ENGINEERING FIRE SAFETY

Some Selected Papers
by Margaret Law

ARUP

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Contents

Foreword

Margaret joined Arup in 1974, and these papers were first published in 2002 in honour of her retirement.

Margaret represents to me, and to many other fire safety scientists and fire safety engineers, the epitome of placing applied and rigorous technical excellence at the heart of the design and construction of the built environment.

Serious fires continue to impact people's safety, the environment, and our critical infrastructure. Therefore, continues to be important to reflect and focus on proven routes to evidence-based safety methods and solutions.

Margaret passed away in August 2017. In her honour, we are republishing her papers as a mark of our ongoing respect to her incredible body of work. We want to carry on her legacy of knowledge transfer from science, engineering and applied research into the creation of a safe built environment.

Margaret expected fire safety engineers to be *"tough enough to stand up to a good deal of questioning"*, and in turn *"to be able to push other people in the same way: justify what you are saying if you expect to be taken seriously"*.

Her own work, published here, withstands this test; and it is for this rigour that she remains so deeply respected and so greatly admired.

To those who knew her well, she was above all a devoted, kind and patient teacher. Margaret stayed in touch with us over the years, and until her death. She was always a much beloved and respected member of Arup Fire.

We hope these papers will continue to serve the fire safety profession and all those who participate in the creation of our built environment. And that they will continue to act as a beacon of excellence.

These papers, nearly two decades later, remain a unique collection.

And a fitting tribute to Margaret's profound influence.

Barbara Lane.

Dr Barbara Lane FREng FRSE CEng
Arup Fellow, Fire Safety Engineering

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Acknowledgements

We gratefully acknowledge all the publishers for their kind permission in allowing us to facsimile the papers. In particular:

Institute of Physics, for Paper 1 *British Journal of Applied Physics,* Vol. 9 December 1958, pp 470-474. **www.iop.org**

Her Majesty's Stationery Office (HMSO), for Paper 2 *Fire Research Technical Paper No. 5, 1963, Department of Scientific and Industrial Research and Fire Offices' Committee,* Joint Fire Research Organisation. Reprinted in REH Read, (ed) 1991. *External fire spread: building separation and boundary distance.* Building Research Establishment Report BR 187, Borehamwood; Paper 3 *Fire Research Technical Paper No. 18,* 1967 Ministry of Technology and Fire Offices' Committee, Joint Fire Research Organisation; Paper 5 *Fire Research Technical Paper No. 20,* 1968 Ministry of Technology and Fire Offices' Committee, Joint Fire Research Organisation; and Paper 6, *Paper No. 2 of Symposium No. 5, Fire resistance requirements of buildings - a new approach.* 28 September 1971. Department of the Environment and Fire Offices' Committee Joint Fire Research Organisation. **www.hmso.gov.uk**

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Worcester Polytechnic Institute, for Paper 19 *Conference on Fire Safety Design in the 21st Century,* Worcester, Massachusetts, USA, 8-10 May 1991, Proceedings pp 228-235. **www.wpi.edu**

International Association For Fire Safety Science, for Paper 21 *International Symposium on Fire Safety Science,* No. 4, Ottawa, Canada, 13 - 17 June 1994. Organised by IAFSS. Proceedings, pp78-84, 1994; and Paper 28 *Fifth International Symposium on Fire Safety Science,* 3-7 March 1997, Melbourne: Australia. **www.iafss.org**

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Society of Fire Protection Engineers (SFPE), for Paper 22 *Arthur B Guise Lecture,* SFPE Seminar May 1994. **www.sfpe.org**

SP Swedish National Testing and Research Institute, Boras, Sweden, for Paper 23 *Proceedings of the International Conference on Fires in Tunnels,* Boras, Sweden October 10-11 1994. SP Report 1994:54. **www.sp.se**

Institution of Fire Engineers (IFE), for Paper 24 *Seminar Fire Safety Management in the Process Industry,* 21 March 1995, AEA Conference Centre, Warrington; and Paper 26 *Partnership in Fire Safety Engineering Design of Buildings,* Seminar at AEA Technology, Warrington, 4 and 5 May 1995. **www.ife.org.uk**

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University of Greenwich, for Paper 29 *An inaugural lecture delivered at the University of Greenwich,* 3 June 1997. **www.gre.ac.uk**

With regards to Paper 16 *Journal of Applied Fire Science,* 1 (1) 3-6 1990-1, every effort has been made to trace the owner of this article without success. It has been retained in this edition as it was include in the original edition of “Selected Papers by Margaret Law”.

We also gratefully acknowledge the photographers for the following pictures used in the introduction to each paper:

Mike Taylor/Arup for the Lloyds Building, Paper 11

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Rail Link Engineering for St Pancras Station, Paper 27

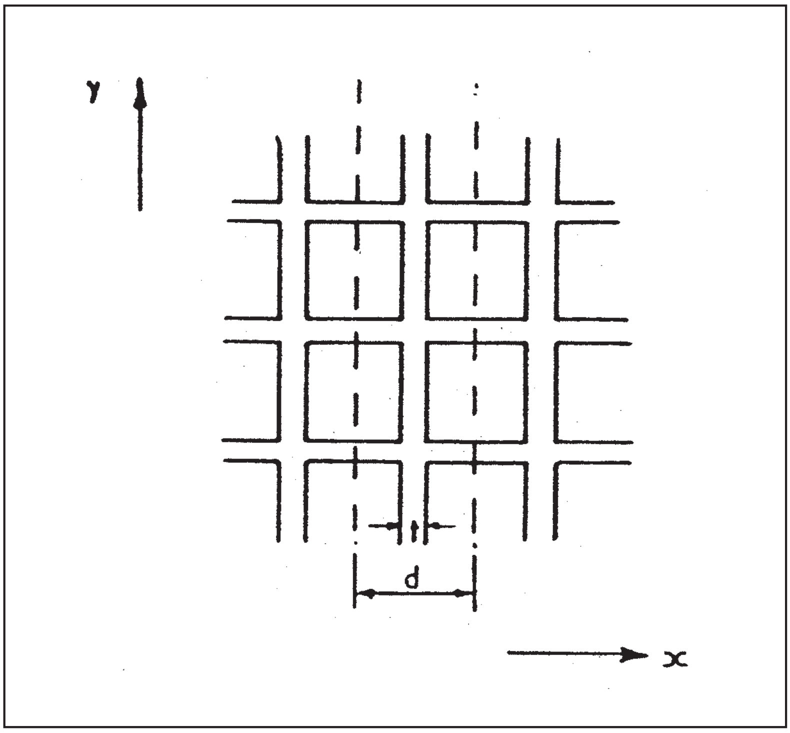
Her Majesty’s Stationery Office for the front cover of the Fire Research Station 1952 Annual Report, Paper 29.

PAPER 1

The performance of spark guards

J.H. McGuire, BSc, AMIEE, AInstP and Margaret Law, BSc, Fire Research Station, Boreham Wood, Herts, British Journal of Applied Physics, Vol. 9 December 1958, pp 470-474. Institute of Physics, UK

Figure used to describe the probabilistic analysis of a spherical particle passing through the mesh of a spark guard.



Many fires in the home used to be started by glowing coals, flying embers, and sparks from open grates. Although fireguards were widely used, fine mesh spark guards were not popular because they cut down too much radiation. Accordingly, we at the Fire Research Station were asked to investigate the effect on the ignition hazard if the mesh size of these spark guards was increased. At the same time, Dennis Lawson (Head of the Physics Section and later Director of the FRS) came up with the idea of using newly developed plastic fibre mesh instead of the traditional metal mesh. Lawson also introduced me to probit analysis.

Before long, the spark guard problem was solved in a completely different way. After a winter when there was an appalling number of deaths caused by fog, legislation was brought in to permit only smokeless fuel to be used for home heating.

ORIGINAL CONTRIBUTIONS

The performance of spark guards*

By J. H. McGuire, B.Sc., A.M.I.E.E., A.Inst.P., and Margaret Law, B.Sc., Fire Research Station,
Boreham Wood, Herts.

[*Paper received* 23 *April*, 1958]

The probabilities that various sizes of live coal will ignite various domestic materials have been determined. In addition the maximum probability that a coal will pass through a mesh has been calculated. Combining the two results has given a measure of the efficiency of spark guards in reducing fire risk. It is suggested that non-flammable Nylon net is a suitable material for a combined fire and spark guard.

INTRODUCTION

The Fire Brigades in the United Kingdom are notified of about 6000 incidents each year in which domestic open fires, either guarded or not, are responsible for igniting nearby materials other than structural timber underneath the hearth. Although all means of ignition (e.g. clothing falling on to the fire whilst being aired, ignition by radiation, etc.) are included in arriving at the above figure, it is probable that the use of almost any form of spark or fireguard would substantially reduce the figure since it would ensure that combustible materials were kept clear of hot coals. (A fireguard is a rigidly fixed device intended, firstly, to prevent children and infirm people from falling on to the fire, and secondly, to reduce the risk of ignition of clothing which, whilst being worn, might otherwise be brought into contact with hot coals. A spark guard is a device intended to retain flying coals and sparks, and is usually not as robust as a fireguard.) The importance of guarding an open fire, with a view to reducing burn injuries caused by contact with hot coals and by clothing igniting, has been stressed by Colebrook and Colebrook(1) and has been recognized in law.(2) The scope of this paper is confined to the fire risk created by flying coals and sparks, and the reduction in this risk which can be brought about by the use of a spark guard. The ignitability of materials by flying coals and sparks has been determined experimentally, and the effect of using a spark guard has been assessed by combining the above results with predictions of the probability that a live coal will pass through a specified spark guard mesh.

The effect of the use of a spark guard on room heating is also discussed, and the possible use of non-flammable Nylon net as a spark guard is examined.

THE IGNITION OF DOMESTIC MATERIALS BY LIVE COALS

The coal used in all the tests was Midland Singles, which is a bituminous, high volatile, non-coking coal. Standard conditions were obtained by heating the coals in a bunsen flame. They were thus ignited quickly and could be projected on to the samples of material whilst still distilling volatiles at a rate sufficient to maintain flaming. To represent the most hazardous conditions likely to be encountered in practice, the coals were dropped directly on to the material, a distance of about 3 in.

Table 1 lists the materials tested for ignition by burning coals. They were chosen as examples of the more easily ignitable materials likely to be found near to an open fire.

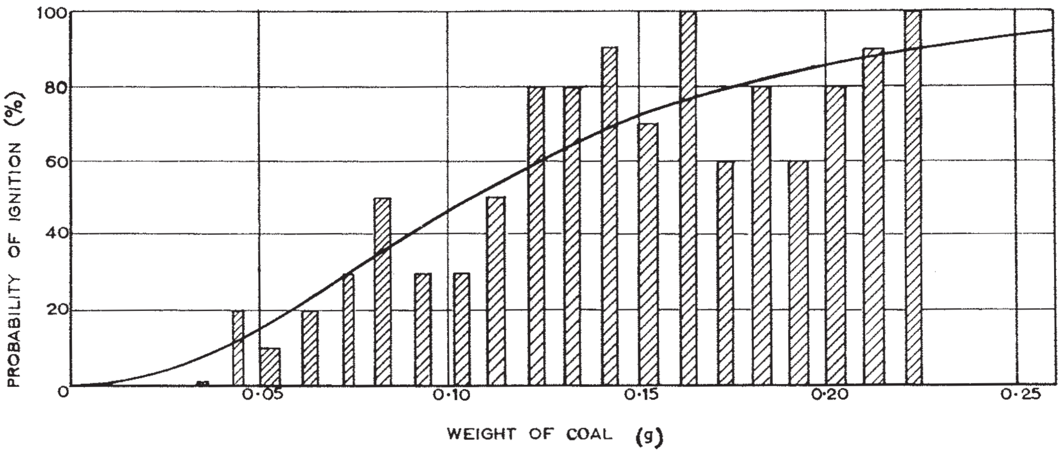


Fig. 1. Probability of a piece of burning coal igniting brushed scrim

Table 1. *Materials tested*

Material	*Weight/unit area* (*g/cm*^{2})
Cotton	$1{\cdot}2 \times 10^{-2}$
Viscose rayon net	$1{\cdot}8 \times 10^{-3}$
Hessian scrim	$2{\cdot}2 \times 10^{-2}$
Newspaper	$5{\cdot}5 \times 10^{-3}$
Belgian cotton carpet	$0{\cdot}12$
Surgical cotton wool	—

All the specimens of material were dried before testing and the scrim was brushed, since it was found to be more easily ignited in this condition. Its appearance, when brushed, resembled that of the scrim commonly found underneath arm chairs.

Cotton wool, irrespective of its disposition, was readily ignited by pieces of coal weighing only 0·005 g. As this weight corresponds to a diameter of only 0·075 in. for a spherical particle, it was concluded that cotton wool would always present a hazard and that it would not be practicable to design a spark guard to overcome this.

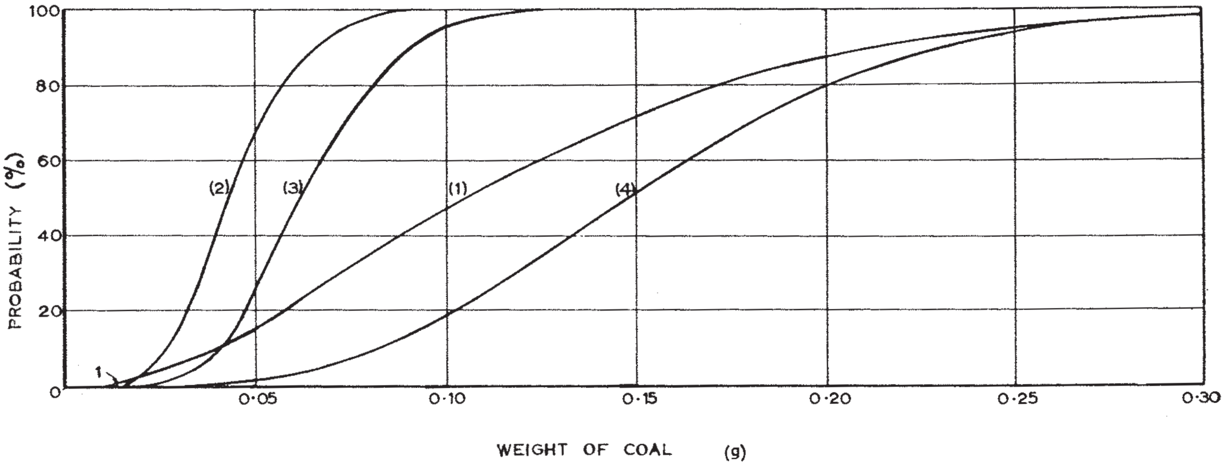


Fig. 2. Probability of a piece of burning coal igniting various materials

Curve (1), scrim; curve (2), viscose rayon net; curve (3), newspaper; curve (4), cotton.

With Belgian cotton carpet, laid horizontally, no continuing fire was started when pieces of flaming coal with dimensions of the order of 0·5 in. were dropped on it. It was therefore concluded that this material did not present an appreciable hazard from this point of view and no further tests were made on it.

The results for brushed scrim are shown in Fig. 1 in the form of a histogram in which each block represents ten experiments. It has been assumed that a finite probability of igniting materials exists for coals even smaller than those tested and a probability curve for all ranges of weight of coal has been calculated by probit analysis (see Appendix I). This is also shown in Fig. 1. The adoption of probit analysis automatically involves the assumption that a finite (though very small) probability of igniting a material exists for every size of coal however small, whereas theoretically there is possibly a threshold energy level below which a fire cannot be initiated. The consequent exaggeration of the hazard where very small coals are concerned will not greatly influence the estimation of the performance of spark guards.

A probit analysis was made of the histograms derived from testing the remaining materials and the resulting probability curves (including that for brushed scrim) are shown in Fig. 2.

THE PERFORMANCE OF SPARK GUARDS

The reduction in fire risk. No information is available as to the distribution of the geometrical shapes of the particles emitted by a domestic open fire. In deriving expressions for the probability that a piece of coal will pass through a mesh (Appendix II), two shapes, a sphere and a cylindrical particle, with a length/diameter ratio of eight have therefore been assumed as the practical extremes. The probability for a spherical particle may be greater or less than that for a cylindrical particle, depending on the actual mass and on the size of the mesh. Whichever is the larger is referred to as the probability for any given mass. Some calculated results are shown in Fig. 3. From these and the experimental results for the probability of ignition of a fabric by a given mass of coal, the combined probability that a coal will both pass through a mesh and ignite a fabric can be obtained.

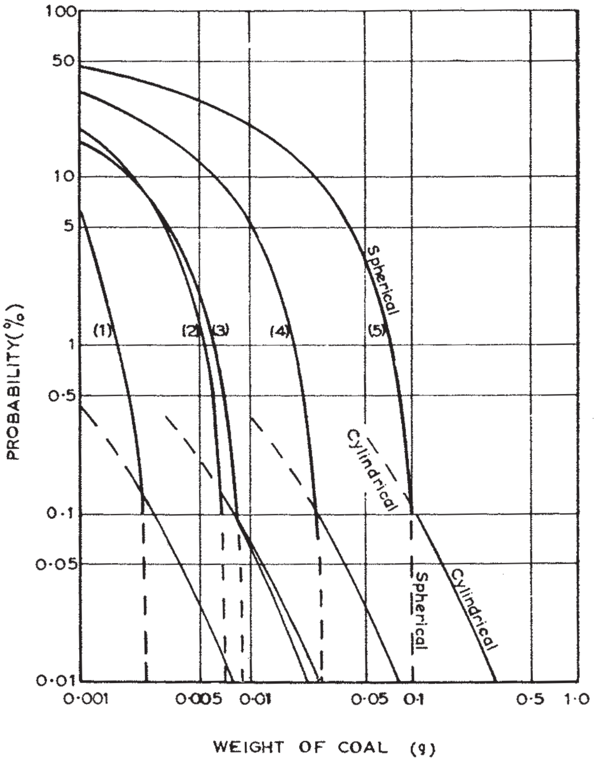


Fig. 3. Probability of a piece of coal passing freely through a mesh

Curve (1), non-flammable Nylon net *A*; curve (2), non-flammable Nylon net *B*; curve (3), 8-mesh (22 s.w.g.); curve (4), 6-mesh (22 s.w.g.); curve (5), 4-mesh (20 s.w.g.).

Fig. 4 shows the combined probability curves for an eight-mesh (22 s.w.g.) guard. Similar curves have been obtained for six-mesh (22 s.w.g.) and four-mesh (20 s.w.g.) guards and for two permanent finish non-flammable Nylon meshes, *A*, 45 denier, and *B*, 150 denier. For any given mesh size and fabric there is a mass of coal for which this combined probability is greatest. The largest of these peak values for the four materials tested has been called the maximum probability, and for the various meshes considered these values are given in Table 2.

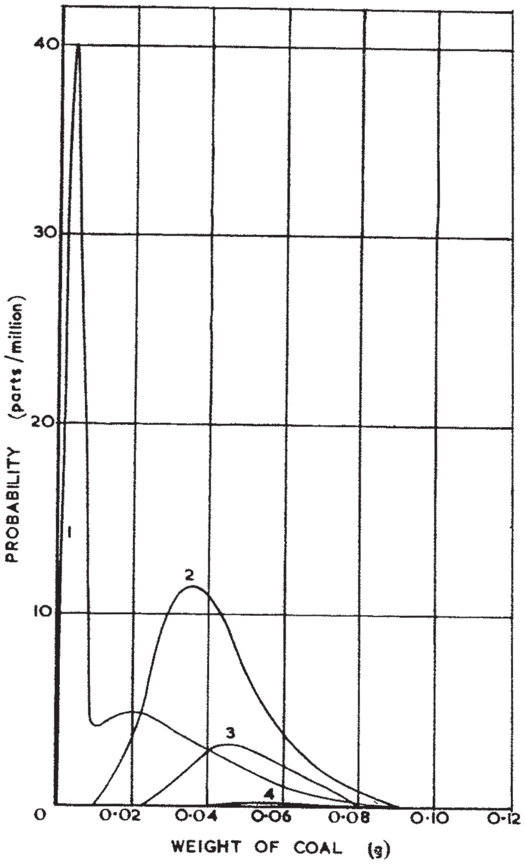


Fig. 4. Probability of a piece of coal both passing through eight-mesh (22 s.w.g.) and igniting various materials

Curve (1), scrim; curve (2), viscose rayon net; curve (3), newspaper; curve (4), cotton.

Table 2. *Maximum probabilities of ignition of the materials listed in Table 1 (excluding cotton wool and Belgian cotton carpet)*

Guard		*Maximum probability of ignition (parts per million)*
8-mesh (22 s.w.g.)		40
6-mesh (22 s.w.g.)		340
4-mesh (20 s.w.g.)		24 000
Non-flammable	Nylon *A*	3·3
	Nylon *B*	34

To confirm that the non-flammable Nylon nets would, in fact, not melt in practice, they were hung vertically and, whilst subjected to an intensity of radiation of 0·5 cal $cm^{-2} s^{-1}$ (representing the maximum intensity they would receive from an open fire), flaming coals with linear dimensions up to $\frac{1}{2}$ in. were projected on to them. The nets were structurally undamaged. If a hot coal rested against either of the nets, however, the Nylon in contact with the coal melted.

The effect on room heating. A domestic open fire heats a room largely by radiation and the use of a guard will, to a close approximation, reduce radiative heating by the amount which is intercepted by the elements of the mesh. The consequent heating of the guard contributes little to the heating of a room because the guard is cooled by the substantial air flow from the room which passes directly up the flue. As a measure of the reduction in radiation the obscuration has been calculated in the case of the metal meshes and measured experimentally in the case of the Nylon nets. The results are given in Table 3.

Table 3. *Obscuration of radiation by guards*

Guard		*Obscuration* (%)
8-mesh (22 s.w.g.)		40
6-mesh (22 s.w.g.)		30
4-mesh (20 s.w.g.)		27
Non-flammable	Nylon *A*	13
	Nylon *B*	18

Strength of meshes. Spark guards with metal meshes have been widely used for many years and have been found to be satisfactory from the strength point of view. The three meshes considered are typical of those on the market and are adequately strong. Nylon net guards, however, have never been available, and although they are strong enough to deflect hot coals they might be damaged by misuse. It was found that Nylon *A* could be punctured by forcing a pencil against it, but that Nylon *B* was considerably more robust and should be able to stand considerable rough usage.

CONCLUSIONS

The results in Tables 2 and 3 show that the six- and eight-mesh guards are far more effective than the four-mesh guard in reducing fire risk, whilst the amounts by which they reduce room heating are increased by much smaller factors.

The Nylon meshes are superior to the wire meshes both in their efficiency in reducing fire risk and in the extent to which they reduce obstruction of radiation. They are, however, not quite so robust and if hot coals come to rest against them they will melt. This might happen if the Nylon net extends down to hearth level and large coals fall on the hearth.

Nylon net will have a valuable application in the manufacture of combined fire and spark guards. To date these have not been popular since, if constructed of fine wire mesh, they substantially reduce room heating. By using a Nylon instead of a fine wire mesh this effect will be much less marked.

It should be noted that, of the domestic materials tested, cotton wool was found to present so exceptional a hazard that it would not be practicable to design a spark guard giving a substantial reduction in the risk.

ACKNOWLEDGEMENT

The work described in this paper forms part of the programme of the Joint Fire Research Organization of the Department of Scientific and Industrial Research and Fire Offices' Committee; the paper is published by permission of the Director of Fire Research.

Acknowledgement is due to the Assistant Director, Mr. D. I. Lawson, for drawing attention to the potentialities of non-flammable Nylon net as a spark guard, and to Miss J. E. Miller for undertaking much of the work described.

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(1) Colebrook, L., and Colebrook, V. *Lancet*, 2 (6570), pp. 181–188 (1949).

(2) *Children and Young Persons (Amendment) Act*, 1952 (London: H.M. Stationery Office, 1952).

(3) Finney, D. J. *Probit analysis. A statistical treatment of the Sigmoid response curve.* 2nd Ed. Chapters 3 and 4 (London: Cambridge University Press, 1952).

APPENDIX I

Probit analysis

Analysis of the experimental results has been carried out on the hypothesis that the probability of ignition is Gaussian with respect to the cube root of the mass of the coal. Probit lines have been calculated on this assumption; their linearity has been tested by the χ^2 test and there is no significant heterogeneity.(3)

The equations of the probit lines for the four materials are given in Table 4, together with the 95% confidence limits,

where y is the probit corresponding to a probability of ignition p

$x = m^{\frac{1}{3}} \times 10$

and m is the mass of coal in grammes which gives probability of ignition p

Table 4. *Probit analysis of the ignition of various materials*

Material	*Probit line*	*95% confidence limits to x*
Cotton	$y = 1{\cdot}441x - 2{\cdot}634$	$1{\cdot}12x - 0{\cdot}65 \pm 1{\cdot}52\sqrt{[0{\cdot}018 + 0{\cdot}057\,(x - 5{\cdot}45)^2]}$
Viscose rayon net	$y = 2{\cdot}509x - 3{\cdot}842$	$1{\cdot}17x - 0{\cdot}62 \pm 0{\cdot}92\sqrt{[0{\cdot}034 + 0{\cdot}241\,(x - 3{\cdot}62)^2]}$
Hessian scrim	$y = 0{\cdot}986x + 0{\cdot}338$	$1{\cdot}08x - 0{\cdot}37 \pm 2{\cdot}14\sqrt{[0{\cdot}009 + 0{\cdot}018\,(x - 4{\cdot}9)^2]}$
Newspaper	$y = 2{\cdot}437x - 4{\cdot}634$	$1{\cdot}15x - 0{\cdot}61 \pm 0{\cdot}93\sqrt{[0{\cdot}026 + 0{\cdot}204\,(x - 4{\cdot}04)^2]}$

APPENDIX II

The probability of a particle passing freely through a mesh

Spherical particle. The total probability may be considered as the product of the probability of a sphere not engaging on a horizontal wire and the probability of a sphere not striking a vertical wire (Fig. 5). The probability of a particle not striking a vertical wire will now be discussed. If the centre of a particle of diameter D lies within the x co-ordinate zero and d, the probability of its centre lying in any range δx is $\delta x/d$. The particle will not strike the wire if the x co-ordinate of its centre lies within the range zero and $\frac{d}{2} - \frac{t}{2} - \frac{D}{2}$ or the range $\frac{d}{2} + \frac{t}{2} + \frac{D}{2}$ and d, i.e. a range $d - t - D$. The probability of this occurring is $\frac{(d - t - D)}{d} = 1 - [(D + t)/d]$

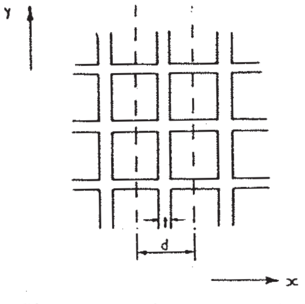


Fig. 5. Section of guard

Of the particles which will not strike the vertical wires the fraction which will not strike the horizontal wires is also $1 - [(D + t)/d]$. The probability of a particle passing freely through the mesh is therefore $\{1 - [(D + t)/d]\}^2$.

Cylindrical particle. The particle is considered to have random orientation and direction of flight normal to the mesh (Fig. 6). This latter assumption will lead to the hazard being somewhat over-estimated and the results will therefore be conservative. From symmetry, only values of ϕ and θ between zero and $\pi/2$ need be considered.

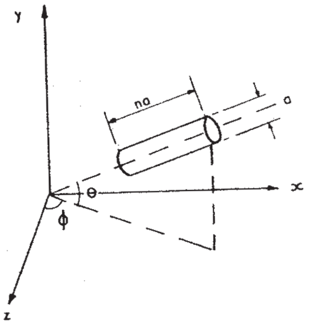


Fig. 6. Orientation of particle to mesh in *yx* plane

If the cylinder has diameter a and length na and the axis makes an angle θ with the zx plane, then the projection of the cylinder in the y dimension is

$$D_H = na \sin\theta + a \cos\theta$$

For a given value of θ the probability of passing freely between the horizontal wires is (from above)

$$P_H = 1 - \left(\frac{D_H + t}{d} = 1 - \right)\frac{a}{d}(n \sin\theta + \cos\theta) - \frac{t}{d}$$

The probability that θ will lie within the limits θ and $\theta + \delta\theta$ is $\cos\theta\delta\theta$. Combining these two probabilities gives

$$dP_H = \left[1 - \frac{a}{d}(n \sin\theta + \cos\theta) - \frac{t}{d}\right] \cos\theta d\theta$$

where the limits of θ are 0 and θ'

and $$a(n \sin\theta' + \cos\theta') = d - t$$

If the projection of the cylinder in the xz plane makes an angle ϕ with the z axis then the projection of the cylinder in the x dimension is given, for small values of θ

by $$D_V \simeq na \cos\theta \sin\phi + a \cos\phi$$

The probability of passing between the vertical wires for a given value of θ and ϕ is

$$P_V = 1 - \frac{D_V + t}{d} = 1 - \frac{a}{d}(n \cos\theta \sin\phi + \cos\phi) - \frac{t}{d}$$

The probability that ϕ will lie between ϕ and $\phi + \delta\phi$ is $2\delta\phi/\pi$. Combining these two probabilities gives

$$dP_V = \frac{2}{\pi}\left[1 - \frac{a}{d}(n \cos\theta \sin\phi + \cos\phi) - \frac{t}{d}\right]d\phi$$

where the limits of ϕ are 0 and ϕ'

and $\qquad a(n \cos\theta \sin\phi' + \cos\phi') = d - t$

The total probability of passing freely through the mesh is given by

$$P = \int_0^{\theta'} \int_0^{\phi'} dP_H dP_V$$

For particles of such dimensions that θ' and ϕ' are small, this expression reduces to

$$P = (d - t - a)/2\pi n^2 a^2 d^2$$

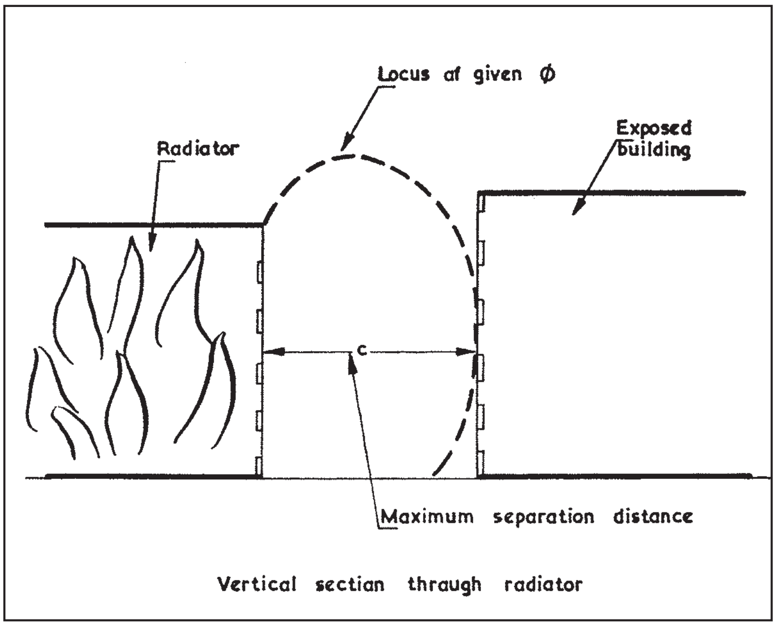
Combination of results. The two expressions derived in the above paragraphs have been evaluated and plotted in Fig. 3 for the various meshes, taking the density of coal as $1 \cdot 27$ g/cm^3 and $n = 8$ in the case of the cylinders. The extreme probabilities for all shapes of particle are given by the solid curves in Fig. 3.

PAPER 2

Heat radiation from fires and building separation

Margaret Law, BSc, Fire Research Technical Paper No. 5, 1963, Department of Scientific and Industrial Research and Fire Offices' Committee, Joint Fire Research Organisation. Reprinted in REH Read, (ed) 1991. External fire spread: building separation and boundary distance. Building Research Establishment Report BR 187, Borehamwood. HMSO, UK

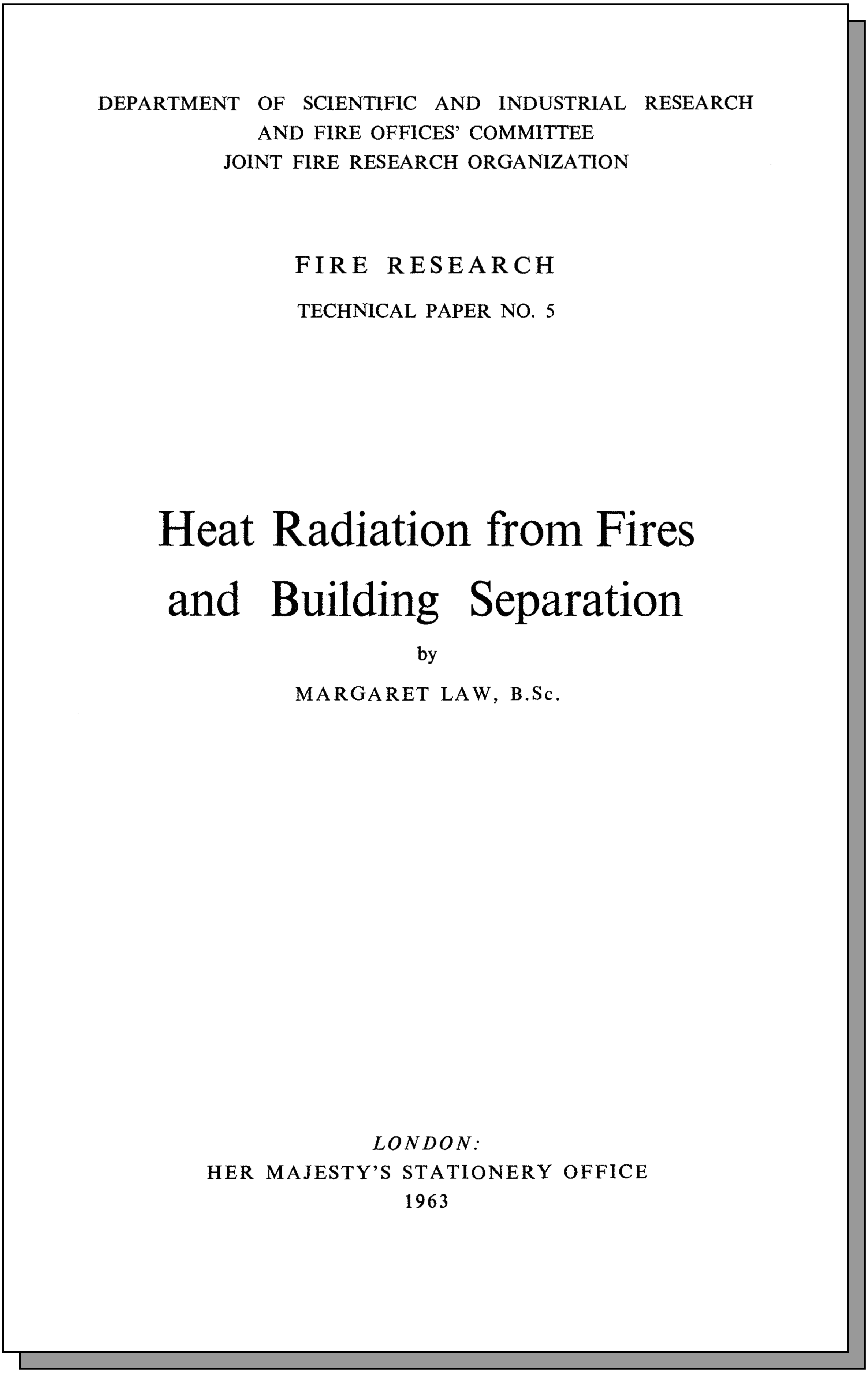
Figure used to describe the locus of a given configuration factor, which defines the necessary separation distance between buildings to minimise the risk of fire spread.



After the Great Fire of London in 1666, rules were drawn up that controlled street widths according to the size of buildings, and specified that external walls should be of fire resistant construction such as brick and stone. Through the succeeding centuries the windows normally occupied only some 30% of these walls, although the city by-laws actually placed no limit on the proportion of glazing that could be installed. When curtain-walling systems were introduced after the Second World War most were rejected because they did not have the fire resistance required by the by-laws. However, a curtain wall that was 100% glass and thus of negligible fire resistance could be accepted because it was called a 'window'. A new approach was needed. This paper gives the technical background to changes in the regulations, based on an estimation of the limiting intensity of radiation to be received by an exposed building and on the intensity of radiation emitted by the building on fire.

The legal system controlled the design method in two important ways. First, equations or diagrams were not permitted in a regulation. Secondly, there could only be control of the spacing of a building in relation to its site boundary and not to how far away it was from the building across the road. This problem was solved by the so-called 'mirror image' method: you calculated how far away you should be from a facing building and halved it to give the minimum distance to the boundary. Since the other building had to do the same from the other side of the boundary, the method was most exactly solved for buildings of similar size. This approach was checked out by the regulators on a number of city layouts and gave answers that were considered good enough.

This was my first experience of turning research results into a practical application. The regulators tried to find ways that the rules might be circumvented, but the method was robust enough to cope because the underlying assumptions –albeit very simple – were scientifically consistent.



DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH
AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

FIRE RESEARCH

TECHNICAL PAPER NO. 5

Heat Radiation from Fires and Building Separation

by

MARGARET LAW, B.Sc.

LONDON:
HER MAJESTY'S STATIONERY OFFICE
1963

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PREFACE

THE risk of spreading fire is one of the factors which must be taken into account in deciding the spacing between buildings. By studying the conditions under which materials ignite and the amount of radiation at various distances from buildings, it is possible to arrive at adequate separating distances.

The information in the report was used to assist the Building Regulations Inter-Departmental Committee in drafting building regulations for Scotland and it is hoped that the discussion of the principles will be of value in deciding adequate standards of fire protection.

It would be economically impracticable to provide for building separation such that spread of fire from one building to another could never occur. This paper provides a method for calculating separation so that the risk may be minimized, and where ignition of a neighbouring building may occur, to ensure that it will be sufficiently delayed to enable action by the Fire Brigade to be taken.

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January, 1963

Heat Radiation from Fires and Building Separation

SUMMARY

THIS report discusses the spread of fire by radiation from a burning building to neighbouring property. The levels of radiation likely to be encountered and their effect on combustible materials are considered. Flying brands are a hazard but it is considered that fires started by them would develop slowly and could be dealt with by the Fire Brigade. From these considerations, simple rules are developed for arriving at the separation between buildings to avoid fire spread.

INTRODUCTION

THIS report discusses the risk of fire spreading from a burning building to surrounding property due to heat radiation. It describes ways of determining the separation between buildings so as to reduce the hazard to an acceptable level, and considers methods of specifying requirements for building separation.

