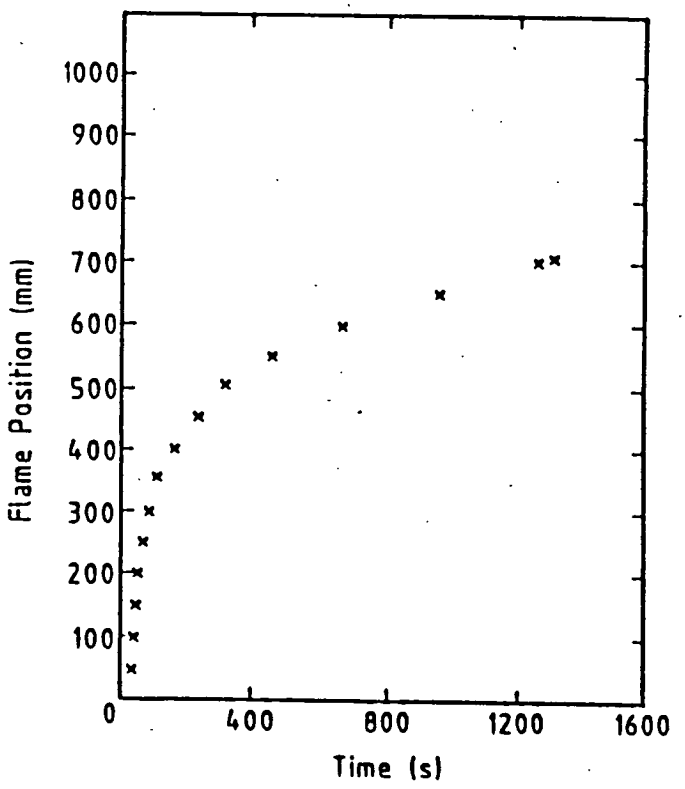


Fig. 4.4

The graph of flame position versus time for Birchfaced Plywood (ISO spread of flame test).

From table 4.1, the Birchfaced Plywood gave the lowest value of the heat for sustained burning (2.2 MJ/m^2) and required a minimum flux of 4.3 kW/m^2 for flame to spread along its surface. When compared to the Fire Retardant plywood, it was noted that its value of heat to sustain burning and the critical irradiance for flame spread was much higher than the Birchfaced Plywood. Both of these samples behaved alike and underwent vigorous flaming after ignition and charring. Three tests were performed for each material and agreement between the sets of data is reasonable, considering the variation in density which was observed. This can be envisaged from figures 4.1 and 4.2. The average time to ignition was 9s and 15s for the Fire Retardant Plywood and Birchfaced Plywood respectively. Although the ignition time for the Fire Retardant plywood is shorter compared to the Birchfaced Plywood the rate of flame spread along the individual 50mm spaced distance is slower and flame ceased to spread before reaching the 500 mm marked distance. Besides the charring of the surface which protects the underlying wood and reduces the flow of volatile gases, the limited thickness of 4mm of the Fire Retardant plywood (4mm) led to heat losses to the substrate. Thus the flame did not spread beyond 500mm. This can be confirmed by the calculation of the depth of the heated layer, approximated by $(\alpha t)^{1/2}$ where α is the thermal diffusivity ($k/\rho c$) and t is the duration of heating [6]. In the above calculation the value of the thermal conductivity (k), density (ρ) and specific heat (c) is taken from ref [108] and t is the value of the flame time (refers to the time of the arrival of the flame front at the marked position on the sample surface). The values of the depth of the heated layer at the individual marked position for the Fire Retardant Plywood and Birchfaced Plywood are presented in (table I, IV in Appendix A). It can be seen that at the 400mm position the depth of the heated layer is nearly 4mm which is equivalent to the sample thickness indicating that heat is being lost to the substrate. A similar argument can be applied to PMMA (Table VII) but the flame spread until the end of the sample.

Figure (4.5) shows the plot of the heat for sustained burning versus distance on specimen for Fire Retardant Plywood, Birchfaced Plywood and PMMA. Generally, it can be observed that the "heat for sustained burning" increases with distance, but showed an inflection in the region of 200-300mm for these 3 samples. Initially at high heat flux where heat losses are relatively less important, the heat for sustained burning depends on the time taken for the flame to reach the individual marked

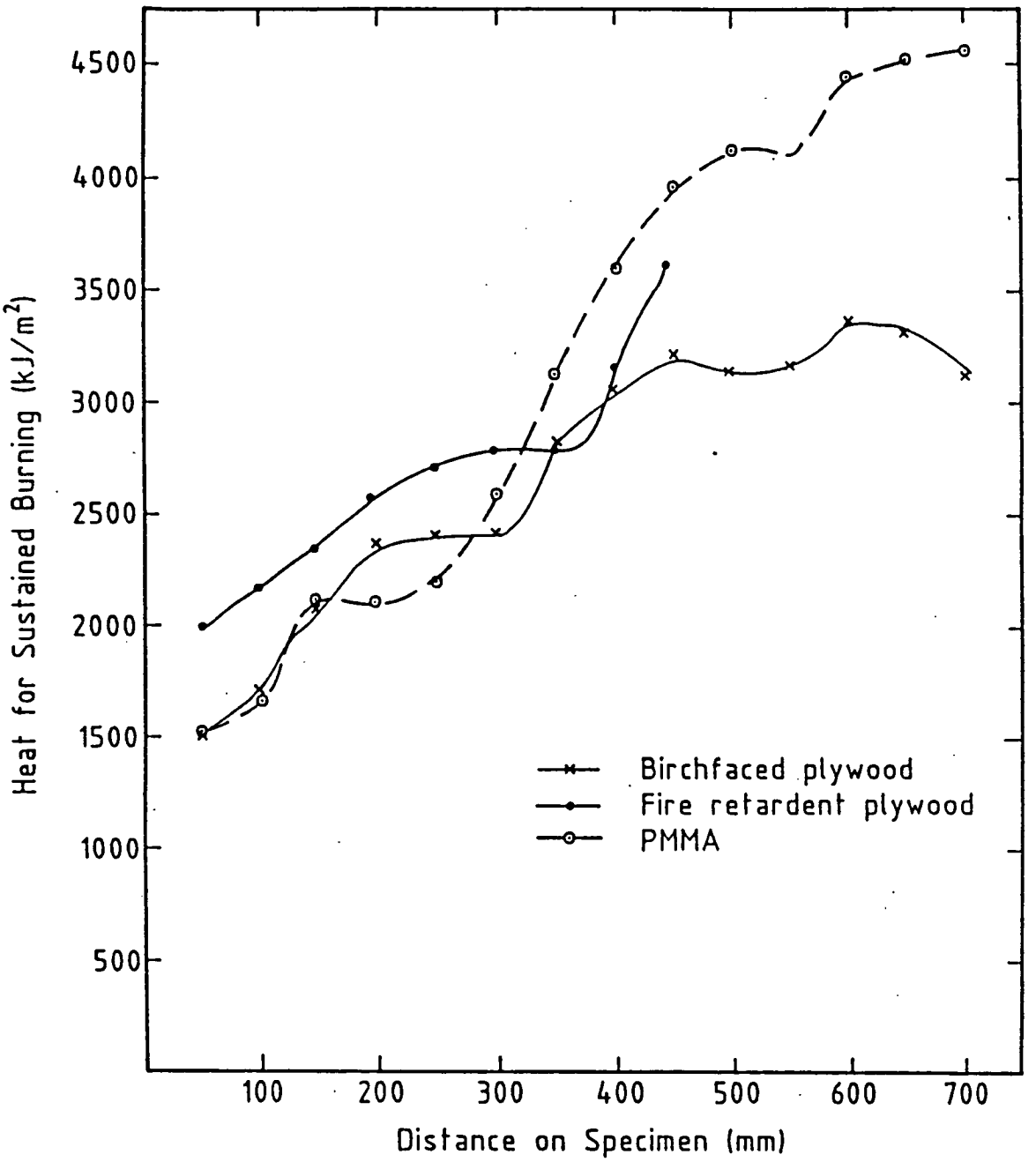


Fig. 4.5

The graph of "heat for sustained burning" versus distance on specimen for Birchfaced Plywood, Fire Retardant Plywood and PMMA (ISO spread of flame test).

position including the time for the sample to ignite. Once the sample has achieved a steady-state equilibrium (approximately 60s) the heat for sustained burning appears to level off, but gradually increases again as the flame spread further decreases. The heat losses are relatively more important at lower heat fluxes and influence the time taken for the flame to spread at the positions. The heat for sustained burning tabulated in table (4.1) as defined in the draft proposal [76] is the "average of the values of heat for sustained burning from 150mm position and then at each subsequent position up to and including the last position before the point of furthest flame propagation or the 400mm position whichever is the less". These values are taken where the samples are considered in its equilibrium state. This method of determining the average heat for sustained burning is not applicable to material that resists flame spread as has been shown by samples of Phenolic GRP, PVC faced Plasterboard and Al. foil faced PIR foam where the heat for sustained burning is taken as the product of the flame time and the irradiance at the corresponding distance. Here the flame ceased to spread before reaching the 150mm position.

Generally the test method which employs the heat for sustained burning as a means to evaluate the performance of the material in respect of its flame spread behaviour is dubious as the results are highly dependent on experimental factors. The standardisation of irradiance along the calibration board is of prime importance as the values of the irradiance at the corresponding positions are based on this and used in the derivation of the results. The transient heating effects due to the imposed heat flux on the sample and the thermal properties of the material are not considered in the test method.

4.2 Surface Spread of Flame Test by LIFT Method

The experimental results for both ignition and flame spread data are computed by the program LIFTDATA, based on Quintiere's analysis provided by the Warrington Fire Research Centre.

4.2.1 Ignitability

Ignition tests were performed on the 7 materials and their individual results are tabulated in Tables (4.2a-4.2g). From Table 4.2g, it can be seen that no ignition was recorded for the PVC faced Plasterboard even at 58.5kW/m^2. As for the Al foil faced PIR foam sample (Table 4.2e), ignition of the sample surface was only observed at the highest incident heat flux of 60kW/m^2. The maximum delay time

Table 4.2: IGNITION DATA

a)

Fire Retardant Plywood	
Experimental irradiance (kW/m^2)	Time of Ignition (t_{ig}) [s]
19.0	No ignition
22.6	412
24.7	213
30.2	135
40.2	70
49.2	63
58.5	44

b)

Birchfaced Plywood	
Experimental irradiance (kW/m^2)	Time of Ignition (t_{ig}) [s]
15.9	No ignition
19.7	940
25.0	241
30.0	127
40.0	73
50.2	60
59.1	38

c)

Phenolic GRP	
Experimental irradiance (kW/m^2)	Time of ignition (t_{ig}) [s]
29.9	No ignition
34.5	No ignition
38.6	965
40.2	415
50.2	280
59.2	289

d)

EPS on Calcium Silicate Board	
Experimental irradiance (kW/m^2)	Time of ignition (t_{ig}) [s]
24.4	No ignition
27.2	No ignition
29.8	335
39.6	234
49.9	135
59.1	106

IGNITION DATA

e)

Al foil faced on PIR foam	
Experimental irradiance (kW/m^2)	Time of ignition (t_{ig}) [s]
30.0	No ignitiion
35.0	No ignition
39.8	No ignition
45.1	No ignition
50.1	No ignition
54.8	No ignition
59.9	248

f)

PMMA	
Experimental irradiance (kW/m^2)	Time of ignition t_{ig} [s]
5.8	No ignition
8.7	No ignition
10.3	520
15.1	409
19.9	201
24.7	120
29.6	75
39.3	60
50.6	43

g)

PVC faced plasterboard	
Experimen-tal irradiance (kW/m^2)	Time of ignition (t_{ig}) [s]
29.9	No ignition
39.1	No ignition
45.1	No ignition
52.9	No ignition
58.5	No ignition

for ignition has been arbitrarily set at 20 minutes. This is in contrast to the results obtained for these samples when tested by the ISO method where ignition occurred at incident heat flux of about 50kW/m^2 at the hot end. The reason behind this may be due to the pilot flame location, and possibly the size of the sample. The positioning of the pilot flame for the ISO method in which its flame length of 230mm relative to, and extending across, the face of the test sample (figure 3.6) transfer heat and contribute a significant heat flux to the sample. As for the LIFT method, the pilot flame is located on top of the sample (figure 3.9), the entrained air tends to dilute the boundary layer containing the pyrolysed gases and this reduces its flammable concentration before reaching the pilot flame. In addition, the sample size of 800mm x 155mm for the ISO method accounted for greater surface area where large volumes of pyrolysed gases are seen to emit whereas the sample size of 155mm square for the ignition test in the LIFT method may have insufficient pyrolysed gases to reach a flammable concentration.

The plot of the reciprocal of the ignition time ($1/t_{ig}$) versus the external heat flux ($\dot{q}''_e$) give a linear relationship where it is assumed that there are no heat losses, especially at high fluxes. The interception with the $\dot{q}''_e$ axis estimates the critical radiant heat flux for pilot ignition. Similarly, from the graph of ignition time versus the external flux will also produce the critical flux. The latter value is indicated by the vertical line which is the asymptote value of the flux for the time tending to infinity. An example of this illustration is displayed in figures 4.6 and 4.7 for Birchfaced Plywood giving the value of 17.9kW/m^2 for its critical radiant heat flux for ignition.

Table 4.3 comprises the values of the critical heat flux for ignition (q''_{ig}) for the other materials tested. When compared with the results tabulated in tables (4.2a-4.2g), it was generally demonstrated that the values of $\dot{q}''_{ig}$ computed through LIFTDATA for these materials are much lower than the results obtained by experimental deduction except for PMMA and Birchfaced Plywood. An example to illustrate this is to compare the values of $\dot{q}''_{ig}$ for Fire Retardant Plywood. From Table 4.2a at an external incident heat flux of 19kW/m^2 there was no ignition observed. Subsequently, ignition did happen when the heat flux is increased to 22.6kW/m^2. Thus, $\dot{q}''_{ig}$ will lie between 19kW/m^2 and 22.6kW/m^2. The application of the least square method in LIFTDATA to fit a straight line through the data, the critical heat flux for this sample was deduced at 16.5kW/m^2. Similar

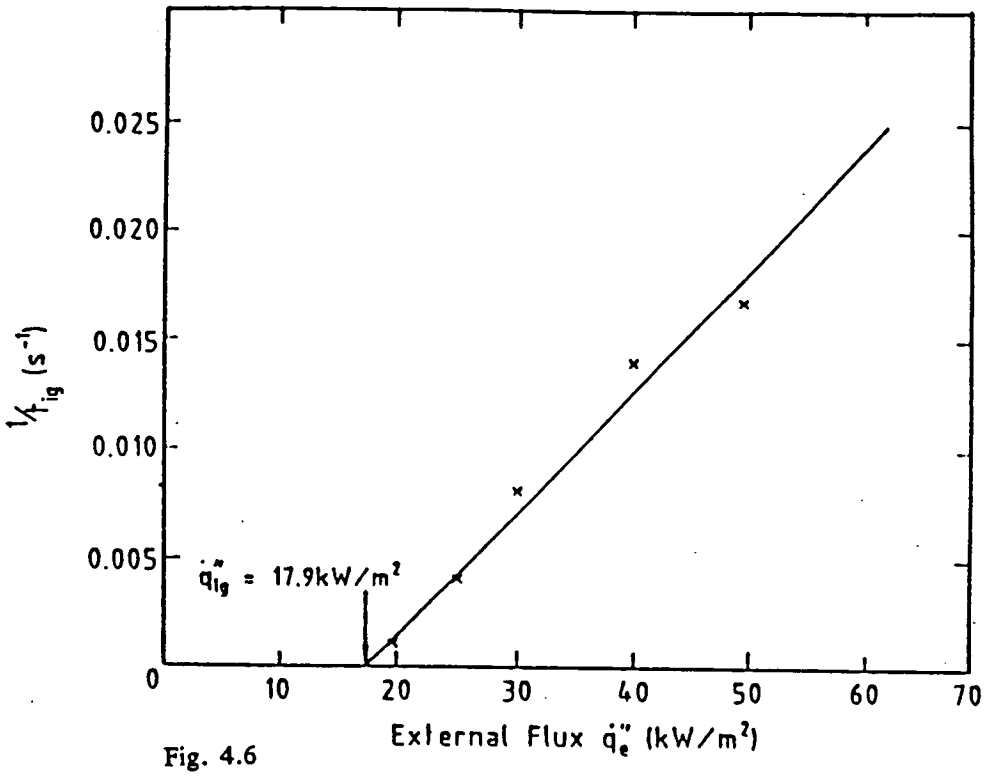


Fig. 4.6

The graph of the reciprocal of the ignition time ($1/t_{ig}$) versus the external flux ($\dot{q}''_e$) by LIFTDATA for Birchfaced Plywood.

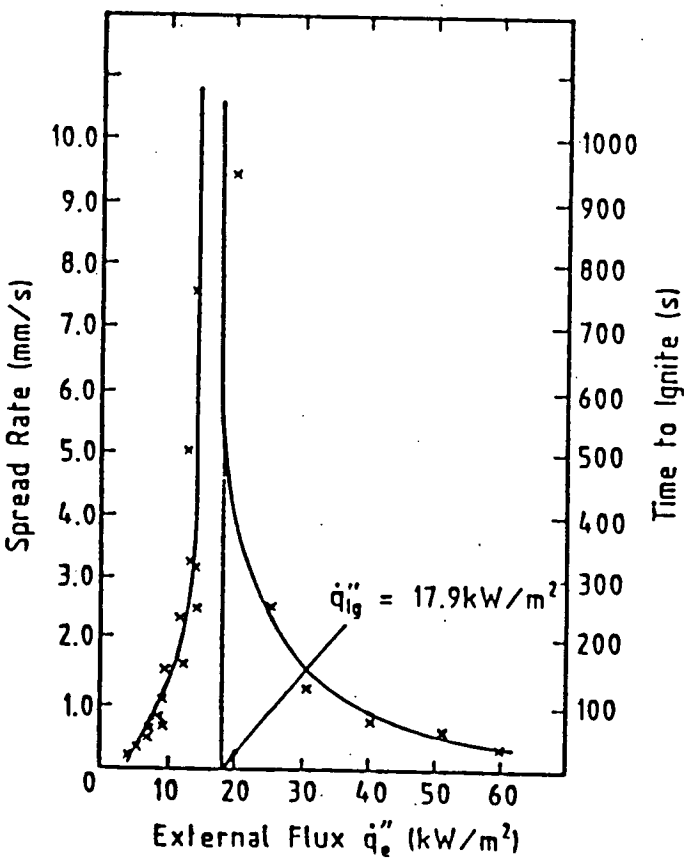


Fig. 4.7

This is a graph showing the spread and ignition results for Birchfaced Plywood.