It has long been recognized that buildings must be adequately separated to reduce the risk of fire spreading from one to another. Buildings are not normally close enough for fire to be transferred by actual flame contact, nor are most building materials ignited by flying brands when these alight on a cold surface. However when brands alight on a surface heated by radiation from a fire, ignition is much more likely to occur and there is a very real possibility of secondary fires being started. Increasing the separation between buildings reduces the radiation hazard but, for a given separation distance, the intensity of radiation received by the exposed building depends on the area of the burning facade and the flames. Clearly a fire in a building with large windows or other large openings emitting radiation is more hazardous than one in a building with a small amount of openings and, with the trend in modern architecture towards larger windows, combustible cladding and curtain walling of low fire-resistance, the reliable assessment of exposure hazard is becoming increasingly important.

It is necessary, therefore, when planning the separation of buildings, to have a knowledge of two major factors:

(i) The levels of radiation which will ignite materials both on the outside of an exposed building and within the rooms due to radiation entering through the window.

(ii) The level of radiation from a fire in a building.

These factors have been investigated in a series of experiments by the Joint Fire Research Organization and by other workers, and the first part of this report is concerned with a discussion of their effect on building separation.

Once the basic requirements for building separation have been decided, it is possible to calculate the minimum separation necessary between two buildings. The report shows how this may be calculated for any size and type of building.

Since it is hoped that the information in this report could be used as a basis for legal requirements, and since the calculations may be somewhat complex, simplified methods of determining separation distance have also been devised. These simple methods give distances which are sufficiently accurate for most purposes. They have been designed so that any inaccuracy tends to over-estimation of the distances, but where this is considered undesirable then the more accurate calculation may be undertaken.

In practice the position of a building is planned in relation to its site boundary rather than to neighbouring buildings. The implications of this are discussed later.

EFFECT OF RADIATION ON COMBUSTIBLE MATERIALS

WHEN a building is exposed to radiation there is not only a hazard to any combustible material on the outside of the building, but also to the combustible contents of a room from radiation entering the windows.

The most commonly found combustible material on the exterior of buildings is wood and its behaviour when exposed to radiation is representative of a large variety of building materials. If it is exposed to a sufficiently high intensity it will ignite spontaneously; at a lower intensity it will only ignite if a subsidiary source of ignition is sufficiently near to the surface to ignite the flammable gases released by the heated surface (pilot ignition)(1). For a vertical surface this is generally within about ½ in.

Spontaneous ignition of wood will only occur for incident intensities above 0·8 cal $cm^{-2}s^{-1}$ (177 Btu $ft^{-2}min^{-1}$) and, except for certain types of behaviour (Appendix I) which will be disregarded, pilot ignition only occurs with intensities above 0·3 cal $cm^{-2}s^{-1}$. Spontaneous ignition in the open takes place fairly quickly after exposure to radiation and either occurs within about 2 min or not at all(2) but the ignition time for pilot ignition in the open can be much longer, and near the threshold level of radiation, heating times of the order of 10 min are needed before ignition can take place. Since with building fires a spark or flying brand can act as a subsidiary source of ignition, it is clear that pilot ignition is possible. It is not practicable at present to assess the effect of wind on dispersing sparks, flying brands etc., but it would seem desirable that the incident intensity should not exceed the minimum for pilot ignition, though at distances sufficiently large for the intensity to be near this minimum value, many sparks will have burnt out before they reach the exposed surface or indeed may not reach it at all. Even if the intensity should slightly exceed this minimum, there would still be a margin of safety since ignition would only occur some 10 min after the primary fire had become fully developed and it may be assumed that the Fire Brigade would be available to afford protection to the exposed building. The report of the Joint Committee on Standards for Fire Cover(3) recommends that for areas of concentrated building in industrial and commercial cities, the time of attendance of the first appliance should be 5 min after the call. Statistics for some large fires show that four out of five Fire Brigades in County Boroughs in the United Kingdom attend within 4 min(4). It would appear reasonable therefore to adopt as the criterion, a distance such that the intensity of radiation on the exposed building will not exceed the minimum for pilot ignition i.e. it should not exceed 0·3 cal $cm^{-2}s^{-1}$ (66 Btu $ft^{-2}min^{-1}$). Though minimizing risk, the possibility of an ember starting a fire is not completely eliminated but if such a fire were started it would develop slowly and would be dealt with by the Fire Brigade.

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The minimum intensities given above are for ignition of oven-dried wood unprotected by paint. In practice the wood will always contain some moisture which may have the effect of raising the minimum intensity at which ignition will occur(2). The amount of moisture in the exposed wood may vary but there is no condition which will be more hazardous than the oven-dried one. Most paints also raise the minimum intensity but, since weathering and cracking may expose bare wood, the protective value of any paint has not been taken into account. It will thus be seen that the figure taken of 0·3 cal $cm^{-2}s^{-1}$ errs on the side of safety.

Experiments(5) have shown that a material in an enclosure will ignite at a lower intensity of radiation than in the open, so that although the intensity of radiation falling on an exposed building may be below the minimum for pilot ignition in the open, there may still be a hazard to the contents of a room because of radiation coming through the window. Although the plate glass in a window can absorb some 40 to 60 per cent of the radiation from a building fire, it cannot be relied on to afford protection to the contents of the room since large areas are liable to crack and fall out. No figure of a maximum " safe " intensity for glass can be given with confidence since such variable factors as restraint at the edges and stresses in the glass itself affect its behaviour. The worst case of immediate cracking and falling out must therefore be assumed. Experiments(6) with one-tenth scale model rooms with an opening either 33 or 100 per cent of the area of the exposed wall showed there was a greater hazard with the larger opening. The rooms were furnished and lined either with plasterboard or fibre insulating board. A small gas flame was introduced to represent a subsidiary source of ignition such as a fire in the grate or other heating appliance. The experiments showed that with the larger opening and either type of lining, spontaneous ignition of one of the articles of furniture near the window would occur after 20-min exposure to an intensity at the opening of 0·3 cal $cm^{-2}s^{-1}$. With the 33 per cent opening, pilot ignition of the lining would occur within half an hour for an intensity of 0·8 cal $cm^{-2}s^{-1}$ with the plasterboard lining and 0·56 cal $cm^{-2}s^{-1}$ with the fibre insulating board lining. There is reason to believe that on full scale rather higher intensities of radiation would be needed to produce the above effects(5). The worst situation that can be envisaged is a room with one whole side occupied by a window, the glazing destroyed, and exposed to the peak radiation from a building fire for at least 20 min. When in addition the time taken for a fire to develop to its peak is considered, then the Fire Brigade, even at night, should be able to arrive sufficiently soon to protect the exposed building. It therefore appears reasonable to specify that the separation of buildings must be such that the incident intensity of radiation will not exceed 0·3 cal $cm^{-2}s^{-1}$.

INTENSITY OF RADIATION FROM COMPARTMENT FIRES

In general, the intensity of radiation, I, emitted from a hot body is related to its absolute temperature, T, according to the well-known law:

$$I = \varepsilon \sigma T^4 \qquad (1)$$

where ε is emissivity, less than or equal to unity

and σ is the Stefan-Boltzmann constant $= 1{\cdot}36 \times 10^{-12}$ cal $cm^{-2}s^{-1}$ deg C^{-4}.

The emissivity of a surface has a maximum value of unity and a small opening in a uniformly heated enclosure will radiate with an emissivity approaching unity. Thus a room or compartment fully involved in fire may be considered as approximating to this condition. For a large opening this assumption is not strictly correct but the hazard is only overestimated to a slight extent. The temperature and hence the radiation from a fire in a compartment varies with time, as the walls become hotter, and differs between compartments. Differences in the distribution and amount of fuel, in the geometry of the window and the compartment can affect the rate of burning and this will affect the temperatures attained. To make useful regulations, considerable simplifications have to be introduced and in this report only a typical value of the intensity emitted by fires for a wide class of buildings and occupancies is sought. The temperature of a burning compartment will obviously have an important effect on the heat radiated since this depends on a fourth-power relation (equation (1)) and it is necessary now to consider the temperature attained in fires in compartments.

The temperature of the fire depends on the rate of burning and fires may be considered as divided into two types:

(i) Those in which the ventilation is restricted and the rate of burning depends on the size of the window, and

(ii) Those in which the window area is comparable with the floor area where the rate of burning depends on the fire load*, its surface area and arrangement, and not on the window area. Such fires may be said to be fully ventilated.

These two types of fire will now be considered in more detail. It will be shown that for practical purposes the effect of ventilation on the rate of burning may be disregarded, and that for both types, the radiating intensity tends to an upper limit of 4 cal $cm^{-2}s^{-1}$ and the intensity is reduced if the fire load is small.

TYPE 1. FIRES WITH RESTRICTED VENTILATION

With this type of fire there are many more experimental values available for temperature than for radiation, and in using these data, temperatures measured near the ceiling are assumed to be typical of the maximum in the compartment. Some results are shown in Fig. 1 plotted as a function of $A\sqrt{H}$ where A is the area of the single window opening and H is the height of the window. $A\sqrt{H}$ is the most important parameter affecting the rate of burning irrespective of compartment size.

The temperatures attained increase with ventilation, the results tending to a limiting value of less than 1100° C which corresponds to a theoretical maximum radiating level of 4 cal $cm^{-}s^{2-1}$. The results indicate that there is no evidence of any marked increase of intensity as $A\sqrt{H}$ increases above 8 $m^{5/2}$, so that 4 cal $cm^{-2}s^{-1}$ can be taken as the maximum intensity for this type of fire.

It is clear from Fig. 1 that it is only when $A\sqrt{H}$ is less than 5 $m^{5/2}$ that ventilation has a significant effect on the temperature of the enclosure. Since one window measuring $1\cdot5$ m × 3 m (5 ft × 10 ft) gives a value of $5\cdot5\,m^{5/2}$ for $A\sqrt{H}$, it is apparent that for the majority of buildings a fire may always be considered capable of reaching temperatures of 1100° C.

There are however two conditions where the temperatures are significantly less than 1100° C.

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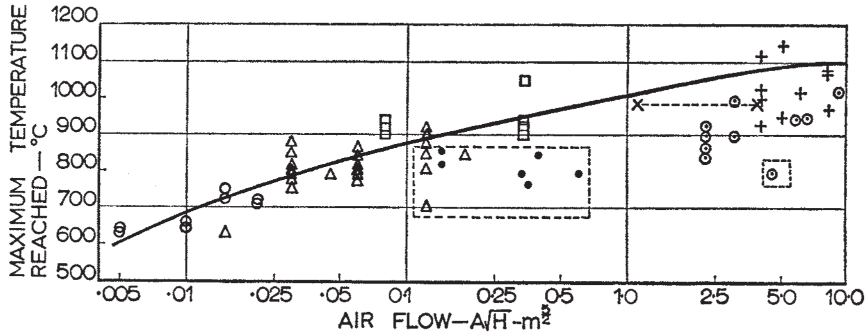
* " Fire load " denotes the total amount of combustible material in the enclosure.



Points within the broken lines are those where the fire load is less than 25 kg/m² (5 lb/ft²)

	Scale I floor area 0·09 m²	Scale II floor area 0·49 m²	Scale III floor area 1 m²	Large-scale floor area 9 m²
J.F.R.O. (7)(8)(10)	o	Δ	□	+
Swedish test (9)				×------×
Kawagoe (11)(12)			•	⊙

FIG. 1. Maximum temperature and air flow

Compartments with $A\sqrt{H}$ less than 5 $m^{5/2}$

It is assumed that the data for small values of $A\sqrt{H}$ in Fig. 1 can be used for full-scale compartments with small windows. It is clear that, for small values of $A\sqrt{H}$, separation would always be small simply on account of the small size of the window. Thus a reduced intensity, due to restricted ventilation, would introduce only a small absolute change in separation and the effect can therefore be disregarded.

Compartments with a small fire load

Where the fire load/unit floor area is 25 kg/m² (5 lb/ft²) or less, the fire does not last long enough for the compartment itself to become sufficiently hot and the radiating intensity is significantly less than 4 cal $cm^{-2}s^{-1}$. The data for such fires are shown enclosed by dotted lines in Fig. 1. It is therefore justifiable to take a lower intensity of radiation for fires of low fire load. The value of the reduced intensity is discussed below.

TYPE 2. FULLY-VENTILATED FIRES

When the window is comparable with or larger than the floor area, the fires burn at a rate which is largely independent of $A\sqrt{H}$ and the intensity emitted for a given size of compartment is found experimentally to be related to the rate of burning. The intensity of radiation gives a better correlation with the rate of burning per unit *window* area than the rate of burning per unit *floor* area and since the rate of burning in fully-ventilated fires is approximately proportional to the total amount of fuel, the intensity of radiation is shown in Fig. 2 in terms of the fire load per unit window area. However, for a fire of this type the window area must be comparable with the floor area, so that the horizontal scale of Fig. 2 may be taken, for the purposes of these arguments,

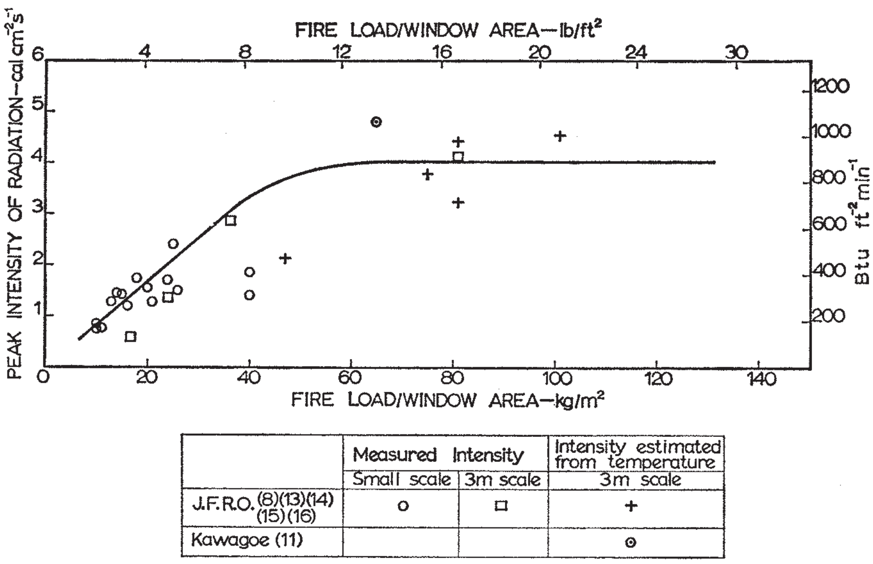


FIG. 2. Peak intensity of radiation at opening for fires where window and floor areas are comparable

as being nominally the same as the fire load per unit floor area, this being a familiar concept in the context of building regulations. In Fig. 2 there is a certain amount of scatter in the results and the line has been drawn to err on the side of safety. For comparison, peak intensities for some full-scale fires(8) (11), with openings exceeding half the floor area, have been estimated from their peak temperatures using equation (1), assuming an emissivity of unity. These are also plotted in Fig. 2.

The intensity emitted by fires of Type 2, as for Type 1, tends to an upper limit of about 4 cal $cm^{-2}s^{-1}$, and for fires of low fire load of Type 2 the intensity is proportional to the fire load. It is also justifiable therefore to allow a reduced intensity for fires of low fire load of Type 2 and in this context low fire load can be described in terms of fire load per unit floor area.

It is seen from Fig. 2 that for cubical compartments with large windows, the intensity of radiation is 2 cal $cm^{-2}s^{-1}$ for a fire load per unit floor area of about 25 kg/m^2 (5 lb/ft^2) and this has been taken as a secondary standard lower than the primary one of 4 cal $cm^{-2}s^{-1}$. Fires with less than 25 kg/m^2 (5 lb/ft^2) fire load per unit floor area would give temperatures less than about the value 800° C which corresponds to an intensity of radiation of 2 cal $cm^{-2}s^{-1}$.

Hence, for the purpose of devising regulations on space separation, 4 cal $cm^{-2}s^{-1}$ is taken as the normal standard and 2 cal $cm^{-2}s^{-1}$ for fire loads per unit floor area less than 25 kg/m^2 (5 lb/ft^2), for both Type 1 and 2 fires.

RADIATION FROM FACADES OF BURNING BUILDINGS

THE number of openings in a building which radiate will depend on how far the fire spreads inside the building. A fire in a building will tend to grow until it completely involves the room in which it started. It will spread to other rooms within the building until stopped by a fire division wall or ceiling. In theory the fire will involve the whole building if there are no such fire division walls but if there are it can be assumed that only the space bounded by them is involved. This space enclosed by fire division walls is called a fire compartment. Only one compartment would in theory radiate at a time and the required separation distance would be based on the compartment with the largest area of openings.

An opening can be considered here as any part of an external wall which has less fire-resistance than that specified for the building under consideration and hence could allow the transmission of radiation. A sub-standard part of a wall would be regarded as an opening. A wall clad with timber would be considered as an opening since the burning timber would act as a source of radiation and the area of any timber on part of the wall should be added to the area of openings. This procedure tends to over-estimate the hazard. On the other hand the contribution of flames outside a window to the radiation has been neglected. This is reasonable for a first approximation although there have been cases where large flames have been observed outside a window contributing radiation⁽⁵⁾. The size of these flames and the factors affecting them, both in still air and in the presence of a wind, are now being investigated and

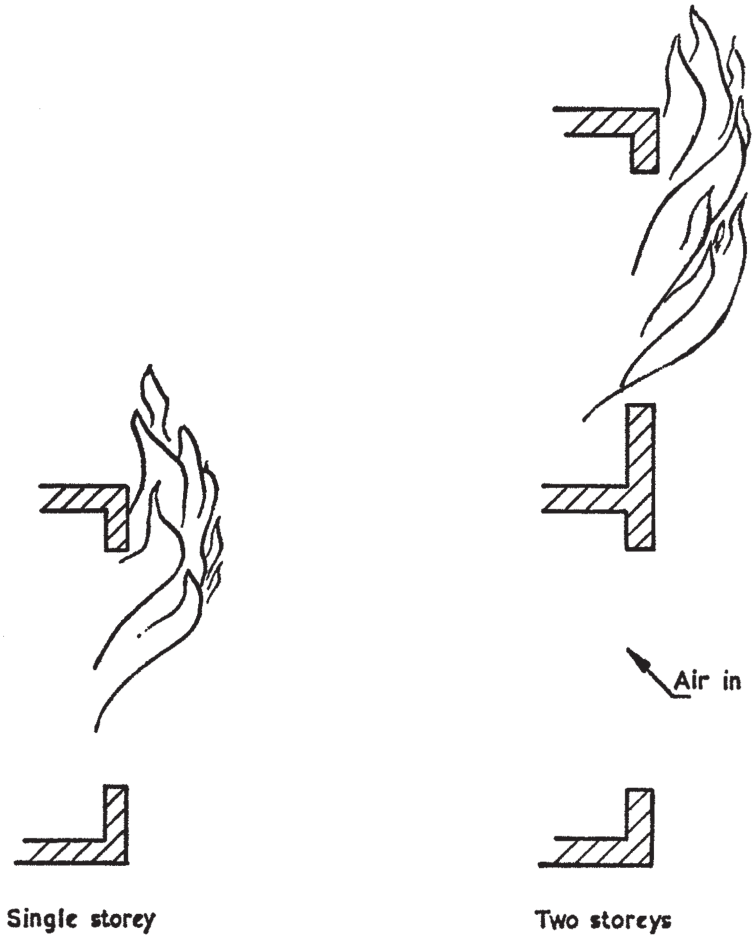


FIG. 3. Flames from burning buildings.

may lead to some modification, in certain cases, of the separation distances recommended in this report. One way of modifying the distances without changing the basis of these recommendations would be to ascribe an effective window area greater than the actual window area by some factor which could be determined separately. For unprotected buildings of more than one storey there will be a tendency for air to enter the lower openings and flames to emerge only from the upper ones, Fig. 3. The exposed building would be placed in position on the assumption (p. 11) that the point opposite the centre of the burning building would receive maximum radiation but the upper portion, exposed to the flames, would necessarily be, at least, at the same distance. The largest error in separation, due to the emergence of the flames, is likely to be for a single-storey building or a building with fire division floors.

CALCULATION OF INTENSITY OF RADIATION AT ANY POINT

HAVING dealt with the radiation emitted from a burning building, it is now necessary to discuss how much of the radiation will fall on a neighbouring building. If a point source is emitting radiation, then the intensity of radiation at any other point is inversely proportional to the square of the distance between them, i.e. the well-known inverse square law. If, however, the source of energy is not a point but an extended area (or volume) then this simple law does not hold and the intensity received at any point depends on the shape and orientation of the radiator with respect to the receiver.

Consider a small elemental area dA, at P' on a radiating surface of temperature T, at a distance R from a point P on a receiving surface (Fig. 4).

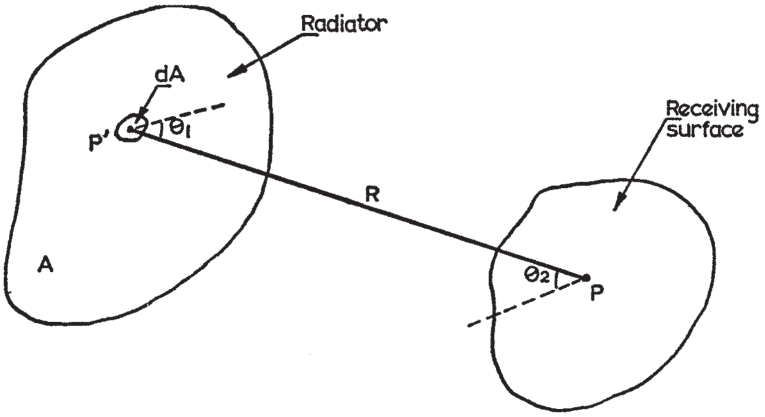


FIG. 4. Radiator and receiving surface

The normals to these surfaces make angles θ_1 and θ_2 with the direction $P'P$. It is assumed that the radiating surface emits radiation according to Lambert's cosine law; i.e. the amount of radiation per unit area in the direction $P'P$ is proportional to cos θ_1 so that in the direction of the normal it is a maximum, and parallel to the surface, when θ_1 is a right angle, it is zero. The law does not hold for all surfaces but may be assumed to hold for the purposes of this report with little loss of accuracy. The projection of the receiving surface at point P is similarly proportional to cos θ_2 and the intensity at P is:

$$dI \propto dA \cos \theta_1 \cos \theta_2 \varepsilon \sigma T^4$$

Since dA is small compared with R^2 the inverse square law holds and

$$dI \propto \frac{dA \cos \theta_1 \cos \theta_2 \varepsilon \sigma T^4}{R^2}$$

The values of dI are then summed for all the elemental areas dA over the area A for all the values of R giving:

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

The expression for dI only involves distance as a ratio $\frac{dA}{R^2}$ so that the integrated sum I at a point P is of the form $I \propto \varepsilon \sigma T^4$ and the constant of proportionality does not depend on distance or scale but only on relative shapes and relative distances. It is called ϕ the shape factor or configuration factor(17) and since the maximum intensity close to the radiation source is $\varepsilon \sigma T^4$, ϕ is always less than unity and measures the reduction in intensity at a distance. For large separations:

$$\phi \propto \frac{A}{R^2}$$

where

A is the radiating area

and

R is the separation.

Values of ϕ for different radiators have been calculated by various authorities(17) (18) for certain simple geometries so that given ϕ and A it is possible to find R.

A useful property of configuration factors is that they can be added or subtracted. Thus the value of ϕ for a number of radiators, is the sum of the values for each separate radiator. For example, the value of ϕ for area AEFGCD in Fig. 5 is that for ABCD minus that for EBGF.

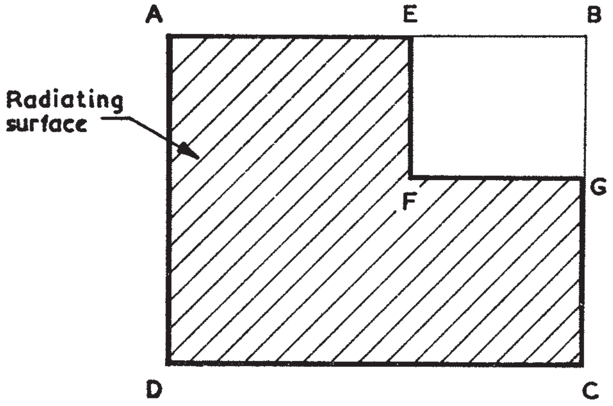


FIG. 5. Radiator with corner removed

Given the intensity of radiation emitted by a fire, assumed to be the same for all openings, and the dimensions and distribution of the windows and other openings of the building, it is therefore possible to calculate the maximum distance at which the intensity at a point on a vertical facade facing this building, if on fire, would not exceed $0 \cdot 3$ cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the minimum intensity for ignition.

If a burning enclosure is emitting I_o cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, where I_o is 4 or 2 according to the fire load per unit floor area, then the intensity at the point is given by:

$$I = \phi I_o$$

For a number of windows, n, similarly radiating:

$$I = (\phi_1 + \phi_2 + \phi_3 + \ldots + \phi_n)\, I_o$$

So that if $I = 0 \cdot 3$ cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$:

$$\sum \phi_n = \frac{0 \cdot 3}{I_o} \quad .$$

For I_o equivalent to 2 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, this defines separation as the distance where the maximum value of ϕ_n is less than $0 \cdot 15$ and for I_o equivalent to 4 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, less than $0 \cdot 075$. ϕ relates dimensions and shape of the radiating source to the separation distance so that, given the dimensions and dispositions of the windows, it is possible to find the distance to give the required value of $\sum \phi_n$.

The calculation of separation distance can thus be expressed as a purely geometrical problem which is the approach discussed by Bevan and Webster(19). Since windows are almost invariably rectangular in shape, only configuration factors for rectangular radiators will be considered, and the exposed point will

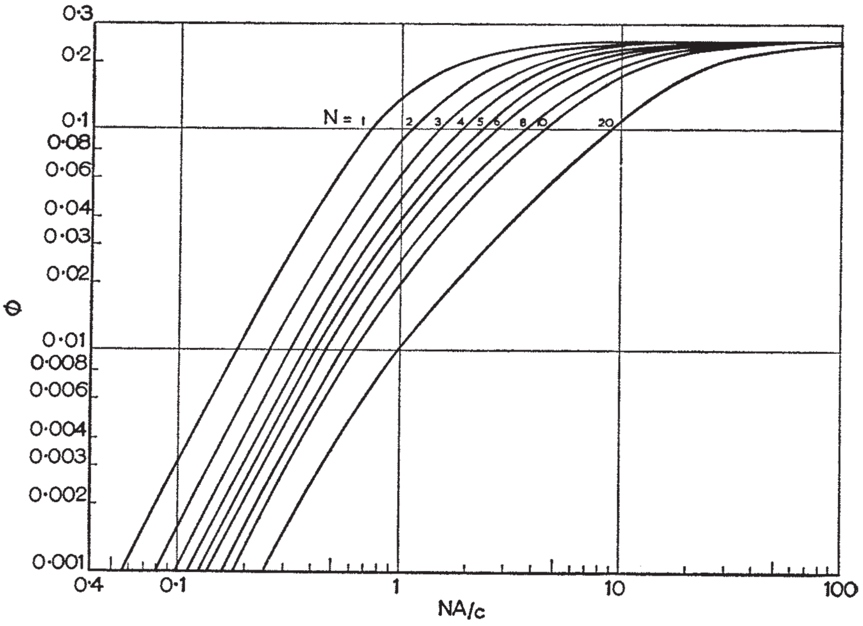


FIG. 6. Configuration factor ϕ for differently shaped radiators

be assumed to be on a vertical plane parallel to the plane of the radiator, since opposite the centre of the radiator a parallel plane receives the maximum level of radiation. For other shapes and other orientations, reference can be made to the authorities already quoted. Values of ϕ(17) (18) are given in Fig. 6 for a point P on a perpendicular axis through the corner of the rectangular radiator, as shown in Fig. 7(a). By using the additive property of configuration factors, the value of ϕ at any point can be found. Thus in Fig. 7(b) the value of ϕ at P is the sum of ϕ for the rectangles AEP′H, EBFP′, P′FCG and HP′GD, and in Fig. 7(c) the sum for rectangles AEP′G, GP′FD minus the sum for BEP′H and HP′FC. Fig. 6 shows that for a point opposite the corner of a rectangular radiator ϕ cannot exceed 0·25, and it is clear that for ϕ to approach unity the point must be opposite the centre of the rectangle, since the point will then receive radiation from four rectangles. In general, for a rectangular radiator, the maximum intensity at any distance lies on the perpendicular axis through the centre of the rectangle and for more general application it is convenient to employ the additive property and Fig. 6. For more than one radiator, the position at which there is maximum intensity in any plane depends on the relative positions and sizes of the radiators.

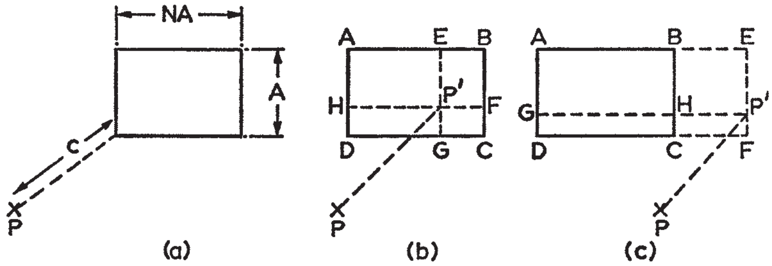


FIG. 7. Additive property of configuration factors

The minimum separation distance is the maximum distance at which an intensity of 0·3 cal $cm^{-2}s^{-1}$ can be received. This, as has been shown above, introduces a safety factor which tends to counteract the neglect of flame radiation.

The above outline of the principle of evaluating the necessary separation distance from the required value of ϕ and the size of radiator, usually rectangular, leads to tedious calculations and any application of the general method will not be discussed here. The remainder of the report is concerned with practical application in the light of simplifications to the above arguments.

SPECIFICATION OF BOUNDARY DISTANCE

IN practice, when a building is being planned, the position of the potentially exposed neighbouring building is not known and it is necessary to place the former building in relation to its site boundary. For this, and legal reasons it is the boundary distance which is specified in regulations. One obvious way of specifying this boundary distance, is to make it half the separation distance, so that if two similar buildings, one the mirror image of the other, are then placed on opposite sides of the boundary, the distance between them is the correct separation distance. For two dissimilar buildings, however, the building with smaller openings and hence with the smaller boundary distance, may receive a higher intensity of radiation than 0·3 cal $cm^{-2}s^{-1}$, if the other is on fire. To allow for such inequalities as these, a larger fraction than half the separation distance might be specified. However, to ensure that in every situation no less than the correct separation would be attained, there would be land wasted since, in the limiting and absolutely safe condition, the separation would have to be such that the intensity at the boundary did not exceed 0·3 cal $cm^{-2}s^{-1}$. If the principle of placing buildings in relation to the site boundary must be accepted, then some form of compromise is inevitable.

It may be noted that, in general, the maximum intensity of radiation will be received opposite the centre of the facade of a burning building and a small building exposed to fire may be well below this level. Thus a smaller building may not be at so much of a disadvantage as appears at first sight.

It has been suggested that for the " mirror image " criterion it would be simpler to specify an intensity at the boundary, rather than half the distance for an intensity of 0·3 cal $cm^{-2}s^{-1}$. However, for the correct separation distance, the intensity at the boundary depends on the shape of the buildings and amount of openings, since the variation of intensity with distance from a rectangular radiator does not follow a simple law. For example, consider two pairs of buildings with 100 per cent openings, one pair very wide and the other square. The intensity halfway between the wide buildings is 0·6 cal $cm^{-2}s^{-1}$ and halfway between the square ones is 0·95 cal $cm^{-2}s^{-1}$. By choosing an intensity at the boundary to cover all types of building, it can be shown that the boundary distance might be as much as 40 per cent greater than half the separation distance. However, such a specification would remove some of the discrepancies outlined in the preceding paragraph and the possibility of specifying boundary distances in this way, as another form of compromise, could be borne in mind.

The remainder of this report is devoted to illustrating simplified methods of obtaining the separation distance *c*. If the boundary distance *b* is taken as half this value, then *b* can be found by substituting in each case:

$$b = \frac{c}{2} \quad .$$

CALCULATION OF SEPARATION DISTANCE

ELEVATION WITH A NUMBER OF OPENINGS

For most elevations with a number of windows, the problem can be reduced to that of a single radiator. This single radiator is the rectangle which totally encloses all the openings in the elevation (termed the overall enclosing rectangle) considered as radiating at a reduced intensity, the reduction factor being the ratio of the total area of all the openings to the area of the enclosing rectangle. Thus, if the area of the openings were 50 per cent of the area of the enclosing rectangle and the building contained a normal fire load, then the intensity 4 cal $cm^{-2}s^{-1}$ would be reduced by a factor 50/100 and the effective radiating intensity of the rectangle would be taken as 2 cal $cm^{-2}s^{-1}$. The appropriate configuration factor would then be calculated to find the required separation distance.

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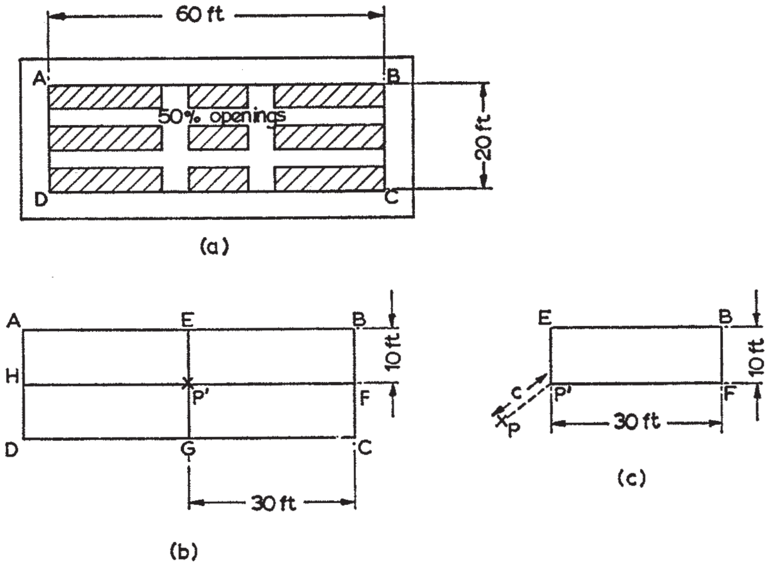

Equivalent radiator with $I_0 = 2$ cal cm^{-2}s^{-1}

FIG. 8. Elevation with a number of openings

Consider the elevation in Fig. 8(a). The rectangle ABCD encloses all the openings and their area is 50 per cent of the area of ABCD. The equivalent radiator is shown in Fig. 8(b) with $I_o = 2{\cdot}0$ cal cm^{-2}s^{-1} .

Therefore:

$$\phi_n = \frac{0{\cdot}3}{2{\cdot}0} = 0{\cdot}15$$

At any distance, ϕ_n is a maximum on the line normal to the centre of the rectangle so that the point on this normal, when $\phi_n = 0{\cdot}15$, gives the minimum separation distance.

ϕ_n for the point P is the sum of ϕ for each of the separate rectangles, as in Fig. 7(b), and since these rectangles are identical:

$$\phi_n = 4 \times \phi \text{ for EBFP}'$$

Therefore:

$$\phi \text{ for EBFP}' = \frac{0{\cdot}15}{4} = 0{\cdot}0375$$

Referring to Fig. 6:

$$A = 10 \text{ ft}$$

$$N = 3$$

and for

$$\phi = 0{\cdot}0375, \frac{NA}{c} = 0{\cdot}69$$

Therefore:

$$c = 44 \text{ ft} \quad .$$

Separation distances have been calculated for different percentages of opening and different length to width ratios and are shown in Figs 9 and 10 for

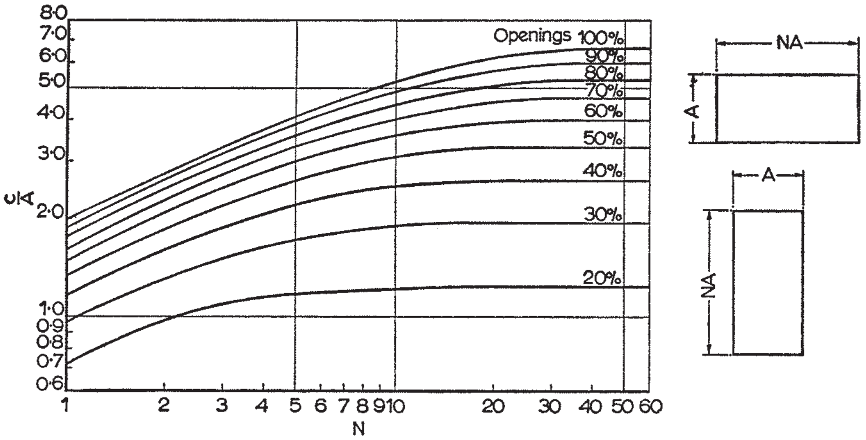

FIG. 9. Separation distance *c* for normal intensity fire (Fire load per unit floor area greater than 5lb/ft²)

fire loadings per unit floor area respectively greater and less than 5 lb/ft². It is clear from these figures that for large values of *N*, *c*/*A* is constant and that once a radiator is a certain length, any increase in length (i.e. any increase in *N*) makes no difference to the separation distance as measured by *c*/*A*. This may be visualized by imagining that an observer is standing in front of a wall sufficiently long for the ends to appear to vanish into the distance, so that if a piece were added to the end, the addition would not be perceived. Similarly, a receiver in front of a sufficiently long radiator cannot " see " extra radiation from the end. For a given incident intensity, the value of *N* at which *c*/*A* becomes constant depends on the radiating intensity and here for small percentages of openings, *c*/*A* rapidly reaches its steady value. It is sufficient for practical purposes that, for percentages of openings with values between those shown in Figs 9 and 10, the curve with the next higher value should be used.

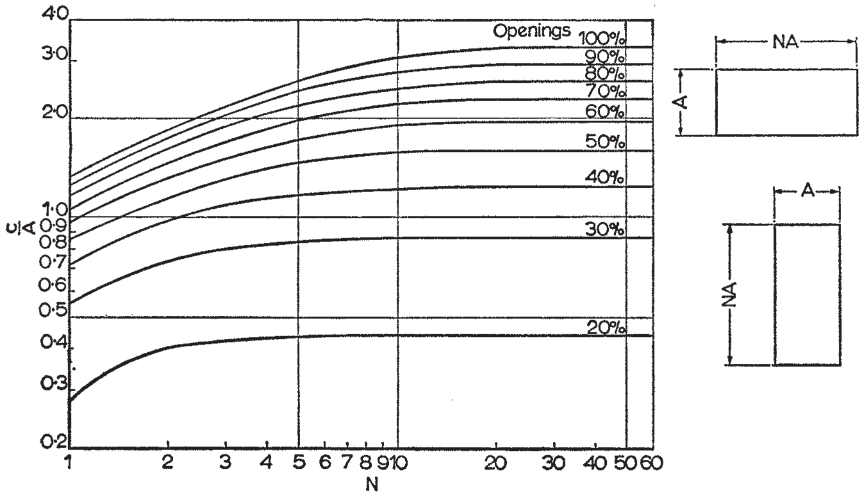

FIG. 10. Separation distance *c* for low intensity fire (Fire load per unit floor area less than 5lb/ft²)

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EXPERIMENTAL DETERMINATION OF CONFIGURATION FACTOR

The configuration factor for an elevation with any number of openings could alternatively be found with an optical analogue, which exploits the similarity between the transmission of light and thermal radiation. A piece of diffusing glass is evenly illuminated and used as the radiator. This glass is then masked except for portions representing the radiating openings and the light intensity at any point is measured by a photo-electric cell(20). The intensity close to an open portion i.e. the maximum intensity, is also measured by the cell. The ratio of the intensity at any distance to this maximum value is the value of ϕ at the point chosen, all distances being scaled in proportion.

With this device it is possible to find the values of ϕ for facades which are of too complicated a shape for simple calculations to be practicable.

VARIATION IN SEPARATION DISTANCE

The distance normal to a rectangular radiator at which the intensity is a given fraction of the intensity at the window, is a maximum opposite the centre and is less opposite the edges. The locus of a given configuration factor, defining the necessary separation distance, is shown diagrammatically in Fig. 11 for vertical and horizontal sections normal to the radiating surface and through its centre point. The vertical section shows that the separation distance of some of the storeys of the exposed building must inevitably be greater than required. This gives a factor of safety.

The locus on the horizontal section, projected on plan, gives the locus of the separation distance and it can be seen that exposed buildings opposite the sides of the radiator could be nearer than those opposite the centre. In most cases, however, little is lost by requiring that the maximum separation distance, opposite the centre, should extend for the full width of the radiator but where, for example, there is an opening next to a portion of blank wall, part of the exposed building could be nearer the blank portion and a simple rule devised to allow for this will now be described.

The difference between the distances opposite the centre and opposite the side becomes less marked as the height of the radiator increases relative to its width. For a very wide radiator of height H, the separation distance opposite the centre, c_1, is given by(17):

$$c_1 = \frac{H}{2\phi}\sqrt{1 - \phi^2}$$

$$\simeq \frac{\mathrm{H}}{2\phi}$$

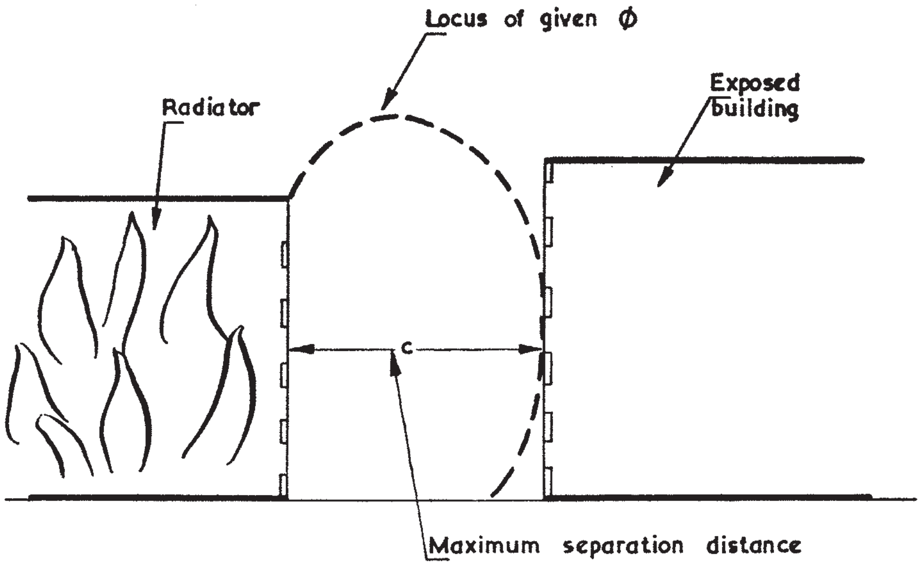
to an accuracy of greater than 5 per cent if ϕ is less than $\frac{1}{3}$, and opposite the edge, the distance, c_2, is given by:

$$c_2 = \frac{H}{4\phi}\sqrt{1 - 4\phi^2}$$

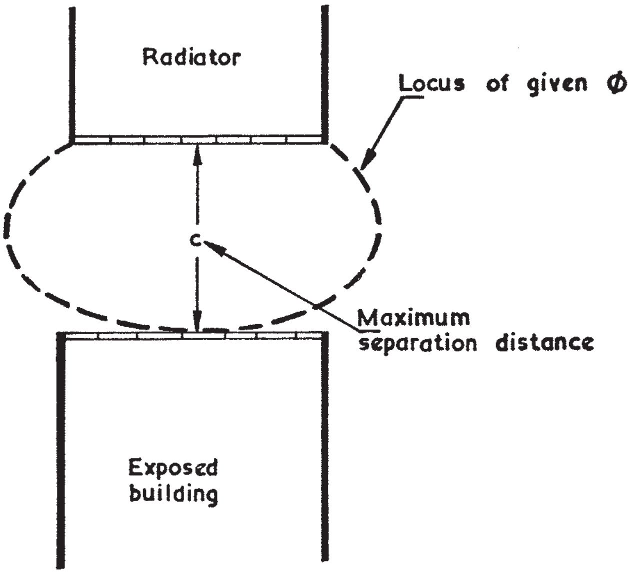
$$\simeq \frac{H}{4\phi}$$

to an accuracy of greater than 5 per cent if ϕ is less than $\frac{1}{6}$.

i.e. $$\frac{c_1}{c_2} \simeq 2$$



Vertical section through radiator



Horizontal section through radiator

FIG. 11. Locus of a given configuration factor

For a very tall radiator of width W, the separation distance opposite the centre, c_1', is given by:

$$c_1' = \frac{W}{2\phi}\sqrt{1-\phi^2}$$

and opposite the edge the distance, c_2', is given by:

$$c_2' = \frac{W}{2\phi}\sqrt{1-4\phi^2}$$

and here it can be seen for small values of ϕ that $\frac{c_1'}{c_2'}$ is approximately unity. For a very wide radiator, the distance opposite the side is approximately half that opposite the centre. For a very tall radiator the distances opposite the side and opposite the centre are approximately the same.

If the separation distance for an infinitely tall radiating strip is determined, then all situations found in practice will be covered. The plane receiving the maximum radiation opposite the centre of this radiator is parallel to the radiator but at any other point, the plane receiving the maximum radiation is at an angle to the radiator. The locus of this plane is shown in Fig. 12, where at any point along the curve a tangential plane has the maximum value of ϕ at that point and along the curve this maximum is constant. In Appendix II this locus is shown to be, on plan, the arc of a circle, the width of the radiator forming a chord and the third point on the circle being on the perpendicular bisector of the chord at the separation distance c. The value of c depends on the percentage of openings, i.e. the effective radiating intensity. Some values for an infinitely tall radiator of width W and normal intensity are given in Table 1.

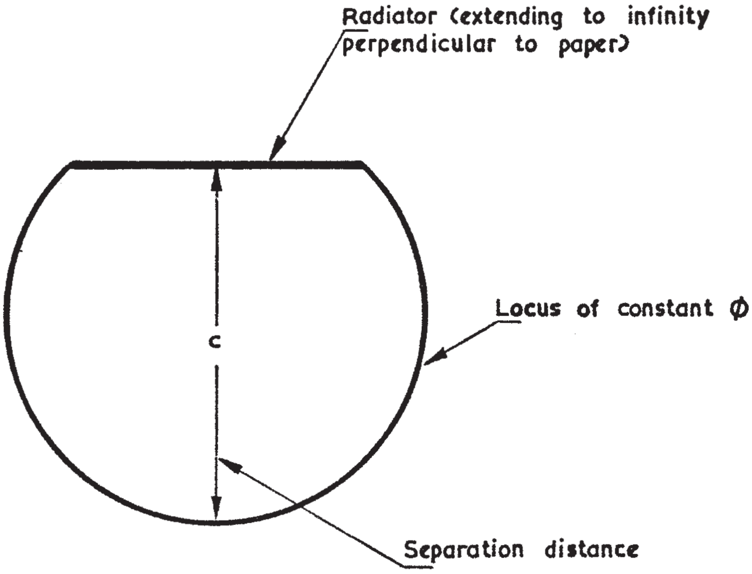


FIG. 12. Locus, on plan, of a given ϕ for an infinitely high radiator

TABLE 1—SEPARATION DISTANCE c
FOR INFINITELY TALL RADIATOR OF WIDTH W

Openings percentage	c/W
100	6·65
70	4·65
50	3·30
40	2·63
30	1·94
20	1·24

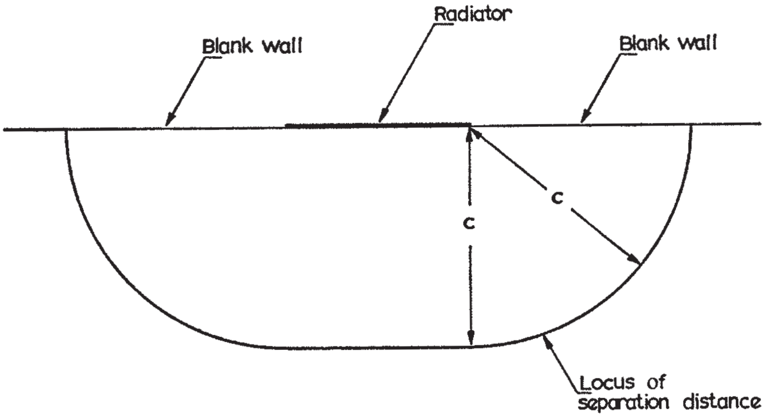


FIG. 13. Simple method of continuing separation distance beyond edges of radiator

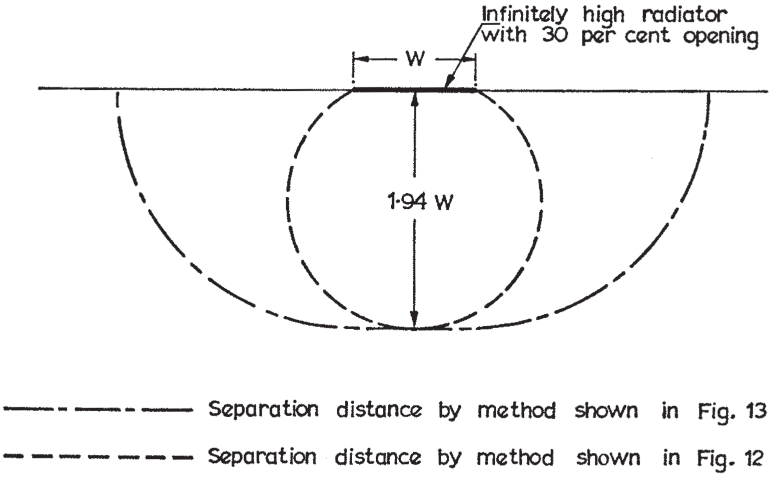


FIG. 14. Comparison of approximate and accurate separation distances for an infinitely high radiator

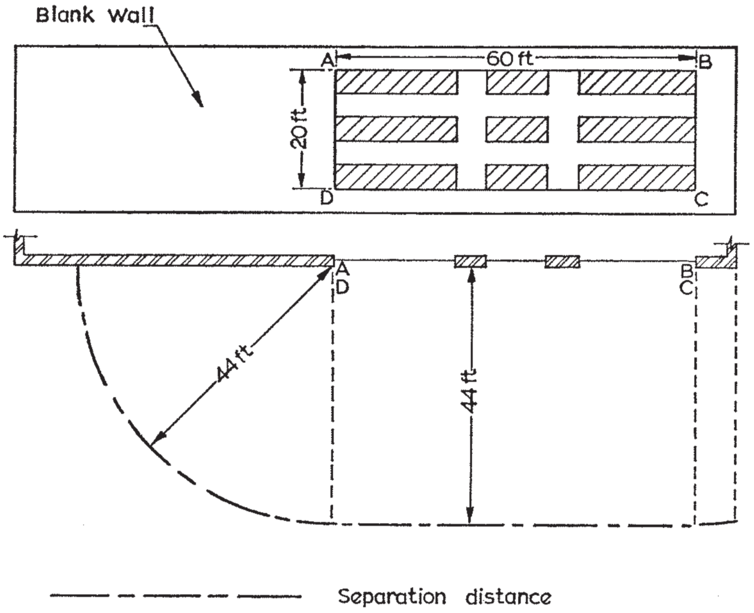


FIG. 15. Separation distance at edge of enclosing rectangle

A simple approximate method of drawing separation distance for any radiator is to extend the distance to the full width of the radiator and continue it as an arc of a circle as shown in Fig. 13. The two methods are compared in Fig. 14 which shows that the approximate method errs on the side of safety. Its application is illustrated in Fig. 15, where the elevation is similar to the one in Fig. 8 but with a long portion of blank wall. The separation distance, already calculated as 44 ft, is drawn as shown in Fig. 15.

IRREGULAR ELEVATIONS

The calculation of separation distance in terms of a single radiator has been outlined for simple elevations with evenly distributed openings. It is also possible to calculate separation distances for irregular elevations in terms of single radiators and this is shown below.

Elevation with uneven distribution of openings

While, for a majority of elevations with a number of openings, the separation distance can be found from the dimensions of the enclosing rectangle and the percentage of openings, there may be one or more openings sufficiently large to require a local increase in the separation distance. Consider the elevation and plan in Fig. 16. For the enclosing rectangle ABCD, there is a 30 per cent area of opening, $N = 5$, $A = 20$ ft and from Fig. 9 the separation distance is:

$$c = 35 \text{ ft} \quad .$$

For EBCF there is a 90 per cent area of opening, $N = 1$, $A = 20$, and from Fig. 9 for a 90 per cent opening:

$$c = 38 \text{ ft} \quad .$$

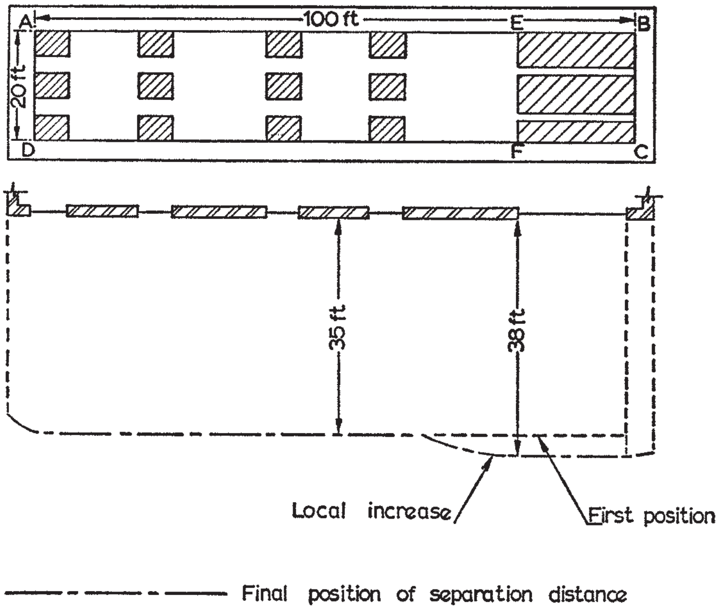


Fig. 16. Local increase of separation distance

It is necessary, therefore, to increase the separation distance in the region of EBCF. The separation position calculated for the whole rectangle ABCD is drawn first. A second separation position is then drawn for the rectangle EBCF and continued as an arc of radius 38 ft until it meets the first position (p. 19).

The procedure therefore in all cases is to find first the separation distance for the overall enclosing rectangle and then to increase this locally where necessary. No simple rule has been devised to guide a designer as to when a local increase is necessary and it can only be found by trial and error. However, it will be found in practice that in most cases no local increase in separation distance will be needed.

Elevation with widely-spaced openings

If openings are spaced very widely apart then a point opposite one may receive negligible amounts of radiation from the next and, for the purposes of calculating separation distance, the openings may be considered separately. The separation distance may be calculated first for the rectangle enclosing all the openings and it is shown in Appendix III that, if the distance between the openings is greater than twice this separation distance, they may be treated as separate radiators.

Considering the elevation in Fig. 17, the enclosing rectangle ABCD has a 20 per cent opening, $N = 5$, $A = 20$ ft and from Fig. 9:

$$c = 24 \text{ ft} \quad .$$

The distance between the two rectangles AEHD and FBCG is 60 ft, which is greater than 2 × c, so that these rectangles may be considered separately. For AEHD with a 50 per cent opening, $N = 1{\cdot}5$, $A = 20$ ft and $c = 32$ ft. For FBCG with a 50 per cent opening, $N = 2$, $A = 10$ ft and $c = 19$ ft.

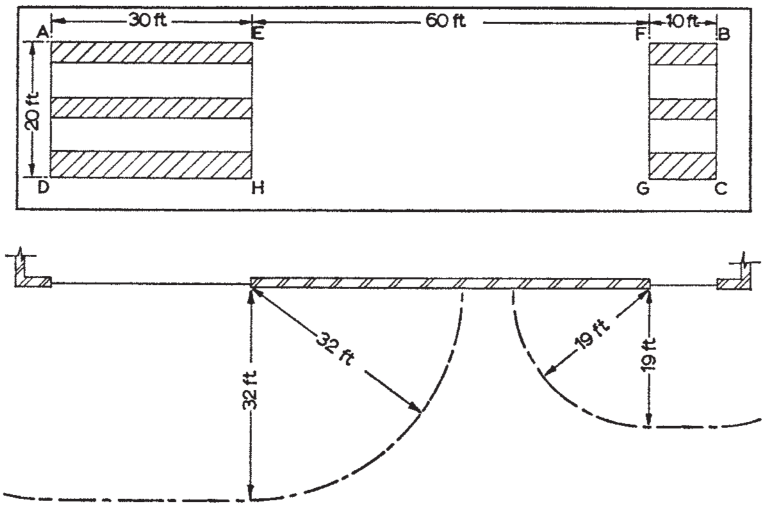


FIG. 17. Elevation with widely-spaced openings

Elevation with recessed portion

If one part of an elevation is recessed, then there may be a corresponding change in the separation distance, the effect of the recess depending on the amount of openings. If the recess contains openings on all three walls, then it will appear as a radiating enclosure and if, for example, there were 100 per cent openings on all the walls, it would have the same effect as a 100 per cent opening at the front of the aperture, i.e. the worst case. In general, the total area of the openings in the recess should be added together, expressed as a percentage of the area of the aperture, the aperture then being considered as a radiator and the distance for the whole elevation found accordingly. Where the total area of the openings is equal to or greater than the area of the aperture, the aperture should be considered as a radiator with 100 per cent openings. These procedures err on the side of safety.

In Fig. 18 the rectangle EFGH is set back 15 ft. The total area of openings in this recess is 60 per cent of the area of the rectangle EFGH. Assuming this area to be at the aperture and with a 40 per cent opening in the other two rectangles, the area of opening for the enclosing rectangle ABCD is 45 per cent.

In Fig. 9 for a 50 per cent opening, $N = 4$, $A = 20$ ft and

$$c = 48 \text{ ft} \quad .$$

Where there are openings on the rear wall only of the recess, then a reduction in the separation distance may be effected as follows. A first value of the distance c_1, may be made assuming as before all the openings to be radiating at the aperture. The area of openings in the recess can then be reduced by the factor, $\left(\frac{c_1}{c_1 + r}\right)^2$, where r is the depth of the recess. The adoption of the reduction factor, $\left(\frac{c_1}{c_1 + r}\right)^2$, is due to simple geometrical considerations of the apparent size of the openings in the recess as compared with the other openings, when viewed from a point at the separation distance. This is illustrated in

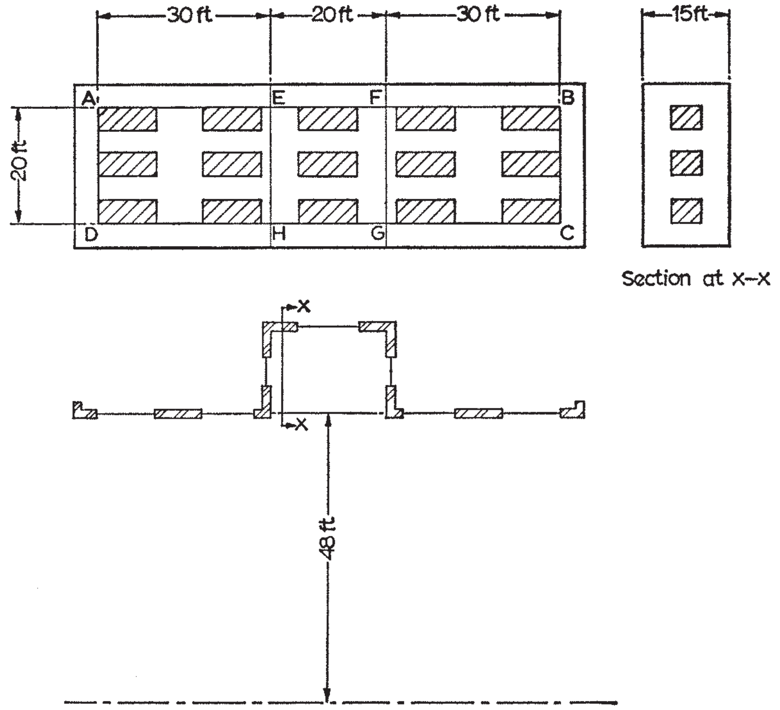


FIG. 18. Recessed elevation: openings in all sides

Fig. 19 which shows the equivalent radiator used. This reduction enables a second distance, c_2 to be found. It would be possible to repeat the process to reduce c_2 and continue until there was no further change in successive values but such refinement is hardly necessary and for practical purposes c_2 may be taken as the final estimate of separation distance.

In Fig. 19 the rectangle EFGH is set back 16 ft and there are no openings on the sides of the recess. Each of the three rectangles contains a 40 per cent area of openings. For the enclosing rectangle ABCD, $N = 5$, $A = 20$ ft and from Fig. 9 for a 40 per cent opening:

$$c_1 = 44 \text{ ft} \quad .$$

The openings in the recess can be reduced by the factor:

$$\left(\frac{c_1}{c_1 + r}\right)^2 = \left(\frac{44}{60}\right)^2$$

so that EFGH can be considered to have a 22 per cent opening. For the enclosing rectangle ABCD, this gives a 30 per cent opening and for $N = 5$, $A = 20$ ft, from Fig. 9:

$$c_2 = 35 \text{ ft} \quad .$$

Alternatively, Table 2 can be used. This indicates when the recess effectively reduces the overall radiating area by a given percentage. A theoretical basis for the table is given in Appendix IV.

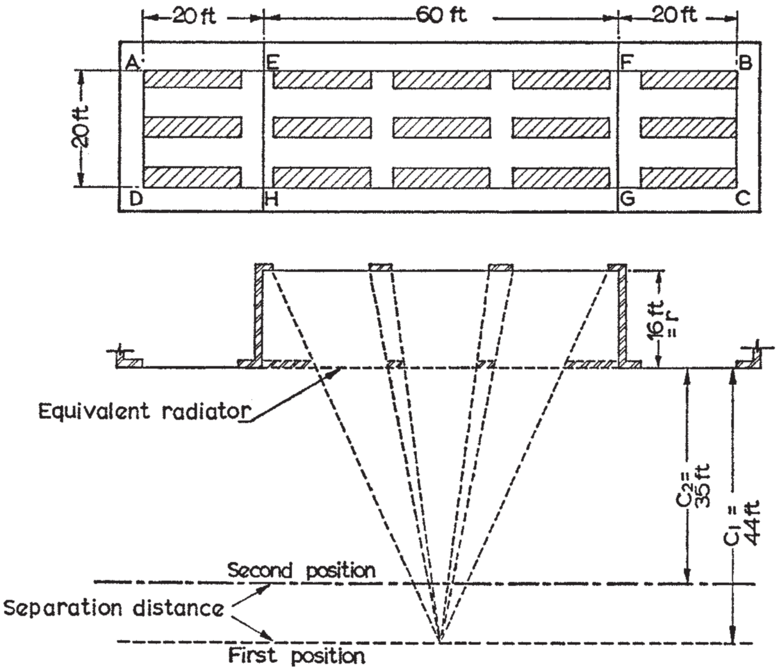


FIG. 19. Recessed elevation : openings in rear wall only

TABLE 2—DEPTH OF RECESS AND EFFECTIVE PERCENTAGE OF OPENINGS

Depth of recess exceeding ft	Openings in recess as percentage of overall enclosing rectangle not exceeding									
	15	20	30	40	50	60	70	80	90	100
	Limiting value of c_1 for reduction of 10 per cent in effective opening									
5	7	12	22	32	42	52	62	72	83	92
10	13	24	44	64	85	105	125	145	166	185
15	20	36	66	97	127	157	188	217	249	278
20	27	48	89	129	170	210	250	290	332	—
25	34	60	111	161	212	262	312	—	—	—
50	68	120	222	323	—	—	—	—	—	—
100	136	241	—	—	—	—	—	—	—	—

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TABLE 2—*contd.*

Depth of recess exceeding ft	Openings in recess as percentage of overall enclosing rectangle not exceeding									
	15	20	30	40	50	60	70	80	90	100
	Limiting value of c_1 for reduction of 20 per cent in effective opening									
5	—	—	7	12	17	22	27	32	37	42
10	—	—	13	24	34	44	54	64	74	85
15	—	—	20	36	51	66	82	97	112	127
20	—	—	27	48	68	89	109	129	149	170
25	—	—	34	60	86	111	137	161	186	212
50	—	—	68	121	172	222	273	323	—	—
100	—	—	136	242	344	—	—	—	—	—

The use of this table can be illustrated with the previous example.

The openings in the recess are 24 per cent of the overall enclosing rectangle. The percentage opening, assuming no recess, is 40 per cent and this can be reduced by 10 per cent if c_1 is less than the value in Table 2. For a recess of 15 ft the value in Table 2 is 66 ft. Therefore the effective radiating area can be considered as 30 per cent and $c_2 = 35$ ft.

The separation distance for a building with some upper floors recessed can be calculated in a similar way. Where some floors are recessed a distance r_1, and others a distance r_2, then the reduction factors $\left(\dfrac{c_1}{c_1 + r_1}\right)^2, \left(\dfrac{c_1}{c_1 + r_2}\right)^2$ should be applied to the area of openings in the relevant portions.

Elevation with set back

When part of a building is set back there can be a corresponding set back in the separation distance and its final position is found by considering the building from two aspects. The position of the line denoting separation is first found assuming the elevation is in one plane and then part is altered to allow for the set back. This allowance is made by viewing from the side and constructing an equivalent radiator which encloses all the openings, these openings being expressed as a percentage of the equivalent radiator and the appropriate separation position found. For the final separation position, the first one is taken until it meets the second.

In Fig. 20 the rectangle FBCG is set back 30 ft behind AEHD. Assuming no set back then for the enclosing rectangle ABCD, $N = 5$, $A = 20$ ft, and for a 40 per cent opening, from Fig. 9:

$$c = c_1 = 44 \text{ ft} \quad .$$

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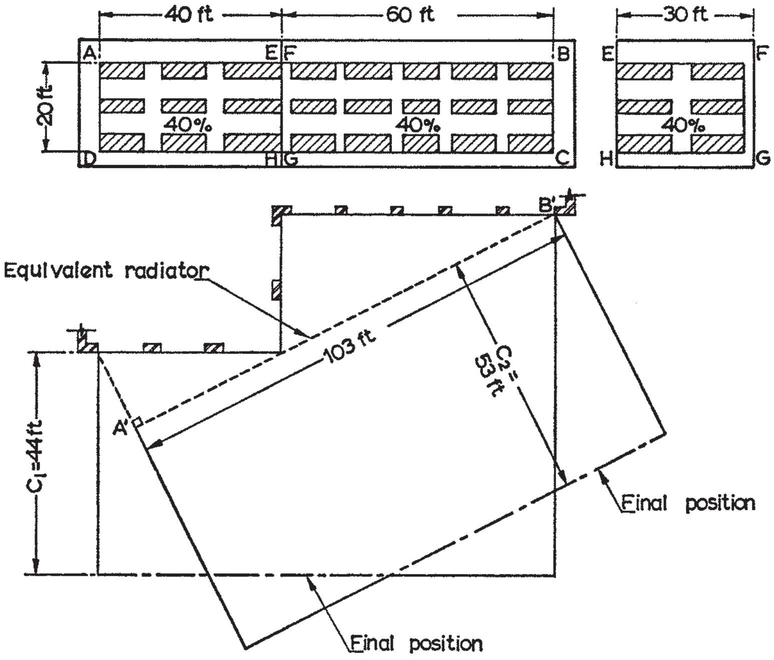

FIG. 20. Elevation with set back

Now consider the equivalent radiator, A′B′ on the plan. A′B′ = 103 ft and the height of this radiator is 20 ft. The openings in AEHD, EFGH, FBCG are 50 per cent of the area of the equivalent radiator. For this radiator $N = 5{\cdot}15$, $A = 20$ ft, and from Fig. 9 for a 50 per cent opening:

$$c = c_2 = 53 \text{ ft} \quad .$$

The positions of the two separation distances are shown in Fig. 20, the portions of each which are nearer to the elevation being taken as the final position.

The basis for this procedure is similar to that for the recess with openings in all three walls, described on p. 21, the set back being viewed from the corner as a radiating enclosure.

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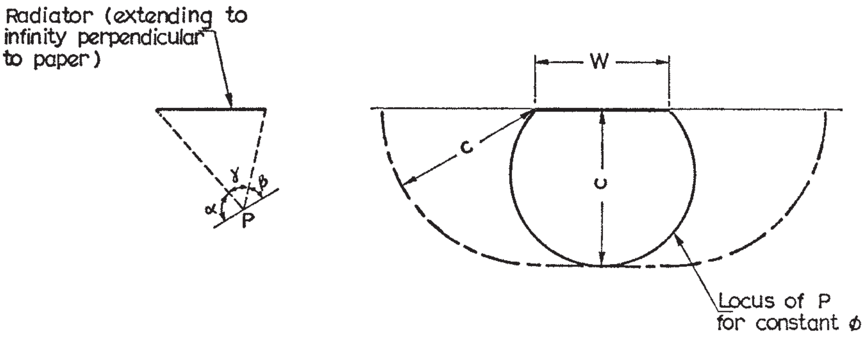
APPENDIX I

PILOT IGNITION WITH THE FLAME ON THE SURFACE

It is possible for ignition of wood to occur, for an incident intensity of radiation of less than 0·3 cal $\text{cm}^{-2}\text{s}^{-1}$, if an igniting flame is in direct contact with the surface of the wood (surface ignition)(21) and it is not clear whether this is a limiting case of pilot ignition or a function of the size and heating effect of the flame itself. When ignition occurs in this way a thin flame appears, its rate of spread being slow, depending on the intensity of the supporting radiation. If a combustible surface is at a great distance from a building fire, then many sparks will have burnt out before they reach the surface and it will probably be only the larger burning particles that may cause ignition. If burning particles reach a surface and the intensity of radiation is too low for pilot ignition, surface ignition is possible only if the particles lodge on the surface. Even then the development of flame is likely to be slow. If it is assumed that the Fire Brigade will be available within a short time of a fire's starting, for the protection of exposed property, it would appear unreasonable therefore to try to guard against the possibility of surface ignition.



(a) (b)

FIG. 21. Variation in separation distance

APPENDIX II

SEPARATION DISTANCE FROM INFINITELY HIGH RADIATOR

CONSIDER a vertical plane radiator of infinite height (Fig. 21(a)). The configuration factor ϕ, at a point P on a vertical plane not necessarily parallel to the plane of the radiator, is given by(17):

$$\phi = \tfrac{1}{2}(\cos\alpha + \cos\beta) \qquad (2)$$

The position of P defines only the angle $\gamma = 180 - (\alpha + \beta)$

The value of β which will give the maximum value of ϕ at any point is required.

Writing

$$\alpha = 180 - (\beta + \gamma)$$

then

$$\frac{d\phi}{d\beta} = \tfrac{1}{2}\,[\sin(\beta + \gamma) - \sin\beta]$$

For ϕ to be a maximum:

$$\gamma = 180 - 2\beta$$

and

$$\alpha = \beta$$

Therefore:

$$\phi_{\max} = \cos\beta = \sin\gamma/2$$

For a given value of $\phi_{\max}$ and $\alpha = \beta =$ constant then γ is constant and the locus of *P* is therefore the circumference of a circle subtended by the radiator as a chord.

If the width of the radiator is *W*, the maximum value of the separation distance *c* from the centre of the radiator is obtained from:

$$\phi_c = \phi_{\max} = \frac{W}{\sqrt{W^2 + 4c^2}} \tag{3}$$

where ϕ_c is the required value of $\phi_{\max}$.
The separation distance is then given by:

$$c = \frac{W}{2}\sqrt{\frac{1}{\phi_c^2} - 1} \tag{4}$$

By requiring the separation distance to be not less than *c* at all points, the separation will always err on the side of safety (Fig. 21(b)).

APPENDIX III

WIDELY-SPACED OPENINGS

CONSIDER two radiators 1 and 2, in the same plane, of widths W_1 and W_2, separated by a blank wall of length *l* (Fig. 22).

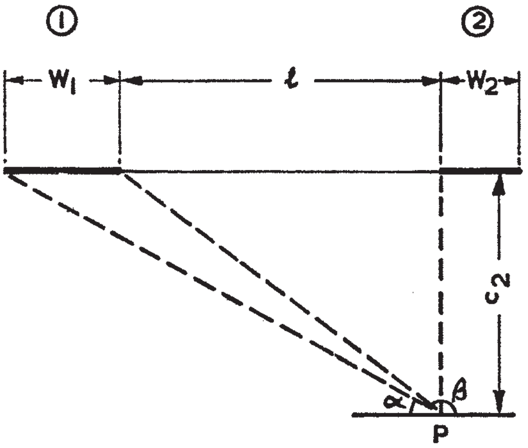


FIG. 22. Widely-spaced openings

Let

$$W_1 = nW_2 \quad \text{where } n \geqslant 1 \tag{5}$$

It is necessary to find the value of l such that for a point P, at a distance c_2, opposite the smaller radiator 2, the radiation received from radiator 1 is negligible, c_2 being the separation distance for radiator 2. Since an infinitely high radiator would have the maximum configuration factor at P, it is assumed that the radiators are of infinite height. For simplification, P has been taken opposite the side of radiator 2, rather than opposite the centre. This means that the configuration factor, ϕ_1, for radiator 1 at P is slightly less than the value opposite the centre. From equation (2), Appendix II:

$$\phi_1 = \tfrac{1}{2}\left[\frac{l + W_1}{\sqrt{c_2^2 + (l + W_1)^2}} - \frac{l}{\sqrt{c_2^2 + l^2}}\right] \tag{6}$$

From equation (4) Appendix II, the separation distance c_2 for the radiator 2, is given by:

$$c_2 = \frac{W_2}{2}\sqrt{\frac{1}{\phi_2^2} - 1}$$

For $I_o = 4{\cdot}0$ cal cm^{-2}s^{-1},

$$\phi_2 = \frac{0{\cdot}3}{4{\cdot}0} = 0{\cdot}075$$

and

$$c_2 = 6{\cdot}65\ W_2 \tag{7}$$

If the effect of radiator 1 is considered negligible when its contribution to the radiation from radiator 2 is not greater than 5 per cent then:

$$\phi_1 \leqslant 0{\cdot}05 \times 0{\cdot}075 \tag{8}$$

Combining equations (5), (6), (7) and (8) gives:

$$\frac{l + nW_2}{\sqrt{6{\cdot}65^2 W_2^2 + (l + nW_2)^2}} - \frac{l}{\sqrt{6{\cdot}65^2 W_2^2 + l^2}} \leqslant 0{\cdot}0075 \tag{9}$$

Equation (9) gives l in terms of W_2 for any value of n. However, it is more convenient to express l in terms of the separation distance for the combined radiators, which is the quantity first calculated on the assumption that the openings are considered together.

For the whole elevation the percentage of openings is:

$$\frac{W_1 + W_2}{W_1 + W_2 + l} \times 100 = \frac{(n + 1)\ W_2}{(n + 1)\ W_2 + l} \times 100$$

and

$$I_o = 4{\cdot}0 \times \frac{(n + 1)\ W_2}{(n + 1)\ W_2 + l}$$

Therefore:

$$\phi_c = \frac{0{\cdot}3}{4} \times \frac{(n + 1)\ W_2 + l}{(n + 1)\ W_2} \tag{10}$$

From equation (3) Appendix III:

$$\phi_e = \frac{(n+1)\,W_2 + l}{\sqrt{[(n+1)\,W_2 + l]^2 + 4c^2}} \qquad (11)$$

where c is the separation distance for the whole elevation.
Combining equations (10) and (11):

$$c = \tfrac{1}{2}\sqrt{\frac{(n+1)^2\,W_2^2}{0{\cdot}075^2} - [(n+1)\,W_2 + l]^2} \qquad (12)$$

From equations (9) and (12) it is possible to obtain values of the ratio l/c for different values of n. It can be shown that the maximum value of l/c is obtained when $n = 1$, i.e. when the two radiators are the same width.

When $W_1 = W_2$, it follows that for the limiting case of

$$c = 9{\cdot}17\ W_2$$

then

$$l = 17{\cdot}4\ W_2$$

i.e. $l \simeq 2c$.

Therefore for $l > 2c$, one radiator has a negligible effect at a point opposite another. Since the interaction of the two radiators is greatest when they are equal in width, this rule holds for all other cases.

Similar equations can be derived for finite radiators but the calculation is complex. Calculations for some finite radiators show that the rule applies generally.

APPENDIX IV

RECESS WITH OPENINGS IN REAR WALL ONLY

LET the overall enclosing rectangle have area A, the front portions areas of openings A_1 and A_2, and the recess area of openings A_R, (Fig. 23). The first value of separation distance, c_1, is based on 100 $\left(\frac{A_1 + A_2 + A_R}{A}\right)$ per cent openings. This gives an overestimate of the effect of the openings.

The effective radiating area of the openings in the recess is less than A_R and to a first approximation is given by:

$$A'_R = \left(\frac{c_1}{r + c_1}\right)^2 \times A_R \qquad (13)$$

where r is the depth of the recess.
Since c_1 exceeds the true separation distance, A'_R itself is slightly overestimated by this equation. Thus the error is on the side of safety.