Table 4.3: Parameters inferred from the LIFT Ignition Data

Material	$\dot{q}''_{ig}$ (kW/m^2)	T_{ig} (^oC)	h (W/m^2/K)	b ($s^{-1/2}$)	t* (s)	$k\rho c$ $\left[\frac{kW}{m^2K}\right]^2 s$
Fire retarded plywood	16.5	395	44.03	0.042	580	1.43
Birchfaced plywood	17.9	411	45.74	0.037	746	1.98
PMMA	9.0	284	34.09	0.034	888	1.31
Phenolic GRP	21.5	449	50.01	0.021	2204	7.02
EPS on Calcium Silicate Board	18.3	416	46.23	0.032	989	2.69

Table 4.4: Comparison of the critical heat flux for ignition ($\dot{q}''_{ig}$) obtained by LIFTDATA and experimental deduction.

Material	$\dot{q}''_{ig}$ (LIFTDATA) (kW/m^2)	$\dot{q}''_{ig}$ (experimental extrapolation) (kW/m^2)
Fire retardant Plywood	16.5	20.0
Birchfaced Plywood	17.9	18.5
PMMA	9.0	10.0
Phenolic GRP	21.5	38.0
EPS on Calcium Silicate Board	18.3	29.0

variations in the values of $\dot{q}''_{ig}$ also apply to Phenolic GRP and EPS on Calcium Silicate Board (refer to tables 4.2c, 4.2d, tables 4.3 and 4.4).

From table 4.2c it is clear that the time to ignition for Phenolic GRP is erratic when the sample is exposed to a heat flux of more than 50kW/m^2. There is no decrease in ignition as anticipated. From observations of the ignition process, it was noted that the sample underwent an explosive (popping sound) delamination during heating the pigmentation of phenolic resins in the composition may have caused the early ignition time recorded upon exposure to high heat flux (50.2kW/m^2). When the incident heat flux of 38.5kW/m^2 was imposed on the sample, it took a considerably longer time (965 s) to ignite. At this stage it was observed that the brown pigmentation at the surface had disappeared exposing the white mat of GRP. The presence of pigmentation of phenolic resins in the sample composition possibly led to the peculiar result. This suggests that the time of ignition is influenced by the presence of the pigmentation.

For EPS on Calcium Silicate Board, the minimum heat flux for ignition by LIFTDATA was 10kW/m^2 less than the value obtained by experimental extrapolation as explained earlier. The sample underwent drastic physical changes. It shrank and melted during heating and flaming droplets were observed. This could be expected for a thermoplastic material tested in vertical orientation. The test had to be repeated an incident heat flux of 27.2kW/m^2 because the sample fell out of the sample holder when the expanded polystyrene melted. This behaviour resulted in the scattered data at the heat flux of 29.8kW/m^2 and 59.1kW/m^2 which can be seen from figure (4.8). When compared the results to that obtained by Quintiere et al [108], table [3.3], they also have difficulty in getting flame spread data but managed to determine the value of critical heat flux as 46kW/m^2 which is so much higher.

The ignition model behind the LIFT method developed by Quintiere [104] has established a correlation for the results by an expression:

$$\frac{\dot{q}''_{ig}}{\dot{q}''_{e}} = F(t) = \begin{bmatrix} b\sqrt{t}, & t \leq t^* \\ 1, & t \geq t^* \end{bmatrix} \qquad (5)$$

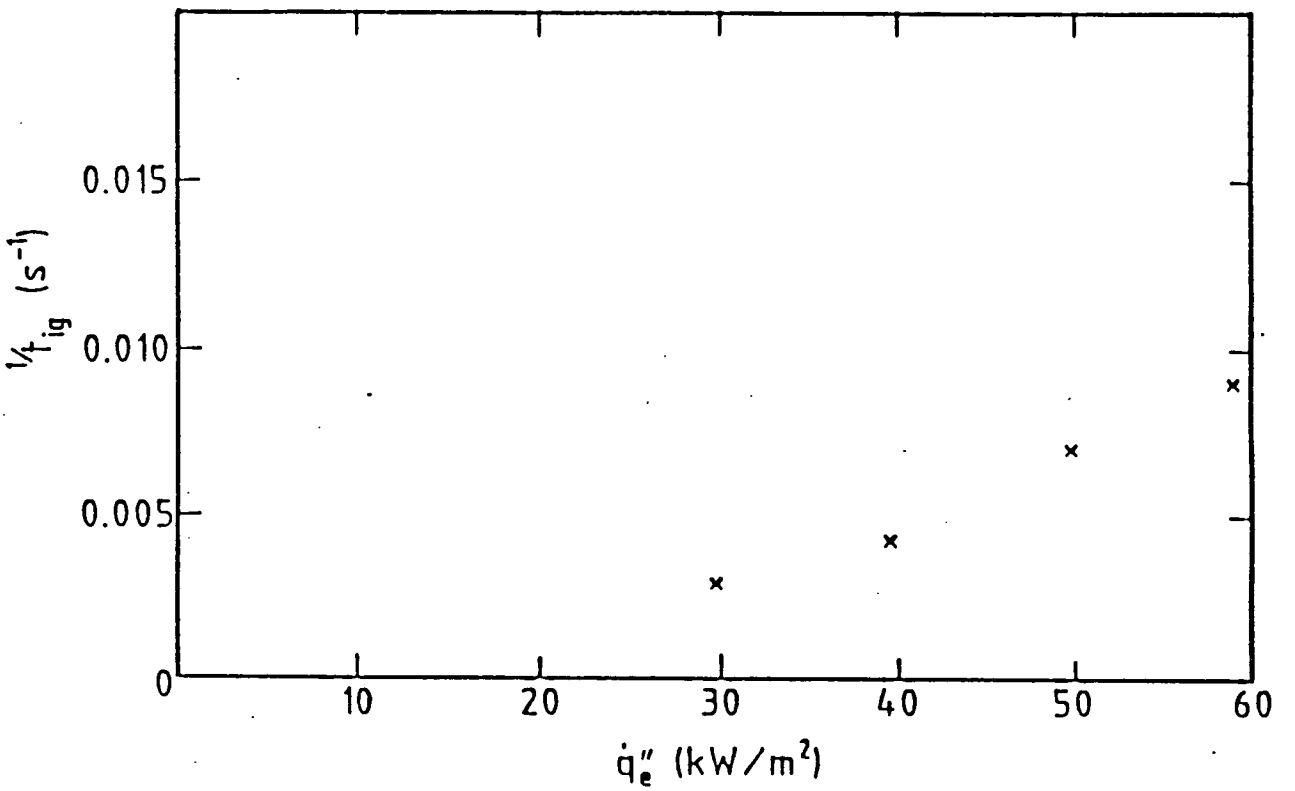


Fig. 4.8

The graph of the reciprocal of the ignition time ($1/t_{ig}$) versus the external flux for EPS on Calcium Silicate Board.

where F(t) is a function of time and thermal properties of the solid. By plotting the flux ratio ($\dot{q}"_{ig}/\dot{q}"_e$) versus the square root of the ignition time which pass through the origin will give a straight line. The intercept of this line with the unity value of the flux ratio gives the value of pre-heat time (t*). This is the time needed for the sample to come to thermal equilibrium with the imposed heat flux. The initiation of the lateral flame spread tests (which will be discussed later) depend on this quantity. From this graph parameter b can be determined from the slope of the straight line and is related in the calculation of the effective thermal inertia for the materials tested (refer to equation 6). An example of this correlation is shown in figure (4.9) for the results of PMMA displaying the slope and pre-heat time.

From the experimental data, a summary of the significant parameters - the minimum flux for piloted ignition $\dot{q}"_{ig}$, effective surface temperature at ignition T_{ig} (inferred from the ignition model) and values of $k\rho c$ the materials tested have been tabulated in table 4.3.

The effective surface temperature at the point of ignition T_{ig} for the 5 materials tested (not included PVC faced Plasterboard and Al foil faced PIR foam) which are presented in table 4.3 are found from the theoretical curve shown in figure (3.11) after the critical heat flux for ignition is known. Note that the ignition temperature is not a direct measurement, and is largely dependent on the inter-related experimental factors. The critical heat flux is used to determine T_{ig}. Thus, if different values of $\dot{q}"_{ig}$ are obtained for the same material, different ignition temperatures will result. As an example, consider the Fire Retardant Plywood sample. For a critical heat flux of 16.5kW/m^2 obtained by LIFTDATA, the value of T_{ig} is 395^{o}C whereas the ignition temperature will be 440^{o}C when the critical heat flux for ignition obtained by experimental extrapolation is 20kW/m^2. It was also observed that the ignition temperature T_{ig} was higher than the value obtained by others as shown in table 4.4. Experiments were carried out to determine the ignition temperature T_{ig} by direct measurement for Fire Retardant Plywood, Birchfaced Plywood and Phenolic GRP. Here the "Firepoint Apparatus" (figure 4.10) of Thompson [55] was used to measure the ignition temperatures of the materials. The method of fixing the thermocouple on to the face of the sample was similar to that developed by Atreya [119]. This proved to be adequate because quite consistent results are obtained for the materials ad displayed in table (4.5).

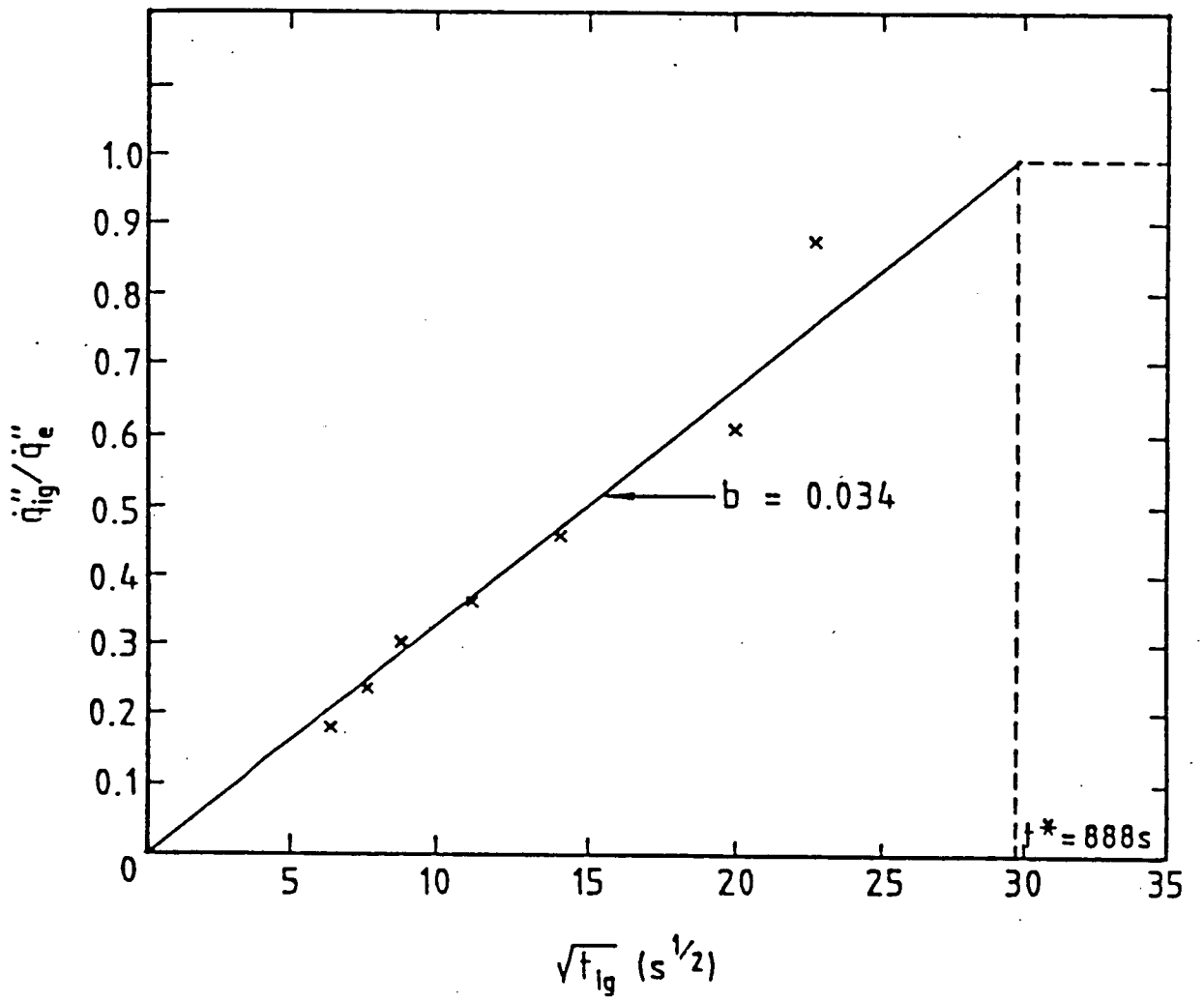


Fig. 4.9

The relationship between $\dot{q}''_{ig}/\dot{q}''_e$ and $\sqrt{t}$ obtained from the LIFT ignition test for PMMA showing the slope b and the pre-heat time t*.

Table 4.4: Ignition Temperature obtained by Linear Measurement

Material	Ignition Temperature T_{ig} (°C)
PMMA	270[a]
Fire retardant plywood	310[b]
Birchfaced Plywood	320[c]
Phenolic GRP	561[d]
Polystyrene	361[e]

a) Deepak and Drysdale (1983)

b,c) Own experimental data. Measurement taken at heat flux of 30kW/m^2.

d) Own experimental data. Measurement taken at heat flux of 47.5kW/m^2.

e) Thomson H.E. and Drysdale D.D. (1987).

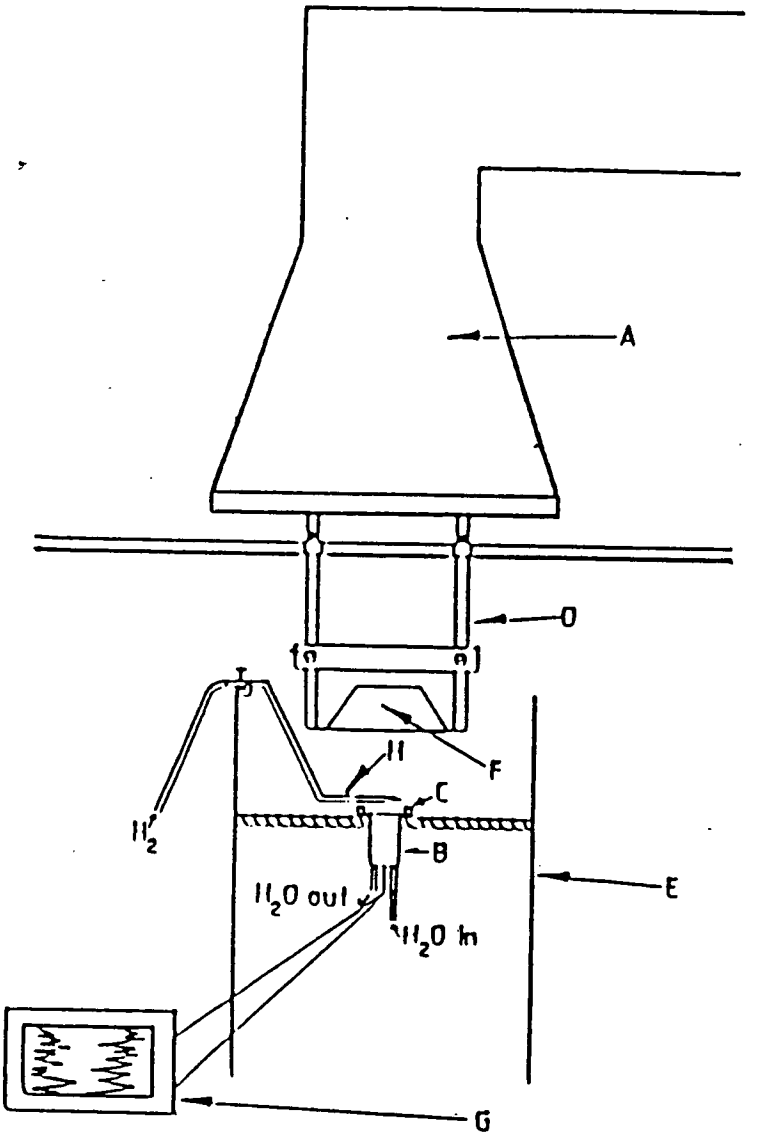


Fig. 4.10

Schematic diagram of the Firepoint Apparatus (scale 1:10). A, extract hood; B, water-cooled heat flux meter; C, guide rails; D, adjustable support; E, draught shield; F, conical heater; G, pen-chart recorder; H, hydrogen pilot flame. (55)

Table 4.5: Results of Ignition Temperature obtained from own experiments carried out at the laboratory.

a) Heat Flux of 30kW/m^2

Material		Ignition Temperature (°C)	Ignition Time (s)
Fire retardant Plywood	Sample 1	340.3	94
	Sample 2	300.5	94
	Sample 3	300.2	98
	Sample 4	300.2	74
	Average	310.3	90
Birchfaced Plywood	Sample 1	300.5	98
	Sample 2	310.0	62
	Sample 3	330.1	64
	Sampe 4	340.8	104
	Average	320.4	82

b) Heat Flux of 47.5kW/m^2

Material		Ignition Temperature (°C)	Ignition Time (s)
Phenolic GRP	Sample 1	610.5	194
	Sample 2	500.8	192
	Sample 3	570.9	184
	Average	560.7	190

The values of the ignition time obtained for the "Firepoint Apparatus" and LIFT spread of flame apparatus are different since the configuration and orientation of the sample are different. When compared the time of ignition (t_{ig}) at respective heat fluxes to the results in tables (4.2a-4.2c), it clearly indicates that the ignition times are shorter when the sample is at horizontal orientation than in the vertical orientation. The measured ignition temperatures was lower in horizontal than in the vertical orientation. This may be due to the different radiant energy sources used in the two apparatuses; the radiant panel in the flame test used a gas-air mixture to boost its radiant intensity and this causes much greater air disturbance than the electric cone heater used in the "Firepoint Apparatus". The high convective flow rate of air passing across the vertical sample will dilute the volume of pyrolysates and thus delay the ignition. On the other hand, the convective cooling of the horizontal sample is less than the vertical sample, this accounted for the same surface temperature at ignition to be reached earlier for horizontal samples. This sample orientation effect has also been noted by Atreya et al for mahogany specimens [122], Kashiwagi [123] in his studies of orientation effects (although only in auto-ignition mode), and Babrauskas et al [39] in his ignitability measurements with the Cone Calorimeter.