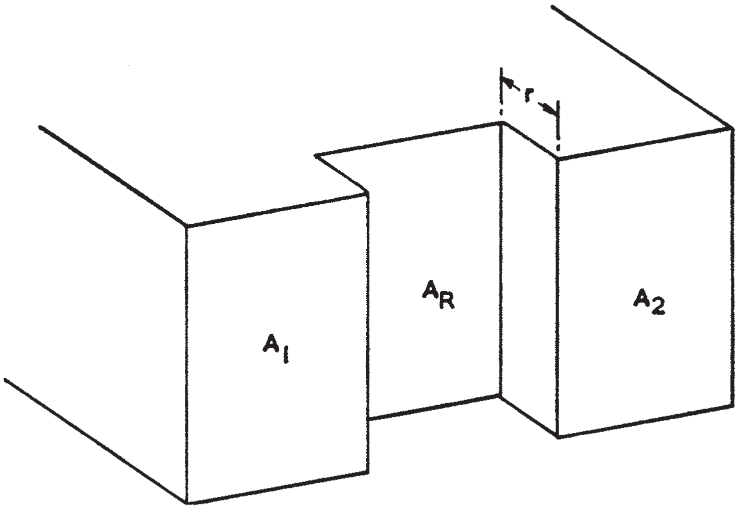


FIG. 23. Recess with openings in rear wall only

The difference between this and the former value, A_R, expressed as a percentage of the overall enclosing rectangle, is:

$$100\left(\frac{A_R - A'_R}{A}\right) = 100\frac{A_R}{A}\left[1 - \left(\frac{c_1}{r + c_1}\right)^2\right] \text{ per cent}$$

$100\frac{A_R}{A}$ is the area of openings in the recess, expressed as a percentage of the overall enclosing rectangle.

The limiting values of c for

$$100\left(\frac{A_R - A'_R}{A}\right) \geqslant 10 \text{ per cent}$$

or

$$\geqslant 20 \text{ per cent}$$

have been calculated for various values of 100 A_R/A and r and are given in Table 2. In theory this method can be used to give successively more accurate approximations by repeated application of equation (13) with successively smaller values of c. However, in practice one such application will usually be sufficient and any error will be less than the increments used in Table 2.

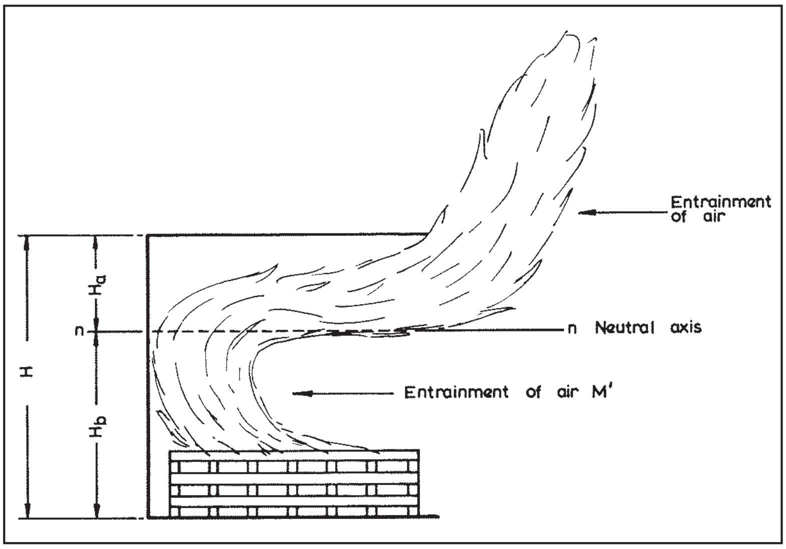
PAPER 3

Fully-developed fires - two kinds of behaviour

PH Thomas, MA, PhD, AMIMechE, MIFireE, AJM Heselden, BSc and Margaret Law, BSc, Fire Research Technical Paper No. 18, 1967 Ministry of Technology and Fire Offices' Committee, Joint Fire Research Organisation. HMSO, UK

In the 1960s there were various research programmes related to the behaviour of fires inside buildings. One of the projects was a study of the fully developed compartment fire, which was very relevant to the standards of structural fire protection required by building regulations, a topic discussed in Post War Building Studies No. 20 'Fire Grading of Buildings: Part 1'. This paper brings together results of various experiments, both model and full-scale, that contributed to a fundamental analysis of the features that influence fire behaviour inside compartments.

Figure showing a section through a wide compartment. It is used to describe the mass flow rate of air into the compartment in relation to the height of the openings.



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Ministry of Technology and Fire Offices' Committee
Joint Fire Research Organization

Fully-developed compartment fires
—two kinds of behaviour

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Fire Research Technical Paper No. 18

LONDON: HER MAJESTY'S STATIONERY OFFICE 1967

Preface

The cost of implementing the fire requirements of the Building Regulations is in the region of £50 to £100 million per annum. An important factor in this cost is the provision of adequate structural fire protection and this is largely determined by the expected duration of fires.

This paper summarizes existing knowledge of behaviour of fully-developed compartment fires, and discusses general questions of scaling and the fundamental factors controlling fire temperature and duration. It is written to provide a foundation for later papers dealing directly with the practical evaluation of fire-resistance requirements and is intended for the fire technologist concerned with applying experimental data and understanding the physical basis for fire grading.

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October 1967

Fully-developed compartment fires
—two kinds of behaviour

Summary

This paper summarizes some of the work done at the Fire Research Station on fully-developed compartment fires and explains the two types of behaviour that have been observed. It is shown that fire load per unit window area and fuel thickness are more important than other factors in determining the duration of such fires and a theory is presented which shows how this arises.

There is a relationship between the radiation emitted from windows and the burning rate, and this has important practical and theoretical consequences.

Introduction

There are two main reasons for providing a sound technical basis for fire regulations. One is that the development of new constructional methods, materials and social habits may lead to new fire hazards. The other is that an unnecessarily stringent regulation brings an economic penalty. A regulation which, in the past, did not impose a limit on the design may do so if, as a result of changes in construction, materials and design, other considerations no longer override the fire regulations. Thus, on the one hand, there is a need for new regulations and on the other, a demand for the revision of some of the existing ones. If these demands arise, as now, in a situation where past experience is not directly relevant, the regulations must be based on a sound technical appraisal. It is also worth noting that although fire regulations are concerned with the protection of human life, once the building becomes large they inevitably provide protection for the building and its contents as well, and thus indirectly make a considerable economic contribution.

This paper discusses the duration and severity of a fire in a single compartment. These properties of a fire are particularly important in defining the conditions which a fire-resisting structure has to withstand if it has to contain the fire, and therefore an understanding of how they are determined is essential if the many building regulations that control the design of buildings are to be based on sound principles.

For any given amount of fuel in a compartment the duration of the fire will depend on the burning rate and much of this paper will be devoted to discussing how this is determined, with special emphasis on the role of the window openings.

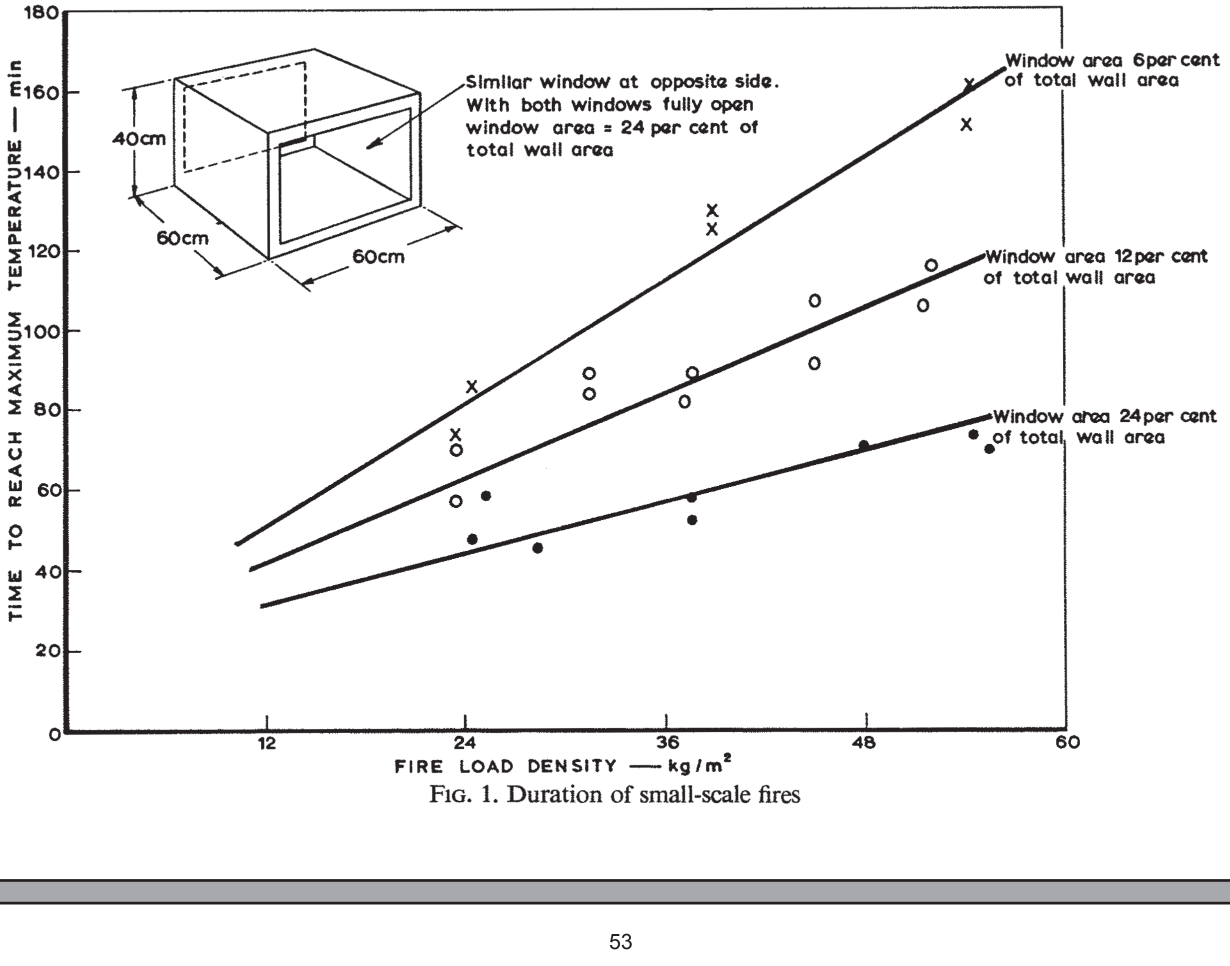


FIG. 1. Duration of small-scale fires

Effect of window size on burning rate

Fujita[1] and Kawagoe[2], as a result of many experiments in compartments of various sizes, showed that the mean burning rate in a fully-developed fire was largely independent of the amount of fuel, but varied with the rate of flow of air which entered the window by natural convection. Similar observations have been reported by Ptchelintzev[3], Gross and Robertson[4] and Simms, Hird and Wraight[5] whose results are shown in Fig. 1. The vertical scale is an approximate measure of the duration of the fire which, particularly for the smaller window openings, is seen to be almost proportional to the amount of the fuel. This implies a burning rate which is almost independent of the amount of fuel, and the results show that this rate is larger, the larger the window. Kawagoe[2] has shown that the rates of weight loss R could be expressed by the relationship:

$$R = 5{\cdot}5\, A_w H^{\frac{1}{2}} \quad \text{kg/min} \qquad (1)$$

where A_w is the window area in metres^2
and H is the window height in metres.

Based on the work of Simms, Hird and Wraight[5,6], Thomas[7] has given the constant of proportionality as 6·0 and Ptchelintzev[3] has published data which enable a value of about 5·0 to be derived assuming window heights of the order of 1 m. In view of the variation in methods of assessing the mean burning rate, 5·5 is probably sufficiently accurate.

However, there is evidence that as $A_w H^{\frac{1}{2}}$ increases for a given compartment the above relationship ceases to hold. Figure 2 shows some results obtained by Thomas[7] for a compartment in which a small crib of wood was burning. For small air flows, the burning rate was small, and approximately proportional to the air flow, but when the air flow became larger, the burning rate tended to a value independent of the air flow, showing that more air was drawn into the compartment than took part in combustion. There are, therefore, at least two regimes of behaviour, and for air flows which are small enough for flaming to be inhibited and in which a process of destructive distillation proceeds there is a third regime, but we shall not discuss this further in the present paper. Equation (1) with one or other constant of proportionality has of late assumed a considerable importance in assessing the burning rates of fires in compartments and is worth considering in some detail to demonstrate its significance.

SMALL OPENINGS

Calculations of the amount of air entering a small window in a fully-developed fire were first made by Fujita[1] and Kawagoe[2] who assumed the compartment to be effectively filled with stationary gas at a uniform temperature except near the opening. Air enters the compartment and combustion products leave it under the action of pressure differences caused by the differences in density between hot and cold gases. The calculation is as follows. Consider a window of height H, breadth B, and area A_w. Let the neutral pressure axis be at a height H_b above the base of the window and H_a below the top of the window (Fig. 3), the total mass flow of air be M, and the mass rate of fuel leaving the combustible surfaces within the enclosure be R, which is the rate of weight loss of the fire. Provided there is no vertical acceleration the velocity head of the exit gases at any height h_a above the neutral pressure axis is nominally:

$$\frac{\rho_e v_e^2}{2g} = h_a(\rho_o - \rho_e)$$

where v is the velocity
ρ is the density
and g is the acceleration due to gravity.

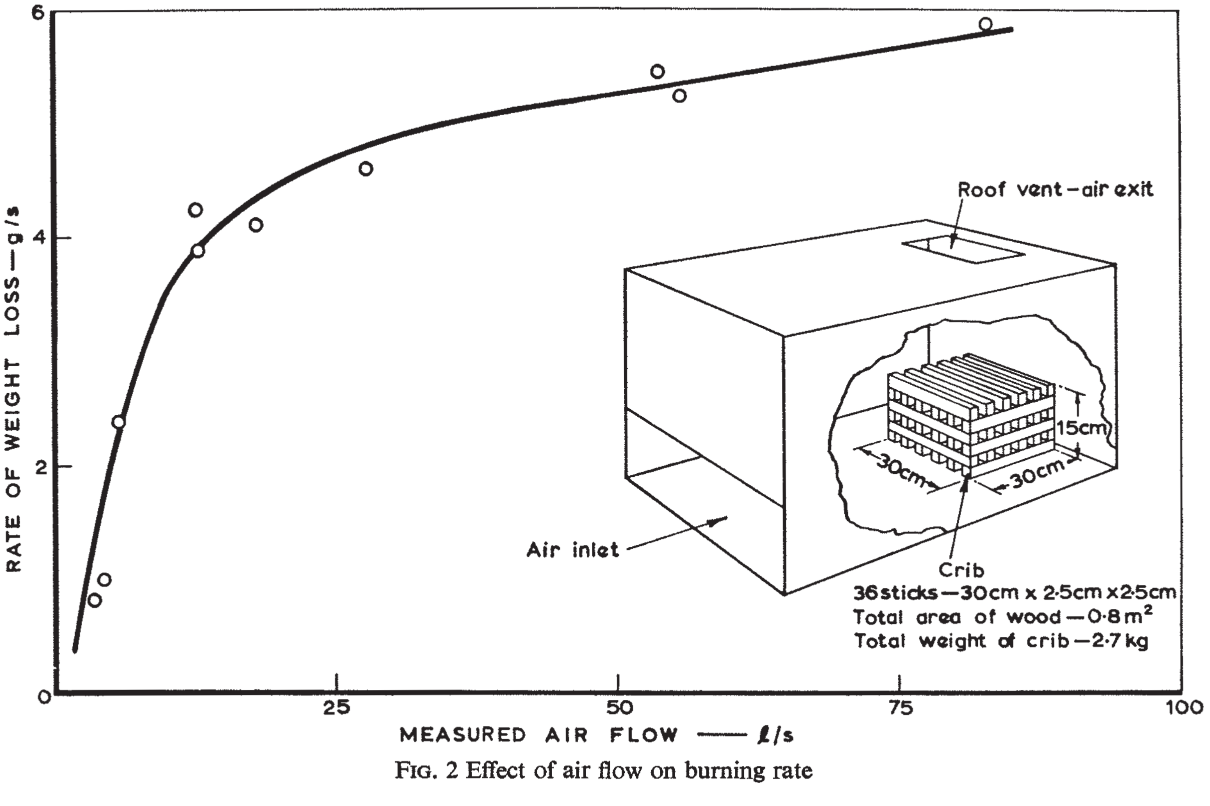


FIG. 2 Effect of air flow on burning rate

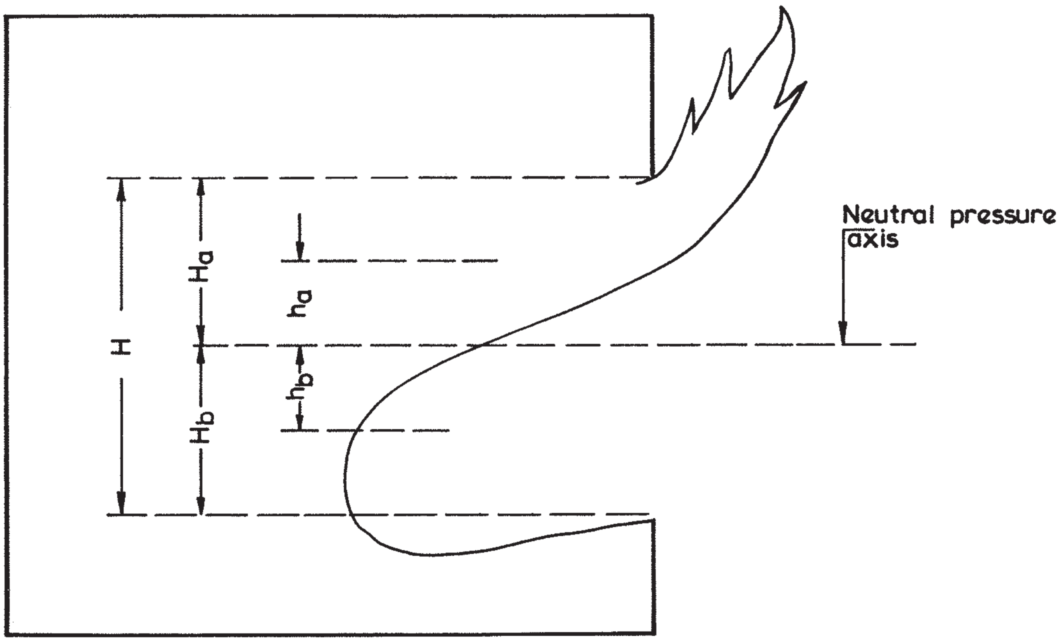


FIG. 3. Flow in and out of small opening

The suffices *e* and *o* denote exit and ambient conditions respectively. At h_b below the neutral axis the inlet velocity head is, with the same qualification regarding vertical acceleration:

$$\frac{\rho_o V_o^2}{2g} = h_b (\rho_o - \rho_e)$$

Because the induced velocity varies as the square root of the distance from the neutral axis, the mean velocity is equal to two-thirds of the maximum. A discharge coefficient is allowed for by the quantity *a*. Hence, we have the following equation for the inlet flow:

$$M = \tfrac{2}{3} a \rho_o H_b B \sqrt{2gH_b(1-\rho_e/\rho_o)}$$

where ρ_o and ρ_e are the densities of cold and hot gases of absolute temperature T_o and T_1 respectively.

The flow of gases leaving the upper part of the window is:

$$M+R = \tfrac{2}{3} a \rho_e H_a B \sqrt{2gH_a(\rho_o/\rho_e - 1)}$$

If we assume the gases to be ideal, and the mean molecular weight of the effluent gases to be equal to that of air, we obtain from these equations the following expression for M:

$$M = \tfrac{2}{3} a A_w H^{\frac{1}{2}} \rho_o \cdot \frac{\sqrt{2g\,(1-T_o/T_1)}}{[1+(T_1/T_o)^{\frac{1}{3}}\,(1+R/M)^{\frac{2}{3}}]^{\frac{3}{2}}}$$

At high values of the temperature inside T_1, M decreases slowly with increasing T_1, but for the purposes of these calculations, M can be regarded as almost independent of T_1 above $T_1 = 500$°K. We assume $T_1 = 1200$°K, $\rho_o = 1{\cdot}3$ kg/m^3, $T_o = 300$°K, $g = 9{\cdot}81$ m/s^2 and $a = 0{\cdot}7$, as used by Fujita[1] and Kawagoe[2]. The following equation is then obtained:

$$M = \frac{2{\cdot}33\, A_w\, H^{\frac{1}{2}}}{[1+1{\cdot}6\,(1+R/M)^{\frac{2}{3}}]^{\frac{3}{2}}} \quad \text{kg/s} \qquad (2)$$

where A_w and H are in (metres)^2 and metres respectively. Given the same assumptions, the modification of this to two or more windows is straightforward.

From equations (1) and (2) we have:

$$\frac{R}{M} = \frac{5{\cdot}5[1+1{\cdot}6\,(R/M+1)^{\frac{2}{3}}]^{\frac{3}{2}}}{2{\cdot}33 \times 60}$$

from which

$$\frac{R}{M} = 0{\cdot}185 \qquad (2\text{i})$$

and hence

$$M = 0{\cdot}50 A_w H^{\frac{1}{2}} \quad \text{kg/s} \qquad (3)$$

No attempt has been made here to include the effect of acceleration terms within the enclosure nor the friction between the two streams except by the introduction of the discharge coefficient *a*. These effects become relatively more important the greater the value of $A_w H^{\frac{1}{2}}$. In view of the insensitivity of the inlet velocity to variations in temperature, the fact that the temperature is not uniform is not of great consequence and the best single value for T_1 will be the exit temperature, because the most important influence of T_1 is on the density and velocity head of the emerging gases. Equation (1), therefore, expresses a constant proportion between the burning rate and the air flow. It is probably limited to those conditions where equation (2) applies i.e. to where the air flow is caused by the hot gas in the compartment being effectively stagnant and so causing a chimney effect.

There must, however, be a zone near the base of the window opening where the ambient air temperature prevails. The linear dimensions of this zone will be related to the height of the opening and as this becomes larger, so a larger part of the enclosure is at or near ambient temperature. When the opening is very large it is no longer possible to regard the space away from the opening as a region in which the gases have no vertical acceleration. The above theory is then insufficient.

LARGE OPENINGS

When the window area is large, relative to, say, the floor area, the flow will tend to a limiting situation where there are effectively no pressure changes, only velocity changes, as in a buoyant plume. In these circumstances it is friction, i.e. turbulence, which entrains air into the flame zone and draws air in through the window. The fundamental distinction between the two regimes may be seen from the equation of vertical motion: Mass × acceleration = buoyancy force + vertical pressure gradient force.

If the window openings are small, we have small vertical accelerations and the buoyancy is balanced by a pressure gradient which causes horizontal flows. If the accelerations are large, the pressure gradients become small and there are only small inflows. This inflow is termed entrainment. We shall assume here that the velocity of entrainment is proportional to the vertical velocity of the main stream, as in the buoyant plume and that the mean velocity over a height Z is proportional to $Z^{\frac{1}{2}}$. We shall provisionally neglect the entrainment of cold air upwards into a horizontal hot stream because this is much less than horizontal entrainment into a vertical stream. Consequently, the amount of air entering the opening and entrained into the flame zone is proportional to $A_wH^{\frac{1}{2}}$ for geometrically similar compartments of various sizes having windows which are geometrically similar to each other and a large fraction of the wall area. The constant of proportionality between M and $A_wH^{\frac{1}{2}}$ is, of course, less than in equation (3) and presumably depends on other factors such as the shape of the window and the compartment. Whereas with small openings experiments have shown that the burning rate is insensitive to the amount of fuel or its surface area, this is no longer so if the opening is large.

Figure 4 shows some results obtained by Webster and Raftery[8] for fires in cubical compartments, having one side open. It is seen that by increasing the amount of fuel, the burning rate was increased in effectively the same proportion. More recently Webster, Raftery and Smith[9] have suggested that for certain cribs it is the increase in surface area, not the amount of fuel, which is responsible for the increased burning rate. This makes the duration of such a fire dependent primarily on fuel thickness.

Gross and Robertson[4] have employed fuel surface area in correlating data for differing scales and fuel beds. There are however considerable complications involved in relating the burning rate to the properties of a crib over a wide range of designs. Increasing the surface area increases the rate of decomposition. The 'extra' fuel burns as a taller flame outside the compartment if the windows are large. If they are small the effect of surface area on the burning rate is weak[10].

RELATIONSHIP BETWEEN THE TWO REGIMES OF BEHAVIOUR OF FULLY-DEVELOPED FIRES

As yet no direct measurements have been made of the low velocity air flow into large windows but it is possible to obtain an estimate of the flow from considerations of turbulent entrainment. Burning rates are known and so comparisons can be made of the ratio R/M for the two types of fire.

We will first consider the burning rate of a fire of the second regime, taking the condition when the flames are just contained within the compartment, i.e. when the air required by the flames is all entrained within the compartment. We will then compare this burning rate with the rate for a fire of the first regime.

The lengths of the flames, as measured by Webster, Smith and Raftery[8,9,11] for the cubical compartments have been correlated by the method described by Thomas, Webster and Raftery[12] which gives:

$$L = 18\cdot 6\,(R')^{\frac{2}{3}} \quad \text{metres} \tag{4}$$

where L is the flame height measured from the base of a cubical compartment of side dimension D,
and R' is the burning rate per unit width of opening in units of kg m^{-1} s^{-1}.

For most of the experiments L exceeded D but if we put L equal to D, for the condition that the flames are just wholly within the compartment then:

$$R' = 0\cdot 0125\, D^{\frac{3}{2}} \quad \text{kg m}^{-1}\,\text{s}^{-1} \tag{5}$$

If in equation (1) we put $A_w = D^2$ and $H = D$, we have the burning rate for a window with the same dimensions

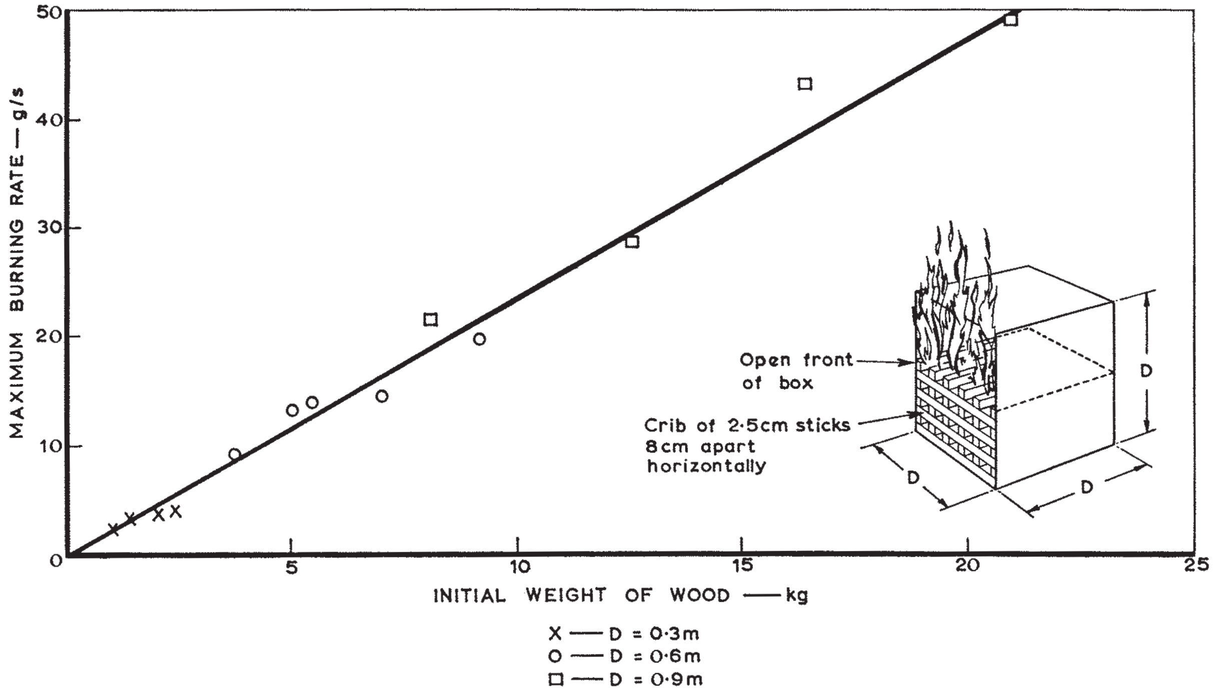


FIG. 4. Burning rate of well-ventilated fire

as that of the cube but in a large compartment. Then changing the units of R to kg/s we obtain:

$$R' = 0\cdot 1\ D^{\frac{3}{2}} \quad \mathrm{kg\,m^{-1}\,s^{-1}} \tag{6}$$

where here R' denotes the burning rate per unit width of window. The burning rate in a cubical compartment having one side fully open is therefore calculated as about one-eighth as much as in a much larger compartment having the same size of opening. Less air enters a compartment when entrainment determines the flow, than when the pressure differences, set up by an approximately stagnant zone, determine the flow. We now turn to estimating the air flow.

Consider the situation shown in Fig. 5 which represents a section across a wide compartment. The plane n—n is the boundary between the inlet and outlet flows and as such is comparable to the neutral axis. The air flow into an opening according to Kawagoe's formula is calculated by equation (3).

Thomas[13] has expressed the rate of turbulent entrainment of air into one side of a flame of height Z(m) as a mean mass velocity of

$$M^* = 0\cdot 062 \times 10^{-3}\,(100gZ)^{\frac{1}{2}} \quad g\ \mathrm{cm^{-2}\,s^{-1}}$$

where the units of g are cm s^{-2}.

In m.k.s. units, and inserting a value for g:

$$M^* = 0\cdot 195\, Z^{\frac{1}{2}} \quad \mathrm{kg\,m^{-2}\,s^{-1}} \tag{7}$$

A substantial fraction of such air does not take part in combustion but is lifted by the combustion products. Over a height H_b this inflow corresponds to a total of

$$M' = 0\cdot 195\, H_b^{\frac{3}{2}} \quad \mathrm{kg\,m^{-1}\,s^{-1}} \tag{8}$$

From equation (2i) the total outflow is less than 1·185 greater than this, i.e.

$$R' + M' \simeq 0\cdot 23\, H_b^{\frac{3}{2}} \quad \mathrm{kg\,m^{-2}\,s^{-1}} \tag{9}$$

To obtain the thickness of the layer of gases flowing out of the compartment we obtain the outflow in terms of the layer depth by the conventional 'hydraulic weir' equation:

$$\begin{aligned} R' + {}'M &\simeq \rho_{300} \times \tfrac{2}{3} \times H_a \left(\frac{gH_a\Delta\rho}{\rho_{300}}\right)^{\frac{1}{2}} \\ &\simeq 1\cdot 3\, H_a^{\frac{3}{2}} \quad \mathrm{kg\,m^{-1}\,s^{-1}} \end{aligned} \tag{10}$$

where ρ_{300} is the gas density at 300°C—the mean temperature assumed for the gases at exit,

and $\Delta\rho$ is the difference in density between this outflow and the ambient air.

The factor $\frac{2}{3}$ arises from averaging a velocity varying as $Z^{\frac{1}{2}}$ over the depth H_a.

Equating $R' + M'$ in equations (9) and (10) gives:

$$H_a = 0\cdot 32 H_b$$

The total depth is given by:

$$H = H_a + H_b$$

i.e.

$$H_b = 0\cdot 76\ H$$

Substituting in equation (8) the total air inflow is therefore

$$M' = 0\cdot 13\ H^{\frac{3}{2}} \quad \mathrm{kg\,m^{-1}\,s^{-1}}$$

as compared with the value $0\cdot 5\ H^{\frac{3}{2}}$ for the first regime, obtained from equation (3).

The ratio of these air inflows is less than the ratio of the burning rates, given as 8:1 by equations (5) and (6), and this indicates that a smaller proportion of the air is used for combustion in the entrainment regime. If the values used for the entrainment calculation are realistic, and if it is assumed that all the air inflow in the first regime is used for combustion, then the fraction of entrained air used is given by:

$$\frac{0\cdot 50}{0\cdot 13 \times 8} = 0\cdot 48.$$

This is rather more than has been found for open fires[14].

In view of the approximations embodied in these calculations, notably in equation (7), it is doubtful if the value 0·48 is very accurate but the calculations do show that the difference in burning rates between the two regimes can be associated with differences in the air flow.

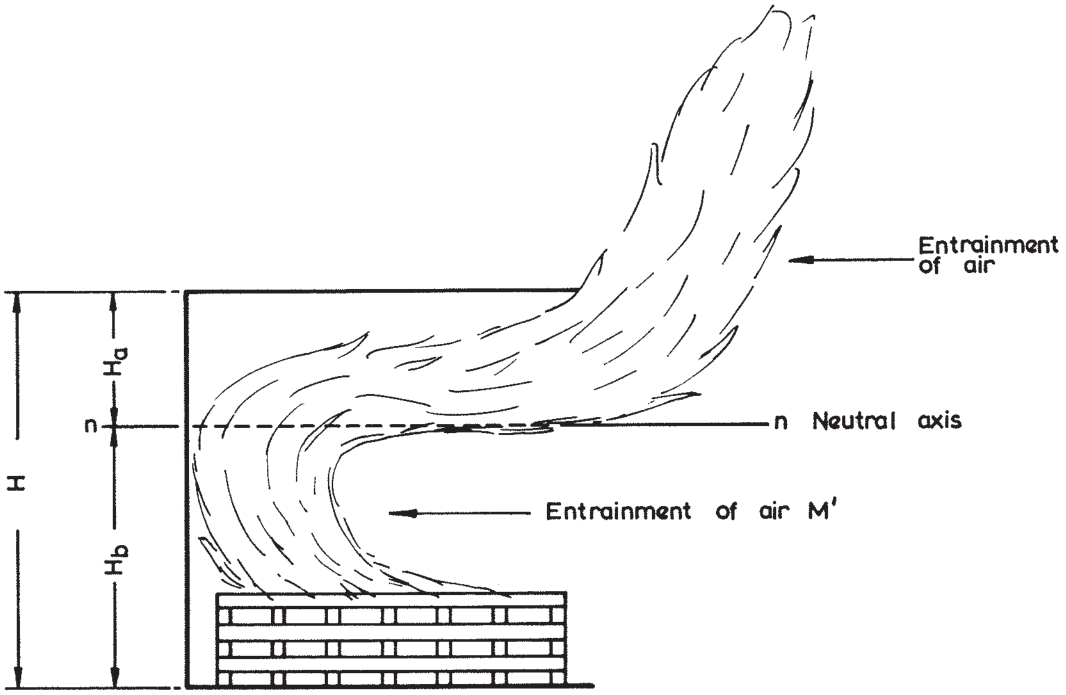


FIG. 5. Cross section of flow into and out of cubical compartment with one side open

Determination of burning rate

Any theory must explain the two regimes described on pages 2–4.

Regime I (Applicable to small ventilation openings)
(i) the burning rate is almost independent of the amount of fuel and its surface area
and (ii) is almost proportional to the air supply through the windows. This may not be the whole of the air involved in combustion if there is flaming out of the window.

Regime II (Large ventilation openings)
(i) the burning rate is determined by the type of fuel and the design of the fuel bed
and (ii) is largely independent of air supply through the window.

Thomas has pointed out a difficulty in interpreting the first regime. Fujita and Kawagoe assumed, because they could measure no systematic variation in the degree of complete combustion or the excess air factor in the combustion products from a burning compartment, that the ratio of the burning rate of the fuel to the rate of air supply was constant, but it is not immediately apparent how this arises. Firstly, the incomplete combustion was measured only by assessment of the carbon monoxide/carbon dioxide concentrations, whereas there can be an incomplete combustion arising from the formation of hydrocarbons, some of which burn outside the window. The significance of the approximately constant air flow, independent of the amount of fuel, is that the rate of heat liberation within the room is independent of the amount of fuel, but for a given thermal condition in a compartment, extending the surface area of the fuel might, to a first approximation, be thought to increase its rate of decomposition. The extra fuel, being unable to burn inside, could burn outside as a diffusion flame, but this does not happen to any large extent so that there are factors which compensate for this effect of increased surface. In order to explore the reasons for this behaviour and continue the theoretical discussion outlined earlier by Thomas[7] we shall proceed to discuss the decomposition of fuel.

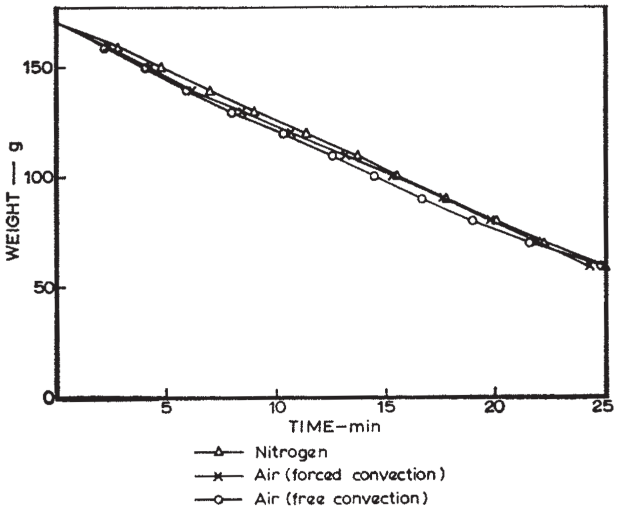


FIG. 6. Decomposition of wood by radiant heat

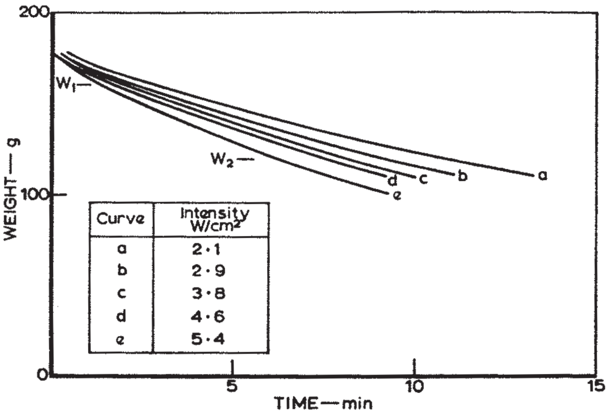


FIG. 7A. Weight loss of 2·5-cm thick fibre insulating board 230 cm^2 in area for different levels of radiant intensity

EFFECT OF HEAT TRANSFER ON RATE OF DECOMPOSITION

By placing pieces of wood in front of a radiant source and recording their loss in weight, Law[15] obtained data of the kind plotted in Fig. 6, which shows that the rate of weight loss was almost constant and was little affected by the piece of wood being enclosed in an inert atmosphere such as nitrogen, if allowance were made for the presence or absence of the extra heat from the flame. Increasing the intensity of the radiation by moving the piece of wood nearer the source increased the rate of decomposition. If we plot results for different levels of radiant intensity, we obtain the curves in Fig. 7. Recently experimental data on the details of such decomposition have been published by Blackshear and Murty[16], and Tinney[17]. Attempts have been made to make mathematical analyses of such results, notably by Bamford, Crank and Malan in 1946[18], who also were responsible for the first experiments in this field, and more recently by Squire and Foster[19], but there is considerable uncertainty in the numerical values for certain of the chemical and physical properties that must be included in any such mathematical formulation.

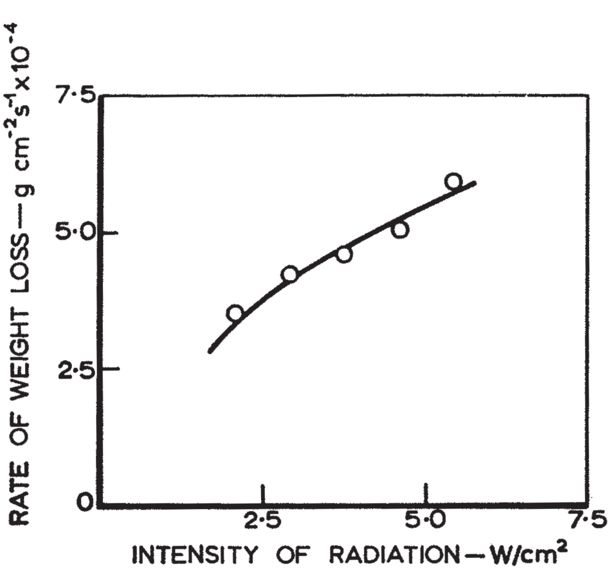


FIG. 7B. Rate of weight loss per unit area between weights w_1 and w_2

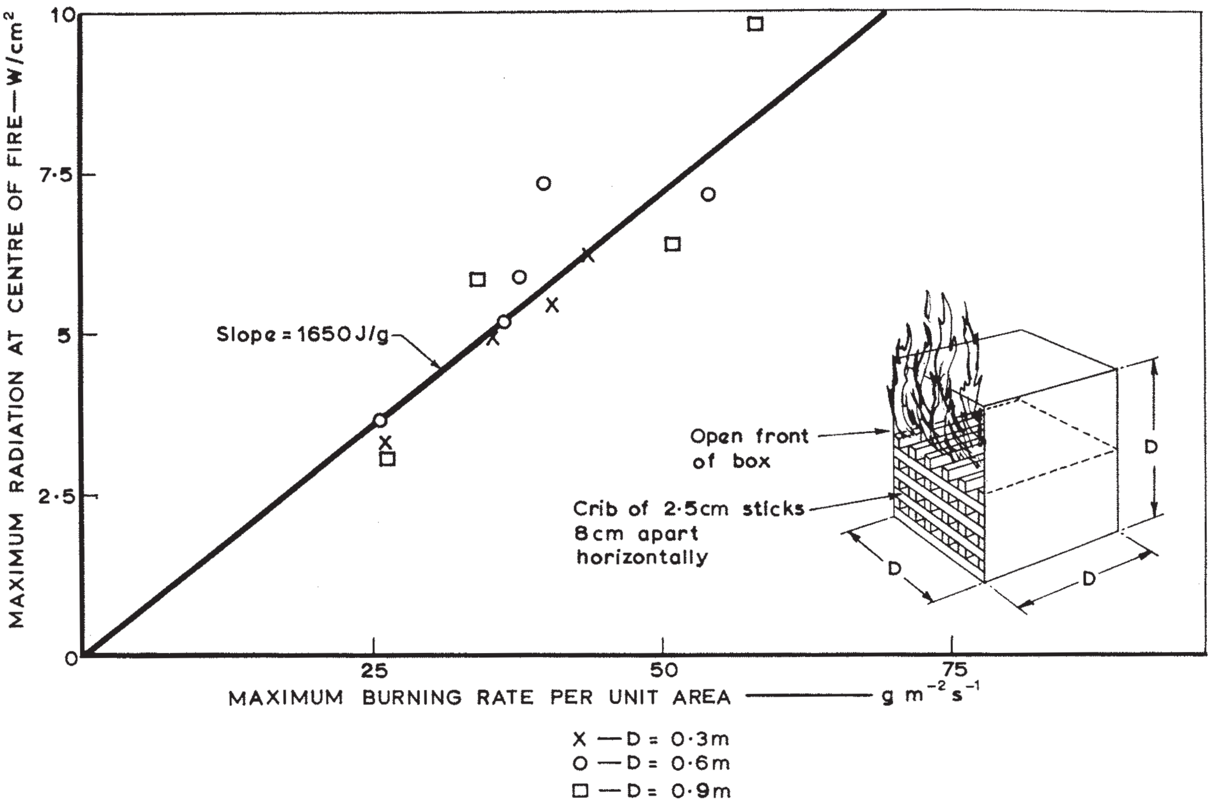
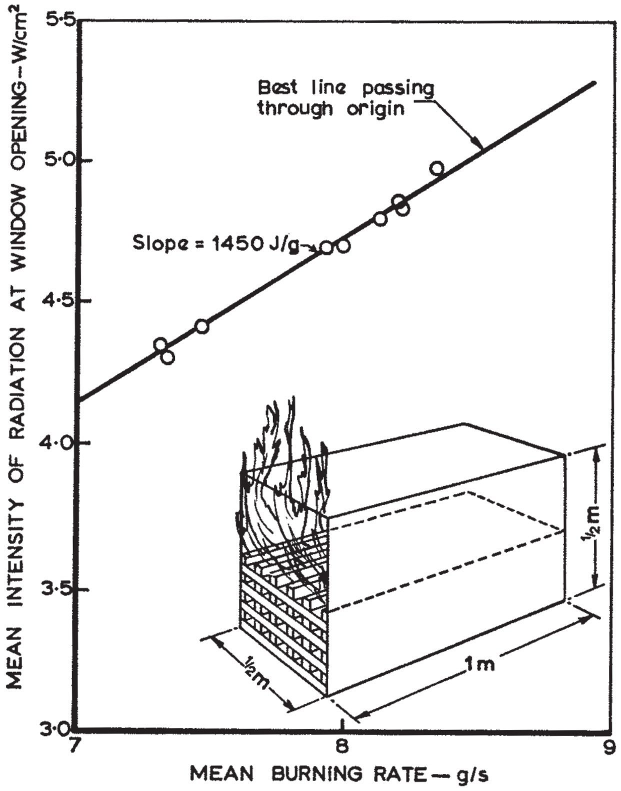


FIG. 8A. Radiation from opening

Difficulties arise, for example, because the carbonaceous surface layers are not uniformly porous and reactions may occur there. Also the heat transfer through this zone may include radiative and convective components as well as a conductive one.



Each result is the mean of a pair in a balanced set of data from three laboratories with three slightly different woods

FIG. 8B. Correlation of radiation and burning rate

These experimental results show an increase in decomposition rate with increasing thermal flux, though this relationship varies slightly with time and the increasing thickness of char tends to depress the decomposition rate. More recently some estimates have been obtained indirectly for cribs of wood from actual small-scale experiments. Thus, in experiments using cubical compartments of dimension D, with one side open, Webster *et al*[8,9] obtained the results shown in Fig. 8A for the effective radiating intensity from the plane of the opening I. There is a region where the intensity is proportional to R/D^2 and Thomas[20] has attributed significance to the slope of this line viz:

$$\frac{ID^2}{R}=1650 \quad J/g \tag{11}$$

where R is the burning rate.

In a balanced set of experiments carried out in laboratories in different countries, a close correlation was found between the measurements of radiation from the window of area A_w and the burning rate R. The results are shown in Fig. 8B where again it is seen that there is a close proportionality between burning rate and radiation.

Here

$$\frac{IA_w}{R}=1450 \quad J/g.$$

Since the window area was here half the floor area it seems reasonable to identify D^2 in equation (11), which refers to cubes, with window area, not floor area.

The radiation level outside the window must reflect similar levels of radiation within the enclosure, but not necessarily identical ones, and so this relationship is consistent with the rate of decomposition being thermally-controlled.

Figure 8C shows the results of some recent large-scale tests. They were carried out in compartments 7·7 m wide, 3·7 m deep and 3·0 m high with two

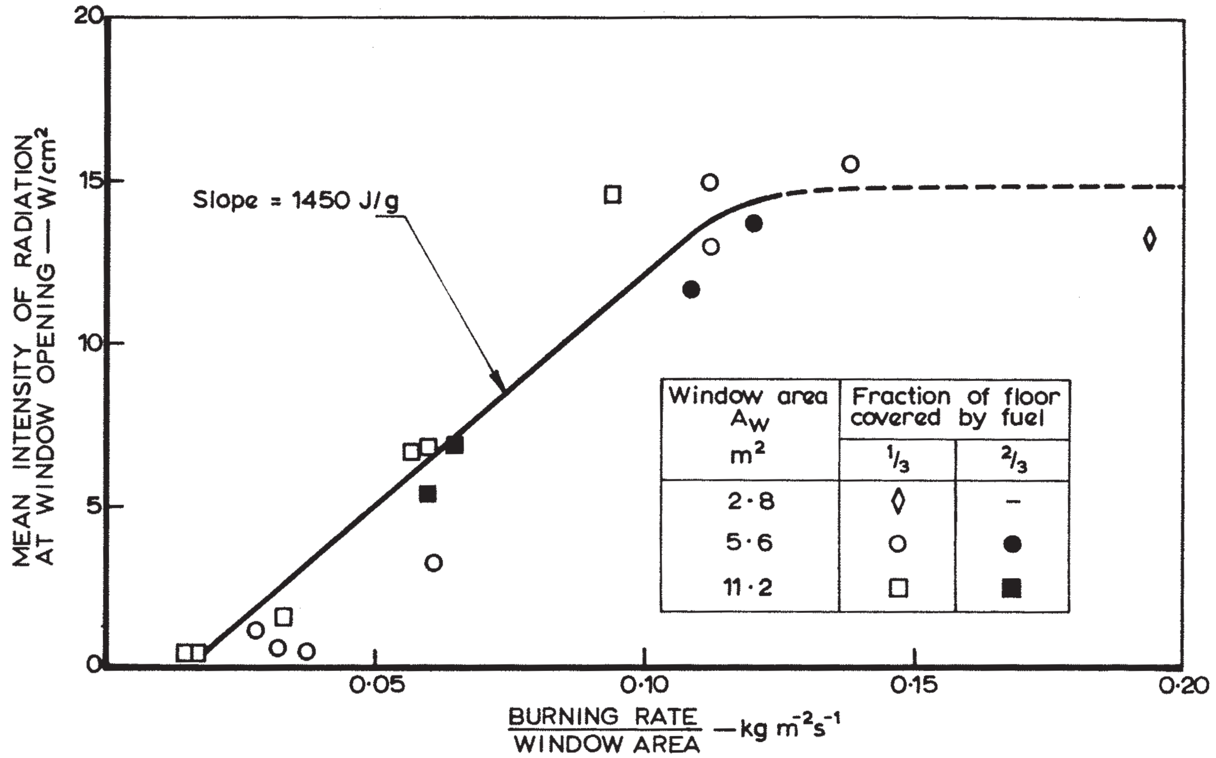


FIG. 8C. Burning rate and intensity emitted from windows of a compartment 7·7 m × 3·7 m × 3·0 m

window openings each 1·8 m high and either 1·5 or 3·0 m wide. Wood sticks, 4·5 cm thick, were placed in eight or eighteen cribs each about 1 m square, distributed evenly over the floor and covering about $\frac{1}{3}$ or $\frac{2}{3}$ of the floor area. Some of the cribs were weighed during the test and a burning rate for the whole of the fuel was deduced. The slope of the line in Fig. 8C also corresponds to 1450 J/g for the value of IA_w/R.

The value of the constant IA_w/R could be expected to depend on the arrangement of the fuel and on the relative geometry of window and compartment but three rather different sets of experiments give very similar values, in the range 1450–1650 J/g.

Although expressing the 'feedback' these relationships have their own importance in providing a direct connexion between the burning rate (and hence duration), radiation emitted (exposure hazard) and radiating temperature (i.e. effective exposure temperatures of contents of the compartment and its structure).

EFFECT OF RATE OF DECOMPOSITION ON HEAT TRANSFER

The heat transfer level at any point within the compartment depends upon the heat balance of the compartment, in particular the effect of wall loss, and on the intensity of combustion within the compartment, which in turn depends on the amount of air entering the compartment and the rate of supply of gaseous fuel. The total amount of heat will be largely determined by the amount of air which enters the compartment and this is approximately constant for a given window opening. Changes in the amount of fuel will change the mixing pattern of flow in that compartment and alter the position of the combustion zone so that the distribution of heat flux and therefore the heat flux rate to any one point are changed. If the fuel is in excess some fuel will not burn in the compartment and will take up heat and thereby reduce the thermal feedback to the solid fuel.

Experiments have recently been made by Heselden[21] to investigate this 'negative feedback'. Town gas was injected at various controlled rates into a simulated fuel bed. Measurements of heat transfer rate, F were made at various points within the compartment and some results are shown in Fig. 9 (Curve (a)). The temperatures of the walls and the heights of flame were also measured. In order to alter the amount of air entering the compartment, without altering the overall size of the window, it was necessary to employ some artificial restriction to the air flow, and this was done by putting strips of metal vertically across the window, thereby reducing the flow within the same window boundary. For a strip 2 cm wide one may reasonably assume that the flow would have become approximately uniform again about 5 cm within the compartment, and therefore the bulk flow would be reduced in approximate proportion to the reduction in area.

Figure 10 shows the results that were obtained. It will be seen that, except near the peak of the heat transfer curve, this method of correlating results is very satisfactory; the discrepancy near the peak intensity is that the flames rise only a little above the burner, and do not emerge out of the window. In this region the amount of window opening is largely irrelevant.

EQUILIBRIUM BURNING RATE

Application of these results to a solid fuel fire in a compartment is now possible on the assumption that the forms of the relationship in Figs 9 and 10 will be similar for wood volatiles even though the emissivity of the resultant flames may be different from that of town-gas flames. Curve (b_1) in Fig. 9 represents the relationship

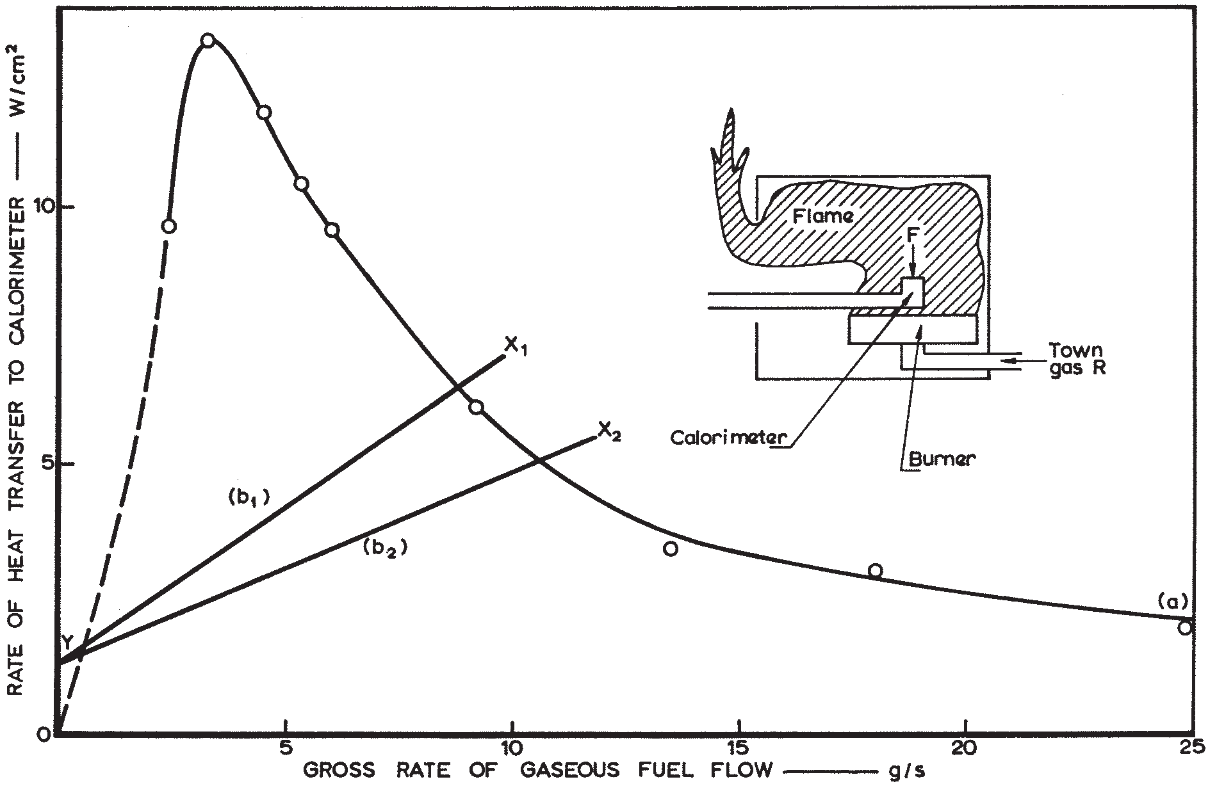


FIG. 9. Heat transfer and gross rate of gaseous fuel flow

referred to above between the heat transfer rate *F* to the solid fuel and the rate at which the fuel decomposes. In general the curve has two intersections *X* and *Y* with curve (a), denoting equilibria, but only the higher one *X* is stable, and represents the quasi-steady burning rate of a fully-developed fire in the compartment.* If the fuel surface area is increased, curve (a) will in principle be unaltered, but curve (b_2), denoting a higher rate of evolution of volatiles from a larger surface for the same rate of heat transfer per unit area, will replace curve (b_1). Thus the equilibrium value of the burning rate is increased from X_1 to X_2, a smaller proportional increase than that of the surface area.

Increasing the window size involves a change in geometry and therefore in flow pattern as well as in total air inflow: however, if Fig. 11 may be taken as an idealization of Fig. 10, the effect of increasing the air flow for a given size of window will be to raise curve (b_1) to a new curve (b_2), since the physical relationship between the heat transfer rate *F* and the resultant burning rate of the fuel will be the same. Increasing the air flow tends to move the equilibrium conditions denoted by point X_1 towards lower values of R/M in accordance with experimental results. At high values

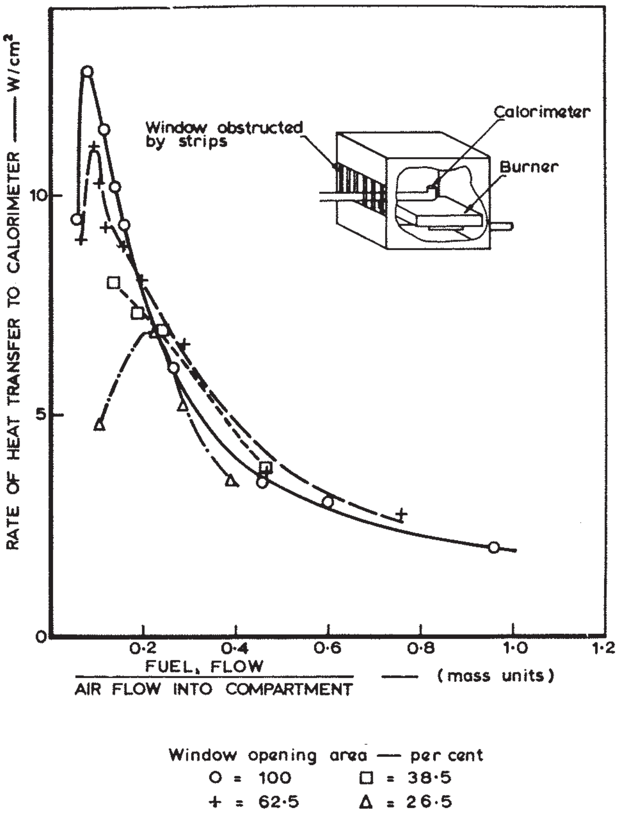


FIG. 10. Correlation of effect of different fuel and air flows

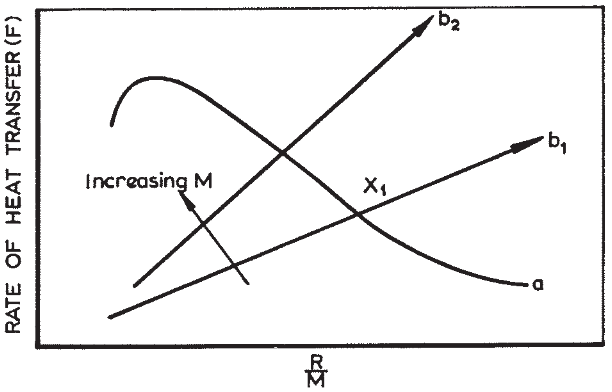


FIG. 11. Effect on equilibrium value of R/M of increasing M

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* The lower unsteady equilibrium may well have some significance in the growth of fire to flash-over but this theory must be extended to allow for the transience introduced by the phenomena of fire spread.

of M, the equilibrium moves to the region of the maximum in curve (a), yielding an approximately constant heat transfer rate corresponding to a constant burning rate, i.e. a burning rate independent of air flow as in fires in the open or in compartments with large windows.

Figures 10 and 11 describe the effect on F of changes in R/M for a given overall size of window. One expects different curves between F and R/M for different geometries, i.e. for different sizes of the area enclosing the window. The effect of changing the window size e.g. changing its height will be to produce a curve lying across the family of F–R/M curves for different window openings, but as yet no data are available for this. At least two effects may be expected. Increasing the window opening tends to make all the interior points relatively nearer the window and hence nearer the combustion zone and therefore F may be expected to increase. On the other hand, the radiation loss through the opening is increased and the value of F could be reduced. The former effect may well be the larger since radiation losses through small window openings are only of the order of 5 per cent of the heat released[22, 23] and this would mean that an F–R/M curve is raised as the window area is increased as shown in Fig. 12.

These effects sharpen the distinction between 'small' and 'large' opening regimes. When the fire load is low, the burning rate R at a given F is lower than when the fire load is high. This moves the equilibrium to the top of the F curve, i.e. the 'high ventilation' regime is in fact a regime characterized by a large opening in relation to the amount of fuel.

The relationships discussed here do not provide in themselves a complete system of scaling, though they are part of the basis of one. Curve (a), for example, depends on the thermal properties of the walls, but, in principle, (b) does not, and this separation is itself important. Here however, we shall not pursue the question of scaling in detail but confine the following discussion to deriving relationships which express the results of the above discussion functionally and can be used as a basis for correlating data.

In view of the discussion on pp. 8–9, we could assume a functional relationship for curve (b) in Fig. 9 which, for any given shape of compartment and relative position of window, takes the form:

$$F = G_1(R'')$$

where G_1 is some unspecified function and $''$ denotes per unit floor area. If we stipulate that G_1 refers to a given shape of compartment and window the use of floor area is effectively equivalent to the use of window area which, as was shown on pp. 7–8, is physically more appropriate.

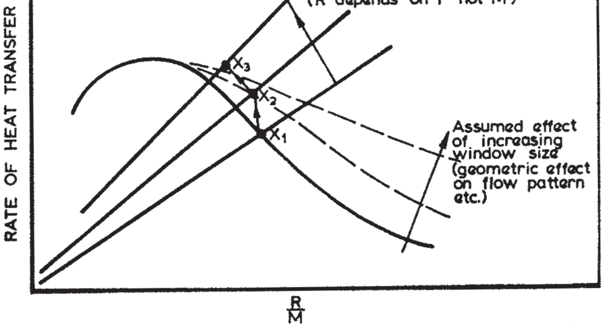

FIG. 12. Effects on equilibrium X of increases of window opening size and air flow

With the same restrictions regarding compartment and window shapes, curve (a) in Fig. 11 is of the form:

$$F = G_2(R/M)$$

We now need to generalize the relation between M and $A_w H^{\frac{1}{2}}$. In equation (2) the ratio $M/A_w H^{\frac{1}{2}}$ has been shown to depend on temperature and R/M. We shall disregard variations in temperature but, quite generally, even if the windows are not small one must allow for the effect of changing R/M. This is not only because the position of the neutral axis varies with R/M but also because this ratio controls the ratio of the momenta of the fuel flow and the air flow and this too determines the flow pattern inside the compartment.

Thus, omitting quantities like g, and ρ_0, the ratio of the variable quantities M and $A_w H^{\frac{1}{2}}$ is:

$$\frac{M}{A_w H^{\frac{1}{2}}} = G_3\left(\frac{R}{M}\right)$$

Combining the three equations involving G_1, G_2, and G_3 and eliminating F and M gives:

$$R \propto A_w H^{\frac{1}{2}} G_4((A_w H^{\frac{1}{2}})'')$$
$$R'' \propto (A_w H^{\frac{1}{2}})'' \cdot G_4((A_w H^{\frac{1}{2}})'')$$

Implicit in each function G_{1-4} are shape factors for the compartment and the window, but if the above arguments are good enough approximations, no scale-dependent factors are included, except possibly in G_1. G_1 would vary with the flame thickness which controls emissivity. G_1 and, consequently, G_4 depend on the type and arrangement of the fuel bed although only at large values of $(A_w H^{\frac{1}{2}})''$

Discussion

Experimental data can be plotted in terms of the variables R'' and $(A_w H^{\frac{1}{2}})''$, where $''$ denotes per unit floor area. Figure 13 shows some experimental points for a series of experiments, brief details of which have been given in connexion with Fig. 8C. The diagonal line is equation (1) and the ordinates of the horizontal asymptotes of the three lowest curves are given by:

$$R_e'' = \frac{q''}{t} \qquad (12)$$

where q'' is the fire load per unit floor area (fire load density) and t is a time which is dependent on the properties of the fuel bed design, especially the fuel thickness and surface area, and is approximately 200–300s (3–5) min for wood 2·5 cm thick[8] and about 20 min for the data plotted in Fig. 13, which are for wood 4·5 cm thick.

Combining equations (1) and (12) with the constant of proportionality written as 6·0, we obtain the demarcation between fires controlled by ventilation and fuel as:

$$\frac{6A_w H^{\frac{1}{2}}}{60} = \frac{q'' A_f}{t} = \frac{q}{t} \qquad (13)$$

where A_f is the floor area and q is the total amount of fuel.

The demarcation is shown diagrammatically in Fig. 14. It follows from equation (10) that if $\frac{q}{A_w H^{\frac{1}{2}}} > \frac{t}{10}$ the fire is controlled by ventilation, and if otherwise is controlled by the fuel bed.

For $H \sim 1 \cdot 8$ m and $t \sim 20$ min (1200s) this demarcation is at 160 kg/m^2. In terms of floor area it is 32 kg/m^2 for the smaller windows and 64 kg/m^2 for the larger ones. In practice these denote a transition zone since the demarcation is not sharply defined.

The above procedure is essentially the same as that employed by Gross and Robertson[4,10]. Their use of burning rate per fuel surface area has the advantage that if the burning rate is proportional to fuel surface area at large values of $A_wH^{\frac{1}{2}}$, the graph would approximate to a universal curve for all window openings and fuel surface areas. However, this need not always be so. There is probably no simple parameter like Q to which R_e is proportional and one may have to employ experimental data for large windows as a means of normalizing onto a single curve.

Some recent experiments covering a range of scales and shapes of compartment appear to show an intermediate region where R_e'' appears to be higher than the limiting value reached when $A_wH^{\frac{1}{2}}$ is large. This may be due to the enclosing walls providing thermal feedback by re-radiation or some effect of changes in the air flow pattern enabling the ventilation-controlled regime to persist to higher values of $A_wH^{\frac{1}{2}}$ than expected. The results have not yet been fully analysed and in the meantime the above description of the behaviour of fully-developed fires can be regarded as a tentative approximation to what is in fact a more complex phenomenon.

The disadvantage of using floor area as a denominator is the loss of universality. The advantage is that the term ($A_wH^{\frac{1}{2}}$ per unit floor area) depends only on the compartment and the window, not on the fuel. For practical purposes, where the distinctions between specific fuel surface are probably associated with building occupancy, distinctions which are already recognized, fire load per unit floor area is probably

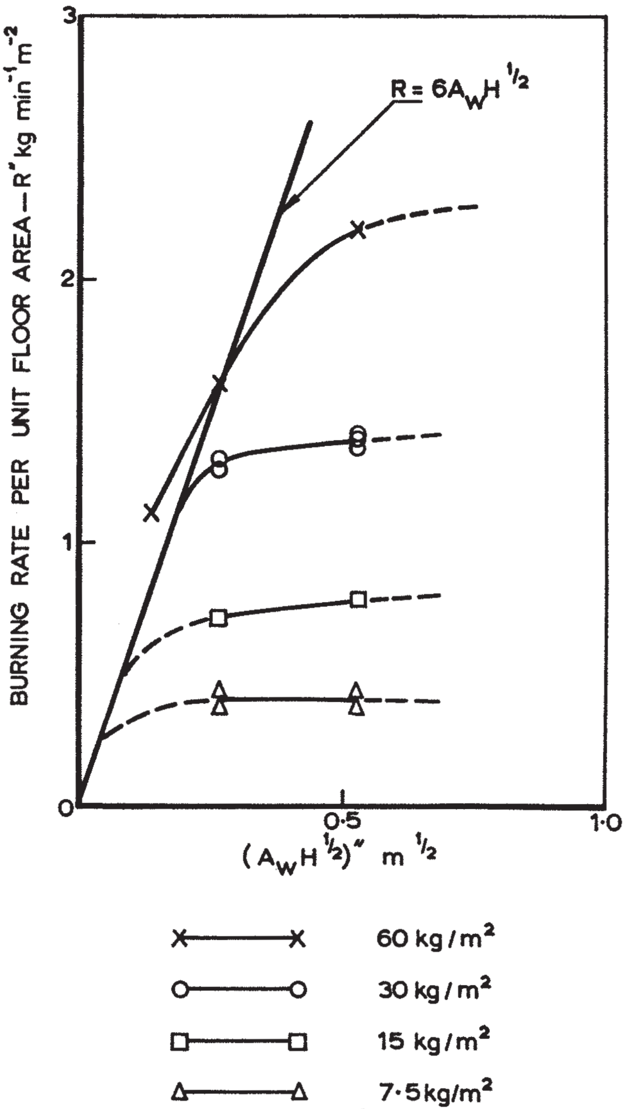

FIG. 13. Burning rate data for a compartment 7·7 m × 3·7 m × 3·0 m

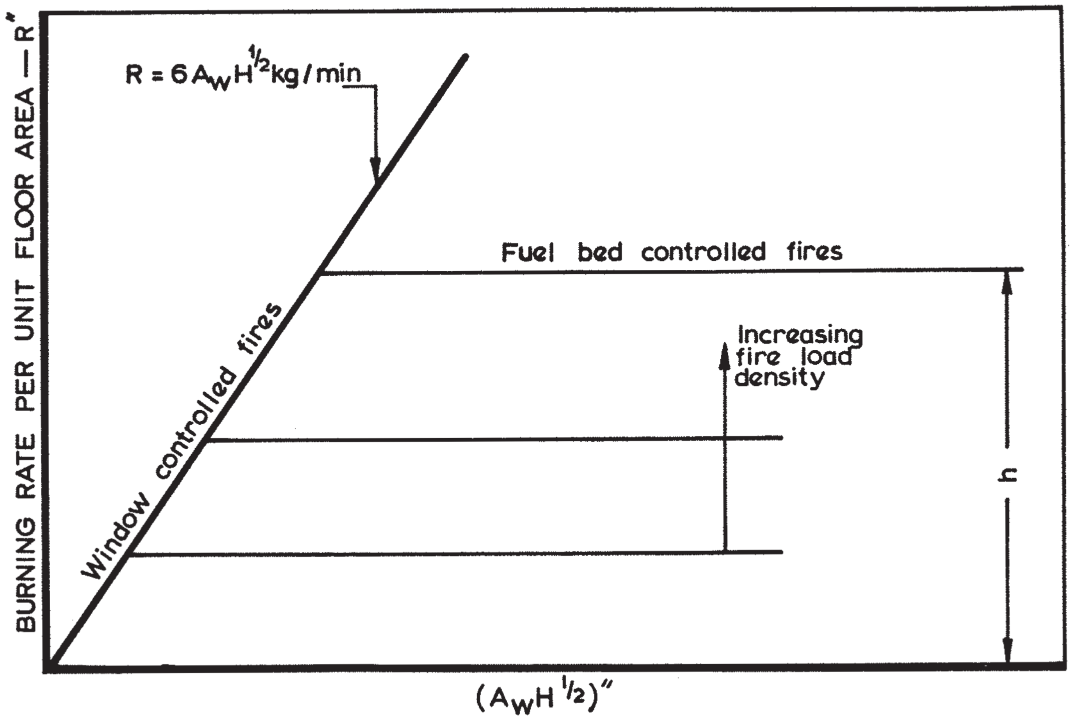

FIG. 14. Burning rates of fully-developed fires

acceptable as an alternative to fuel surface area. It is probably somewhat less useful as a sole measure of burning rate in the region of high ventilation but it has the considerable advantage of being more readily measurable and easier to accommodate in legislative codes. Fire load per unit floor area, convenient though it is as a design quantity, is physically only meaningful in determining fire duration for compartments of a given shape and having windows of a given size relative to the compartment. Even with this limitation it is inappropriate for compartments with large windows where fuel thickness becomes important.

Conclusions

(1) As a window area increases the processes by which air is drawn into a fire in a compartment change from being predominantly the pressure differences caused by a stagnant stack of hot gas to those smaller pressure differences associated with entrainment of air into moving streams of gas.

(2) While the window is small an increase in window area or height leads to an increased burning rate and consequently a decrease in the duration of the fire. For a narrow range of window height, this duration is proportional to the fire load per unit window area.

When the window becomes sufficiently large in relation to the fire load, the burning rate becomes virtually independent of the window area but depends on the fuel itself so that the amount of fuel (particularly its surface area) and its thickness have an important influence on the burning rate. This may result in the burning rate increasing with the amount of fuel and the duration being largely determined by the fuel thickness.

(3) A high correlation appears to exist between the burning rate per unit window area and the intensity of radiation emitted from the window. In view of the association between the effective duration and fire load per unit window area it follows that the intensity of radiation emitted from the window and therefore the effective temperature is expected to be dependent on fire load per unit window area. This has important practical significance for estimating the temperatures attained in fires and the safe distance between buildings and relating them to the burning rate.

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PAPER 4

The ignition of wet and dry wood by radiation

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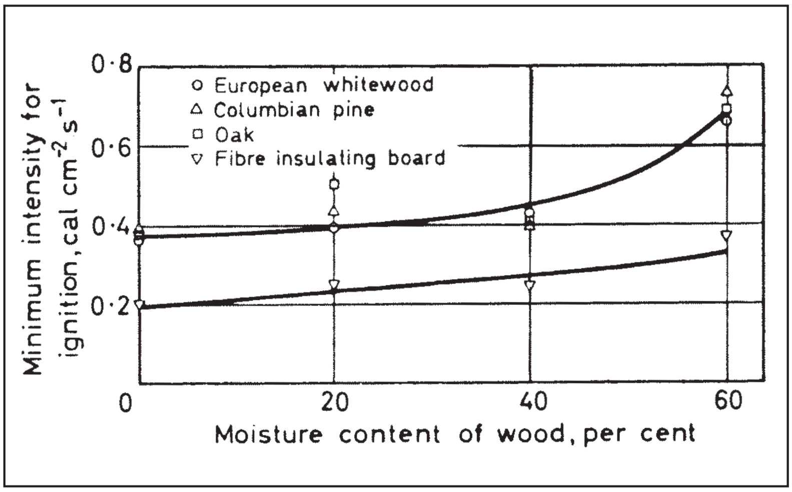
Figure showing the minimum intensity of radiation required to cause pilot ignition of different types of wood and with varying moisture content.



In the years after the Second World War the threat of nuclear attack was a major concern. Thermal radiation from the fireballs of atom bombs had caused extensive fire spread and many human injuries. Consequently, much attention was paid to likely effects in terms of ignition of buildings and skin injuries. Some research projects were directed at assessing the intensity of radiation that could cause ignition during the relatively short duration pulse of heat from an atomic explosion, and wood was selected as the most representative combustible building material. This paper summarises the results of various experiments and illustrates a simple model of ignition: the attainment of a 'critical temperature' at the irradiated surface of the wood specimen.

The results of the research may have been incorporated in civil defence manuals but they were also available for more general use, as demonstrated in Paper No 2.

THE IGNITION OF WET AND DRY WOOD BY RADIATION

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The effect of varying the moisture content on both the pilot and spontaneous ignition times of specimens of different woods 7·6 and 15 cm square has been measured over a wide range of intensities of radiation. Moisture increases the energy required for ignition; it also increases the minimum intensity for ignition, though with pilot ignition its effect is only marked for moisture contents above 40 per cent.

Results have been correlated on the assumption that the material is inert and ignites at a fixed temperature. Simple heat transfer theory has been used to calculate this temperature, taking values for the thermal properties appropriate to the given moisture content and allowing within the term for thermal capacity the heat required to remove the water; the effects of moisture migration have been neglected, following the results of Williams (see ref. 1).

For pilot ignition the correlating temperature was found to be 380°C, corresponding to a critical intensity of 0·31 cal $cm^{-2}s^{-1}$, except for fibre insulating board which appeared to ignite at the somewhat lower temperature of 330°C. Earlier experiments, with smaller specimens, gave a similar result, of 360°C, with the results for fibre insulating board included. The present correlation, however, extends to much longer times (up to 59 min). The results show that the choice of 0·3 cal $cm^{-2}s^{-1}$, as the maximum acceptable level of radiation for building regulation purposes, gives a larger margin of safety than was originally thought.

For spontaneous ignition the correlating temperature was found to be 545°C, the same as found previously for smaller areas, corresponding to a critical intensity of 0·74 cal $cm^{-2}s^{-1}$. The present correlation extends to much longer times (up to 16 min) and the results suggest that the empirical correction necessary for the effect of area on ignition time is linked with density.

Introduction

PREVIOUS work[2,3] has shown that the ignition times of oven-dry woods and other cellulosic materials can be correlated with their thermal properties by assuming they are inert and ignite at a fixed temperature which is independent of density and species, and by using parameters (including that relating to cooling) derived from thermal conduction theory. Other workers, notably Martin[4], have also employed this type of procedure, using similar apparatus and methods though with some difference in detail and emphasis. In particular, work at the Fire Research Station claimed to show that the size of a heated specimen influences ignition behaviour and that the magnitude of this effect is dependent on the ignition time and type of ignition and almost certainly on the apparatus as well; these differences of interpretation have not yet been resolved[4,5].

Experiments have now been carried out to investigate the ignition of woods containing various amounts of moisture, and to extend the model assumed for dry wood to wet wood by discussing the effect of moisture on the thermal properties.

Specimens of wood have been exposed to radiation and their ignition times noted. Ignition with a pilot flame in the stream of evolved gases, (Figure 1), is here called pilot ignition; without a pilot flame it is called spontaneous ignition.