Table 4.3 presents the computed values of thermal inertia ($k\rho c$) for the materials tested. According to Quintiere, an effective ($k\rho c$) can be computed from the expression:

$$k\rho c = \frac{4}{\pi}\left(\frac{h}{b}\right)^2 \qquad (6)$$

Although it is possible to calculate the thermal inertia of a material from tabulated values of thermal conductivity, density and heat capacity, it is difficult to measure under fire conditions. Thus the relationship derived above will give the effective thermal inertia of a material when undergoing the LIFT ignition test.

When the experimental results with the thermal inertia values are compared with literature values (table 4.6), it is found that the experimental thermal inertia is very much higher. From the above expression, it is obvious that $k\rho c$ is entirely dependent upon the value of heat transfer coefficient (h) and b. As stated earlier, the value of b is the slope of the linear region of the graph of $\dot{q}''_{ig}/\dot{q}''_{e}$ vs $\sqrt{t}$ for a

Table 4.6: Values of thermal inertia ($k\rho c$[kW/m^{2}K]^{2}s) obtained by compilation [108] and own experiments for some materials.

Material	Experimental $k\rho c$ (kW/m^{2}k)^{2}s	Compilation $k\rho c$ (kW/m^{2}k)^{2}s
Fire retardant plywood	1.43	0.16
Birchfaced plywood	1.99	0.16
PMMA	1.31	0.66
EPS on Calcium Silicate Board	2.69	0.0010

given material. To obtain this correlation it is clear that the critical heat flux for ignition $\dot{q}''_{ig}$ did influence the value of b. As an example refer to figure (4.11) where the plot of $\dot{q}''_{ig}/\dot{q}''_{e}$ vs $\sqrt{t}$ was done for Fire Retardant Plywood based on the critical heat flux for ignition (q''_{ig}) of 16.5kW/m^2 (LIFTDATA) and 20kW/m^2 (experimental extrapolation). The heat flux ratio decreased about 17% and subsequently affected the value of b. The graph also shows that as the value of external heat flux q''_e approaches that of q''_{ig} then the behaviour deviates from linearity. This indicates that assumption, for a semi-infinite solid that the relationship between $\dot{q}''_{ig}/\dot{q}''_{e}$ and $\sqrt{t}$ is linear over its entire range to flux ratio equal to one is dubious. Consequently, this can result in an increased value of $k\rho c$ where the value of b would generally be decreased if b was determined according to Quintiere's analysis. This was easily demonstrated as in the case of Fire Retardant Plywood and EPS on Calcium Silicate Board. Table (4.7) presents the compared values of thermal inertia obtained by LIFTDATA and experimental extrapolation. The parameters $\dot{q}''_{ig}$, T_{ig}, b and h are also shown which are related to the determination of thermal inertia. It can be seen that the thermal inertia for Fire Retardant Plywood and EPS on Calcium Silicate Board obtained from experimental extrapolation was 27% and 34% respectively, less than the computed value (refer figures 4.11 and 4.12).

The evaluation of the heat transfer coefficient in the course of determining $k\rho c$ is fairly important and also greatly dependent on $\dot{q}''_{ig}$. This is particularly so as the ignition temperature was determined based on this value as well. As discussed earlier T_{ig} inferred from Quintiere's analysis was in excess of that obtained by direct measurement, thus the value of h can be affected as it was calculated using the inferred T_{ig}. The ignition process of the materials tested giving the values of $\dot{q}''_{ig}$, react differently under different heating regimes and this depends on the variation in the heat losses, change in heat transfer behaviour and also the build up of char layer on the sample surface.

Therefore the most important factor needed pertaining to the calculation of thermal inertia of a material lies in the determination of the critical heat flux for ignition ($\dot{q}''_{ig}$) which links the value of b, T_{ig} and h.

4.2.2 Lateral Flame Spread

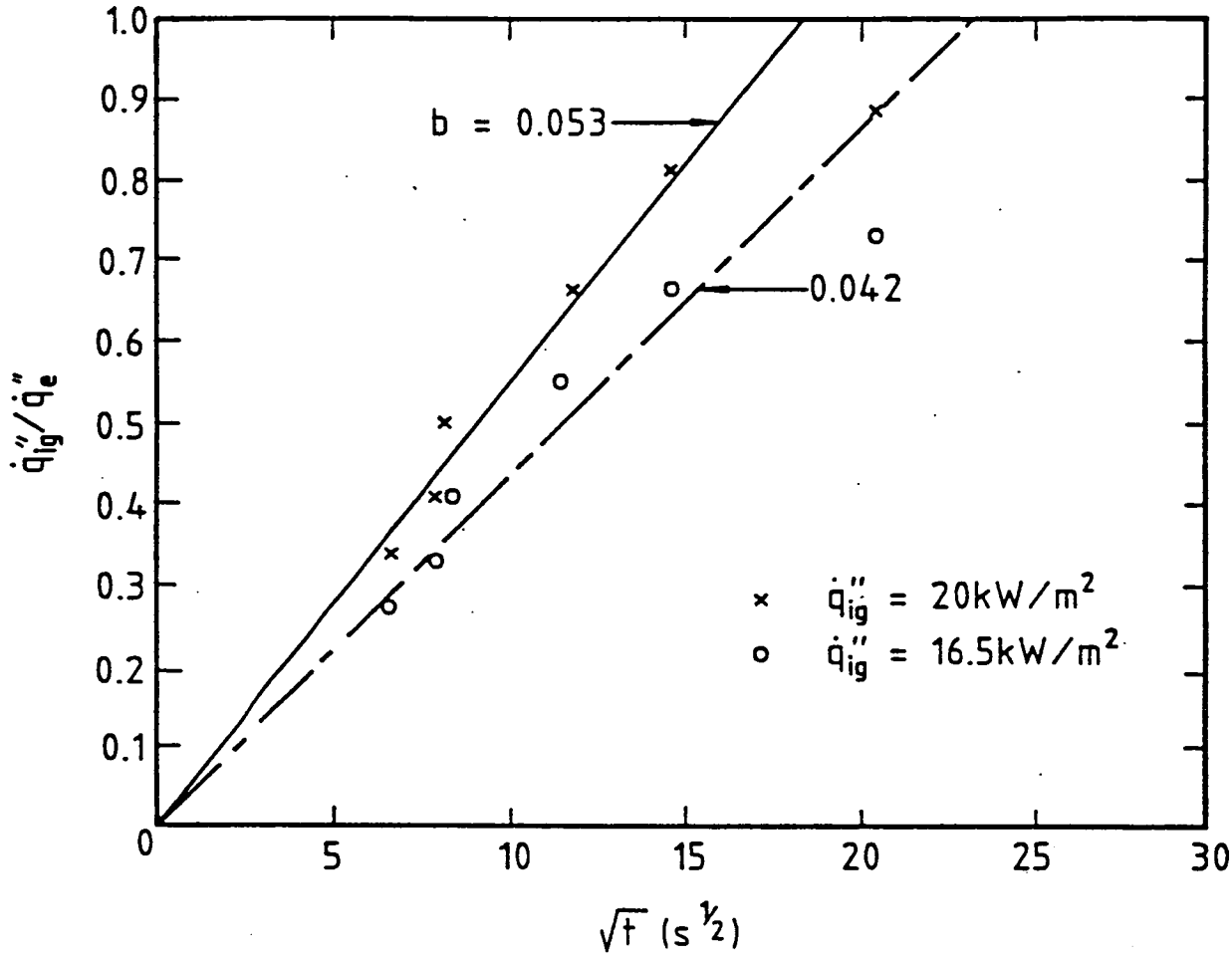


Fig. 4.11

The relationship between $\dot{q}''_{ig}/\dot{q}''_{e}$ and $\sqrt{t}$ obtained from the LIFT ignition test for Fire Retardant Plywood at $\dot{q}''_{ig}$ = 20kW/m^2 (experimental extrapolation) and $\dot{q}''_{ig}$ = 16.5kW/m^2 (LIFTDATA).

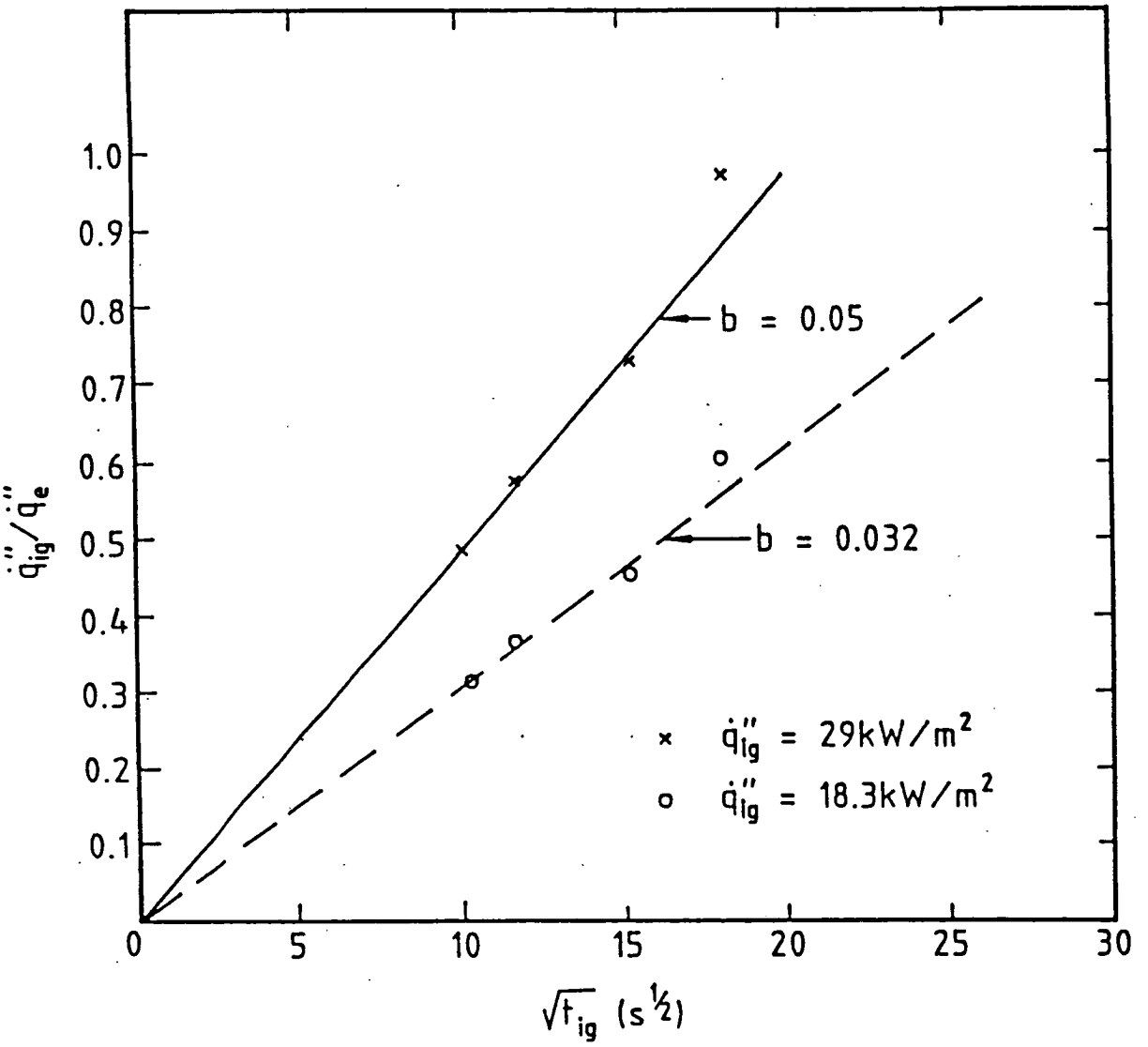


Fig. 4.12

The relationship between $\dot{q}''_{ig}/\dot{q}''_e$ and $\sqrt{t}$ obtained from the LIFT ignition test for EPS on Calcium Silicate Board at $\dot{q}''_{ig}$ = 29kW/m^2 (experimental extrapolation) and $\dot{q}''_{ig}$ = 18.3kW/m^2 (LIFTDATA).

Table (4.7)

Comparisons of the values of thermal inertia between the LIFTDATA and experimental extrapolation.

Parameters	Fire Retardant Plywood		EPS on Calcium Silicate Board	
	LIFTDATA	Experimental extrapolation	LIFTDATA	Experimental extrapolation
$\dot{q}''_{ig}(kW/m^2)$	16.5	20	18.3	29
$T_{ig}(^oC)$	395	440	416	520
$b(s^{-1.2})$	0.042	0.053	0.032	0.05
$h(kW/m^2K)$	0.044	0.048	0.046	0.059
$k\rho c(kW/m^2K)^2s$	1.43	1.04	2.69	1.77

In Quintiere's analysis, the flame spread velocity in eqn (7) is derived when the material is no longer in the transient heating mode. That is, given sufficient time, the surface temperature of the sample material under the imposed external heat flux ($\dot{q}''_e$) will reach thermal equilibrium. Therefore to initiate the flame spread tests, the samples have to undergo the pre-heat period before the pilot flame is ignited. The pre-heat time obtained from the computed data is crucial to the flame spread analysis. If the preheat is not of a duration sufficient to attain steady-state, then the surface temperature will be lower than the equilibrium values.

Experiments were performed again on separate occasions for Fire Retardant Plywood, Birchfaced Plywood and PMMA. The experiments were carried out based o the critical heat flux for ignition ($\dot{q}''_{ig}$) for setting the external flux ($\dot{q}''_e$) and the preheat time (t*) computed from the first run. There was no ignition and spreading of flame recorded for Fire Retardant Plywood. Under the extended pre-heat time (580s) compared to the first run (315s from $\dot{q}''_{ig}$ = 20kW/m^2), all the three samples exhibited the same behaviour. It was observed that volatiles were released rapidly from the sample surfaces by 60s, accompanied by blackening of the surface (charring). Cracking of the surface appeared by 300s by which the rate of release of volatiles had decreased. Not only did the char covering the surface protect the underlying wood from further decomposition, but also the limited thickness of the wood meant that the supply of volatiles was sufficiently exhausted by the time the pilot flame was introduced to ignite the sample. This indicates that the pre-heat time used in the first run was adequate for the $\dot{q}''_{ig}$ deduced from the experiment as explained in section 4.2.1. A slight difference in the value of $\dot{q}''_{ig}$ can affect the determination of the pre-heat time and also the setting of the external flux ($\dot{q}''_e$) to initiate the flame spread tests.

Table (4.8a-b) displayed the comparison of the parameters inferred from the flame spread data using the different pre-heat times for the Birchfaced Plywood and PMMA respectively. For Birchfaced Plywood, there is considerable difference in the inferred parameters when the samples are pre-heated at longer times (746s). When the values of $V_f^{-1/2}$ are plotted as a function of incident heat flux, corrected for transient effects ($\dot{q}''_e.F(t)$) (Figure 4.13), it can be seen that there is a large scatter of data at the high flux for pre-heat time of 431s whereas there appears to be more linear behaviour of the data with a pre-heat time of 746s. This indicates that there is a transient heating effect in the pre-heat time of 431s because the samples

Table (4.8): Comparison of the parameters inferred from the Flame Spread data using different preheat time.

a) Birchfaced Plywood

Parameters	Preheat Time (t*)	
	431 (s)[a]	746 (s)[b]
Critical Flux for ignition $\dot{q}''_{ig}$ (kW/m^2)	17.4	14.6
Minimum Flux for spread, $\dot{q}''_s$ (kW/m^2)	4.25	2.40
Minimum Temperature for Spread, T_s, min (^oC	112	72
Rate Coefficient C $(s/mm)^{1/2}$ (m^2/kW)	0.14	0.16
Flame Heating Parameter, Φ $(kW)^2/m^3$	50.91	38.58

(a) The external flux ($\dot{q}''_e$) was set based on $\dot{q}''_{ig}$ = 18.5kW/m^2 (by experimental deduction).

(b) The external flux ($\dot{q}''_e$) was set based on $\dot{q}''_{ig}$ = 17.9kW/m^2 (by LIFTDATA).

Table (4.8)

b) PMMA

Parameters	Preheat Time (t*)	
	729(s)[a]	888 (s)[b]
Critical Flux for Ignition, $\dot{q}''_{ig}$ (kW/m^2)	12.4	11.2
Minimum Flux for Spread, $\dot{q}''_{s}$ (kW/m^2)	0.6	0.6
Minimum Temperature for spread, T_s, min (^oC)	36	36
Rate coefficient C(s/mm)$^{1/2}$ (m^2/kW)	0.29	0.31
Flame Heating Parameter, Φ $(kW)^2/m^3$	13.28	11.89

(a) The external flux ($\dot{q}''_{e}$) was set based on $\dot{q}''_{ig}$ = 10.0 kW/m^2 (by experimental deduction).

(b) The external flux ($\dot{q}''_{e}$) was set based on $\dot{q}''_{ig}$ = 9 kW/m^2 (by LIFTDATA).