Experimental Method and Results

It is desirable to experiment with as large a specimen as possible since the spontaneous ignition time, and possibly the pilot ignition time, increases as the area irradiated decreases[3], but the size is limited by the size of the radiation source. For the present experiments the source was a 30 cm square radiant panel[6] and the specimens of wood were no larger than 7·6 cm square so that they could be uniformly irradiated at intensities as high as 1·8 cal $cm^{-2}s^{-1}$. This size was found to give results for spontaneous ignition close to those for an infinite area[3]. The specimens used in the pilot ignition experiments were also 7·6 cm square and since the area effect is always less significant for pilot ignition this

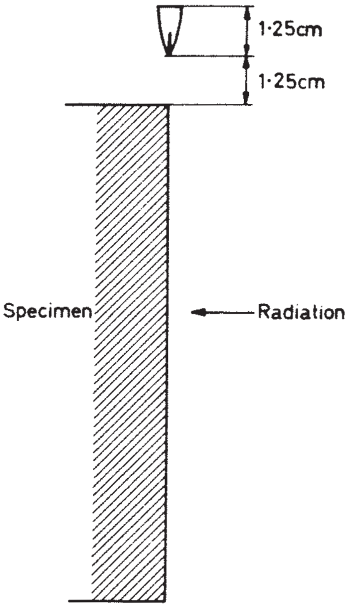

FIGURE 1. Position of pilot flame

size should also give results close to those for an infinite area. A few results from another series of spontaneous ignition experiments were already available for specimens 15 cm square that had been exposed to lower intensities of radiation. All specimens were thermally thick[3].

The specimens of wood were oven-dried and then conditioned to moisture contents of approximately 20, 40 and 60 per cent of oven-dry weight by repeatedly dipping them in water and allowing the water to soak in. Although this leaches out some volatile material the effect on the ignition time is unlikely to be important[7]. The densities of the woods were obtained from their volumes and weights when oven-dried at 95°C. Variations in density between individual specimens of the same type of wood were found to be small.

The details of the specimens for the pilot ignition experiments are given in Table 1 and in Table 2 for those for the spontaneous ignition.

The experimental procedure was similar to that described earlier[8] except that a modified water-cooled Moll thermopile was used to measure radiation instead of the Thwing-type radiation pyrometer. The pilot flame was in the position giving the shortest ignition time[3]. Specimens were exposed to decreasing levels of radiation until eventually it was reasonable to assume that ignition would not occur, i.e. when the rate of production of volatiles became very low. With both pilot and spontaneous ignition, flame could often be seen to appear in the volatile stream and then flash down to the wood where it persisted on the surface. With a few specimens during pilot ignition, there was intermittent flashing between the pilot flame and the surface for several seconds before flaming finally

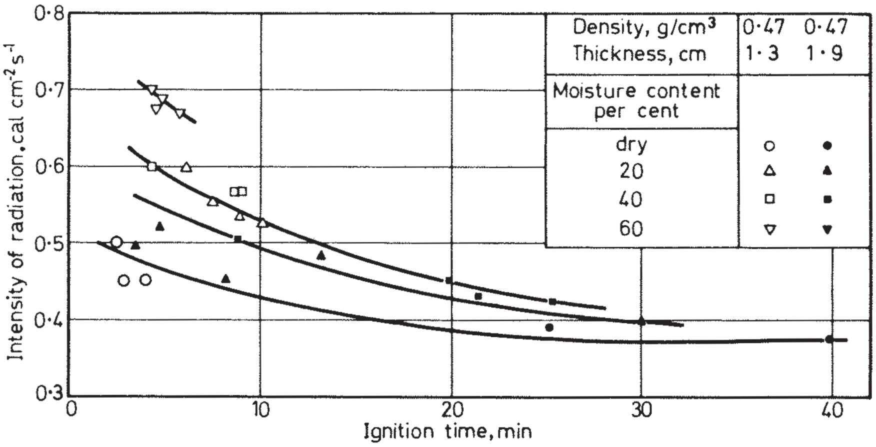

FIGURE 2. Pilot ignition of European whitewood

persisted, and with a few others the flame reached the wood but was intermittent before becoming established. For these the ignition time was recorded as the first appearance of flame. Specimens of European whitewood, other than those that were oven-dry, behaved differently from the other woods; the moisture emerged from the surface in small jets of steam. The results for pilot ignition are summarized in Table 1 and a typical record is shown in Figure 2. The results for spontaneous ignition are given in Table 2. The minimum intensities at which ignition took place are shown in Figures 3 and 4.

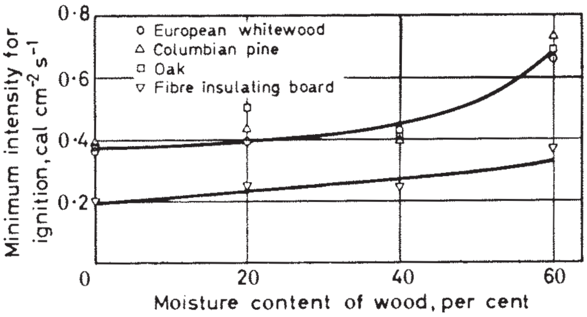

FIGURE 3. Minimum intensity of radiation for pilot ignition (specimens 7·6 cm square)

TABLE 1. Details of woods used in pilot ignition experiments and range of experimental results. Area = 7·6 cm × 7·6 cm

Wood	*Density g/cm^3*	*Thickness cm*	*Moisture content per cent*	*Range of intensities cal cm^{-2}s^{-1}*	*Range of ignition times, s*
Fibre insulating board	0·25	1·3	Dry	0·25–0·40	610–84
			20	0·32–0·50	555–80
			40	0·34–0·35	535
			60	0·37–0·45	465–365
		1·9	Dry	0·20–0·30	1440–215
			20	0·25	1010
			40	0·24–0·30	2540–760
Oak (*Quercus* sp.)	0·66	1·3	Dry	0·38–0·50	415–140
			20	0·55	605
			40	0·59–0·65	635–530
			60	0·69–0·75	510–435
	0·80	1·9	Dry	0·38–0·40	1260–1115
			20	0·50–0·55	1020–630
			40	0·41–0·45	2580–2020
Columbian pine (*Pseudotsuga taxifolia*)	0·46	1·3	Dry	0·46–0·50	430–160
			20	0·54–0·55	460–500
			40	0·63–0·70	380–180
			60	0·74–0·76	310–140
	0·71	1·9	Dry	0·39–0·40	2130–1440
			20	0·43–0·45	1940–1770
			40	0·39–0·41	3540–2230
European whitewood (*Picea abies*)	0·46	1·3	Dry	0·45–0·50	240–180
			20	0·52–0·60	610–370
			40	0·57–0·60	550–260
			60	0·67–0·70	350–270
		1·9	Dry	0·37–0·39	2380–1520
			20	0·40–0·52	1800–300
			40	0·42–0·50	1520–530

Contents

Earlier experiments on the effect of moisture content on spontaneous ignition were carried out with smaller specimens 5 cm × 5 cm in area. The procedure was the same except that the desired moisture content was obtained by storing the specimens over saturated solutions of various salts. The results are reported in detail elsewhere[9] and are compared with the present results in a later section of this paper.

Experiments had also been carried out on the pilot ignition of dry specimens 5 cm × 5 cm in area and these results[2] are also discussed later.

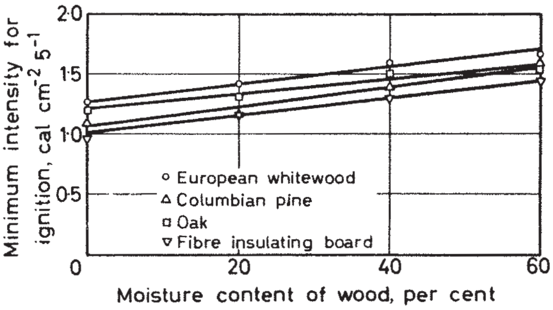

FIGURE 4. Minimum intensity of radiation for spontaneous ignition (specimens 7·6 cm square)

TABLE 2. Details of woods used and experimental results for spontaneous ignition

Wood	*Area cm × cm*	*Thickness cm*	*Density oven-dry g/cm^3*	*Moisture content per cent*	*Intensity of radiation cal cm^{-2}s^{-1}*	*Ignition time s*
Fibre insulating board	7·6 × 7·6	1·3	0·25	Oven-dry	1·00	25
					0·97	32
					0·95	—
				20	1·50	15
					1·30	21
					1·25	33
					1·22	28
					1·21	33
					1·20	—
				40	1·50	27
					1·40	30
					1·30	37
					1·27	—
				60	1·45	45
					1·45	—
Columbian pine (*Pseudotsuga taxifolia*)	7·6 × 7·6	1·9	0·4	Oven-dry	1·20	53
					1·12	70
					1·10	70
					1·10	—
				20	1·50	37
					1·20	88
					1·20	64
					1·17	—
				40	1·50	47
					1·45	68
					1·43	55
					1·41	45
					1·40	—
				60	1·60	45
					1·58	50
					1·55	—

Table 2—*continued*

Wood	*Area* cm × cm	*Thickness* cm	*Density* oven-dry g/cm^3	*Moisture content* per cent	*Intensity of radiation* cal cm^{-2}s^{-1}	*Ignition time* s
Oak (*Quercus* sp.)	7·6 × 7·6	1·9	0·7	Oven-dry	1·80	75
					1·20	93
					1·16	—
				20	1·50	62
					1·40	72
					1·30	105
					1·28	—
				40	1·60	74
					1·55	84
					1·52	80
					1·50	—
				60	1·60	96
					1·58	94
					1·57	119
					1·55	—
European whitewood (*Picea abies*)	7·6 × 7·6	1·9	0·45	Oven-dry	1·35	45
					1·30	48
					1·22	—
				20	1·50	52
					1·45	56
					1·42	55
					1·40	—
				40	1·60	50
					1·58	—
				60	1·70	45
					1·68	51
					1·65	61
					1·62	—
					1·60	—
	15 × 15	2·5	0·5	Oven-dry	1·1	79
				10	1·1	650
				40	1·1	1000
Larch (*Larix decidua*)	15 × 15	2·5	0·5	Oven-dry	1·0	130
Abura (*Mitragyna* spp.)	15 × 15	2·5	0·5	Oven-dry	1·0	680
					1·0	360
Makoré (*Mimusops heckelii*)	15 × 15	2·5	0·6	Oven-dry	1·0	890
					1·0	100

Discussion of Results

The effect of moisture for any given wood is to increase the ignition time, the total ignition energy and the minimum intensity for both spontaneous and pilot ignition. For example, the intensity of radiation required for the pilot ignition of dry wood is about half that for wood with a moisture content of 60 per cent. Similarly, at the same intensity of radiation (say 0·5 cal $cm^{-2}s^{-1}$), the pilot ignition time may be increased from $2\frac{1}{2}$ min for oven-dry oak, to 24 min for oak at a moisture content of 40 per cent. The minimum intensity required for pilot ignition in these experiments with 7·6cm square specimens appears to be independent of the density of the wood except for fibre insulating board which, as found before[2], is much easier to ignite (Figure 3). There appears to be a sharp increase in the minimum intensity between 40 and 60 per cent moisture content.

The increased size of specimens used for the experiments on spontaneous ignition has resulted in the minimum intensity for ignition being lowered with a consequent increase in the maximum ignition time. Thus 2·5cm square dry wood with a minimum ignition intensity of about 1·2 cal $cm^{-2}s^{-1}$ ignites within 30 s or not at all. If it is 7·6 cm square the minimum intensity is reduced to 1·1 cal $cm^{-2}s^{-1}$ with a maximum ignition time of about 70 s and if it is 15 cm square it ignites within 800 s for an intensity of 1·0 cal $cm^{-2}s^{-1}$.

Discussion of the Effects of Moisture

The presence of moisture increases the ignition time by changing the heat transfer and hence the temperature rise in at least three ways:

(1) Moisture increases the values of the thermal properties, i.e. the thermal conductivity and the volumetric specific heat;
(2) Heat is transferred directly by molecular diffusion of the water;
(3) Evaporation cools the hotter regions and condensation heats the cooler regions.

Water vapour in the atmosphere or in the volatiles emitted from the surface is an inerting gas, but the effect is negligibly small compared with its effect on the moisture content in the materials.

Williams[1] measured the temperature/time profiles in oven-dry woods, and in woods of different moisture contents of up to 30 per cent at intensities of irradiation between 2·0 and 3·1 cal $cm^{-2}s^{-1}$, using a graphite panel furnace. He found, as expected, a plateau near 100°C, the duration of which increased with increasing depth; this he suggested was due to the lower rates of heat conduction and consequently smaller temperature gradients. On the assumption that the water converted the wood into an opaque solid, the dry wood being diathermanous, Williams found it possible, within a wide scatter, to correlate his results for the temperature rise, prior to local exothermic heating, using the thermal properties corresponding to the appropriate moisture contents and making an allowance for the desorption of water. This suggested that the temperature histories, both near the surface and within the body of the wood, were unaffected by moisture migration. Williams thought, however, that there was probably only a small difference between the heat released in the interior by the steam migrating from the surface and the heat required to vaporize the liquid there. It is for this reason he was able to neglect the migration effect.

Gardon[10] also found little effect due to moisture migration and correlated his results using a technique similar to that of Williams. Gardon pointed out that this kind of correlation was based on calculating the extra enthalpy required to raise the temperature of the wet wood by the same amount as the dry wood, i.e. on differences, and so the method was not a sensitive one.

Williams[1] also calculated the rate at which the zone of vaporization moved into the solid, by a method based on the work of von Neumann*; this divided the solid into two regions separated by an isothermal plane, the 100°C plateau, the plane of vaporization. The rate at which this plane moved at any depth x was assumed to depend only upon the net rate of heat transfer by conduction to that depth.

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* See, for example, CRANK, J. *The Mathematics of Diffusion*, Oxford, 1954.

This led to the following trial equation for the depth x of the plane at time t

$$\frac{(kt)^{\frac{1}{2}}}{K}\,\mathrm{ierfc}\,\frac{x}{2(kt)^{\frac{1}{2}}} = \text{constant} \qquad [1]$$

where k is the thermal diffusivity, K is the thermal conductivity and

$$\mathrm{ierfc}\beta = \frac{2}{(\pi)^{\frac{1}{2}}}\int_{\beta}^{\infty}\int_{\beta}^{\infty}\exp(-z^2)\,\mathrm{d}z$$

When Williams analysed his data on the times at which the 100°C plateau reached a given depth, he found that equation 1 fitted them reasonably well; this was additional evidence that the effects of moisture migration might be neglected. A further set of experiments carried out using woods containing 220 per cent moisture gave similar results except that no desorption effect had to be assumed, possibly because the wood was saturated.

Fons[11] has suggested a simple means of allowing for the effects of moisture on ignition on this basis. This enables three effects, the change in the value of the thermal constants, the heat of wetting and the latent heat to be considered within the term for specific heat, namely

$$c_m = c_0 + \{\Delta W + 0{\cdot}01(L + \theta_0)M\}/\theta_F \qquad [2]$$

where c_0 is the specific heat of the dry wood taken as[12] 0·34 cal g^{-1} deg.C^{-1} and c_m is the specific heat of the wet wood, M is the moisture content expressed as a percentage of the dry weight, ΔW is the heat of wetting taken as[13] 16 cal/g, L is the latent heat of steam (520 cal/g), θ_0 is the temperature rise from ambient to 100°C, at which temperature all the water is assumed to evaporate, and θ_F is the surface temperature at ignition.

The effect of moisture content on the thermal conductivity K of moist wood has been measured and is given by[14]

$$K_m = 10^{-4}\{\rho_0(4{\cdot}78 + 10{\cdot}2m) + 0{\cdot}57\} \qquad [3]$$

where $m = 0{\cdot}01M$, ρ_0 is the density of dry wood and suffix m denotes the value when the moisture content is M. Its effect on density, ρ, can be estimated from the method of mixtures, neglecting any change in volume, i.e.

$$\rho_m = (1 + m)\rho_0 \qquad [4]$$

The variations in both K and ρ due to moisture are smaller than the variation in c, so that for simplicity the values for the wet wood can be assumed to apply throughout the heating period up to the time of ignition, although strictly, once the water has been driven off the values for dry wood apply and a weighted average for the heating period should be taken.

The ignition time, t, of oven-dry wood in the form of a semi-infinite solid, assumed to be inert, opaque and totally absorbing, irradiated on one face by intensity I, and losing heat from that face by Newtonian cooling may be obtained from[3]

$$\frac{It}{\rho c(kt)^{\frac{1}{2}}\,\theta_F} = \frac{\beta}{1 - \exp\beta^2\,\mathrm{erfc}\,\beta} \qquad [5]$$

where $\beta = (H/K)(kt)^{\frac{1}{2}} = Ht/\rho c(kt)^{\frac{1}{2}}$, the cooling modulus

$$\mathrm{erfc}\,\beta = \frac{2}{(\pi)^{\frac{1}{2}}}\int_{\beta}^{\infty}\exp(-z^2)\,\mathrm{d}z$$

$$k = K/\rho c$$

and H is the Newtonian cooling coefficient corresponding to θ_F.

By substituting values of c_m, K_m and ρ_m given by equations 2, 3 and 4 and inserting the experimental values of I and t in equation 5 a value for θ_F may be found. Fuller details of the method employed are given elsewhere[3].

Correlation of Results

Pilot ignition

Previous results for dry wood, with the pilot flame in a nearly identical position, were correlated[2] using the following values, $\theta_F = 340$ deg.C, $H = 8 \times 10^{-4}$ cal $cm^{-2}s^{-1}$ deg.C^{-1}, $c_0 = 0{\cdot}34$ cal g^{-1} deg.C^{-1}. The correlation was satisfactory except for fibre insulating board at low values of I, i.e. at high values of $Ht/\rho c(kt)^{\frac{1}{2}}$ where the points lay below the line. The results for the new series of oven-dry materials are shown in Figure 5; there is a reasonably close fit between the experimental points and equation 5 using the same constants but a better correlation is obtained by ignoring the results for fibre insulating board for high $t/\rho c(kt)^{\frac{1}{2}}$ and using $\theta_F = 360$ deg.C, $H = 8{\cdot}6 \times 10^{-4}$ cal cm^{-2}s^{-1} deg.C^{-1}. The experimental results for the specimens of different moisture contents and densities are plotted in Figure 6 using equation 5 and $\theta_F = 360$ deg.C. There is reasonable agreement between the experimental points and equation 5 except for fibre insulating board, for which the numerical value of $It/\theta_F \rho_m c_m (kt)^{\frac{1}{2}}$ must be raised, i.e. θ_F reduced. This is achieved by using values of $\theta_F = 310$ deg.C, $H = 7{\cdot}4 \times 10^{-4}$ cal cm^{-2}s^{-1} deg.C^{-1}. This leads to a value for the critical intensity of wood ($I_0 = H\theta_F$) of 0·31 cal cm^{-2}s^{-1} and for fibre insulating board of 0·23 cal cm^{-2}s^{-1}.

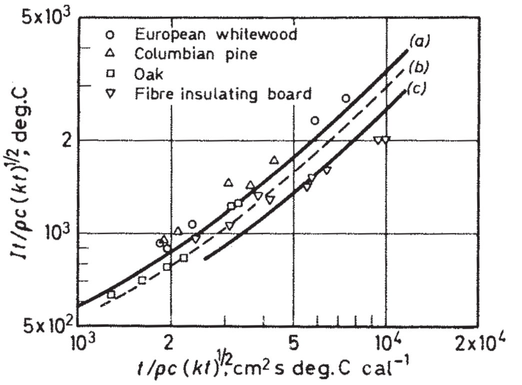

FIGURE 5. Pilot ignition of dry wood 7·6 cm square. Curves given by equation 5 with values assigned to θ_F and H

Curve	θ_F, *deg.C*	*H, cal cm^{-2} s^{-1} deg.C^{-1}*
(*a*)	360	$8{\cdot}6 \times 10^{-4}$
(*b*)	340	$8{\cdot}0 \times 10^{-4}$
(*c*)	310	$7{\cdot}4 \times 10^{-4}$

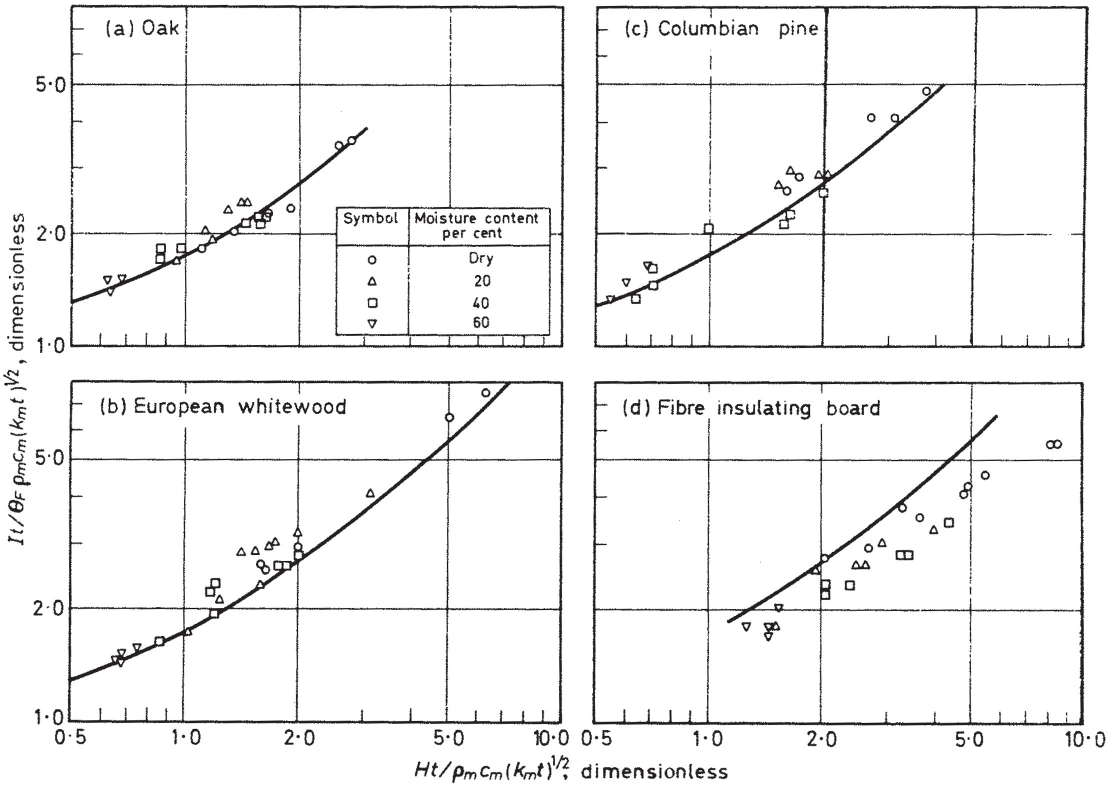

FIGURE 6. Correlation of pilot ignition results for specimens 7·6 cm square. Curves given by equation 5 with $\theta_F = 360$ deg.C and $H = 8{\cdot}6 \times 10^{-4}$ cal cm^{-2} s^{-1} deg.C^{-1}

The correlation shown in Figure 6 appears to account for both the effects of different moisture contents and of different densities on the pilot ignition time of the woods. The results for fibre insulating board are a little below those for wood, as was found earlier[8], but the residual effect associated with density for the remaining woods, found earlier[2] with smaller specimens is absent here. Additionally, although the ignition times are much longer than those studied previously—nearly an hour in one experiment and several specimens took about 40 min to ignite—there is no sign of a trend away from the correlation even at the highest values of $Ht/\rho c(kt)^{\frac{1}{2}}$. This suggests that any effect due to self-heating (an earlier explanation[2]) is small even for fibre insulating board. The temperature found to correlate these and the earlier results is similar; the rise in the value of the correlating temperature from 340 deg.C to 360 deg.C is due to the exclusion of the results for fibre insulating board. This confirms that any effect of area on pilot ignition time is small, but since the residual effect associated with density has been removed, it also suggests that the effect of area on pilot ignition time as well as on the minimum intensity for pilot ignition may be associated with the density of the wood.

Assuming that the ambient temperature is 20°C, the surface temperature at ignition is 380°C for the species of wood tested and 330°C for the fibre insulating board.

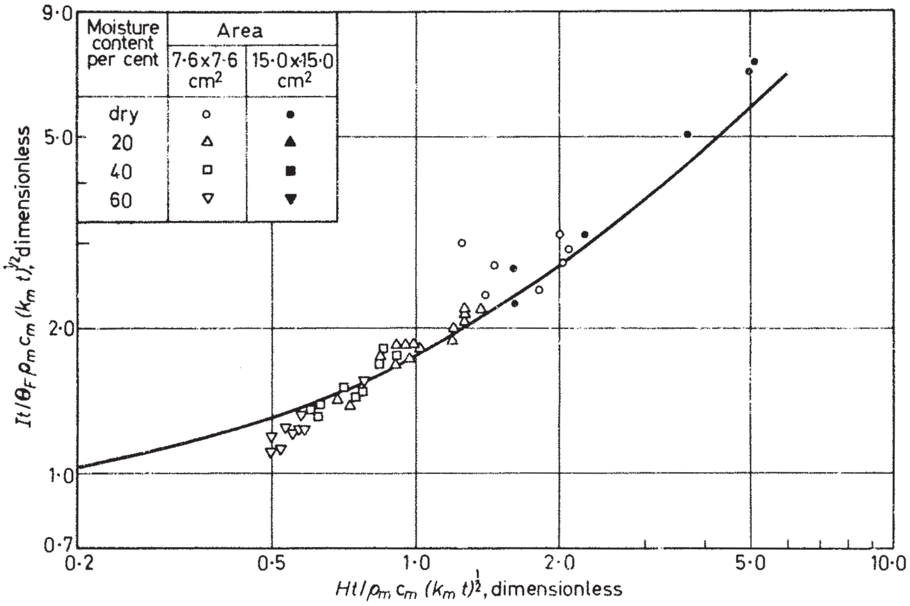

FIGURE 7. Spontaneous ignition of seven species of wood 7·6 cm square and 15 cm square specimens. Curve given by equation 5 with $\theta_F = 525$ deg.C, $H = 1{\cdot}4 \times 10^{-3}$ cal cm^{-2} s^{-1} deg.C^{-1}

Spontaneous ignition

Previous results[2] for dry wood were correlated using the following values, $\theta_F = 525$ deg.C, $H = 1{\cdot}4 \times 10^{-3}$ cal cm^{-2}s^{-1} deg.C^{-1}, $c_0 = 0{\cdot}34$ cal g^{-1} deg.C^{-1}. The results for the new series of oven-dry woods 7·6 cm square and 15 cm square are shown in Figure 7. There is a reasonably close fit between the experimental points and equation 5 using the same constants and since there appeared to be no difference between the results for the different species, these have not been shown separately. The results for the 7·6 cm square specimens of different moisture contents and densities are also plotted in Figure 7 and there is again a reasonably close fit between the experimental results and equation 5, although the results tend to lie above the curve at long ignition times and below it at short times.

Previous results[9] for woods cut 5 cm square with densities ranging from 0·24 to 0·66 g/cm^3 and moisture contents ranging from 0 to nearly 30 per cent and covering a range of intensities of radiation from 1·5 to 2·4 cal cm^{-2}s^{-1} have been analysed in a similar way. The best fit is obtained with a value of θ_F of 525 deg.C and for H of 1·4 × 10^{-3} cal cm^{-2} deg.C^{-1}s^{-1} and the results follow the trend of the curve fairly well (Figure 8). However, although the effect of moisture content has been absorbed by the correlation, the effect of density has not; the denser woods lie below the lighter ones, i.e. they appear to ignite at a lower temperature. This is a similar effect to that found[2] for pilot ignition of specimens of the same size, namely 5 cm square.

No correction to the ignition times for the effect of area[3] has been applied to these results.

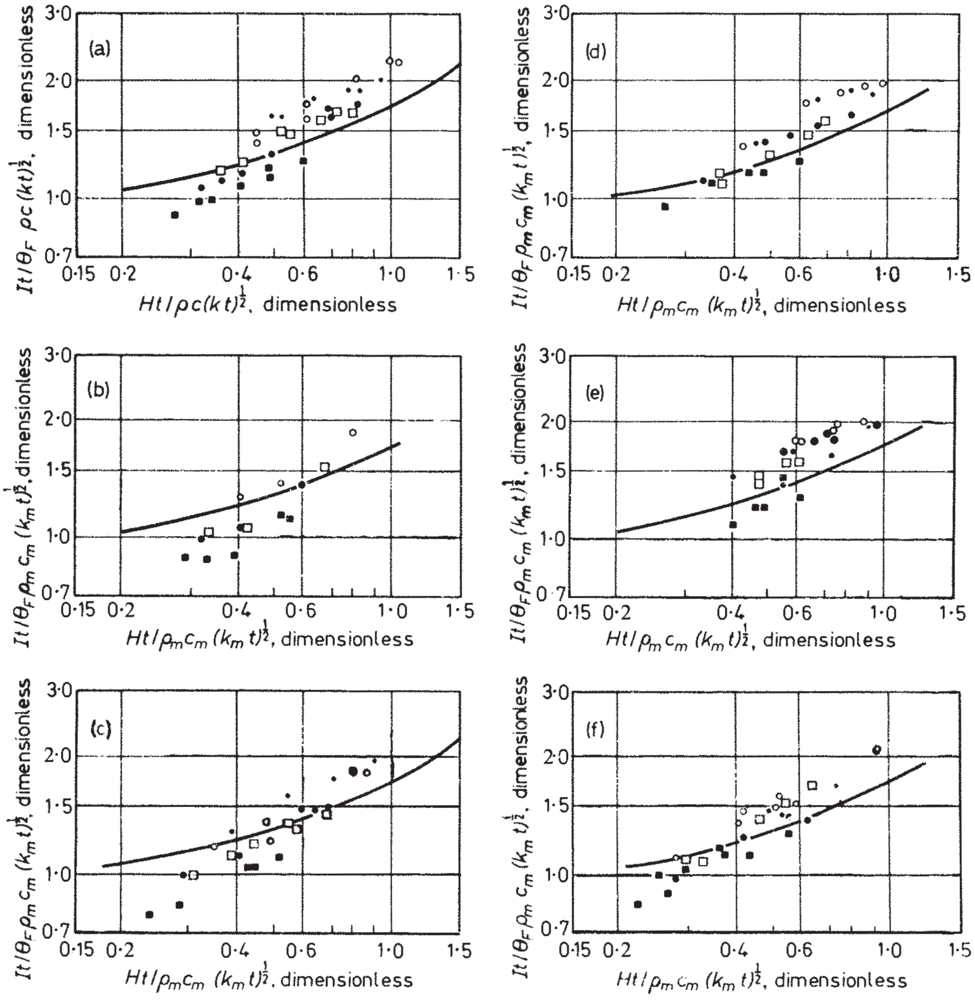

FIGURE 8. Spontaneous ignition of 5 cm square specimens. Curves given by equation5 with $\theta_F = 525$ deg.C, $H = 1{\cdot}4 \times 10^{-3}$ cal cm^{-2} s^{-1} deg.C^{-1}. Range of approximate moisture contents: (a) dry, (b) 5, (c) 8, (d) 12, (e) 15 and (f) 18 per cent (moisture content of fibre insulating board about 28 per cent). The specimens, symbols and oven-dry densities (g/cm^3) are as follows: fibre insulating board, •, 0·24; cedar, ○, 0·37; mahogany, □, 0·52; Columbian pine, ●, 0·55; oak, ■, 0·66

Nonetheless, the residual effect due to density is similar to, though somewhat larger than, that found for pilot ignition with specimens 5 cm square and since it is not found with either form of ignition with those 7·6 cm square this suggests that the area effect does depend on density. Assuming that the ambient temperature is 20°C the surface temperature at ignition is 545°C for the species of wood tested.

Application of Results

Safe separation of buildings

In devising safe separation distances from burning buildings[15] and timber stacks[16] in order to reduce the risk of fire spreading to neighbouring property the critical intensity for pilot ignition of wood was taken as 0·3 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$; ($I = H\theta_F = 0{\cdot}31$ cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$). In none of the present results did pilot ignition occur in less than 20 min at an intensity of radiation less than 0·37 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Thus, the lowest value at which the pilot ignition is likely to occur is above 0·35 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Even at an intensity of radiation of 0·4 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the ignition time of dry wood will be at least 5 min and at the lowest likely moisture content of 10 per cent, it will be 10 min. Such an intensity of radiation near the extreme distance at which ignition may occur will only be reached some time after the outbreak of the fire: the fire brigade should therefore have ample time to arrive and protect the exposed property. Notwithstanding this, the dry material presents the greatest danger and regulations have been based on the hazard of the dry rather than the wet material.

Conclusions

Increasing the moisture content increases the time for both pilot ignition and spontaneous ignition for any given intensity of radiation. The increase has been accounted for satisfactorily by using the values of the thermal properties appropriate to the different moisture contents, and allowing for the effect of heat of wetting and latent heat of evaporation within the term for specific heat, as in equation 2. This confirms Williams's experiments and calculations which showed that it was possible to neglect the effect of moisture migration on the temperature rise.

The pilot ignition time for the position of the pilot flame shown in Figure 1 may be calculated using equation 5 assuming a fixed surface temperature criterion of 380°C for wood and 330°C for fibre insulating board. This correlating temperature for pilot ignition is the same for specimens 5 and 7·6 cm square and this suggests that the effect of area on pilot ignition time is small. The new correlation appears to be more satisfactory than that found earlier[2] since there is no residual effect linked with density, and although fibre insulating board, the lightest material, again appears to ignite at a slightly lower temperature, there is little sign of any systematic departure from the curve at high values of $Ht/\rho c(kt)^{\frac{1}{2}}$ which would denote self-heating. Moisture contents of up to about 40 per cent by weight appear to have little effect on the minimum intensity at which ignition occurs, although there may be an increase above this level. The energy required for ignition increases markedly for all moisture contents. The expermental results suggest that there is an amply safe margin in the choice of 0·3 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ as the maximum acceptable level of radiation used in the *Building Regulations* to determine separation of buildings.

The spontaneous ignition time can also be calculated from equation 5 assuming a fixed surface temperature criterion of 545°C. This correlating temperature for the larger specimens (7·6 and 15 cm square) is about the same as that given earlier for smaller specimens and the range of ignition times for which it is applicable has been extended to at least 130s. However, for the results of the smaller specimens (5 cm square), analysed in this paper, there is a residual effect due to density similar to that found for pilot ignition for the same size of specimen which suggests that the area correction factor is associated with the density both for ignition time and for minimum intensity of ignition. The concept of a fixed temperature criterion for ignition of dry woods is thus valid for woods of up to 60 per cent moisture content. The experimental range reported earlier has been extended to give ignition times of 0·25 to 16 min with intensities of 1·0 to 12·0 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for spontaneous ignition and times of 60 min and intensities of 0·2 cal $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for pilot ignition.

(*Received October 1966*; *revised July 1967*)

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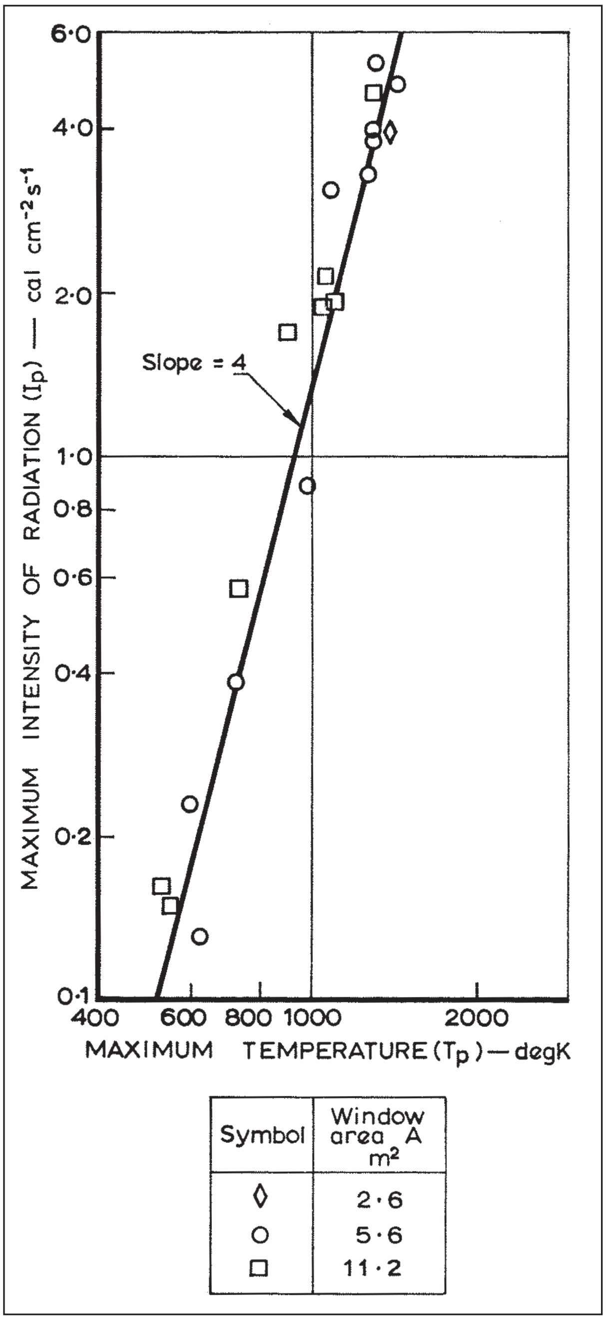
Contents

PAPER 5

Radiation from fires in a compartment

Margaret Law, BSc, Fire Research Technical Paper No. 20, 1968
Ministry of Technology and Fire Offices' Committee, Joint Fire Research Organization. HMSO, UK

Figure 3 from this paper: a log-log plot showing that the maximum value of window radiation is directly proportional to the maximum compartment temperature raised to the fourth power.



This paper contains an analysis of radiation from compartment fires using data not available when Paper No 2 was in preparation. It also profits from other work, such as that in Paper No 3. It confirmed that the model underlying the Building Regulations for building separation was reasonable. It is worth noting that our statistical colleagues planned the experimental programme so that the significance of various effects could be analysed efficiently. This is illustrated in the paper.

Gordon Butcher was one of the people directly involved in the compartment fire programme. When his experiments were completed, I was transferred to work in his Section with instructions to 'get something useful out of the results'. On the first day I looked at the measurements of radiation, plotting them against the absolute compartment temperatures. I then burst into Gordon's office, shouting 'Planck was right!' The graph I was waving in my hand is reproduced here as Figure 3.

Ministry of Technology and Fire Offices' Committee
Joint Fire Research Organization

Radiation from fires in a compartment

Margaret Law, B.Sc.