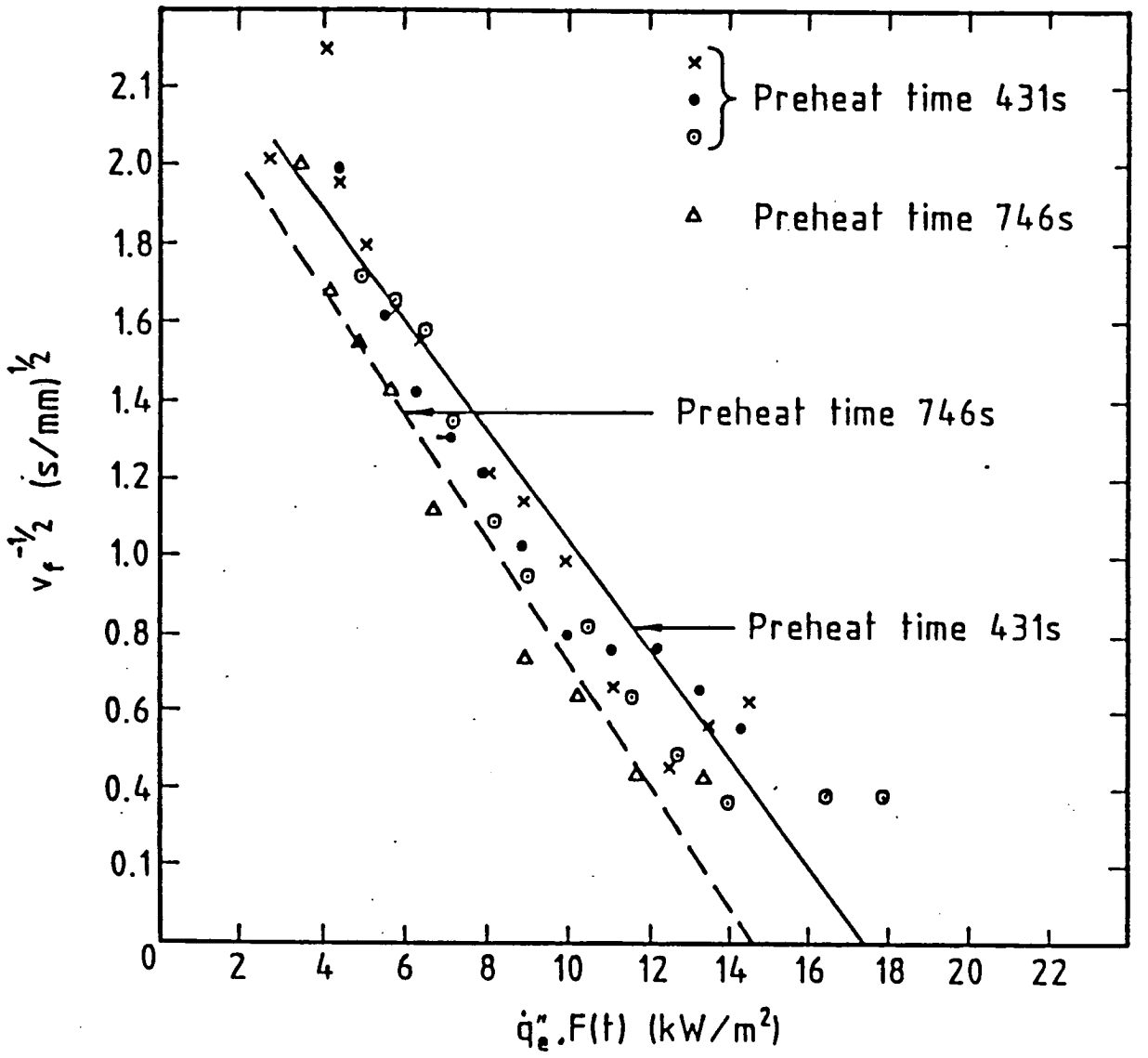


Fig. 4.13

The graph of $V_f^{-1/2}$ versus the incident irradiance (corrected for transient effects) for Birchfaced Plywood at pre-heat time of 431 s(x, sample 1; •, sample 2 and ⊙, sample 3) and pre-heat time of 746s.

ignited at the high flux have not reached thermal equilibrium, and thus the flame spread velocity is below its equilibrium value. As for PMMA, the results obtained for the pre-heat time of 888s are compatible with the pre-heat time deduced from the first run (729s), achieving the same value for minimum flux for flame spread ($\dot{q}''_s$) and the minimum temperature for flame spread (T_s min) although there is a slight difference in the values of the other parameters. The rate coefficient (C) and $\dot{q}''_{ig}$ are extrapolated by the relationship of $V_f^{-1/2}$ against $\dot{q}''_e.F(t)$ represented by the slope and the interception with the abscissa respectively. Since C is related to the flame heating parameter (Φ) as shown in eqn. (12), it therefore influences its value. Hence the pre-heat of 888s is acceptable for PMMA samples to reach thermal equilibrium as consistent results of flame spread velocity are obtained (figure 4.14).

During the flame spread process of PMMA, it was observed that the flame spread to the end of the sample, as recorded for the previous ISO flame spread test [76]. Sufficient heat is transferred ahead of the flame to enable the flame to continue to spread along the surface with minimum heat flux ($0.6kW/m^2$, table 4.8b). However, the flame can still spread along the sample surface without the influence of an external flux. This was confirmed by a simple test carried out at the laboratory. A PMMA sample of 200mm x 100mm, with lines marked every 10mm, was held vertically with the longitudinal axis horizontal. The edges of the sample length were covered with 10mm metal strips to prevent the edges from burning. The sample was ignited by a Bunsen burner applied at the edges of its width to initiate the burning. Once flaming had been established and started to spread, the time taken for the flame to spread to the individual marked distances was recorded. The schematic of the test arrangement and the results are shown in Appendix B. From the results, the rate of flame spread was found to be 0.072mm/s which is in good agreement with the value obtained in the LIFT method, i,.e. 0.077mm/s (indicated by the interception of $V_f^{-1/2}$ axis as shown in figure 4.14).

The significant parameters inferred from the ignition and flame spread data for the materials tested are tabulated in table (4.9).

It can be clearly envisaged that there is a marked difference in the value of the critical heat flux for ignition $\dot{q}''_{ig}$ computed from the flame spread data for EPS on Calcium Silicate Board when compared to $\dot{q}''_{ig}$ calculated from the ignition data. During the pre-heat time, under the imposed external heat flux all 3 samples tested

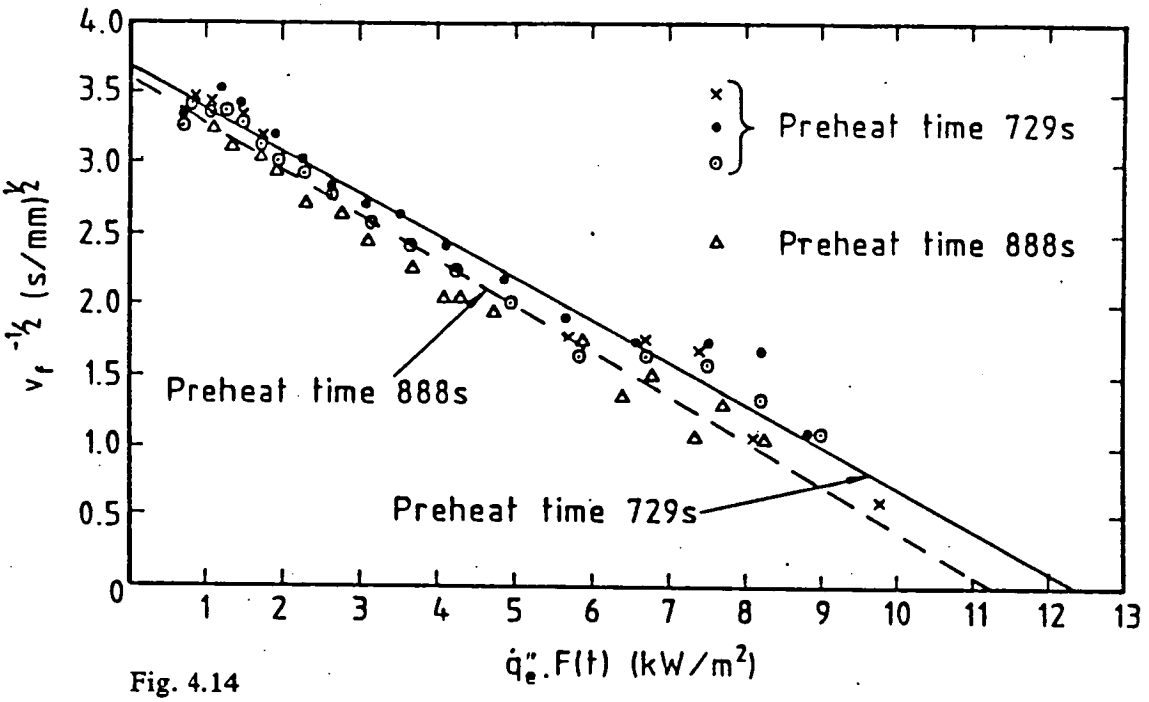


Fig. 4.14

The graph of $V_f^{-1/2}$ versus the incident irradiance (corrected for transient effects) for PMMA at pre-heat time of 729s (x, sample 1; •, sample 2 and ⊙, sample 3) and pre-heat time of 888s.

Table 4.9: Parameters inferred from the Ignition and Flame Spread data by LIFT Method.

Material	b ($s^{-1.2}$)	t* (s)	$k\rho c$ $(kW/m^2K)^2s$	T_{ig} (^oC)	$\dot{q}''_{ig}$(a) (kW/m^2)	$\dot{q}''_{ig}$(b) (kW^2/m)	C $(s/mm)^{1/2}$ (m_2/kW)	Φ (kW^2/m^3)	$\dot{q}''_s$ (kW/m^2)	T_s min (^oC)
Fire Retardant Plywood	0.042	580	1.43	395	16.5	13.3	0.32	7.35	9.8	242
Birchfaced Plywood[1]	0.037	746	1.99	411	17.9	14.6	0.16	38.58	2.4	72
PMMA [2]	0.034	888	1.31	284	9.0	11.2	0.31	11.89	0.6	36
Phenolic GRP	0.021	2204	7.02	449	21.5	21.9	1.76	0.90	41.2	843
EPS on Calcium Silicate Board	0.032	989	2.69	416	18.3	123.8	0.01	5946.27	13.1	3.03

Ignition Data — Flame Spread Data

[1,2] - The parameters obtained at pre-heat time of 746s and 888s respectively.

(a) from ignition data

(b) from flame spread data

shrank and melted to a thin film on the substrate, particularly at the hot end (up to 250mm). There was an immediate ignition of the sample when the pilot flame was lit followed by vigorous flaming and initial rapid spread. Flaming droplets were also observed. Figure (4.15) displays the scattered data of the flame spread velocity as a function of the imposed heat flux indicating the erratic behaviour of the flame spread. This lead to the peculiar value of $\dot{q}''_{ig}$ (123.8kW/m^2) deduced from this relationship. Thus the flame spread model which assumed that the material is thermally thick does not apply to EPS on Calcium Silicate Board which behaves as thermally thin when the expanded polystyrene foam melted to form a thin layer (film) on the substrate.

Quintiere has established a correlation for the flame spread data in determining the flame spread velocity (eqn 8) as follows:

$$V_f^{-1/2} = C(\dot{q}''_{ig} - \dot{q}''_e) \qquad (8)$$

where C is termed as "rate coefficient". A plot of $V_f^{-1/2}$ versus $\dot{q}''_e.f(t)$ will be linear for $\dot{q}''_s < \dot{q}''_e < \dot{q}''_{ig}$, and C is the slope. An extrapolated value of $\dot{q}''_{ig}$ is found that corresponds to the flame spread test for $V_f^{-1/2} = 0$ and $\dot{q}''_s$ is the value of q''_e at the asymptote (refer figure 3.13). These parameters for the 5 materials tested are tabulated in table (4.9). The relationship in the range of applicability of the analysis ($\dot{q}''_s < \dot{q}''_e < \dot{q}''_{ig}$) is linear if the surface temperature of the material, prior to the arrival of the flame front, is at steady state or thermal equilibrium. This is illustrated by figure (4.13) and figure (4.16) for Birchfaced Plywood. Figure (4.16) shows the data obtained from experiments previously carried out using the ISO flame spread test method [76] where no pre-heating was applied, i.e. the material is not at thermal equilibrium, particularly during the early stages of flame propagation (at the higher heat fluxes). The effect of transient heating on the data can be clearly seen such that the relationship between $V_f^{-1/2}$ and incident irradiance is not linear.

The minimum incident heat flux necessary to support lateral flame spread $\dot{q}''_s$, deduced from the above relationship is used to determine the minimum surface temperature for flame spread (T_s, min). Using figure (3.11), T_s, min is inferred from the value of $\dot{q}''_s$. The results are shown in table (4.9).Here it was observed that for Phenolic GRP, the minimum sample surface temperature for flame spread is

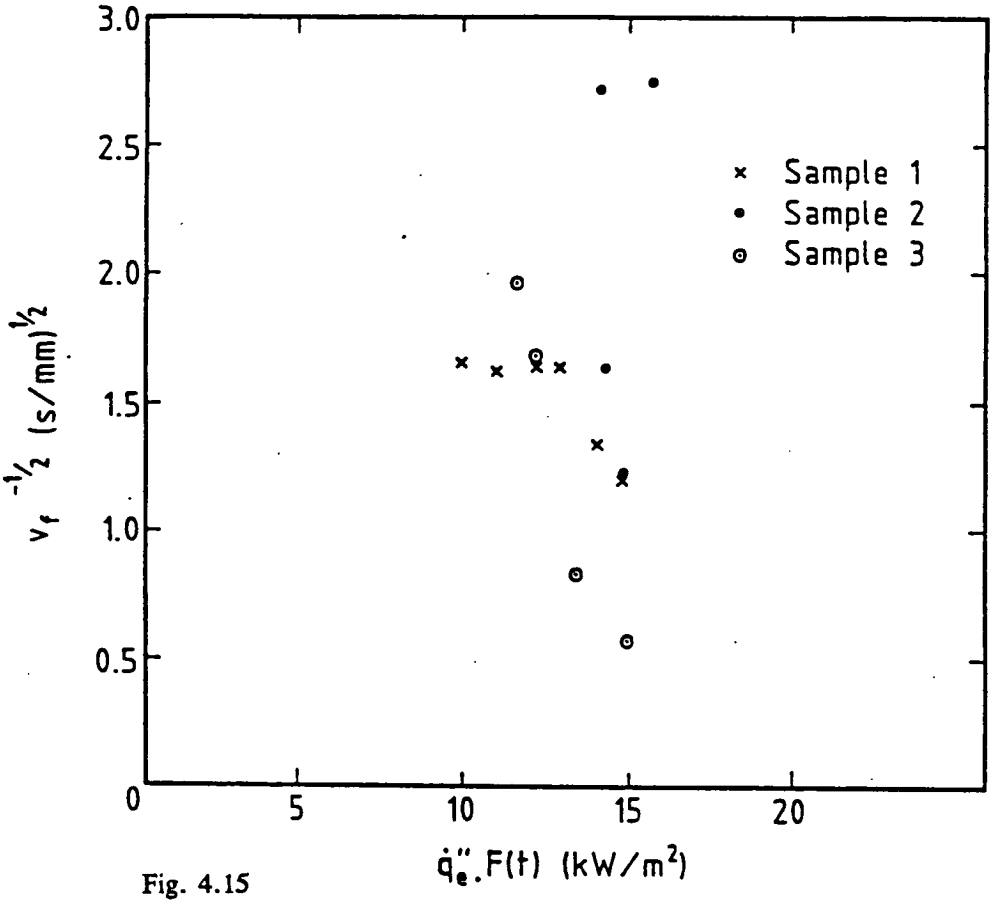


Fig. 4.15

The graph of $V_f^{-1/2}$ versus the incident irradiance (corrected for transient effects) for EPS on Calcium Silicate Board).

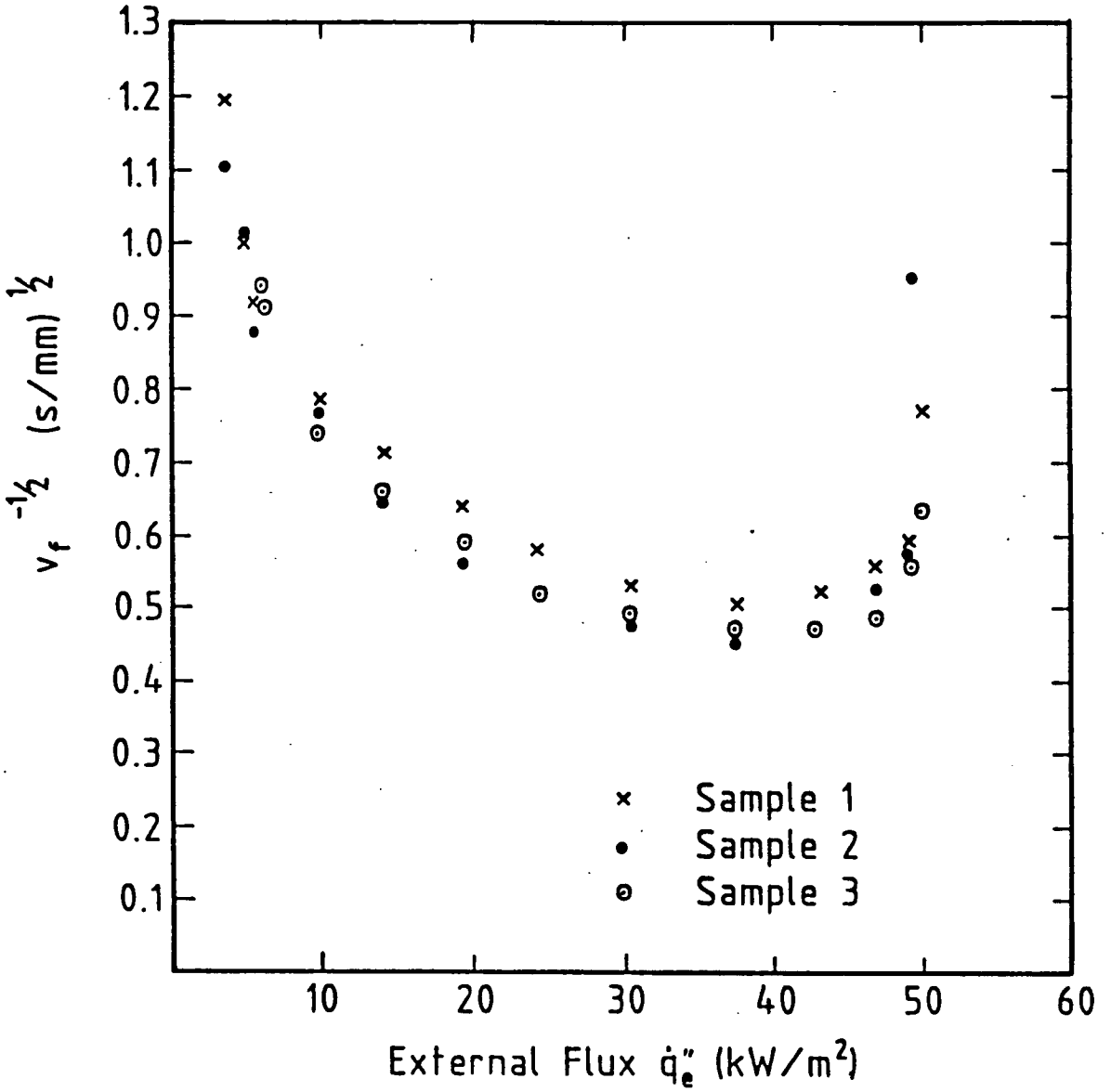


Fig. 4.16

The graph of $V_f^{-1/2}$ versus the external flux (not corrected for transient effects) for Birchfaced Plywood.

higher than the minimum ignition temperature deduced for this material (T_s, min > T_{ig}). The sample surface charred during the pre-heat time which accounted for the reduction in the formation of volatiles and the sample was ignited in different manner to that specified in the draft proposal [77] (the sample was ignited by locating the pilot flame at the bottom surface of the sample). This peculiar result indicates that the technique of measuring the flame spread by LIFT method is not applicable for this type of material.

The lateral flame spread velocity in the flame spread model is given as:

$$V_f = \Phi \Big/ (k\rho c)\,(T_{ig} - T_s)^2 \qquad (10)$$

where Φ is referred as to the flame heating parameter; it is a measure of the heat transferred from the flame to the sample surface ahead of the flame. Here, the only unknown in the above expression is Φ since the other parameters are already inferred from the ignition and flame spread data. Φ takes account of the opposed flow air velocity and flame temperature and is related to constant C (rate coefficient) in equation 12. Thus Φ can be computed by the following expression:

$$\Phi = 4/(Cb)^2 \qquad (12)$$

It should be noted that C may not be a true constant since it has been shown that external heating affects the radiation transfer from the flame, as well as the surface temperature, far ahead of the advancing flame. The computation of Φ can be said to be greatly dependent on the estimate for b and C, in which any uncertainties in the estimations of these values will affect the value for Φ. The values of Φ for the 5 materials tested are tabulated in table (4.9) which indicate that the greater the value of Φ, the poorer the performance of a material with respect to flame spread (EPS on Calcium Silicate Board on top of the list whilst Phenolic GRP is the least). Hence, the parameter Φ may be used for comparing material hazard.

4.2.2.1 Design of the Apparatus and its Applicability

a) Pilot Flame

Of concern here is the use of acetylene gas as the fuel for the pilot flame. Having an acetylene cylinder in the laboratory introduces an unnecessary hazard. It is essential that the cylinder is handled and stored properly. Acetylene can decompose and

explode if subjected to heat or shock [124]. Precautions such as: the acetylene cylinder valve should be 1 1/2 turns when in use and the gas must not be withdrawn from the cylinder or manifold at a rate in excess of one-seventh of the total cylinder capacity per hour are important to reduce hazard posed by acetylene cylinders. All the preliminary work has been carried out using acetylene; propane would be much less of a hazard to e used for the pilot flame.

Experiments for lateral flame spread were carried out on Birchfaced Plywood and PMMA using propane gas as the fuel for the pilot flame. Although the blue conical pilot flame cannot be extended to the full length of the steel flange (about 180mm as specified for acetylene) i.e. halfway for propane, it was observed that this is adequate as the difference in the flame spread results is not significant. This is clearly illustrated by table (4.10 a-b) which compares the parameters derived from the flame spread data for the acetylene and propane as the fuel for the pilot flame. Table (4.10a) shows that the critical heat flux for ignition ($\dot{q}''_{ig}$) for Birchfaced Plywood obtained by propane gas is 7% more than the $\dot{q}''_{ig}$ deduced using acetylene. Here the q''_{ig} was deduced from the relationship of $V_f^{-1/2}$ as a function of $\dot{q}''_e.F(t)$ where $V_f^{-1/2} = 0$. From figure (4.17) it can be clearly seen that the few data were scattered especially at high flux due to transient effects. Since the computing of the flame front velocity was by applying a running 3-point least square fit to the measured flame front position time, the lines have been drawn by weighing the data points over the centre of the data. This influences the determination of the critical heat flux and also the rate coefficient (C) which is the slope of the straight line. This affects the value of the flame heating parameter (Φ). The slight variation in the $\dot{q}''_{ig}$, C, and Φ was also recorded for PMMA (table 4.10b, figure 4.18).

There are other problems concerning the pilot flame which hindered the smooth running of the experimental work. In the present design of the apparatus, the air supplied to the pilot flame is on the same lines with the main test equipment. To get a better blue flame and of desired length, i.e. about 180mm, the air and gas must be mixed and in the right proportions. There is an effect on the air supply to the pilot flame whenever the radiant panel is being adjusted for the various heat flux required for the test, especially at higher fluxes. Therefore, a separate air supply, independent from the main apparatus, should be provided for the pilot flame.

Table 4.10: Comparison of the parameter inferred from the Flame Spread Data using different gas for the Pilot Flame.

a) Birchfaced Plywood

Parameters	Pilot Flame	
	Acetylene + Air	Propane + Air
Critical Flux for Ignition, $\dot{q}''_{ig}$ (kW/m^2)	14.6	15.7
Minimum Flux for Spread, $\dot{q}''_s$ (kW/m^2)	2.40	2.46
Minimum Temperature for spread, T_s, min (^oC)	72	73
Rate coefficient $C(s/mm)^{1/2}$ (m^2/kW)	0.16	0.15
Flame Heating Parameter, Φ $(kW)^2/m^3$	38.58	44.68

*The external flux ($\dot{q}''_e$) was set based on $\dot{q}''_{ig} = 17.9 kW/m^2$.

Table 4.10:

b) PMMA

Parameters	Pilot Flame	
	Acetylene + Air	Propane + Air
Critical Flux for Ignition, $\dot{q}''_{ig}$ (kW/m^2)	11.2*	10.3
Minimum Flux for Spread, $\dot{q}''_{s}$ (kW/m^2)	0.56	0.56
Minimum Temperature for spread, T_s, min (^oC)	36	36
Rate coefficient C $(s/mm)^{1/2}$ (m^2/kW)	0.31	0.33
Flame Heating Parameter, Φ^2 $(kW)^2/m^3$	11.89	10.06

*The external flux ($\dot{q}''_e$) was set based on $\dot{q}''_{ig}$ = 9 kW/m^2.

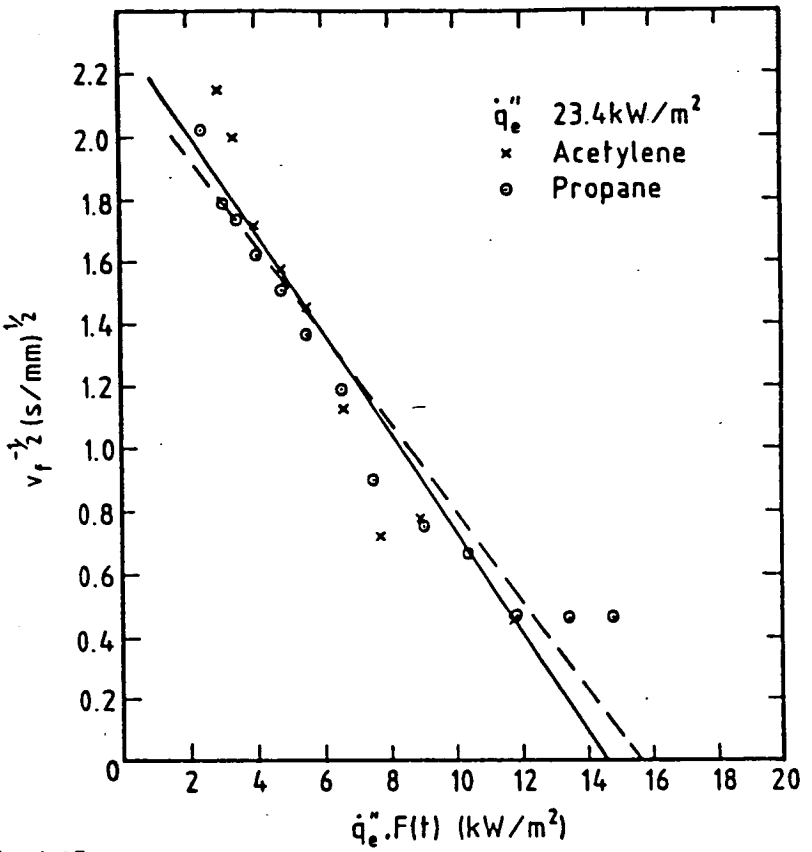


Fig. 4.17

The graph of $V_f^{-1/2}$ versus $\dot{q}''_e$. F(t) for Birchfaced Plywood using acetylene and propane as the fuel for the pilot flame at $\dot{q}''_e$ = 23.4kW/m^2.

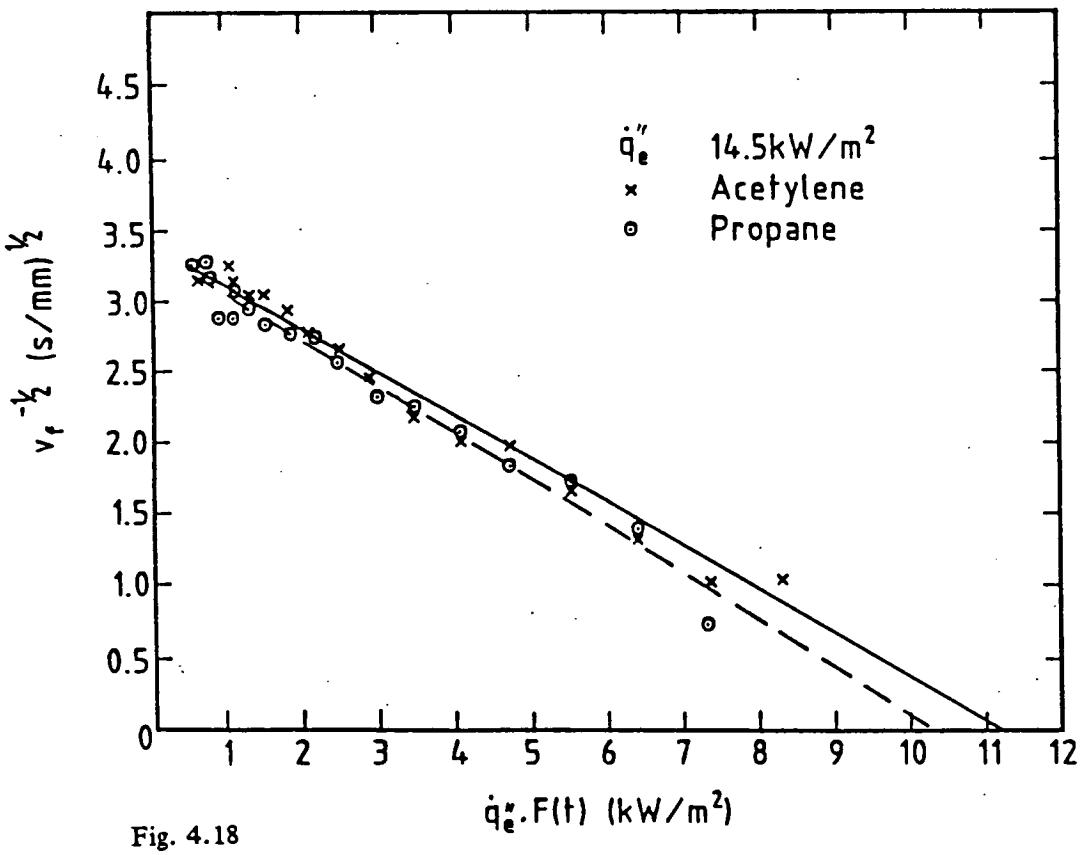


Fig. 4.18

The graph of $V_f^{-1/2}$ versus $\dot{q}''_e$. F(t) for PMMA using acetylene and propane as the fuel for the pilot flame at $\dot{q}''_e$ = 14.5kW/m^2.

Furthermore, for the LIFT flame spread tests, there is a problem of recording the spread once the specimen holder is inserted as the air and gas must be adjusted before the pilot flame is lit. Note that experiments were conducted single-handed without audio-visual aids. Observations were made during the experiments and the timing of the spread of the flame was done by stop-watch. In those cases where the sample ignited immediately after the pre-heat period, there was a delay in recording the initial spread of flame along the sample surface. Thus to be able to operate the apparatus single-handedly and effectively, the pilot flame controls should be situated in a position in clear view of the recording of the flame spread where after the specified pre-heat time, the switch can be activated to give the required pilot flame. This set up can be similar to BS 476: Part 7 [74]. For the sample which does not ignite by the normal procedure, e.g. Phenolic GRP, the pilot flame has to be applied at the bottom part of the sample. The proposed draft standard states that the pilot flame should be held and moved along the bottom part of the sample: this was difficult because of the intense radiant heat which could be felt through thick leather gloves. Simultaneous recording of the lateral flame spread once ignition has occurred is almost impossible. This problem can be overcome by positioning and securing the pilot ignitor at two positions; one located at the top of the sample (normal) while the other one to cater for the sample that could not be ignited by the normal procedure (ideally at a position near the bottom part of the sample). Both the pilot ignitors can be controlled by separate switches to light the pilot flame.

b) Sample Holder

The apparatus is very awkward to operate, particularly with regard to the sample holder and mounting of the samples at testing. The whole assembly of the sample holder is heavy and bulky. The mechanism used is of the "line-up" and "slide-in" which caused many difficulties i.e. operator strength, ease of movement on bottom rail and alignment of forks.

It will be easier to operate single-handedly if the sample holder was permanently fixed in position. A water-cooled sample holder is preferred. The sample, dummy sample and calibration board can be put in place quickly and held by the substrate and a spring loaded clamp. It would be possible to adopt the water-cooled sample holder and spring loaded clamp used in BS 476: Part 7 [74].

(c) Gas Supply

It is essential for the apparatus to have an independent gas supply since slight fluctuations in gas pressure can greatly affect the output of the radiant panel. In my experience, it was necessary to repeat the experiments when this occurred.

In addition, the apparatus should be located in an enclosed area with good extraction exhaust systems remote from the door. It is extremely sensitive to draughts caused by the opening of a door, the draughts can influence the heat flux reading particularly during calibration.

4.2.2.2 Lateral flame spread in compartment fire

It is of great importance to know the performance or behaviour of lining materials with respect to lateral flame spread in a compartment fire.

Let us consider two possible fire scenarios in a room or compartment; firstly the ignition source is at the centre of the compartment, and secondly the ignition source is in a corner, at the intersection of two walls.

The compartment under consideration is the standard ASTM room [125] (3.6m (long) x 2.4m (wide) x 2.4m (high)). It is assumed that the four walls are covered with combustible lining materials and the floor and the ceiling are made of non-combustible material such as concrete or plaster. Figure (4.19) depicts an item first ignited in the centre of the compartment, burning within the enclosure bounded by the 4 walls and ceiling. After localised burning has established, there are three scenarios that may happen. The first is that in which the original fire is small, compared to the surroundings, and is in an isolated position sufficiently distant from other fuels so that the object is consumed by the fire without involving other items of combustible materials. The second scenario in which there is inadequate ventilation where the fire may self-extinguish or continue to burn at a very slow rate depending on the availability of oxygen. The third scenario is that given sufficient fuel and ventilation, the initial fire develops to become large enough to form a hot smokey layer at ceiling level that gives strong radiative feedback to the lower parts of the room. This will subsequently lead to full room involvement in which all combustible surfaces are burning. Bruce [85] had observed this phenomena in his study of full-scale compartment fires with central ignition where he noted that combustible wall linings did not become involved until the fire was well advanced

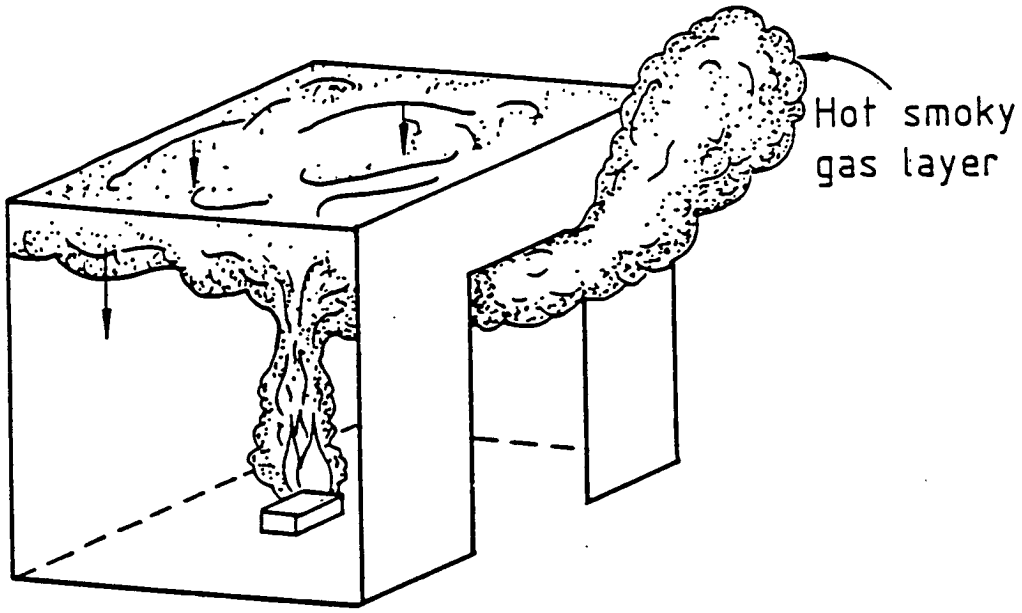


Fig. 4.19

Schematic diagram of a compartment fire with central ignition.

(after flashover when the flame touched the ceiling). It is in this third scenario that the flame spread of lining materials on walls will be discussed.

As the item burns, the rising plume of hot gases and entrained air accumulate below the ceiling, producing a layer of hot smokey gas. This will transfer heat directly to the ceiling and walls and to the floor by radiation. At this point downward radiation is significant to lower parts of the room with increasing intensity as the smoke concentration, the layer thickness and the temperature all increase. As the fire grows the smokey gas layer deepens and comes closer to the floor. The rate at which the hot smokey gas layer forms and approaches the floor is governed by the size of the fire relative to the size of the compartment. We wish to know the intensity of the radiant heat flux at floor level. Assuming the bottom of the hot smokey gas layer as a radiant panel, it is possible to calculate the heat flux intensity at the floor level. The configuration factor between the hot smokey gas layer and the floor is calculated according to McGuire [126]. Using the expression below, the heat flux intensity can be determined at various ceiling temperatures.

$$I = \sigma\varepsilon\phi T^4$$

where I is the heat flux intensity in kW/m^2, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-11} kW/m^2K$), ε is the emissivity (assumed 0.8 for the hot smokey gas layer) and T is the temperature in degrees Kelvin.

The heat flux intensity at different heights between the bottom of the hot smokey gas layer and the floor) for temperatures at 600°C, 700°C and 800°C are presented in table (C1), Appendix C and figure (4.20).

From Figure (4.20), it can be seen that the heat flux intensity at floor level increases as the height between the bottom of the hot smokey gas layer and the floor decreasing at the three temperatures stated.