Fire Research Technical Paper No. 20

LONDON: HER MAJESTY'S STATIONERY OFFICE: 1968

Preface

Previous work of the Fire Research Station has been used as a basis for those Building Regulations which control separation between buildings to reduce the risk of spread of fire by radiation. During some recent experiments with fires in a compartment, further radiation measurements have been taken to supplement the earlier data.

This paper discusses these results, particularly the radiation contributed by the flames emerging from the windows, and relates them to the general study of the behaviour of fully-developed fires in compartments.

It is hoped therefore that this paper will interest not only those concerned with problems of building separation but also with relating fire behaviour to the fire grading of buildings.

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Fire Research Station
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January 1968

Radiation from fires in a compartment

Summary

Intensities of radiation from fires in a compartment have been measured, both from the windows and from the emerging flames. The emitted intensity depends on the fire load in the compartment and on the ventilation area. The flame radiation is in general small compared with the window radiation and although for the highest fire load and the smaller window area used in the experiments the flames gave a significant increase in radiation, this was not large enough to warrant recommending any increase in separation distances between buildings, which have been based on window radiation only.

When the intensity reaches its maximum value the compartment can be assumed to be a black body. The average intensity of radiation shows the same relationship with rate of burning per unit window area as found in other experiments. Thus intensity of radiation and compartment temperature can be predicted for other compartments.

Introduction

Safe separation distances from burning buildings have been calculated[1] on the assumption that the window openings alone radiate and the contribution of radiation from the flames, if any, outside the openings has been ignored. Until recently too little information has been available on either the size and thickness of flames from windows or the effects of wind on their size and deflection to give a reliable estimate of flame effects.

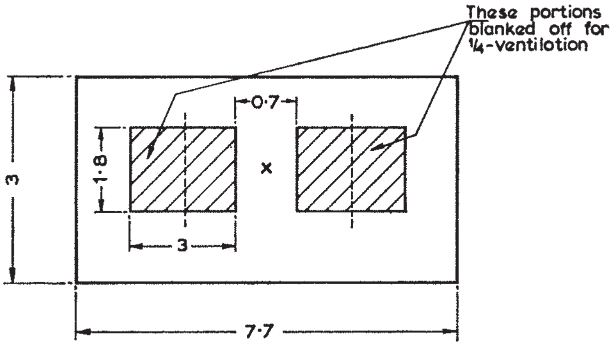
Radiation measurements have now been taken for a series of fires in a compartment having a range of fire load densities and window openings, and separate records have been made of the intensity from the window openings alone and from the openings plus the flames. Thus not only do these records give an assessment of the flame effect but they also supplement the rather scanty information available on radiation from burning buildings. Most workers have measured, instead, temperatures inside the burning compartments and only McGuire seems to have made a comprehensive series of radiation measurements on full scale, during the St. Lawrence burns[2].

The range of fire load densities used covered values typical of domestic occupancies and offices but excluded very high fire loads such as those found in warehouses. The effect of higher fire loads is considered later.

The measurements reported here were taken only in light winds of less than 14 km/h (9 mile/h). This was because they were one small part of a large experimental programme[3] studying many factors of fire growth and spread for which high winds would have produced unwanted variations in results. A separate programme of experiments[4] carried out with models in a wind tunnel indicates that the assessment of the effects of higher wind conditions is complex. This will be discussed later.

Compartment tested

Two identical brick-walled compartments were used in the tests and it has been shown[5] that these give the same results. An elevation is given in Fig. 1. The sum of the areas of the two windows was 5·6 or 11·2 m^2, being either $\frac{1}{4}$ or $\frac{1}{2}$ of the area of the wall containing them, except that in one test (V) the area was reduced to 2·6 m^2 i.e. approximately $\frac{1}{8}$ of the area of the longer wall. Two radiometers were set up to receive the maximum intensity, facing the point midway between the two windows; one was shielded from the flames above the windows so that it measured only the radiation from the windows, while the other was unshielded and measured the total radiation. Thus the difference between the two readings gave the flame contribution. The radiometers were at a distance of 4·6 m for the



Dimensions in metres

Depth of compartment = 3·7m

Radiometer facing x

FIG. 1. Elevation of compartment

north compartment and 6·1 m for the south compartment.

The fuel was in the form of cribs made with wood sticks 4·5 cm thick and was distributed at a fire load density (in terms of floor area) of 7·5, 15, 30 and 60 kg/m^2 i.e. total fire loads of 218, 436, 872 and 1744 kg.

In twelve tests, listed in Table 1 (A–L, U, V), the fuel was distributed on $\frac{1}{3}$ of the floor area, in two tests (M, N) on $\frac{2}{3}$ floor area, in two tests (Q, R) on $\frac{2}{3}$ floor area with the compartment lined on walls and ceiling with a 2·5-cm thick mineral wool slab, and in two tests (O, P), on $\frac{1}{3}$ floor area also with the mineral wool lining. In one test (S) there was a combustible lining of 1·3-cm thick fibre insulating board which counted as part of the fire load. Thus both the insulating effect of a lining and its contribution, if any, to the fire load were investigated. Thermocouples were placed in the hot gases at various positions inside the compartment and an average of their readings has been taken as the compartment temperature. Fuller details of the test conditions are given elsewhere[3,6] and the complete data obtained are to be published later. General observations of the fire behaviour and detailed results of the intensity measurements are given below.

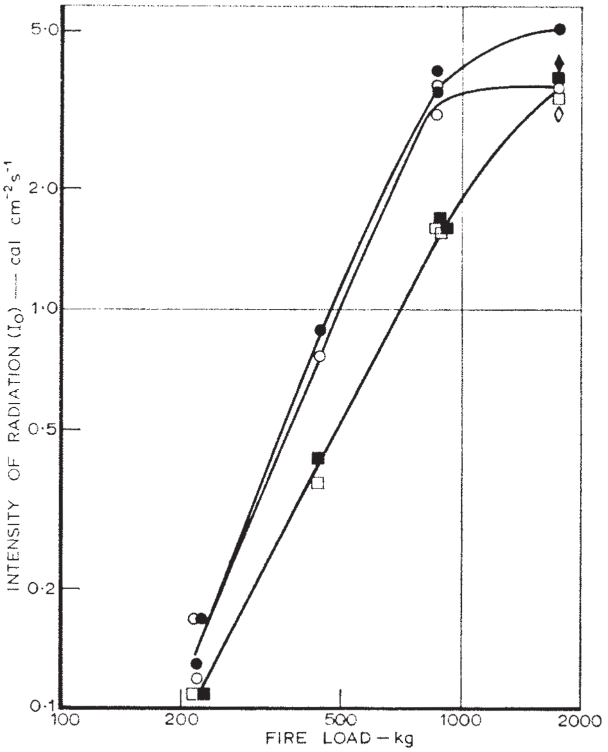
General observations of fire behaviour

With the lowest fire loads the fire did not completely fill the compartment; the flames were small and none emerged from the windows. Large amounts of flame appeared only with the higher fire loads and they were taller with the smaller window. The fibre insulating board lining produced large flames which built up to a peak twice before dying out. Some typical fires are shown in Plates 1–4 (B).

Experimental results

The average intensity of radiation over the time for which the fire was burning at an approximately steady rate is shown in Table 1 for each test; the radiation levels during the initial and final stages of the fires have not been considered in this paper. The initial stage of the fire is taken as the stage when less than the first 20 per cent of the fire load is burnt i.e. until 80 per cent remains (t_{80}) and the final stage is taken as beginning when only 30 per cent remains (t_{30}). In order to compare the readings for the two compartments, i.e. for the two radiometer distances, the configuration factors, φ, from the openings to the radiometers have been calculated*; these have been used to normalize the measured intensities I to give effective intensities in the plane of the window of $I_o = \frac{I}{\varphi}$. The value of φ has been calculated in the way used for building regulations[1] by assuming that the windows alone radiate, from the front of the building, the small effect of wall thickness being ignored. In some of the experiments a steel column obscured a small part of the window opening and the value of φ has been adjusted to allow for this.

The maximum value of normalized intensity, denoted by I_p, the maximum value of the temperature rise of the gas in the compartment, θ_{pf}, and the estimated† rate of burning, $R_{80/30}$, are also given in Table 1.



Window radiation	Total radiation	Window area A — m^2
◊	♦	2·6
○	●	5·6
□	■	11·2

FIG. 2. Results for unlined compartments with fire load on one-third floor area

The variation of average intensity I_o with fire load and ventilation is shown in Fig. 2 for the first twelve tests listed in Table 1, i.e. the ones with $\frac{1}{3}$ fuel distribution and no wall lining. As would be expected I_o first increases with fire load and then tends to a steady value. I_o is higher for the 5·6-m^2 window than the 11·2-m^2 one. There appears to be no significant difference between the window and total radiation values for the 11·2-m^2 window but the total value appears to be greater for the smaller windows. The values for the 2·6-m^2 area straddle those for the 11·2-m^2 size.

* The intensity of radiation decreases with distance from the windows and φ is a reduction factor with a value depending on the area and shape of the windows. It cannot exceed unity.

† Estimated by continuously weighing selected cribs.

Table 1
Results

Test	Window area A m^2	Fire load L kg	Configuration factor φ	Average radiation over t_{80}—t_{30} $I_o = I/\varphi$ cal $cm^{-2}s^{-1}$		t_{80} min	t_{30} min	$R_{80/30}$ kg/s	Maximum values			Fire load distribution	Wall lining
				Window radiation	Total radiation				Radiation I_p cal $cm^{-2}s^{-1}$		Average gas temperature rise in compartment θ_{pf} degC		
									Window radiation	Total radiation			
A	5·6	218	0·069	0·17	0·17	7·4	17·3	0·18	0·23	0·23	315	$\frac{1}{3}$ floor area	NIL
B	5·6	218	0·069	0·12	0·13	6·5	15·2	0·21	0·13	0·15	340		
D	11·2	436	0·114	0·37	0·43	7·4	17·2	0·37	0·57	0·75	465		
E	11·2	872	0·114	1·61	1·68	8·3	19·6	0·64	1·90	1·98	755		
F	11·2	872	0·114	1·63	1·63	8·2	19·0	0·67	1·93	1·84	800		
G	5·6	436	0·040	0·78	0·90	8·2	18·8	0·34	0·88	1·00	700		
H	5·6	872	0·040	3·60	4·00	9·7	21·3	0·63	5·30	5·37	1040		
I	5·6	872	0·040	3·12	3·55	8·1	19·7	0·63	3·95	4·30	1035		
*K	11·2	218	0·074	0·11	0·11	8·3	18·1	0·19	0·15	0·16	275		
L	11·2	1744	0·074	3·51	3·74	10·1	24·0	1·05	4·64	4·64	1055		
U	5·6	1744	0·038	3·66	5·10	15·8	34·0	0·77	4·74	5·79	1160		
V	2·6	1744	0·021	3·16	4·15	24·6	51·3	0·54	3·91	4·73	1115		
M	5·6	872	0·040	2·82	3·20	12·0	23·9	0·61	3·38	4·05	1010	$\frac{2}{3}$ floor area	
N	11·2	872	0·074	1·30	1·39	10·4	21·3	0·67	1·74	1·81	630		
O	5·6	218	0·038	0·29	0·29	9·0	20·7	0·16	0·39	0·39	470	$\frac{1}{3}$ floor area	MINERAL WOOL SLAB
P	11·2	218	0·074	0·14	0·15	8·1	18·7	0·17	0·16	0·24	260		
Q	5·6	872	0·038	3·29	3·60	13·1	23·9	0·67	3·84	4·47	1045	$\frac{2}{3}$ floor area	
R	11·2	872	0·074	1·65	1·77	9·2	19·2	0·73	2·16	2·30	800		
S	5·6	218	0·038	2·25	3·00	1·9†	4·3†	—	3·17	5·13	805	COMBUSTIBLE LINING AND CRIB	

Radiation values were not obtained for test J, a replicate of test K. Floor area $\simeq$ 29m^2

*The radiometers were obstructed for part of the test and it is possible that the reading may have a small error

†Visual estimate

Analyses of results

EFFECT OF FIRE LOAD AND WINDOW AREA

The results illustrated in Fig. 2, i.e. those for fires with $\frac{1}{3}$ fire load distribution and no wall lining, have been analysed statistically (Appendix). In this analysis the changes in intensity due to the flames and to varying the fire load and window area have been compared with the differences in results for repeat tests to see if the changes are significantly different from those due to random variation.

The results for the first eleven tests, which had either 5·6– or 11·2–m² window area have been examined first. Both fire load and window area have a highly significant effect on the intensity. The effect of fire load on increasing the flame radiation depends on the window area. With the 5·6–m² area the increase is significant but only at the 20 per cent level i.e. there is a one-in-five chance of getting such a result by random variation, and with the 11·2–m² area it is not significant at all. Thus the analysis of these eleven tests indicates that there is a small but not highly significant increase in intensity due to the flames from the smaller window; it can therefore be neglected.

Since reducing the window area from 11·2 to 5·6 m² gives a more intense fire and relatively more flame radiation, it is interesting to consider the effect of further reduction in window area on these two factors. This can be observed here for the highest fire load only, using the result for test V, where it is clear that reduction to the 2·6–m² area does not significantly increase the intensity of radiation since in fact the window and total values straddle those for the 11·2–m² area. Analysis for all three areas, shows that the flame radiation is significant and that its size does not significantly vary with window area. Its average effect is to increase the radiation by 25 per cent.

Directly comparable results for larger windows i.e. above $\frac{1}{2}$-window opening have not been obtained. However Webster and Smith[7] measured the intensity of radiation from a 2·4–m cubical compartment with one side completely open, using an unshielded radiometer. The fire loads were of cribs of 2·5–cm sticks ranging from 99 to 217 kg (fire load densities of 17 – 38 kg/m²). No shielded radiometer measurements were taken but a radiometer was placed immediately above the compartment in the plane of the opening. From these readings and the recorded flame height it is estimated that the flame effect on the intensity received by the radiometer viewing the opening would be no more than 2 per cent. The actual values of intensity recorded by Webster and Smith are discussed later (p. 6).

At first sight the attainment of a hotter fire with a smaller window appears to contradict the assumption that 'less air means less fire'. However the importance of the window area depends on the way in which it controls the rate of burning and heat losses. It will be noted from Table 1 that for all except the highest fire load, the rate of burning $R_{80/30}$ is not affected by window area but depends only on the fire load, i.e. even with the smaller window there is ample ventilation. Because the larger window gives a greater heat loss there is a cooler fire and consequently a lower radiating intensity. For these fires the larger window means that the flames are relatively less important.

For the highest fire load, however, the rate of burning does decrease with decreasing window area and these fires are thus in a regime controlled by ventilation. Further restrictions in ventilation, leading to lower rates of burning, would be expected to lead to lower intensities of radiation and smaller flames, since the reduction in heat output would be more than could be offset by any reduction in heat loss. It appears that for the 2·6–m² area the ventilation is becoming sufficiently restricted for the intensity to be reduced although no firm conclusion can be drawn from only one result.

If on the other hand the effect of increasing the fire load beyond 1744 kg is considered, then little increase in intensity would be expected. This is because once the fire load per unit window area exceeds about 150 kg/m² (which in these experiments means total fire loads of 1680, 840 and 390 kg for the window areas 11·2, 5·6 and 2·6 m² respectively) the rate of burning is controlled by the ventilation or the window area and not by the size of the fire load. Thus the effect of increasing the fire load would be to increase the duration of the fire, and consequently the level of fire-resistance required in the building but not the intensity of radiation emitted by the windows. A fuller discussion of this behaviour is given elsewhere[8].

The value of 0·54 kg/s for the rate of burning with the 2·6–m² window area is rather large and the reason for this is not certain. For a fire controlled by ventilation the rate of burning depends on the area, A, and height, H, of the window. Kawagoe[9] and others have shown:

$$R \simeq 0{\cdot}1AH^{\frac{1}{2}} \text{ kg/s}$$

This equation gives a value of 0·35 kg/s for the 2·6–m² window. The high value of R measured could partly be accounted for by some leaks at the top of the rear wall. The equation gives 0·76 kg/s for the 5·6–m² window which is the same as the measured value.

A fuller discussion of the behaviour of fires in compartments is given elsewhere[8].

FIRE LOAD DISTRIBUTION AND INTERNAL LINING

The results of tests M to R and relevant results from the first set of eleven tests have been analysed statistically (Appendix) to see if varying the fire load distribution from $\frac{1}{3}$ to $\frac{2}{3}$ and adding a mineral wool lining have significant effects on the intensity of radiation.

The analysis shows that once the effect of varying the size of the fire load is allowed for there is no additional significant effect on the intensity due to varying the fuel distribution. It also shows that the mineral wool lining has a significant effect in increasing

A. BUILDING USED FOR TESTS SHOWING THE SHUTTERS WHICH REDUCE THE WINDOW AREA TO 5.6 m^2

B. LOAD OF 218 KG WITH 11.2 m^2 WINDOW AREA (TEST K)

PLATE 1

A. LOAD OF 436 KG WITH 5.6 m^2 WINDOW AREA (TEST G)

B. LOAD OF 872 KG WITH 5.6 m^2 WINDOW AREA (TEST Q)

PLATE 2

A. LOAD OF 1744 KG WITH 5.6 m^2 WINDOW AREA (TEST U)

B. LOAD OF 1744 KG WITH 11.2 m^2 WINDOW AREA (TEST L)

PLATE 3

A. LOAD OF 1744 KG WITH 2.6 M^2 WINDOW AREA (TEST V)

B. LOAD OF 218 KG, CONSISTING MAINLY OF FIBRE INSULATING BOARD LINING TO WALLS AND CEILINGS, WITH 5.6 M^2 WINDOW AREA (TEST S)

(a) Before collapse

(b) After collapse

C. COLLAPSE OF INTERNAL PARTITIONS IN DWELLING HOUSE

PLATE 4

the intensity but this effect appears to be mainly for the low fire load (218 kg) where an increase in thermal insulation is relatively more important. The absolute value of the intensity is still low and the effect is therefore not important.

The fibre insulating board lining in test S, with a rapid rate of burning, gives a large increase in both window and flame radiation, compared with tests A and B, but it burns for only a short time. A small part of the increase in intensity due to the combustible lining can be attributed to its insulating effect but this is not significant in this type of building except for very low fire loads. Its main effect is to raise the intensity because of its rapid burning and for window radiation this would become relatively less important with increasing fire load. For fires with high fire loads its main importance, in the context of radiation, is likely to be the extra flames it produces outside the windows but the additional intensity from these flames would depend on what difference they made to the emissivity and size of the flames from the rest of the fire load. The addition of flames from the lining to flames from the fires with the high fire loads in the form of cribs will now be considered.

In test S the increase in I_o due to the flames from the lining was $0 \cdot 75$ cal $cm^{-2}s^{-1}$, lasting for approximately 2½ min and this probably represents the highest intensity increment to be expected from this lining since the whole lining was ignited at once. In the fire with the most intense high fire load but *without* a lining, test U, the flame increment was $1 \cdot 44$ cal $cm^{-2}s^{-1}$ but if there had been a lining in addition to the fire load of cribs it is unlikely that the total flame increment would have been increased to as much as $1 \cdot 44$ plus $0 \cdot 75$ cal $cm^{-2}s^{-1}$. With a window radiation of $3 \cdot 66$ cal $cm^{-2}s^{-1}$ for test U, the addition of a fibre board lining would thus be expected to give, for 2–3 min at the most, a total value of I_o *between* $5 \cdot 10$ and $5 \cdot 85$ cal $cm^{-2}s^{-1}$.

RADIATION AND TEMPERATURE OF GASES IN COMPARTMENT

The variation of the maximum intensity I_p for the shielded radiometer with T_p, where T_p is the maximum value of the temperature of the gases in the compartment in degrees absolute, is shown in Fig. 3 plotted with log scales. The line is for a black body radiator given by

$$I = \epsilon\sigma T^4$$

with $\epsilon = 1 \cdot 0$

and $\sigma = 1 \cdot 36 \times 10^{-12}$ cal cm $^{-2}s^{-1}$deg C^{-4}.

An enclosure at a uniform temperature with a small aperture may be considered as a black body so that in view of the size of the windows in these tests and the fact that for low fire loads the flames did not fill the compartment, the agreement of the line with the experimental results is somewhat surprising. Figure 3 does indicate, however, that, as has been suggested earlier[10,11], the intensity emitted from the opening of a compartment is a useful measure of what is happening inside.

The thermocouples on the wall surface and in the gases gave practically the same readings and this suggests that the compartment walls heated up rapidly, resulting in little heat loss by radiation from the heated thermocouples[5].

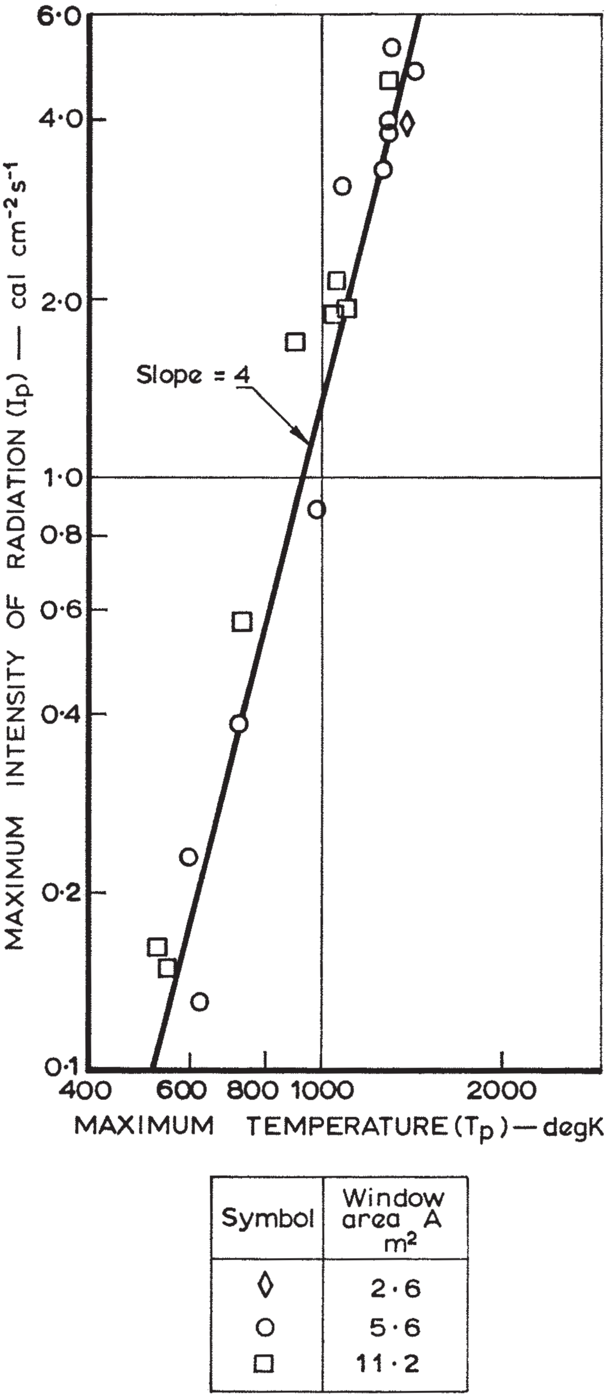
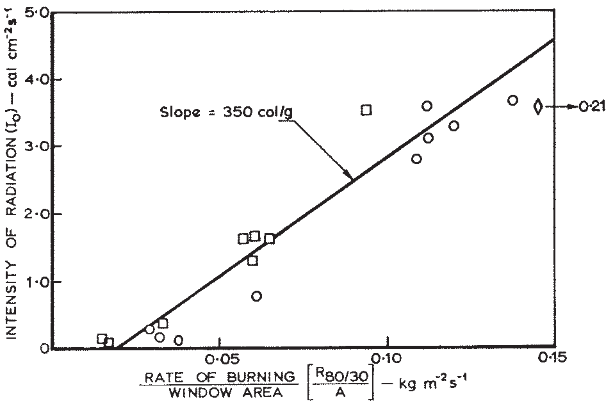


FIG. 3. Maximum gas temperature and maximum value of window radiation

RADIATION AND RATE OF BURNING

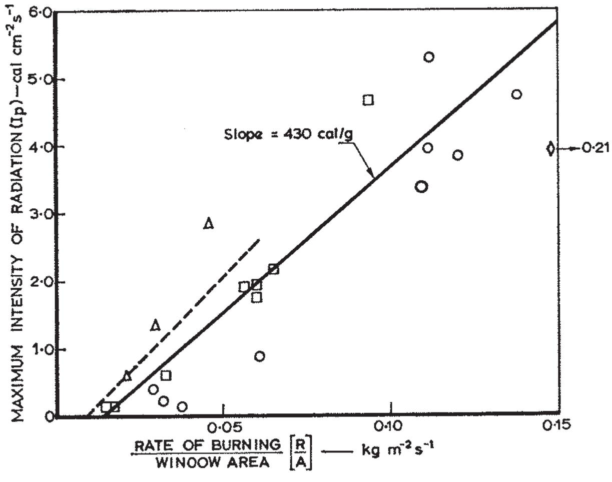
To relate the results of these tests to fires in other compartments it is not possible to use directly a simple parameter such as fire load density since the fire behaviour depends on a number of other factors which include compartment shape and size, and, of course, window area. The effects of these factors are still the subject of research programmes but meanwhile useful comparisons can be made in terms of rate of burning. This is an important parameter since it controls the heat output and the duration of the fire.

The variation of window radiation (shielded I_o) with rate of burning per unit window area is shown in Fig. 4. It has been suggested already[10] that window area rather than floor area should be used. The low results for the 5·6–m² window were for the lowest fire load where the flames were confined to the base of the compartment. The slope in Fig. 4 gives a quantity of 350 cal/g which is the same as found earlier[10] for cribs with 2–cm thick sticks distributed over the whole floor area. The value of 350 cal/g has physical significance as a measure of the amount of fuel which decomposes when heated by radiation.



Symbol	Window oreo A m²
◊	2·6
○	5·6
□	11·2

FIG. 4. Rate of burning and window radiation



Symbol	Test	Window area A m²	Window area / Floor area	R kg/s
◊	Table 1	2·6	0·10	$R_{80/30}$
○		5·6	0·19	
□		11·2	0·38	
Δ	Webster and Smith 2·4m cube(7)	5·8	1·00	$R_{90/60}$

------ Regression line for results obtoined by Webster et ol(7) with cubicol compartments open on one side and sizes ronging from 0·3m to 2·4m

FIG. 5. Rate of burning and maximum value of window radiation

Webster and Smith[7] give results for 2·5–cm sticks in terms of I_p for well-ventilated cubical compartments; for these results the window opening is the whole area of one wall i.e. the same area as the floor, and the rate of burning is averaged over the time $t_{90} - t_{60}$. These are compared with the present tests in Fig. 5 and are in reasonable agreement.

The value of the relationships shown in Figs. 3 to 5 is that for a variety of compartments; once the rate of burning can be estimated the intensity of radiation and compartment temperature can be predicted.

Effects of wind

Experiments[4] in which wind was blown into ½–m cube compartments containing burning wood cribs showed that the presence of ground plates and vertical baffles, representing the ground in front of a ground-floor compartment and walls of adjacent compartments, can have a greater effect on the rate of burning and the intensity of radiation at the window opening than a change of nearly 2 : 1 in the wind speed under certain circumstances. It is clear therefore that the position of a compartment is of major importance and insufficient information is as yet available to give a measure of the size of the effects on full scale of both position and wind speed. It was concluded from these model experiments that the presence of winds up to 29 km/h would change the rate of burning by less than 70 per cent on full scale.

The measurements of radiation at the St. Lawrence burns[2] indicated that the contribution of radiation directly from the openings was substantially less than that from the flames, the peak value of the former being no more than about 3·6 cal cm^{-2}s^{-1} compared with a maximum I/φ of 20 cal cm^{-2}s^{-1} for a building with a non-combustible lining, and 40 cal cm^{-2}s^{-1} with a combustible lining. These experiments were carried out on windy days, (18–19 km/h) and (16–22 km/h) and the radiometers were facing the leeward side of the buildings. However even with no wind a school building, with plaster walls and wooden ceiling, gave a peak value of 17 cal cm^{-2}s^{-1} for I/φ. The reason for such large differences between the St. Lawrence tests and the present series may be due to the greater ventilation of the Canadian houses, with through draughts, and to their exposed situation.

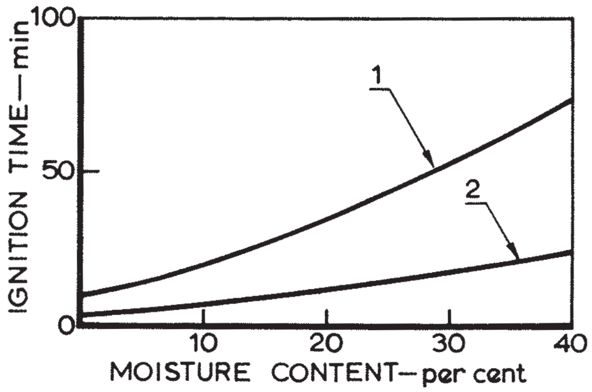
The effect of a through draught was observed in some earlier tests in dwelling houses[12], carried out in 1949, where there was a marked increase in flames once the internal partitions had collapsed (Plate 4(C)), but this was in the later stages of the fires. In the present series of experiments there was no possibility of a through draught so they can be taken to represent conditions in a building at least up to the stage when internal partitions are destroyed. However in a building of any size, divided internally, some time would elapse before such partitions were sufficiently destroyed to allow an appreciable through draught and by this time the fire brigade would be available to protect exposed buildings.

Hazard of ignition of exposed buildings

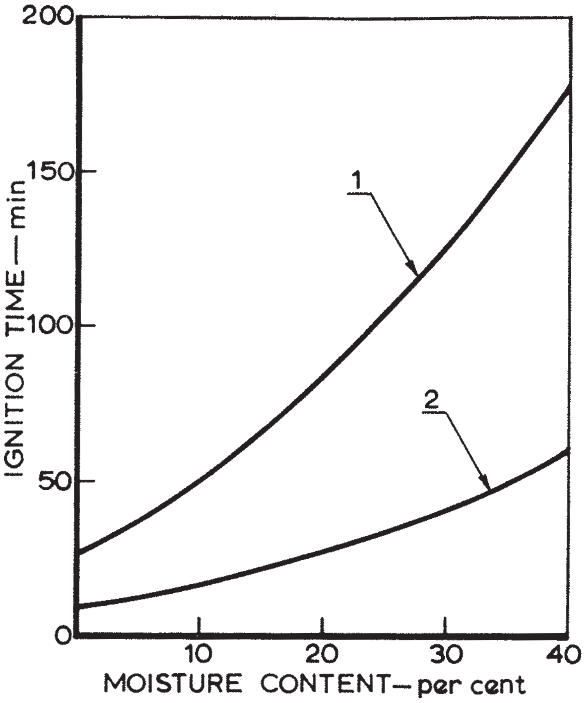
The recommended criterion for building separation[1] is that the configuration factor from the windows in the burning building to the nearest exposed building should not exceed 0·075. Thus for a maximum value of I_o of 4 cal cm^{-2}s^{-1} the exposed building receives a maximum intensity of 0·3 cal cm^{-2}s^{-1}, which is the critical intensity for the pilot ignition of dry wood unprotected by paint. None of the values of I_o for the shielded radiometer exceeded 4 cal cm^{-2}s^{-1} (the maximum was 3·66 cal cm^{-2}s^{-1}) but with test U, which had the highest fire load and the smaller window, the value of I_o for the unshielded radiometer was 5·10 cal cm^{-2}s^{-1}. Thus for a configuration factor of 0·075, (the maximum allowable value) the received intensity would be 0·38 cal cm^{-2}s^{-1}. This would ignite dry wood of density 0·5 g/cm^3, say deal, in about 10 min and of density 0·8 g/cm^3, say oak, in about 24 min, giving ignition some 20–35 min after the start of the fire. However wood normally contains moisture which increases its ignition time[13], as illustrated in Fig. 6, and for 15-per cent moisture content (by weight of dry wood), not a high value for the open air in the British Isles, the ignition times increase to about 27 and 65 min respectively, according to density, i.e. ignition occurring about 37–75 min after the start of the fire. A layer of paint gives a further delay. Thus with test U it is unlikely that the intensity is maintained long enough to cause ignition and even so there is time for the fire brigade to afford protection. In Metropolitan Boroughs in the United Kingdom over 95 per cent of fires are attended within 4 min[14].

With a combustible lining in test U the total value of I_o might for a short time be between 5·10 and 5·85 cal cm^{-2}s^{-1} (an increase due to the lining of 15 per cent), giving an incident intensity between 0·38 and 0·44 cal cm^{-2}s^{-1} (p. 5). For the higher value and 15 per cent moisture content of exposed wood, ignition could occur if this intensity was maintained for 10–20 min, according to density, which is about a third of the time needed from test U without the combustible lining but is at least three times as long as the duration to be expected.

For buildings with fire load densities, in terms of floor area, of less than 25 kg/m^2, the suggested configuration factor is 0·15 on the assumption that the radiating intensity is not greater than 2·0 cal cm^{-2}s^{-1}. None of the values of I_o for the tests with the lower fire loads exceeded 2·0 cal cm^{-2}s^{-1}, whether window or total, except for test S which had the combustible lining. This had a total value of I_o of 3·0 cal cm^{-2}s^{-1} giving an incident intensity of 0·45 cal cm^{-2}s^{-1}, which is about the same as the maximum estimated earlier for test U with a combustible lining.



(a) Density of dry wood 0·5 g/cm^3



(b) Density of dry wood 0·8 g/cm^3

1. Incident intensity 0·38 cal cm^{-2}s^{-1}
2. Incident intensity 0·44 cal cm^{-2}s^{-1}

FIG 6. Pilot ignition and moisture content of wood

The fibre insulating board lining gives for a short time an intensity up to 50 per cent more than that assumed to be coming from the opening alone. However if the incident intensity of 0·38 cal cm^{-2}s^{-1} is considered acceptable then the effect of the lining is to raise it by about 15 per cent. Thus in estimating separation distances from these tests it would be reasonable to allow for the effect of the combustible lining by, in calculation, increasing the window area of such lined rooms by 15 per cent.

The effect of the flames would be expected to be most important for single-storey buildings[1] and the present results indicate that it is more important for the 5·6–m². window. Thus it is likely that for light wind conditions at any rate the result for test U represents the most hazardous situation.

Conclusions

(*i*) The measurements of radiation from the openings in these tests confirm earlier estimates and measurements used as a basis for recommending separation distances between buildings.

(*ii*) The extra radiation from flames outside the openings was not large enough to warrant altering the recommended separation distances on which present building regulations have been based.

(*iii*) These experiments were carried out in light winds only and further information is required before the effects of strong winds can be assessed for a variety of positions of compartment in relation to height above ground and to other buildings. Some of these effects would only be important during the later stages of the fire.

(*iv*) The range of fire load densities used excluded high fire loads such as those found in warehouses, but the results indicate that higher fire loads would not have led to higher intensities of radiation. This was because the rate of burning would have depended on the ventilation and not on the size of the fire load.

(*v*) A fibre insulating board lining on the walls and ceiling can increase the maximum radiating intensity. One way of allowing for this in calculating building separation, would be to increase the effective window area of all such lined rooms when calculating the percentage window area. For these tests it might be up to 15 per cent.

(*vi*) A non-combustible insulating lining increased the intensity of radiation but it appeared to be significant only for the low fire load. Since the absolute value of intensity is small with low fire loads this effect of the lining is not important. Its effect in other compartments would depend on the thermal properties of the walls.

(*vii*) Changing the distribution of the fire load to cover $\frac{2}{3}$ instead of $\frac{1}{3}$ the floor area had no significant effect on intensity of radiation, nor was there any significant interaction between size of load and its distribution.

(*viii*) The maximum intensity of radiation emitted by the opening has been related to the maximum gas temperature within the compartment by assuming that the compartment is a black body radiator and measurement of intensity would thus appear to be a useful way of assessing temperature conditions within the compartment.

(*ix*) The results give a value of 350 cal/g for intensity of radiation emitted at the window opening divided by rate of burning per unit window area. This value has physical significance as a measure of the amount of fuel which decomposes when heated by radiation. It is the same as found in earlier experiments in other compartments for 2–cm sticks distributed over the whole floor area.

(*x*) For any given fire load the fire was cooler and the intensity radiated was less with the 11·2–m² window than with that of 5·6 m². This was because the fires were well-ventilated and the larger window gave a greater heat loss.

(*xi*) A factorial analysis of the results showed that for the 11·2–m² window the extra radiation from the flames was not significant; for the 5·6–m² window it was significant only at the 20 per cent level. The window area and size of fire load had highly significant effects on the radiation from the windows. An analysis of the results for the highest fire load only and 2·6–, 5·6–, 11·2–m² window areas showed that the flame effect was significant at the 5-per cent level and the effect of the window was not significant.

(*xii*) The relationships between intensity, compartment temperature and rate of burning per unit window area may be used to predict conditions in a variety of compartments for which the rate of burning can be estimated.

Acknowledgements

The results discussed here were obtained by Messrs. E. G. Butcher, A. J. M. Heselden and their co-workers. Mrs. J. E. Dunn provided the statistical design of the experiments.