The fire intensity grows exponentially, all the fuel in the room is ignited, the flames engulf the entire compartment and extend out the doorway. The phenomena of rapidly accelerating growth reaching full involvement of the entire compartment is known as "flashover". The flashover criterion was suggested as $20kW/m^2$ at floor level by Waterman [4], the ceiling temperature to be 600°C as found by Fang [5]

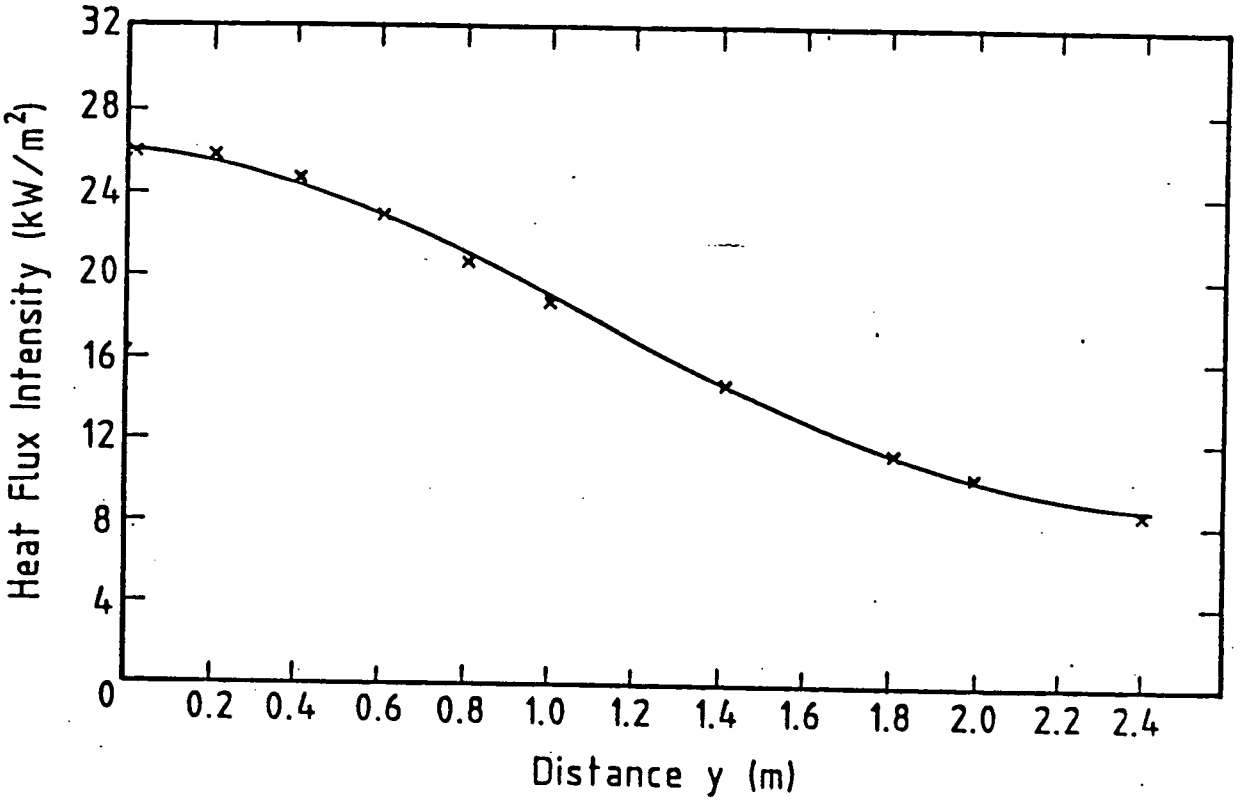


Fig. 4.20

The graph of heat flux intensity versus distance when the bottom of the hot smokey gas layer (radiator) parallel with the floor (receiver).

and as the moment at which flames emerged from the doorway opening by Hagglund et al [127]. Incorporating these flashover criteria to the calculated data (table C1 and figure 4.20) it can be seen that flashover occurs when the thickness of the hot smokey gas layer is 1.5m below the ceiling surface (i.e. y = 0.9m). As mentioned earlier, the rate at which the hot smokey gas layer forms and approaches the floor is governed by the size of the fire relative to the size of the compartment, it is possible to estimate the fire intensity (the heat release from the ignition source) using the following expression for the temperature under the ceiling [128]:

$$T_{ceil} - T = \frac{16.9\, Q^{2/3}}{H^{5/3}}$$

where T_{ceil} is assumed as the flashover temperature (600°C) , T is the ambient temperature taken as 20°C, Q is the fire intensity in (kW) and H is the height from the ceiling surface to the surface of the fuel (item first ignited) and assumed as 2.4m. Thus, the fire intensity was calculated as 1.8MW for this particular scenario. The intense heat caused the combustible wall linings to ignite and spread of flame at the surface occurred although more prominent in the downward direction than in the horizontal (lateral spread). From table (4.9) which presented the parameters inferred from the LIFT spread of flame test, particularly the critical heat flux for ignition (q''_{ig}) , it can be seen that most of the materials tested except for Phenolic GRP ignited and involved in the fire when the hot smokey gas layer had deepened to about 1.2m (Figure 4.20). Phenolic GRP only gets involved after flashover has occurred.

However it is interesting to know the involvement of the wall linings in the compartment fire if the ignition source is located at the intersection of the two walls as depicted in figure (4.21). When the object located in the corner is ignited and sustains combustion, the flame tends to hug the adjacent vertical walls because air entrainment is limited to one direction i.e. towards the corner. Consequently, the combustible wall linings catch fire and upward flame spread occurs. It is known that the flame spread is most rapid if it is directed vertically upward [129]. Soon the established flame will lengthen and fill the boundary layer at the surface (pyrolysing zone). Soon the fire plume is deflected at the ceiling level to form a layer of smokey gas. The depth of layer will then depend on the width of the ceiling and the rate of

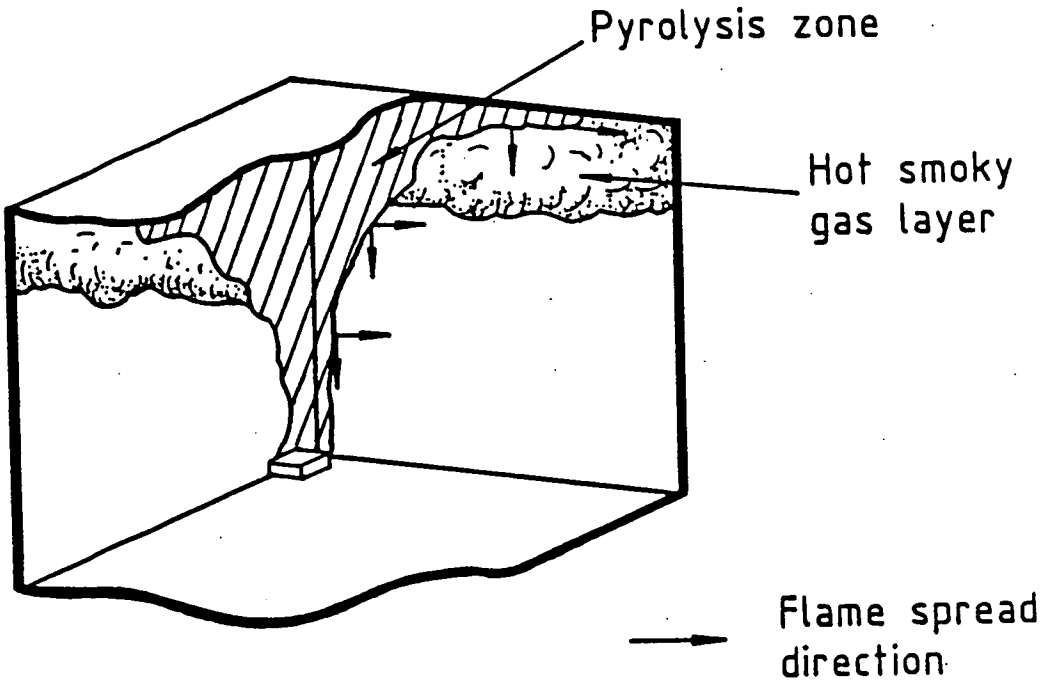


Fig. 4.21

Schematic diagram of a compartment fire with ignition at the corner.

flow of hot gas into the ceiling jet. Similarly the hot smokey gas layer will be radiating heat to the wall and the floor. At the upper surface of the room particularly below the hot gas layer, the flame on the wall lining coverings spread outward away from the corner and along and down from the wall-ceiling intersection. The lateral spread of the wall linings is further enhanced by the downward radiation from the smoky gas layer. The rate of spread and its associated rate of energy release is critical to whether room flashover can occur. Furthermore, the rate of flame spread and the rate of burning of the wall linings per unit area are controlled by the external radiant heat flux due to room thermal feedback, and the oxygen concentration. This is the basis of the LIFT method in which the external heat flux has to be set to initiate the lateral spread of flame on the surface.

It is possible to calculate the distribution of the heat flux intensity on the vertical centreline of the wall. Similarly as in the first situation, the bottom of the hot smokey gas layer is assumed as the radiant panel and the configuration factor between the assumed radiant panel perpendicular to the wall can be determined according to McGuire [126]. The heat flux distribution was calculated at various distances (equivalent to the value of y in table D1) for different smokey layer temperatures assumed at 400°C, 600°C, 700°C and 800°C. The results are presented in table D1, Appendix D. It can be clearly seen that for the different temperatures, the heat flux intensity at the centre of the wall is highest near the smoke layer and reducing as the distance from the ceiling in increased. This is further illustrated in figure (4.22). Assuming 600°C as the temperature of the hot smokey gas layer at flashover, the calculated heat flux intensity on the wall at 0.6m from the bottom of the smoke layer is about 9kW/m^2. From table (4.9) particularly $\dot{q}''_s$ it can be seen that lateral spread of flame will occur for Birchfaced Plywood and PMMA. When y is very close to the bottom of the hot smokey gas layer (i.e. y= 0.02m), the heat flux intensity on the wall will be about 13kW/m^2. Then all the materials tested except for Phenolic GRP will spread flame laterally and cause an increase in the total rate of burning within the compartment.

Generally, the calculated heat flux intensities obtained above are only an estimation to what has been observed in studies of a full-scale compartment fire. However, the argument is useful in illustrating the importance of lateral flame spread in the development of a compartment fire towards flashover. In an actual fire of a full-scale compartment, interaction exists between the variables: height and bulk density

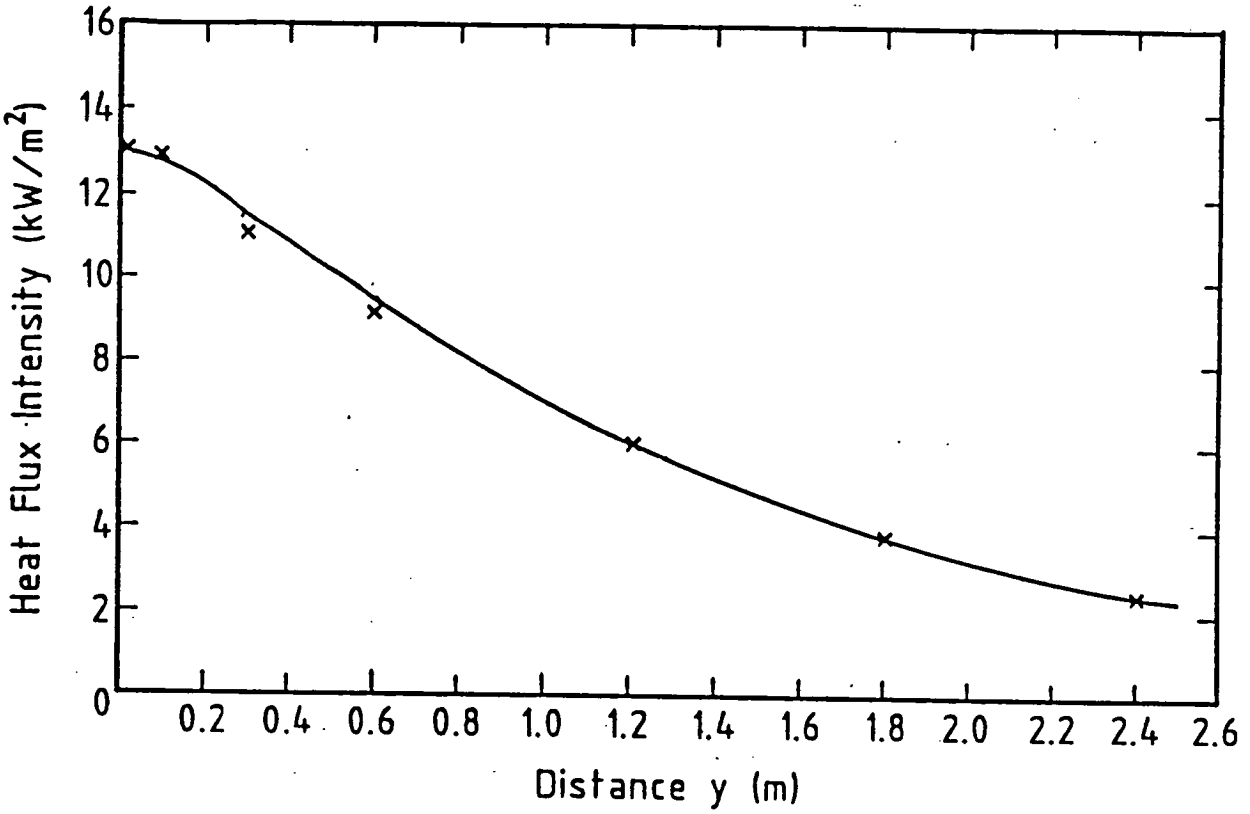


Fig. 4.22

The graph of heat flux intensity versus distance when the bottom of the hot smokey gas layer (radiator) perpendicular with the wall (receiver).

of the fuel bed, the size of compartment, the thermal conductivity of the compartment boundaries, area of the fire and ventilation which can influence the growth of fire in the compartment. Nevertheless with the parameters inferred from the LIFT method, it gives some indication of the performance of materials in respect of their properties such as thermal inertia ($k\rho c$), critical heat flux for ignition ($\dot{q}''_{ig}$), ignition temperature (T_{ig}), critical heat flux for flame spread ($\dot{q}''_{s}$), minimum surface temperature for flame spread (T_s min) and the energy available for spread (Φ) where these values can be applied to mathematical models.

CHAPTER FIVE
CONCLUSIONS

Two spread of flame tests have been studied, namely the ISO spread of flame test [76] and the LIFT spread of flame test [77]. The test methods utilise the same apparatus, and have the same principle of measurement, i.e. recording the progression of the propagating flame front along the sample. But they differed from each other in many ways, e.g. test procedure, pilot flame configuration, parameters derived from the test and interpretation of the results.

In the ISO spread of flame test, the parameters "heat for sustained burning" and "critical irradiance for flame spread" are derived from the results. These purport to give some indication of the material characteristics in respect to lateral flame spread. The results are highly dependent on the actual irradiance imposed on the sample. This is apparatus-dependent: slight fluctuations in the gas pressure change the heat flux enough to affect the flame spread on the sample surface. Furthermore the transient heating following exposure of the sample to the imposed heat flux are not taken into account in the test method. This is far from the goal of minimising apparatus-dependency in the design of test method. The term "heat for sustained burning" is ambiguous and may lead to the wrong interpretation of flame spread behaviour. In addition employing this term to evaluate the performance of materials with respect to later flame spread shows that the test method is of limited value for a wide range of materials, e.g. it is not applicable to materials that resist flame spread such as Phenolic GRP, PVC faced Plasterboard and Al foil faced PIR foam. Similarly, the "critical irradiance for flame spread" which is taken as the flux at the point where the propagating flame front stops cannot be determined if it is less than $1.5kW/m^2$ which is the irradiance at 750mm on the sample surface (e.g. for PMMA, $\dot{q}''_s = 0$).

The analysis used in the LIFT spread of flame test assumes that the solid under test is thermally thick. The test method allows the derivation of several material properties, viz. critical heat flux for ignition ($\dot{q}''_{ig}$), ignition temperature (T_{ig}), thermal inertia ($k\rho c$), minimum heat flux for flame spread ($\dot{q}''_s$), minimum temperature for flame spread (T_s, min), a rate coefficient (C) and a flame heating parameter (Φ) from the results. The estimation of the critical heat flux for ignition ($\dot{q}''_{ig}$) is crucial as the determination of most of the other parameters depend on it.

The flame spread velocity obtained from the flame spread model, in which the surface temperature must be at thermal equilibrium with the imposed heat flux $\dot{q}''_e$ is essential too. The transient heating effects which are particularly significant at high fluxes (when the sample is unlikely to have reached steady state at the onset of ignition) tend to influence the values of the rate coefficient (C) and $\dot{q}''_{ig}$ as discussed for Birchfaced Plywood (refer figure 4.13 and table 4.8).

The derived ignition properties, i.e. the ignition temperature (T_{ig}) and thermal inertia ($k\rho c$) which are relevant to flame spread over thermally thick solids tend to be higher than the values predicted from the literature. However, they give information relating to the condition necessary for combustion (T_{ig}) and the time response of a material to heat ($k\rho c$) under the conditions of the test.

Also, the flame spread rate coefficient, $C = \sqrt{\pi k\rho c}\ /(2\sqrt{h d_f}\ \dot{q}''_f)$, which depends on the material properties and configuration permits the comparison of the flame spread related hazard of various materials. The greater the value of C, the more favourable the performance of the material. It should be noted however, that this parameter is critical to the range of validity of the flame spread analysis. In addition the flame heating parameter (Φ) which takes account of the opposed flow air velocity and flame temperature under natural convective conditions may also be used for comparing the hazard of different materials. The greater the value of Φ, the poorer the performance of the material with respect to flame spread.

The flame spread model used in the LIFT method does not apply to materials which char severely (e.g. Phenolic GRP), or for materials which melt and shrink upon heating (e.g. EPS on Calcium Silicate Board). More detailed modelling of the thermal degradation of these materials is required to widen the scope of application of this test.

The use of acetylene as the fuel for the pilot flame is not critical in the context of this test method. Since acetylene poses an unnecessary hazard in any laboratory, it is suggested that it be changed to propane which has been shown to do the job equally well as acetylene. No significant difference was found in the derived parameters for Birchfaced Plywood and PMMA.

It must be emphasised here that in order to operate the LIFT spread of flame test apparatus effectively and obtain repeatable results, it is suggested that improvements in the design of the existing apparatus have to be made in several areas, viz. pilot flame and its air supply, sample holder and gas supply. Then the LIFT spread of flame test could be considered as a reliable tool in providing the ignition and flame spread properties which may be employed in fire growth mathematical models to develop a more rational and complete risk assessment for wall materials or able to predict the performance of materials.

Thus the LIFT spread of flame test is preferred to the ISO spread of flame test in evaluating the performance of lining materials in respect of their lateral flame spread in opposed air flow conditions.

REFERENCES

1) British Standard Guide to development and presentation of fire tests and their use in hazard assessment; BS 6232. British Standards Institution, 1982.
2) Emmons, H.W., "Fire and Fire Protection. Scientific American Vol. 231, no. 1 (1974), pp 21.
3) Deakin, A.G., "International standardisation of fire tests". Fire Prevention, No. 198, April 1987, pp. 26-30.
4) Waterman, T.E., "Room flashover-criteria and synthesis". Fire Technology, Vol. 4, pp 25-31.
5) Fang, J.B., "Measurement of the behaviour of incidental fires in a compartment". National Bureau of Standards,NBS Technical Note No. 879.
6) Drysdale, D.D., "An Introduction fo Fire Dynamics". 1985.
7) Guide to the principles and application of fire testing; BS 476: Part 10: 1983. British Standards Institution.
8) Test methods and criteria for the fire resistance of elements of building construction; BS 476: Part 8, 1972.
9) Murrell, J.M., "New fire test methodology - Revision of BS 476". Fire Surveyor, Feb. 1988, pp 9-16.
10) Method for determination of the fire resistance of elements of construction (general principle); BS 476: Part 20: 1987, British Standards Institution.
11) Methods for determination of the fire resistance of loadbearing elements of construction; BS 476: Part 21: 1987, British Standards Institution.
12) Methods for determination of the fire resistance of non-loadbearing elements of construction; BS 476: Part 22: 1987, British Standards Institution.
13) Methods for determination of the contribution of components to the fire resistance of a structure; BS 476: Part 23: 1987, British Standars Institution.
14) Methods for determination of the fire resistance of ventilation ducts, BS 476: Part 24: 1987, British Standards Institution.
15) Babrauskas, V. and Williamson, R.B., "The historical basis of fire resistance testing". Fire Technology 1978, 14(4), pp 304-316.
16) Hamilton, S.B., "A short history of the structural fire protection of buildings particularly in England". Special Report No. 27. Department of Scientific and Industrial Research. HMSO. London, 1958.
17) Malhotra, H.L., "Fire resistance versus fire behaviour". Fire Prevention, No. 134, Jan. 1980, pp 21-27.

18) Read, R.E.H., and Morris, W.A., Aspects of fire precautions in buildings, 1983.

19) British Standard definitions for fire resistance, incombustibility and non-inflammability of building materials and structures (including methods of test); BS 476: 1932. British Standards Institution, London, 1932.

20) Ryan, J.E., "Perspective on methods of assessing fire hazards in buildings". Ignition, Heat release and Non-combustibility of materials. ASTM, STP 502, pp. 11-23.

21) ASTM E 119-79: Fire tests of building construction and materials.

22) Harmathy, T.Z., "Experimental study on moisture and fire endurance". Fire Technology, Vol.2, No. 1, Feb. 1966, pg 52.

23) Lie, T.T., "Fire resistance of building". National Research Council of Canada. Technical Translation 1334. 1968.

24) Harmathy, T.Z. and Lie, T.T. "Fire test standard in one light of fire research". Technical Paper NO. 312 of National Research Council of Canada, Jan. 1970.

25) Thomas, P.H., "Recent developments and trends in fire testing for growth in buildings". Combustion Science and Technology, Vol. 40, 1984, pp. 153-165.

26) Fire Propagation Test for Materials; BS 476: Part 6. British Standards Institution.

27) Hot Box Test, Spread of flame temperature rise, smoke density. Test Method SIS 024823,Sveriges Standardiseringks Kommision. (NORDTEST NT FIRE 004).

28) Building Materials Fire Test, NEN 3883. Netherlands Normalistic-Instituut.

29) Rate of Burning (laboratory method); BS 2782: Method 508A. British Standards Institution.

30) Flammability of a specimen 550mm x 35mm of thin PVC sheeting (laboratory method); BS 2782: Method 508C. British Standards Institution.

31) Flammability of a specimen 150mm square, not exceeding 50mm in thickness, of a plastic material (Alcohol cup test) (Laboratory method): BS 2782: Method 508D. British Standards Institution.

32) Discussion of Test Methods. Fire Safety Aspects of Polymeric Materials. Vol. 2. Test Methods, Specifications and Standards, pp. 42-75.

33) Babrauskas, V., "Development of the Cone Calorimeter- A bench-scale heat release rate apparatus based on oxygen consumption". Fire and Materials, Vol. 4, No. 2, 1984, pp 81-95.

34) Thompson N.J. and Cousins E.W., "The FM construction materials calorimeter". Q. National Fire Protection Association, 52 (1959) 186.

35) Brenden, J.J., "Apparatus for measuring rate of heat release from building materials". J. Fire Flammability, 6 (1975) 50.

36) Parker, W.J. and Long, M.E., "Development of a heat release rate calorimeter at NBS". ASTM Spec. Tech. Publisher. 502, ASTM, Philadelphia, June 1972, pp 135.

37) Smith, E.E., "Measuring rate of heat, smoke, and toxic gas release". Fire Technology, 8 (1972), pp. 237-245.

38) Sensenig, D.L., "An oxygen consumption technique for determining the contribution of interior wall finishes to room fires". NBS Tech. Note 1128, U.S. Department of Commerce, Washington D.C., July 1980.

39) Babrauskas, V. and Parker, W.J., "Ignitability measurements with the cone calorimeter". Fire and Materials, Vol. 11, (1987), pp 31-43.

40) Wickstrom, U. and Goransson, U. "Prediction of heat release rates of surface materials in large-scale fire test based on cone calorimeter". U., Journal of Testing and Evaluation, 15, 1987, pp. 364-370.

41) Babrauskas, V. and Krasny, J.F., "Prediction of upholstered chair heat release rates from bench-scale measurements". Fire Safety Science and Engineering (ASTM STP 822), ASTM (1985), pp. 268-284.

42) Ostman, B.A.L. and Nussbaum, R.M., "Correlation between small-scale rate of heat release and full-scale room flashover for surface linings". Fire Safety Science and Engineering (ASTM STP 822), ASTM, 1985, pp. 823-832.

43) Wickstrom, U. "Using the cone calorimeter to classify building products". International Conference on Fires in Buildings 25-26 Sept. 1989, (Toronto, Canada), pp. 13-17.

44) Magnusson, S.E. and Sundstrom, B. "Combustible linings and room fire growth - A first analysis". Fire Safety Science and Engineering, ASTM STP 882, Philadelphia, 1985, pp. 45-69.

45) Proposed Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter (E-5 Proposal P190), Annual Book of ASTM Standards, Vol. 04-07 (1986).

46) Emmons, H.W., "Calculation of a fire in a large building". Presented at the 20the Joint ASME/AICLE. National Heat Transfer Conference, Milwaukee, Wisconsin.

47) Robertson, A.F., "Standardisation News". STDNA. Vol. 9, No. 12, Dec. 1981, pp. 14-20.

48) Drysdale, D.D., "The science of fire testing". Unit of Fire Safety Engineering, University of Edinburgh.

49) Becker, W.H.K., "Test methods and Standards - fire performance of products". Fire and Materials, Vol. 8, No. 2, 1984, pp. 64-68.

50) Ignitability test for materials; BS 476: Part 5. British Standards Institution.

51) Method of measuring the ignitability of products subjected to thermal irradiance; BS 476: Part 13: 1987, British Standards Institution.

52) ISO 5657-1986. Fire Tests. Reaction to Fire. Ignitability of Building Products.

53) Bluhme, D.A., "ISO ignitability test and proposed criteria". Fire and Materials, Vol. 11, 1987, pp. 195-199.

54) XiFang Hu and Clark, F.R.S., "The use of the ISO/TC 92 test ignitability assessment". Fire and Materials, Vol. 12, 1988, pp. 1-5.

55) Thompson, H.E. and Drysdale, D.D., "Flammability of Plastics - Ignition Temperature". Fire and Materials. Vol. 11, 1987, pp. 163-172.

56) Non-combustibility test for materials; BS 476: Part 4: 1970. British Standards Institution.

57) Method for assessing the heat emission from building materials; BS 476: Part 11: 1982, British Standards Institution.

58) Tsuchiya, Y., "Methods of determining heat release rate: state-of-the-art". Fire Safety Journal, 5 (1982), pp. 49-57.

59) "Proposed test method for heat and visible smoke release rates for materials". 1980 Annual ASTM Standards, Part 18, 1982, ASTM, Philadelphia.

60) Bluhme, D. and Getka, R., "Rate of heat release test - calibration, sensitivity and time constants of ISO HRR apparatus". NORDTEST PROJECT 115-77, Part 1, National Institute for Testing of Materials, Copenhagen, Denmark, December 1979.

61) Amaro, A.J., Kanury, A.M., Lipska, A.E. and Martin, S.B., "Thermal indices from heat release rate calorimetry". Fall Meeting of the Western States Section of the Combustion Institute, October 1974.

62) Babrauskas, V., "Performance of the Ohio State University rate of heat release apparatus using PMMA and gaseous fuels". Fire Safety Journal, 5, 1, 1982, pp. 9-20.

63) Hilado, C.J. and Murphy, R.M., "Fire response of organic polymeric materials (organic materials in fire: combustibility)". Design of Buildings for Fire Safety, ASTM STP 685, 1979, PP. 76-105.

64) Smith, E.E., "Heat release rate of building materials". Ignition, Heat Release and Non-combustibility of Materials", ASTM STP 502, ASTM, 1972, pp. 119-134.

65) Blomqvist, J., "Rate of heat release experiments with lining materials". Report LUTVDG/ (TVBB - 3014), Lund Institute of Technology, Sweden, 1983.

66) Huggett, C., "Estimation of rate of heat release by means of oxygen consumption measurements". Fire and Materials, Vol. 4, No. 2, 1980, pp. 61-65.

67) Svensson, G. and Ostman, B., "Rate of heat release for building materials for oxygen consumption". STFI-meddelande serie A, nr. 761 (1982); also as Doc. ISO/TC 92/ SC1/ WG5 B 16.

68) ISO/DP 9705. Fire Tests - Reaction to Fire - Full scale room for surface products. ISO/TC92/SC1 N 178. January 1988.

69) Sundstrom, B., "Full-scale fire testing of surface materials - measurements of heat release and productions of smoke and gas species". Fire Technology, Technical Report SP-RAPP 1986:45.

70) Sundstrom, B. and Goransson, U., "Possible fire classification criteria and their implications for surface materials tested in full scale according to ISO DP 9705 or NT FIRE 025.

71) Babrauskas, V. and Wickstrom, U., "The rational development of bench-scale fire tests for full-scale fire prediction". Fire Safety Science - Proceedings of the Second International Symposium, pp. 813-822.

72) Babrauskas, V., Lawson, J.R., Walton, W.D., and Twilley, W.H., "Upholstered furniture heat release rate measured with a furniture calorimeter". (NBSIR 82-2604). [U.S.] National Bureau of Standards (1982).

73) Babrauskas, V., Journal of Fire Science, Vol. 2, May/June 1983, pp. 205-235.

74) BS 476: Part 7: 1987, Method for classification of surface spread of flame of products.

75) Draft Proposal ISO/DP 5658 (Preliminary proposal). Fire Test. Reaction to Fire. Spread of Flame of Building Materials. ISO/TC 92/WG 4 N 243. June 1977.

76) Draft Proposal ISO/DP 5658. Surface Spread of Flame of Building Products - Vertical Specimen (IMO Version) ISO/TC92/SC1/WG3 N 128. May 1989.

77) Draft Proposal ISO/DP 5658. Surface Spread of Flame of Building Products - LIFT Method. ISO/TC92/SC1/WG3 N 132. May 1989.

78) ASTM E162-78: Test for Surface Flammability of Materials Using a Radiant Heat Energy Source. Annual Book of ASTM Standards, Part 18.

79) ASTM E84 - 81: Test for Surface Burning Characteristics of Building Materials. Annual Book of ASTM Standards, Part 18.

80) Rasbash D.J. and Drysdale D.D., Theory of Fire and Fire Processes". Fire and Materials, Vol. 7, No. 2, 1983, pp, 79-88.

81) Fernandez-Pello A.C., Downward flame spread under the influence of externally applied thermal radiation. Combustion Science and Technology, 17, 1977, pp. 1-9.

82) Quintiere J.G., "A simplified theory for generalising results from a radiant panel rate of flame spread apparatus". Fire and Materials, 5, 1981, pp. 52-60.

83) Friedman, R. (1977). "Ignition and burning of solids", in Fire Standards and Safety. ASTM STP 614 (ed. A.F. Robertson), pp. 91-111. American Society for Testing and Materials, Philadelphia.

84) Ferris, J.E. "Fire hazards of combustible wallboards", Special Report NO. 18. Commonwealth Experimental Building Station, Sydney, (1955).

85) Bruce, H.D., "Experimental dwelling-room fires", No. D1941, Forest Products Laboratory, U.S. Department of Agriculture, Madison, Wisconsin, June 1953.

86) Hinkley, P.L. and Wraight, H., "The contribution of flames under ceilings to fire spread in compartments. Part 2. Combustible Linings". FR Note 743, Fire Research Station, Borehamwood, England 1969.

87) Thomas, P.H., "The Role of Flammable Linings in Fire Spread", Board Manufacture, September 1969.

88) Steiner, A.J., "Symposium of fire test methods". ASTM Special Technical Publication, No. 301, 1961, pp. 80.

89) Christian, W.J. and Waterman, T.E., "Fire Behaviour of Interior Finish Materials", Fire Technology, Vol. 6, No. 3, August 1970.

90) Fang, J.B., "Fire build-up in a Room and the Role of Interior Finish Materials", NBS Technical Note 879, National Bureau of Standards, Washington D.C., June 1975.

91) Castino, G.T., Beyris,J.R. and Metes, W.S. "Flammability Studies of Cellular Plastics and Other Building Materials used for Interior Finishes", Subject 723, Underwriters Lab. Inc., Northbrook (1975).

92) McGuire, J.H. "The Spread of Fire in Corridors", Fire Technology, Vol. 4, No. 2, May 1968.

93) Fire Research on Cellular Plastics: The Final Report of the Products Research Committee, April 1980, pp. 66.

94) Walker, A.G. "Flammability Testing in Europe." Fire and Materials, Vol. 4, No. 3, 1980. pp. 149-153.

95) Hird, D. and Fischl, C.F., "Fire Hazard of Internal Linings". National Building Studies, Special Report No. 22, Joint Fire Research Organisation, 1954.

96) Malhotra, H.L., "An examination of the role and philosophy of fire tests". ISO/TC92/WG7, Doc. No. 58, July 1974.

97) Clark, F.R.S., "Fire Spread Tests - A Critique". Fire Technology, Vol. 17, No. 2, May 1981.

98) Thomas, P.H., "Flashover and fire propagation tests". CIB WG14 Working Part Document, May 1957.

99) De Ris, J. "Spread of a Laminar Diffusion Flame". Twelfth International Symposium on Combustion, pp. 241-252. The Combustion Institute (1969).

100) Gross, D., and Loftus, J. (1963). Surface flame propagation in cellulosic materials exposed to thermal radiation. J. of Research GTC, 3, pp. 251-258, National Bureau of Standards.

101) Kashiwagi, T. (1976). A study of flame spread over porous material under external radiation fluxes. Fifteenth Symposium (International) on Combustion, The Combustion Institute, pp. 255-256.

102) Robertson (1962). "Surface flammability measurements of radiant panel method", Symposium on Fire Test Methods, Special Technical Publication No. 344. Published by the ASTM.

103) Fernandez-Pello, A.C. (1977). "Downward of flame spread under the influence of externally applied thermal radiation. Combustion Science and Technology 17, 1.

104) Quintiere, J.G. (1981). "A simplified theory for generalising results from a radiant panel rate of flame spread apparatus". Fire and Materials 5(2), p. 521.

105) Quintiere, J.G., Harkleroad, M., Walton W., "Measurements of material spread properties", National Bureau of Standards Report, 1982.

106) Troitzsch, J., International Plastics Flammability Handbook. (Principles, Regulations, Testing and Approval). Second edition. pp. 278.

107) Draft Proposal (FP 34/WP.7). Fire Test Procedures for Surface Flammability of Bulkhead, Ceiling and Deck Finish Materials. ISO/TC92/SC1/WG3/N134, 1989, Final Draft.

108) Quintiere, J.G. and Harkleroad, M.T., "New concepts for measuring flame spread properties". Fire Safety Science and Engineering ASTM STP 882 Philadelphia 1985, pp. 239-267.

109) Atreya, A., "Fire growth on horizontal surfaces of wood". Combustion Science and Technology, Vol. 39, 1984, pp. 163-194.

110) Rockett, J.A. (1974). "Mathematical modelling of radiant panel test methods". Fire Safety Research, National Bureau of Standards, NBS SP 411.

111) Quintiere, J.G., "The application and interpretation of a test method to determine the hazard of floor covering fire spread in building corridors. Fire Safety of Combustible Materials, University of Edinburgh, Edinburgh (1975).

112) Robertson, A.F., "A flammability test based on proposed ISO spread of flame test". Third Progress Report, Inter-governmental Maritime Consultative Organisation, IMCO FP/215 (1979).

113) Fernandez-Pello, A. and Williams, F.A. "A theory of laminar flame spread over flat surfaces of solid combustibles". Combustion and Flame 28, pp. 251-277 (1977).

114) Frey, A.R. and Tien, J.S., "A theory of flame spread over a solid fuel including finite chemical kinetics". Combustion and Flame 36, pp. 263-289 (1979).

115) Quintiere, J.G. "The application of flame spread theory to predict material performance, fundamental aspects of polymer flammability", IOP Short Meeting Series No. 4, 14 April 1987, Institute of Physics, Bristol, England.

116) Alvarez, M.J. and Martin, S.B., "Mechanisms of igniting of thermally irradiated cellulose". In 13the Symposium (International) on Combustion, The Combustion Institute, Pittsburg, PA (1970).

117) Weatherford, W.D. Jr., and Shepperd, D.M., "Basic studies of the mechanism of ignition of cellulosic materials". Tenth Symposium (International) on Combustion. pp. 897-910. The Combustion Institute, Pittsburg, PA (1965).

118) Wesson, H.R., Welker, J.R. and Shiepcevich, C.M., "The piloted ignition of wood by thermal radiation". Combustion and Flame 16, pp. 303-310, 1971.

119) Atreya, A., "Pyrolysis, ignition and fire spread on horizontal surfaces of wood". Phd.D. thesis, Harvard University, May 1983.

120) Carslaw, H.R. and Jaeger, J.C., "Conduction of Heat in Solids". 2nd Edition, Oxford University Press, London (1959).

121) Ohlemiller, T. and Dolan, S., "Ignition and lateral flame spread characteristics of certain composite materials". NISTIR 89-4030, January, 1989.

122) Atreya, A., Carpentier, C., and Harkleroad, M., "Effect of sample orientation on piloted ignition and flame spread". Fire Safety Science - Proceedings of the First International Symposium, C.E. Grant and P.J. Pagni (eds.), Hemisphere Publishers, Washington, DC, 1986.

123) Kashiwagi, K., "Effects of sample orientation on radiative ignition". Combustion and Flame 44, 1982, pp. 223-245.

124) Loss Prevention Data, Factory Mutual System, Compressed Gases (7-50), pp. 5, 1974.

125) Proposed Method for Room Fire Test of Wall and Ceiling Materials and Assemblies: Annual Book of ASTM Standards, Vol. 04.07 (1982).

126) McGuire, J.H., "Heat transfer by radiation". Fire Research Special Report no. 2, 1953.

127) Hagglund, B., Jansson, R., and Onnermark, B., "Fire development in residential rooms after ignition from nuclear explosions". FOA Report C 20016-D6 (A3). Forsvarets Forskningsanatalt, Stockholm.

128) Alpert, R.L., "Calculation of response time of ceiling-mounted fire detectors". Fire Technology 8, 1972, pp. 181-195.

129) Magee, R.S., and McAlvey, R.F., "The mechanisms of flame spread".

130) Lawson, D.I. and Simms, D.L., "The ignition of wood by radiation". British Journal of Applied Physics, Vol. 3, Sept. 1952, pp. 288-292.

Appendix A

Flame Spread rsutls from ISO/DP 5658. Flame time refers to the time of the arrival of the flame front at the marked position on the sample surface.

Table I; Birchfaced Plywood

Sample 1; Time of ignition 18s.

Position (mm)	Irradiance (kW/m^2)	Flame Time (s)	Spread rate V_f(mm/s)	$V_f^{-1/2}$ $(s/mm)^{1/2}$	$(\alpha t)^{1/2*}$ mm
50	50.0	30	1.67	0.77	1.63
100	49.0	35	2.86	0.59	1.76
150	47.0	45	3.33	0.55	2.00
200	43.5	55	3.64	0.52	2.21
250	37.5	65	3.85	0.51	2.40
300	30.5	85	3.53	0.53	2.75
350	24.0	117	2.99	0.58	3.22
400	19.0	163	2.45	0.64	3.81
450	14.0	230	1.96	0.71	4.52
500	10.0	315	1.59	0.79	5.29
550	6.5	455	1.21	0.91	6.36
600	5.0	670	0.90	1.05	7.72
650	3.5	945	0.69	1.20	9.16
700	2.5	1254	0.56	1.34	10.56
710	2.5	1305	0.54	1.36	10.77

*Depth of heated layer

where thermal conductivity (k) $= 0.12 \times 10^{-3}$ kW/mK

density (ρ) $= 540$ kg/m^3 [108]

specific heat (c) $= 2.5$ kJ/kgK

Table II: Birchfaced Plywood

Sample 2; Time of ignition 13s

Position (mm)	Irradiance (kW/m^2)	Flame Time (s)	Spread rate V_f(mm/s)	$V_f^{-1/2}$ $(s/mm)^{1/2}$
50	50.0	20	2.50	0.63
100	49.0	33	3.03	0.57
150	47.0	40	3.75	0.52
200	43.5	45	4.44	0.47
250	37.5	50	5.00	0.45
300	30.5	65	4.62	0.47
350	24.0	90	3.89	0.51
400	19.0	125	3.20	0.56
450	14.0	185	2.43	0.64
500	10.0	295	1.69	0.77
550	6.5	422	1.30	0.88
600	5.0	605	0.99	1.00
640	4.0	775	0.83	1.10

Table III: Birchfaced plywood
Sample 3; Time of ignition 13s

Position (mm)	Irradiance (kW/m^2)	Flame Time (s)	Spread rate V_f(mm/s)	$V_f^{-1/2}$ $(s/mm)^{1/2}$
50	50.0	20	2.50	0.63
100	49.0	30	3.33	0.53
150	47.0	35	4.29	0.48
200	43.5	44	4.54	0.47
250	37.5	52	4.81	0.46
300	30.5	70	4.29	0.48
350	24.0	95	3.68	0.52
400	19.0	140	2.86	0.59
450	14.0	195	2.31	0.66
500	10.0	275	1.82	0.74
550	6.5	450	1.22	0.91
560	6.5	495	1.13	0.94

Table IV: Fire retardant Plywood
Sample 1, Time of ignition 10s

Position (mm)	Irradiance (kW/m^2)	Flame Time (s)	Spread rate V_f(mm/s)	Depth of heated layer $(\alpha t)^{1/2}$mm
50	49.5	45	1.11	2.00
100	48.5	50	2.00	2.11
150	46.5	55	2.73	2.21
200	43.0	60	3.33	2.31
250	37.5	65	3.85	2.40
300	31.0	100	3.00	2.98
350	24.0	125	2.80	3.33
400	19.0	177	2.26	3.97
450	14.2	255	1.76	4.76
495	10.0	370	1.34	5.73

*where thermal conductivity (k) = 0.12×10^{-3}kW/m K
density (ρ) = 540 kg/m^3 [108]
specific heat (c) = 2.5 kJ/kgK

Table V: Fire Retardant Plywood
Sample 2, Time of ignition 7s

Position (mm)	Irradiance (kW/m^2)	Flame time (s)	Spread Rate (mm/s)
50	49.5	40	1.25
100	48.5	45	2.22
150	46.5	50	3.00
200	43.0	60	3.33
250	37.5	72	3.47
300	31.0	90	3.33
350	24.0	115	3.04
400	19.0	172	2.32
440	15.0	240	1.83

Table VI: Fire retardant Plywood
Sample 3, Time of ignition 9s

Position (mm)	Irradiance (kW/m^2)	Flame time (s)	Spread Rate (mm/s)
50	49.5	40	1.25
100	48.5	45	2.22
150	46.5	50	3.00
200	43.0	55	3.64
250	37.5	65	3.85
300	31.0	90	3.33
350	24.0	125	2.80
400	19.0	190	2.10
445	15.0	280	1.59

Table VII: PMMA
Sample 1, Time of ignition 5s

Position (mm)	Irradiance (kW/m^2)	Flame Time (s)	Spread rate V_f(mm/s)	Depth of heated layer $(\alpha t)^{1/2}$mm
50	50.0	30	1.67	1.76
100	48.5	35	2.86	1.90
150	45.5	45	3.33	2.15
200	42.0	50	4.00	2.27
250	37.0	60	4.17	2.49
300	31.0	85	3.53	2.96
350	24.0	130	2.69	3.66
400	19.0	185	2.16	4.37
450	13.5	285	1.58	5.42
500	10.0	410	1.22	
550	7.0	585	0.94	
600	5.5	815	0.74	
650	4.0	1130	0.58	
700	3.0	1520	0.46	
750	2.0	1930	0.39	

*where thermal conductivity (k) = 0.26×10^{-3} (kW/mK)
density (ρ) = 1200 kg/m^3 [108]
specific heat (c) = 2.1 kJ/kgK

Table VIII: PMMA
Sample 2, Time of ignition 6s

Position (mm)	Irradiance (kW/m^2)	Flame time (s)	Spread Rate (mm/s)
50	50.0	35	1.43
100	48.5	40	2.50
150	45.5	45	3.33
200	42.0	55	3.64
250	37.0	75	3.33
300	31.0	105	2.86
350	24.0	145	2.41
400	19.0	200	2.0
450	13.5	285	1.58
500	10.0	410	1.22
550	7.0	605	0.91
600	5.5	935	0.64
650	4.0	1305	0.50
700	3.0	1715	0.41
750	2.0	2200	0.34

Table IX: PMMA
Sample 3, Time of ignition 5s

Position (mm)	Irradiance (kW/m^2)	Flame time (s)	Spread Rate (mm/s)
50	50.0	25	2.0
100	48.5	35	2.86
150	45.5	40	3.75
200	42.0	45	4.44
250	37.0	55	4.54
300	31.0	70	4.29
350	24.0	105	3.33
400	19.0	170	2.35
450	13.5	270	1.67
500	10.0	385	1.30
550	7.0	555	0.99
600	5.5	835	0.72
650	4.0	1215	0.53
700	3.0	1610	0.43
750	2.0	2050	0.36

Appendix B

Experiment on lateral flame spread for PMMA carried out at the laboratory.

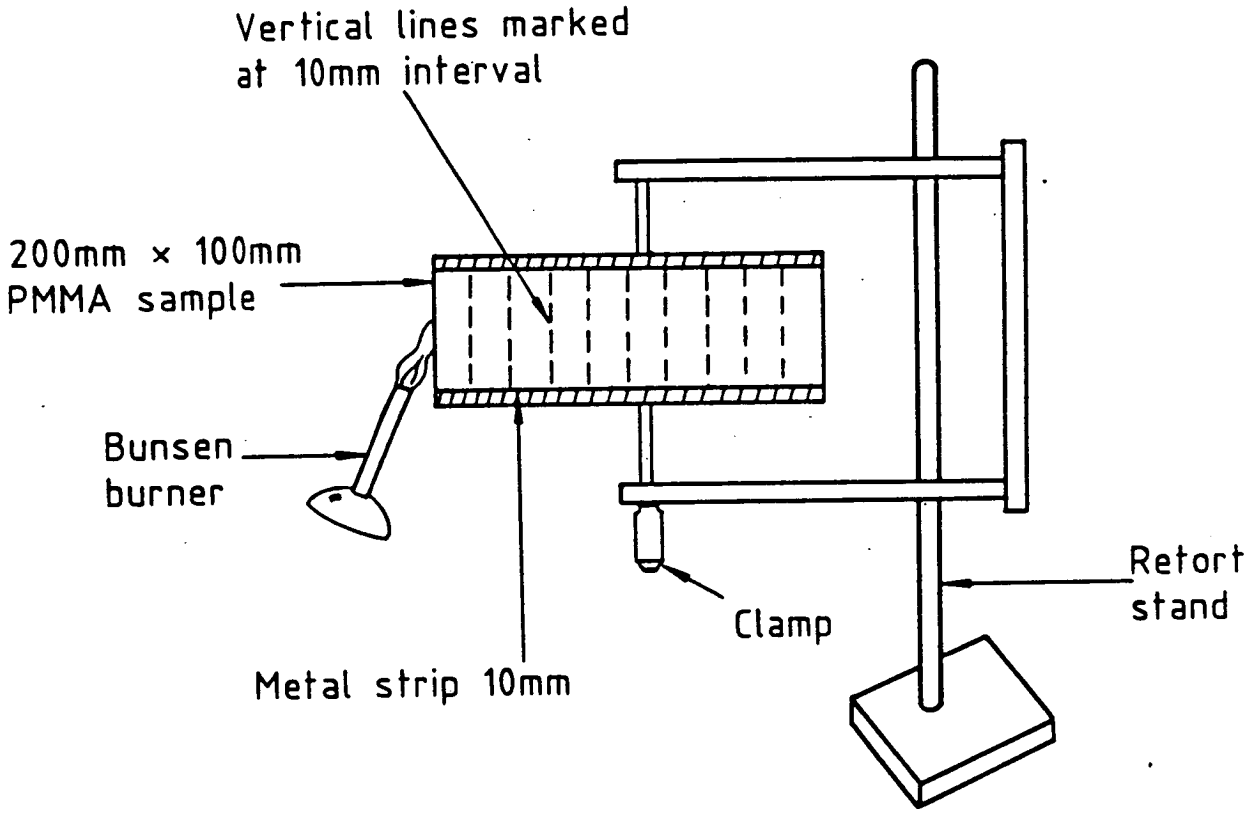


Fig. B1: Schematic arrangement of the test apparatus.

Appendix B:

Table (B1): The lateral flame spread rate for PMMA tested in the laboratory.

Distance (mm)	Sample 1		Sample 2	
	Flame time[a] (s)	Spread rate[b] (mm/s)	Flame time[a] (s)	Spread rate[c] (mm/s)
10	145	0.069	140	0.071
20	275	0.073	275	0.073
30	415	0.072	420	0.071
40	555	0..072	570	0.070
50	705	0.071	710	0.070
60	835	0.072	840	0.071
70	965	0.072	970	0.072
80	1110	0.072	1120	0.071
90	1240	0.072	1255	0.071
100	1375	0.073	1385	0.072
110	1505	0.073	1515	0.070
120	1645	0.073	1655	0.072
130	1785	0.073	1795	0.072
140	1915	0.073	1930	0.072
150	2055	0.073	2065	0.073
160	2195	0.073	2200	0.073
170	2330	0.073	2330	0.073
180	2480	0.072	2475	0.073
190	2615	0.073	2605	0.073
200	2745	0.073	2730	0.073

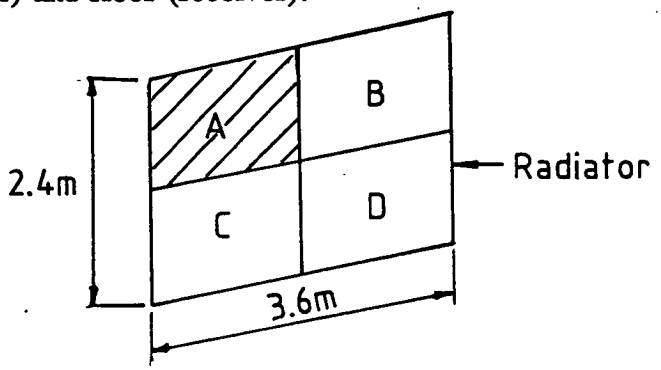
[a]Flame time refers to the time of the arrival of the flame front at the marked position on the sample face.

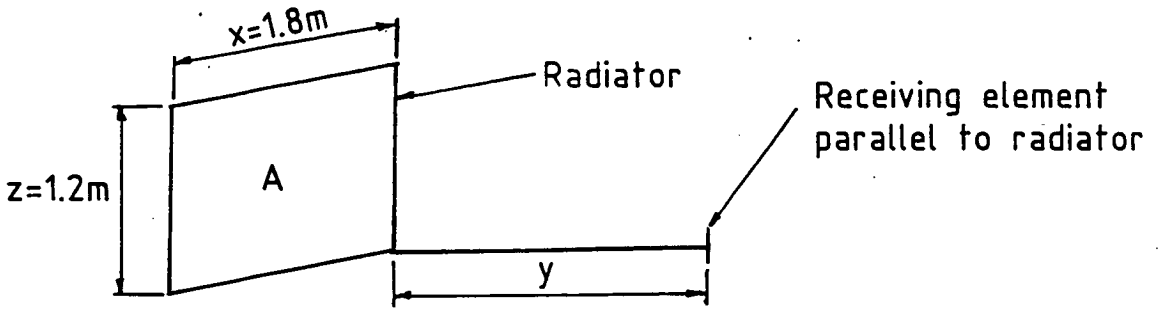
[b]Average spread rate = 0.072mm/s

[c]Average spread rate = 0.072mm/s.

Appendix C

Determination of configuration factor between the bottom of the hot smoky gas layer (radiator) and floor (receiver).





where z = height of radiator

x = width of radiator

y = distance from the radiator to the receiving element

The configuration factor $\Phi(\alpha,s) = \Phi ABCD$

$= 4\Phi A$

where

$$\alpha = \frac{x.z}{y2}$$

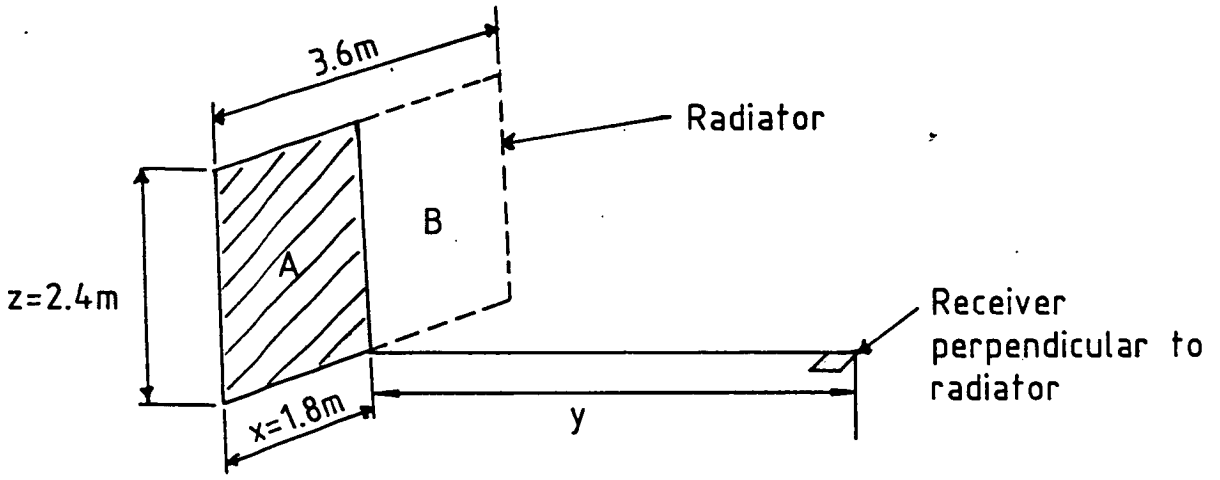
$$s = z/x$$

Table (C1) Heat Flux Intensity for different values of y at temperature 600°C, 700°C and 800°C.

y (m)	Configuration Factor Φ	Heat Flux Intensity I(kW/m^2)		
		600°C	700°C	800°C
0.02	0.99	26.3	40.6	60.1
0.2	0.983	25.9	40.0	59.1
0.4	0.937	24.7	38.1	56.3
0.6	0.870	22.9	35.4	52.3
0.8	0.792	20.9	32.2	47.6
1.0	0.712	18.8	29.0	42.8
1.4	0.556	14.6	22.6	33.4
1.8	0.445	11.7	18.1	26.8
2.0	0.394	10.4	16.0	23.7
2.4	0.320	8.4	13.0	19.2

Appendix D

Determination of configuration factor between the bottom of the hot smoky gas layer (radiation) and wall (receiver).



where z = height of radiator

x = width of radiator

y = distance from the radiator to the receiving element

The configuration factor $\Phi(\alpha,s) = \Phi AB$

$= 2\Phi A$

where Area A = Area B

$\Phi A = \Phi B$

$\alpha = \frac{x.z}{y2}$

$s = z/x$

Table (D1) Heat Flux Intensity for different values of y at temperature 400°C, 600°C, 700°C 800°C

y (m)	Configuration Factor Φ	Heat Flux Intensity, I (kW/m^2)			
		400°C	600°C	700°C	800°C
0.02	0.495	4.6	13.0	20.1	29.8
0.1	0.491	4.6	12.9	20.0	29.6
0.3	0.422	3.9	11.1	17.2	25.4
0.6	0.349	3.2	9.2	14.2	21.0
1.2	0.229	2.1	6.0	9.3	13.8
1.8	0.147	1.4	3.9	6.0	8.8
2.4	0.095	0.9	2.5	3.9	5.7