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Appendix

Statistical analyses of results

INTRODUCTION

Tests A to F were carried out in the north compartment and the rest in the south compartment but these results will be analysed assuming there is no compartment effect. This assumption appears justified since a regression analysis by Heselden[5] has shown that there is no compartment effect for temperature within the compartment, rate of burning and other variables; although it was not possible from the results to assess the compartment effect on I/φ it seems reasonable therefore to assume that it is not significant. An examination of the results of the repeat tests suggests that the distribution is log normal and the analysis has been carried out on the log values. This transformation is consistent with the results of other statistical analyses.[15]

STATISTICAL ANALYSIS OF TESTS A–L, U, V

$i = \log_{10} 10\, I_o$;
i_1 = window
i_2 = total

$V_1 = 2{\cdot}6$–m^2 window area
$V_2 = 5{\cdot}6$–m^2 window area
$V_3 = 11{\cdot}2$–m^2 window area
$L_1 = 218$–kg fire load
$L_2 = 436$–kg fire load
$L_3 = 872$–kg fire load
$L_4 = 1744$–kg fire load

Consider results for V_2 and V_3 only:

Effects

Test			i_1	i_2
A	V_2	L_1	0·23	0·23
G		L_2	0·89	0·95
H		L_3	1·56	1·60
U		L_4	1·56	1·71
K	V_3	L_1	0·04	0·04
D		L_2	0·57	0·63
E		L_3	1·21	1·23
L		L_4	1·55	1·57

Variation

			Mean		Difference	
Test	i_1	i_2	i_1	i_2	i_1	i_2
A	0·23	0·23	0·155	0·17	0·15	0·12
B	0·08	0·11				
H	1·56	1·60	1·525	1·575	0·07	0·05
I	1·49	1·55				
E	1·21	1·23	1·21	1·22	0·00	0·02
F	1·21	1·21				

Variance table

Effect	Sums of squares	Degrees of freedom	Mean squares	Significance level
i	0·00765	1	0·0076	20 per cent
V	0·22325	1	0·2232	Highly significant
L	5·2797625	3	1·7599	Highly significant
Vi	0·0014125	1	0·0014	
Li	0·004075	3	0·0013	
LV	0·050475	3	0·0168	5 per cent
LVi	0·0029125	3	0·0010	
Residual	0·02235	6	0·0037	

$S^2 = 0{\cdot}00274$ with 14 degrees of freedom

Separating results for V_2 and V_3:

V_2

Effect	Sums of squares	Degrees of freedom	Mean squares	Significance level
i	0·0078125	1	0·0078	20 per cent
L	2·6112376	3	0·8704	Highly significant
Li	0·0060375	3	0·0020	

V_3

Effect	Sums of squares	Degrees of freedom	Mean squares	Significance level
i	0·00125	1	0·00125	
L	2·71900	3	0·9063	Highly significant
Li	0·00095	3	0·0003	

Consider results for L_4 only:

Test		i_1	i_2
V	V_1	1·50	1·62
U	V_2	1·56	1·71
L	V_3	1·55	1·57

Effect	Sums of squares	Degrees of freedom	Mean squares	Significance level
i	0·014017	1	0·0140	5 per cent
V	0·007500	2	0·00375	
Vi	0·004633	2	0·0023	

Table 2
Tests with varying fire load distribution and lining

$i = \log_{10} 10 I_0$

Test	Fuel distribution	Lining	Fire load kg	Window m^2	$\log_{10}$ 10 I_0			Deviation from mean of $\frac{1}{3}$ distribution, nil lining	
					window i_1	total i_2		window	total
M	$\frac{2}{3}$	Nil	872	5·6	1·45	1·51		— 0·10	— 0·04
N				11·2	1·11	1·14		— 0·10	— 0·07
O	$\frac{1}{3}$	Mineral slabs	218	5·6	0·46	0·46		+ 0·30	+ 0·30
P				11·2	0·15	0·18		+ 0·11	+ 0·14
Q	$\frac{2}{3}$		872	5·6	1·52	1·56		— 0·03	+ 0·01
R				11·2	1·22	1·25		+ 0·01	+ 0·04
S	Combustible lining and crib		218	5·6	1·35	1·48		+ 1·19	+ 1·32
							MEAN		
H	$\frac{1}{3}$	Nil	872	5·6	1·56	1·60	1·55		
I					1·49	1·55			
E				11·2	1·21	1·23	1·21		
F					1·21	1·21			
A			218	5·6	0·23	0·23	0·16		
B					0·08	0·11			
K				11·2	0·04	0·04	0·04		

REGRESSION ANALYSIS OF RESULTS IN TABLE 2

Tests A, B, E, F, H, I, K, M to R

Table 3
Effect of fuel distribution and mineral wool lining

Effect	Sums of squares	Degrees of freedom	Significance level
L	8·3009	1	Highly significant
V	0·4430	1	Highly significant
lining	0·1098	1	1 per cent
fuel distribution	0·0057	1	
residual	0·1906	21	$S^2 = 0{\cdot}00907$

The above table was obtained taking fire load before fuel distribution. The correlation coefficient for fire load and fuel distribution is 0·526 which is significant at the one-per cent level. It is known that fire load has an effect on radiation and given this the data do not show an additional significant effect of distribution.

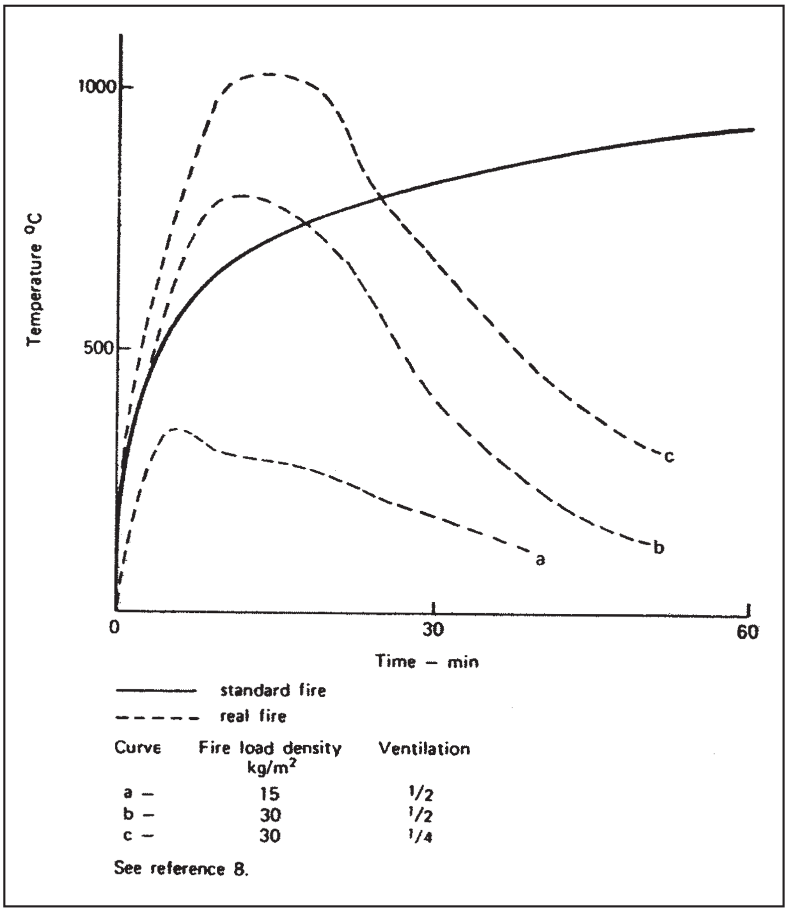
A similar analysis shows that the fire load/distribution interaction is not significant.

PAPER 6

Prediction of fire resistance

Margaret Law (Fire Research Station), Paper No. 2 of Symposium No. 5, Fire resistance requirements of buildings - a new approach. 28 September 1971. Department of the Environment and Fire Offices' Committee Joint Fire Research Organization. HMSO, UK

Figure showing the difference between the standard fire and real fires. The relationship between fuel load density, compartment size and ventilation is described by the 'effective fire resistance'.



In 1971 the Fire Research Station held a symposium to present results of all the work carried out on building fires and fire resistance. I aimed to show to people in building control and consultancy how various aspects could be viewed in context with the current regulations. One example was the standard fire resistance test, which I related to compartment fires in terms of an 'effective fire resistance'. This was the period in the standard test that would have the same heating effect as the compartment fire at a critical point in a protected structure. Effective fire resistance showed explicitly how the effect of fuel load, ventilation, and compartment size affected fire severity, in terms of the standard test. This paper explains and illustrates this work.

I had already reported the work to my colleagues in the European Convention for Constructional Steelwork, and Ove Pettersson offered to do the same analysis to see if the calculated temperature-time curves that he had published with Magnusson and Thor would give a similar relationship. The result was almost the same and accordingly it is his version that is often quoted, being referred to now as 't-equivalent'.

I view the t-equivalent relationship as a useful illustration that works well because it is the area under the time-temperature curve, rather than its shape, which characterises the heating effect on protected elements. However, the t-equivalent concept has limitations. It is often important to estimate the actual temperature and duration of the fire, for example the intensity of radiation may be an important issue, or the structure may be unprotected steelwork.

Contents

Prediction of fire resistance

by

Margaret Law, BSc, MIFireE

(*Fire Research Station*)

Summary

Normally the building designer is not so much interested in a detailed analysis of the behaviour of a building fire as in estimating the total effect that such a fire might have on structural performance. Information about the performance of structures exposed to fire is usually provided by fire-resistance tests using a standard fire, while real fires vary in temperature and duration and are different from the standard fire. Results of fire-resistance tests and results of real fires may be related if the fires can be characterized by 'effective fire resistance', meaning that the effects of the fire on a given structural element are equivalent to the effects of a certain duration of the standard fire-resistance test.

The data available as a result of the international research programme carried out under the auspices of the Conseil International du Bâtiment (CIB) give valuable information on fire behaviour and it has been possible to calculate for each experimental fire the effective fire resistance, t_f, which would be needed by a protected steel column to survive a total burn-out of the fire. The results show that for all compartment scales, shapes and ventilations, all fire load densities and all stick thicknesses:

$$t_f = k\frac{L}{(A_W A_T)^{\frac{1}{2}}}$$

where k is about 1·3 min m²/kg, but varies with fuel spacing

L = total fire load (wood cribs) — kg

A_W = area of ventilation opening (window) — m²

A_T = area of internal surfaces to which heat is lost (excluding A_W) — m²

Results of a number of experiments in larger-scale brick and concrete compartments, with fire loads ranging from wood cribs to furniture and liquid fuels, give a similar correlation but with a value for k of approximately unity. The reasons for this difference are not clear, but given the necessity of matching the results for wood cribs with those for real fuels, a good engineering relationship is:

$$t_f = \frac{L}{(A_W A_T)^{\frac{1}{2}}} = \frac{L}{A_F} \times \frac{A_F}{(A_W A_T)^{\frac{1}{2}}} \text{ min}$$

where A_F is floor area — m².

The first term, L/A_F, is fire load density, traditionally the basis for fire grading; the second term, $A_F/(A_W A_T)^{\frac{1}{2}}$, recognizes explicitly the importance of ventilation and compartment size and shape.

As an example, calculations of t_f for one compartment show that increasing the window area from 25 to 100 per cent halves the effective fire resistance. Keeping the window area at 50 per cent, an increase in floor area from 200 to 2000 m² doubles the effective fire resistance.

Risk measurement, more fully dealt with by Baldwin, has been discussed briefly in this paper in order to set the work in context with the existing Building Regulations.

Calculations of t_f for representative compartments have been compared with the requirements of the Building Regulations, and the importance of ventilation openings is linked to the existing requirements for openings in the external walls, which control the distance between buildings. For example, a reduction in window area could give a threefold reduction in distance but a twofold increase in effective fire resistance. This illustrates the opportunity for the building designer to adopt a more flexible approach.

Symbols

A_F	Floor area	m²
A_T	Area of compartment surfaces (excluding ventilation area) to which heat is lost	m²
A_W	Ventilation area, window area	m²
D	Compartment depth	m
H	Compartment height	m
h	Window height	m
H_W	Calorific value of wood = 19MJ/kg	
I	Intensity of radiation in plane of ventilation opening	kW/m²
I_p	Maximum value of I	kW/m²
k	Thermal diffusivity	m²/min
L	Total fire load	kg
R	Average rate of burning (80/30 value)	kg/s
t_f	Effective fire resistance	min
x	Depth from surface of concrete slab	m
W	Compartment width	m
σ	Stefan-Boltzmann constant $= 5{\cdot}69 \times 10^{-11}$	kW/m²K⁻⁴
θ_{PF}	Maximum temperature of real fire	°C
θ_x	Critical temperature at depth x	°C
θ_t	Temperature in standard fire (ISO curve)	°C
τ	Nominal fire duration $= \frac{L}{60R}$	min

The suffix 80/30 denotes an average value for the period during which the weight of fuel fell from 80 to 30 per cent of its original value.

Introduction

It is commonly supposed that a structural element with ½-hour fire resistance will survive for ½ hour in a 'real' fire. Yet we would expect a real fire lasting ½ hour at a temperature of 1000°C to have a more severe effect on the structure than a ½-hour fire at only 500°C. In fact fire resistance is related to a standard fire[1] which is illustrated in Fig. 2.1. Some real fires are shown for comparison and since it is obvious that real fires vary and can be very different from the standard fire we need to consider the relevance of fire resistance in designing buildings to withstand the effects of real fires.

In principle, the aim of the building designer would be to estimate the temperatures of building elements for a range of real fire conditions, and in particular to determine whether certain critical temperatures would be attained which would cause structural or insulation failure. To achieve this he would not only need to know the properties of the building element but also be able to predict the variation of temperature and rate of fuel consumption (rate of burning) with time for real fires. Most of the information available at present about the properties of building elements is given by results of fire-resistance tests. The comprehensive data which have recently become available as a result of an international research programme undertaken by the members of the Fire Research Working Party of the Conseil International du Bâtiment (CIB) give valuable information on real fire behaviour[2]. This programme examined fully-developed fires in model compartments ½ m, 1 m and 1½ m high, of various shapes with various areas of window opening and various amounts and dispersions of fuel in the form of wood cribs. Data are also available, although in less detail, for a number of larger-scale brick and concrete compartments, containing fires with various types and amounts of fuel and various areas of window opening, but in general confined to approximately cubical shapes.

The analysis of the CIB results indicates that a number of factors have a significant effect on the fire behaviour[2] but it is by no means certain that they would have such a significant effect on structural behaviour. For example, a reduction in rate of burning increases fire duration but it can be associated with a decrease in fire temperature, so that the net effect on structural temperature might be small. Although, for convenience, workers have related real fires to fire resistance, strictly speaking fire resistance is a property of a structure.

One useful way to characterize a real fire is by 'effective fire resistance' where we mean not that the fire itself possesses fire resistance but that in its effects it may be equivalent to a certain duration of the fire-resistance test. Thus the fire may be characterized by an effective fire resistance which is related to a particular effect on a particular building element. For example we could measure the maximum temperature attained by a steel column during the course of a fire and then measure the duration of the standard fire-resistance test which produces the same temperature in an identical column. In particular we would be interested to know the fire resistance needed by the column if its maximum temperature during the fire is not to exceed the critical value for supporting its load.

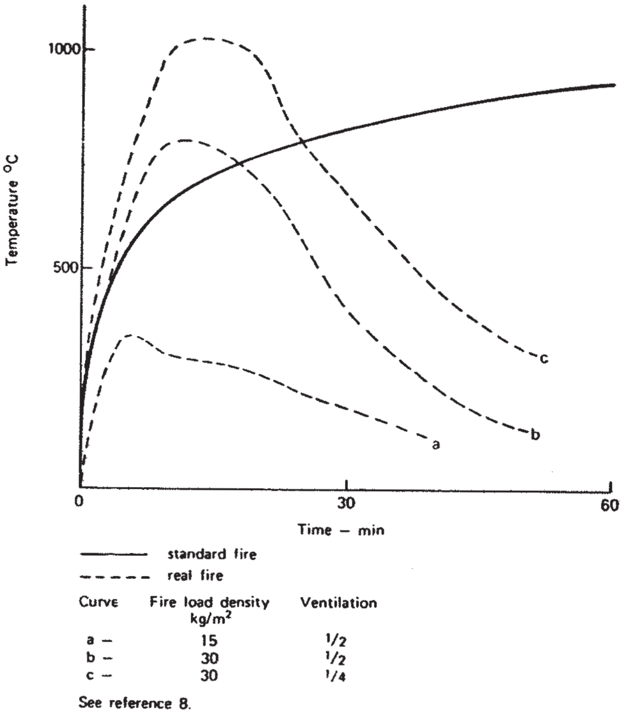


FIG. 2.1 COMPARISON OF STANDARD FIRE AND 'REAL' FIRES

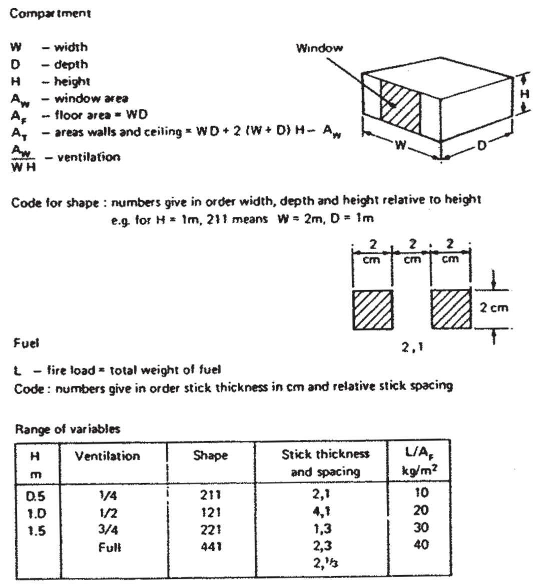
In the following paper, therefore, we select a protected steel column as a representative building element and estimate the fire resistance it would need to survive a total burn out of the fire load in a compartment of a building. It will be shown that similar results can be obtained for reinforced-concrete structures.

A discussion of this work in the broader context of research and regulations has been given by Thomas[3] in his paper at the recent CIB colloquium.

Heating of column in real and standard fires

In order to calculate the heat flow to the steel we shall assume that the temperature of the exposed surface of the protective material is the same as the fire temperature. This assumption is reasonable for building fires, which normally have highly radiant flames, but may give an over-estimation of the surface temperature in standard fires if non-luminous gas flames are used to heat the test furnace. For the moment, however, we shall assume that we have a 'perfect' furnace which gives a surface temperature following the standard curve.

It is possible, using methods of numerical analysis, to calculate the steel temperature of a protected column for any fire temperature-time curve. However, this is a tedious job when data for a large number of fires are to be analysed and it would clearly be convenient to have some kind of equation to describe the fire. We are for the moment interested only in the maximum temperature attained by the steel and it has been shown[4] that to produce the same



W – width
D – depth
H – height
A_W – window area
A_F – floor area = WD
A_T – areas walls and ceiling = WD + 2 (W + D) H – A_W
$\frac{A_W}{WH}$ – ventilation

Code for shape : numbers give in order width, depth and height relative to height
e.g. for H = 1m, 211 means W = 2m, D = 1m

L – fire load = total weight of fuel
Code : numbers give in order stick thickness in cm and relative stick spacing

Range of variables

H m	Ventilation	Shape	Stick thickness and spacing	L/A_F kg/m²
0.5	1/4	211	2,1	10
1.0	1/2	121	4,1	20
1.5	3/4	221	1,3	30
	Full	441	2,3	40
			2,⅓	

FIG. 2.2 VARIABLES FOR CIB EXPERIMENTS

maximum steel temperature, a real fire is equivalent to a constant temperature θ_{PF} lasting for a time $\tau = L/60R$, where θ_{PF} is the maximum fire temperature, L is the total fire load and R is the average rate of burning. Similarly it has been shown[4] that the standard fire is equivalent to a constant temperature $0{\cdot}91\ \theta_t$ lasting for a time t_f where θ_t is the temperature of the standard fire at time t_f. It is then possible to show[4] that the exposure time, t_f, in the standard fire for the steel to reach the same critical temperature as in a real fire is:

$$t_f = 0{\cdot}0033\ \tau^{0\cdot84}\ (\theta_{PF} - 270) \qquad (1)$$

where the critical steel temperature is taken as 550°C. (This is the value measured in fire-resistance tests with United Kingdom design loads). It has been shown[4] that a similar relationship can be obtained for a critical steel temperature of 400°C so that equation (1) can be used for a range of design loads.

Data provided by CIB experiments

The CIB experiments are described fully elsewhere[2] and are illustrated in Fig. 2.2. A value of t_f has been calculated for each experimental fire, using equation (1) in a modified form to take account of the way in which the summary data[2] are presented. Thus radiation readings have been used as a measure of fire temperature, assuming the compartment is a black body, and since radiation is given as an average value, $I_{80/30}$, it is assumed that the maximum value, I_p, is given by:

$$I_p \approx \tfrac{4}{3}\ I_{80/30}$$

θ_{PF} is estimated from:

$$\tfrac{4}{3}\ I_{80/30} \approx \sigma\ (\theta_{PF} + 273)^4$$

where σ is the Stefan-Boltzmann constant. Equation (1) then becomes

$$t_f \approx 1{\cdot}3\ \tau^{0\cdot84}\ [(I_{80/30})^{\frac{1}{4}} - 1{\cdot}39] \qquad (2)$$

It has been shown[4] that equation (2) gives values of t_f in close agreement with equation (1).

The values of t_f calculated for the CIB experiments are listed in Table 2.1 and for some earlier experiments[5] in Table 2.2. Inspection of these values shows that variations of scale (H) and stick thickness have

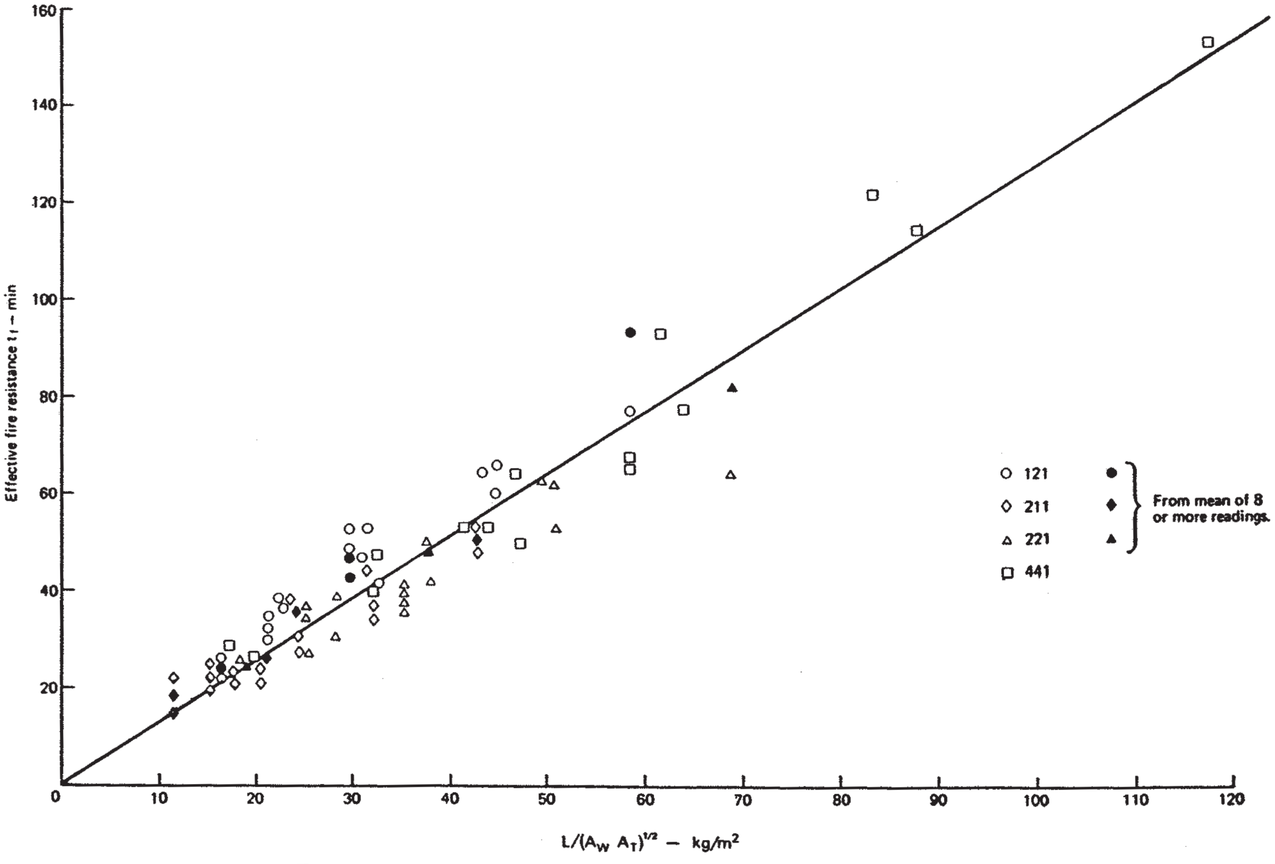


FIG. 2.3 EFFECTIVE FIRE RESISTANCE FOR CIB DATA 1-SPACING

little effect on t_f. Relative stick spacing, however, does have some effect, the values of t_f for 3-spacing (see Fig. 2.2) tending to be lower.

As would be expected, for given fire load densities the compartment shape and amount of ventilation have significant effects and earlier work[6] suggests that t_f should be related to fire load per unit window area (L/A_W). However, while it is clear that L/A_W is a major controlling factor, there still remain effects of compartment shape and ventilation. Kawagoe's[7] heat balance to determine temperature shows that a factor $A_T/A_WH^{\frac{1}{2}}$ has theoretical importance, where H is window height and A_T is the area of enclosing surfaces to which heat is lost. (For the CIB experiments A_T was taken as the surface area of walls and ceiling, assuming the heat loss to the floor was negligible). As noted, H for these experiments appears to be of little importance, and the effect of A_T/A_W has therefore been examined. The best correlation has been obtained with the term:

$$\frac{L}{(A_W A_T)^{\frac{1}{2}}} = \frac{L}{A_W} \times \left(\frac{A_W}{A_T}\right)^{\frac{1}{2}}$$

Values of t_f are plotted against $L/(A_WA_T)^{\frac{1}{2}}$ in Fig. 2.3 for 1-spacing and it appears that the effects of compartment shape, ventilation, fire load density and scale have largely been taken into account. Similar results are obtained for the other spacings, approximate values of slopes $t_f(A_WA_T)^{\frac{1}{2}}/L$ being 1·5, 1·3 and 1·1 min m²/kg for ⅓-, 1- and 3-spacing respectively.

The reasons for the lack of scale effect are not clear[4] and the importance of the effect of fuel spacing needs to be explored. For both these reasons, available data for larger-scale compartments with different types of fire load must be considered, so that the usefulness of the term $L/(A_WA_T)^{\frac{1}{2}}$ can be examined. In addition, the differences in t_f caused by variations in fuel spacing need to be considered in the context of information about the amount and distribution of fire loads in real buildings, discussed later.

TABLE 2.1

Predicted effective fire resistance – t_f – for CIB experiments

Quarter ventilation

Shape	$\frac{L}{A_F}$ kg/m²	Scale H m	t_f min Stick thickness and spacing 2,1	4,1	1,3	2,3	2,⅓	$\frac{L}{A_W}$ kg/m²	$\frac{L}{(A_WA_T)^{\frac{1}{2}}}$ kg/m²
211	20	0·5	24	20	24	24	23	80	20·5
	20	1·0	26*	23	21	23	25	80	20·5
	20	1·5	24	22	22	20	28	80	20·5
	30	1·0	35	49†			38	120	31
	30	1·5	34	34	34	32	44	120	31
	40	1·0	49*	48			72	160	41
	40	1·5	48	50	41	38	68	160	41
121	20	0·5	50	44	41	40	47	160	29
	20	1·0	41*	45	38	40	56	160	29
	30	1·0	64	58	58	56	75	240	43
	40	1·0	88*	75	72	70	97	320	57·5
221	20	0·5	38	34	44	41	41	160	33·5
	20	1·0	39*	33	35	31	46	160	33·5
	30	1·0	60	50	51	48	71	240	50
	40	1·0	79*	62	71	60	88	320	66·5
441	20	0·5	66					320	57·5
	20	1·5	64					320	57·5
	30	0·5	113					480	86
	40	1·5	152					640	115

†Probable error in I
*From mean value of 8 or more readings of I and R

TABLE 2.1 (Continued)

Half ventilation

Shape	$\frac{L}{A_F}$ kg/m²	Scale H m	t_f min Stick thickness and spacing 2,1	4,1	1,3	2,3	2,$\frac{1}{3}$	$\frac{L}{A_W}$ kg/m²	$\frac{L}{(A_W A_T)^{\frac{1}{2}}}$ kg/m²
211	20	0·5	21	18	18	15	18	40	15
	20	1·0	26					40	15
	30	1·0	35					60	22·5
	40	1·0	43		25	27		80	30
121	20	0·5	30	31	28	29	41	80	20·5
	20	1·0	33					80	20·5
	30	1·0	50					120	31
	40	1·0	62					160	41
221	20	0·5	33	26	31	32	37	80	24
	20	1·0	34					80	24
	30	1·0	48					120	36
	40	1·0	61					160	48
441	10	1·5	26					80	20·5
	20	0·5	50					160	41
	20	1·5	50					160	41
	30	0·5	74					240	62
	40	1·5	118					320	82·5

Three-quarter ventilation

211	40	1·0				21		53·5	25·5
441	10	1·5	29					53·5	17

Full ventilation

211	20	0·5	16	14	12	11	11	20	11·5
	20	1·0	18*	†	14	15	†	20	11·5
	20	1·5	16	†	16	14		20	11·5
	30	1·0	24	21	16		18	30	17·5
	30	1·5	23	19	21	17		30	17·5
	40	1·0	34*	25	17	20	23	40	23
	40	1·5	30	26	26	18		40	23
121	20	0·5	25	26	21	21	†	40	15
	20	1·0	25*	23	19	21		40	15
	30	1·0	35	34	25	26	†	60	22·5
	40	1·0	44*	41	30	31	†	80	30
221	20	0·5	26	18	20	20	27	40	18
	20	1·0	24*	19	23	19	23	40	18
	30	1·0	37	29	29	23	40	60	27
	40	1·0	47*	40		26	53	80	36
441	20	0·5	36					80	30
	20	1·5	39					80	30
	30	0·5	48					120	45·5
	30	1·5	62					120	45·5
	40	1·5	88					160	60·5

†$\theta_{PF} < 600$°C

*From mean value of 8 or more readings of I and R

TABLE 2.2

Predicted effective fire resistance – t_f – for cubical compartments[5]

$$\text{Full ventilation}\ \frac{L}{A_F} = \frac{L}{A_W}$$

Shape	$\frac{L}{A_F}$ kg/m²	Scale H m	Stick thickness and spacing	t_f min	$\frac{L}{(A_WA_T)^{\frac{1}{2}}}$ kg/m²
111	29	0·9	5·1, 3	14	14·5
	27	,,	,, ,,	12	13·5
	24	,,	,, ,,	12	12
	36·5	0·6	5·1, 3	17	18
	33	,,	,, ,,	15	16·5
	28	,,	,, ,,	15	14
	23·5	,,	,, ,,	16	11·5

NB: τ derived from $R_{80/20}$

TABLE 2.3

Predicted effective fire resistance – t_f – for larger-scale brick or concrete compartments, calculated from temperature-time curves

Tests	H m	$\frac{W}{H}$	$\frac{D}{H}$	A_W m²	h m	$\frac{L}{A_F}$ kg/m²	$\frac{L}{(A_WA_T)^{\frac{1}{2}}}$ kg/m²	t_f min	Notes
A1	3·05	2·5	1·2	2×5·6	1·83	30	24	24	
						30	24	26	a
						30	24	23	a
						30	24	24	a, b
						60	48·5	47	
				2×2·8	1·83	15	17	20	
						30	33·5	35	
						30	33·5	39	a
						30	33·5	36	a
						30	33·5	35	a, b
						60	67	69	
				2×1·3	1·83	60	97	87	
A2				2×1·3	1·83	15	23·5	21·5	c
						15	23·5	27	d
				2×2·8	1·83	25	27·5	26	e
A3				2×5·6	1·83	7·5*	6	6·5	f
						7·5*	6	6·5	g
A4				2×2·8	1·83	7·5	8·5	7·5	
B	2·40	1·0	1·0	5·76	2·40	25	11·5	12·5	a
						38	17	20	a
C	2·60	1·1	1·2	2×1·63	1·52	49	35	30	
						49	35	30	
				2×1·79	1·68	34	23·5	26	
						61	42	37	
				2×2·60	2·44	49	28	24	
						49	28	22	
						49	28	25	
						61	35·5	39	

*Wood equivalent. Calorific value of wood (H_W) assumed 19MJ/kg

TABLE 2.3 (Continued)

Tests	H m	$\frac{W}{H}$	$\frac{D}{H}$	A_W	h	$\frac{L}{A_F}$ kg/m²	$\frac{L}{(A_W A_T)^{\frac{1}{2}}}$ kg/m²	t_f min	Notes
D	2·5	1·2	1·2	1·67	1·80	45	45·5	34	
	3·0	1·3	1·3	2×2·70	1·5	50	40	22	l
	2·6	1·4 1·0	1·0 1·4	2·52 1·26	1·4 1·4	64	44·5	38	h, m
	2·5	1·7	1·4	2×2·40	1·46	44	38	50	l
	2·7	1·5	1·5	1·80 1·80	1·0 1·1	31	30	24	l
	2·6	2·0	2·0	4×1·7	1·7	46	47	43	l
	3·8	1·05	1·05	2×6·15	2·2	50	25·5	24	i, l
	∼1·2	∼2·5	∼2·8	2×0·64 0·21 1·28	0·75 0·50 0·98	24	25	29	j, l
	∼1·2	∼2·5	∼2·8	2×0·64 0·21 0·48	0·75 0·50 0·75	40	48·5	67	k, l
E	3·13	1·1	1·2	2·58	2·18	15	14	15	
						30	28·5	26	
						60	57	53	
				1·06	0·90	30	44	41	
				4·24	2·18	30	22·5	21	
F	∼3·2	∼1	∼1	1·5	—	25	25·5	29	
						50	51·5	57	
						100	102·5	90	
						150	154	158	
				2·0	—	50	44·5	47	
				1·0	—	50	62·5	77	
G1	3·0	1·2	0·9	1·6	—	106*	112*	119	
G2						35–52·5*	36·5–56*	30	n
						70–105*	73·5–112*	74	n
						140–210*	147–224*	126	n
G3						50	52·5	—	o
G4						50	52·5	—	p
H	—	—	—	1·16–2·76	—	∼16·5	23–15	13·5	q
						∼21	29–18·5	20	q
						∼13	39–26·5	18·5	r, s
				1·88–3·48	—	∼20	34–26	28·5	r, s
				1·88	—	∼ 9	22	21	s
				2·95	—	∼13	22·5	20	s
				3·20	—	∼22	41·5	43·5	t
								37	
I	2·74	6·2	2·7	31·2	1·83	20·5	24	36	

*Wood equivalent. Calorific value of wood (Hw) assumed 19MJ/kg

NOTES FOR TABLE 2.3

Tests	*Notes*
A	Fire Research Station compartment containing steelwork[8]. Brick walls with vermiculite plaster, concrete ceiling.
A1	Wood cribs 45 mm sticks, 1-spacing[9] Note (a) t_f from equation (2) (b) compartment lined with mineral wool slabs.

Tests	*Notes*
A2	Furniture[10] Note (c) 'Medium' furniture, less than 25 mm thick (d) 'Heavy' furniture, over 25 mm thick (e) 'Mixed' furniture
A3	Liquid fuel[11] Note (f) Petrol, calorific value assumed $2{\cdot}45 \times H_w$ (g) Kerosine, calorific value assumed $2{\cdot}45 \times H_w$

NOTES CONTINUED

Tests	*Notes*
A4	Fibre insulating board[11], 25 mm thick, on walls and ceiling
B	Fire Research Station, Webster cube[12] Brick walls and ceiling Wood cribs 25 mm sticks, 3-spacing Note (a) t_f from equation (2)
C	Fire Research Station tower block[13] Brick walls plastered, concrete ceiling Wood cribs 50 mm × 100 mm sticks and 25 mm × 75 mm sticks Fibre insulating board on walls and floor
D	Japan, Kawagoe[14], various buildings Concrete walls and ceiling 'Waste timbers' for fuel Note (h) plastered ceiling (i) lightweight concrete (j) plastered finish (k) high moisture content of fuel (l) windows in two walls, opposing (m) windows in two walls, adjacent
E	Metz[15] Brick walls, concrete ceiling Wood cribs 70 mm × 45 mm, sticks 70 mm apart
F	Pchelintsev[16] 'Non-combustible' construction Probably 50 mm wood sticks
G	Pchelintsev [16] Firebrick walls, concrete ceiling
G1	Rubber, calorific value assumed $2{\cdot}1 \times H_W$
G2	Car tyres, calorific value assumed $(1{\cdot}4\text{–}2{\cdot}1) \times H_W$ Note (n) Tyres contain carbon, fabric and up to ⅓ steel in addition to rubber so that calorific value is uncertain
G3	Paper, probably in bales Note (o) Maximum temperature only 510°C. Less than half burnt
G4	Cotton, probably in bales Note (p) Maximum temperature only 335°C. Less than one-fifth burnt
H	Sjölin[17] Concrete or lightweight concrete structure Furniture Data provided: $A_W\,(h)^{1/2}/(A_T+A_W)$; $L/(A_T+A_W)$; assumed value of $h = 1{\cdot}0$ m Note (q) Door of area 1·6 m² burnt through after 6 min. $A_F = 10{\cdot}4$ m² (r) Door of area 1·6 m² burnt through between 8 and 12 min (s) $A_F = 18{\cdot}8$ m² (t) Test with 2 rooms, separate temperature-time curves. Total $A_F = 29{\cdot}2$ m²
I	Seigel[18] Mock-up two-storey office building Cribs of 38 mm wood sticks

Data provided by larger-scale experiments

Although rate of burning and radiation have been reported for some larger-scale experiments, temperature-time curves for the compartment gases are the most usual measurements. It has been decided therefore to use the temperature-time curves from all the data to calculate values of t_f, these values being for protected steel columns which reach maximum temperatures of 550°C during the course of the fires; as explained earlier, t_f is not sensitive to the value of critical temperature so that the information is valid for a range of design loads. The compartments used were of brick or concrete and because it is thought that there would be heat loss to the floor as well as the walls and ceiling, A_T has been calculated for all enclosing surface areas (excluding ventilation openings). The data are summarized in Table 2.3 and t_f is plotted against $L/(A_W A_T)^{1/2}$ in Fig. 2.4. There appears to be a straight-line relationship with a slope of approximately unity.

It is clear that this is a remarkably good correlation, extending to fire load densities as high as 150 kg/m² and to values of t_f of nearly 3 hours. Although the CIB data showed that the slope varied with fuel spacing, here the type and distribution of the fire load do not appear to have very significant effects. Three results however do depart from the correlation and need to be discussed.

First, the results of Pchelintsev[16] for car tyres (Tests G2) give low values of t_f if it is assumed that the tyres have the same calorific value as rubber (taking calorific values for wood and rubber as 19 and 40 MJ/kg respectively). However, the amounts of carbon, fabric and steel in the tyres were not specified. Up to as much as 33 per cent of a tyre may be steel which could reduce the calorific value to at least 27 MJ/kg, without making any allowance for carbon or fabric. With this lower calorific value the correlation is satisfactory.

Secondly and thirdly there are the results for a fire load density of 50 kg/m² for paper and cotton[16] for which we would expect the results to be similar to that for 50 kg/m² of wood. The low temperatures attained and the small proportions burnt suggest in fact that the rate of burning was very different and that the paper and cotton were almost certainly in bales. It may well be, therefore, that some allowance will need to be made when the fire load is closely packed in this way and indeed this was suggested by the CIB data.

Values of t_f have also been calculated for reinforced concrete and, as shown in the Appendix, are very similar to the ones calculated for the protected steel column.

Engineering relationship for fire resistance

For engineering purposes it appears reasonable to assume that for most types of fire load the effective fire resistance is given by:

$$t_f = \frac{L}{(A_W A_T)^{1/2}} \text{ min}$$

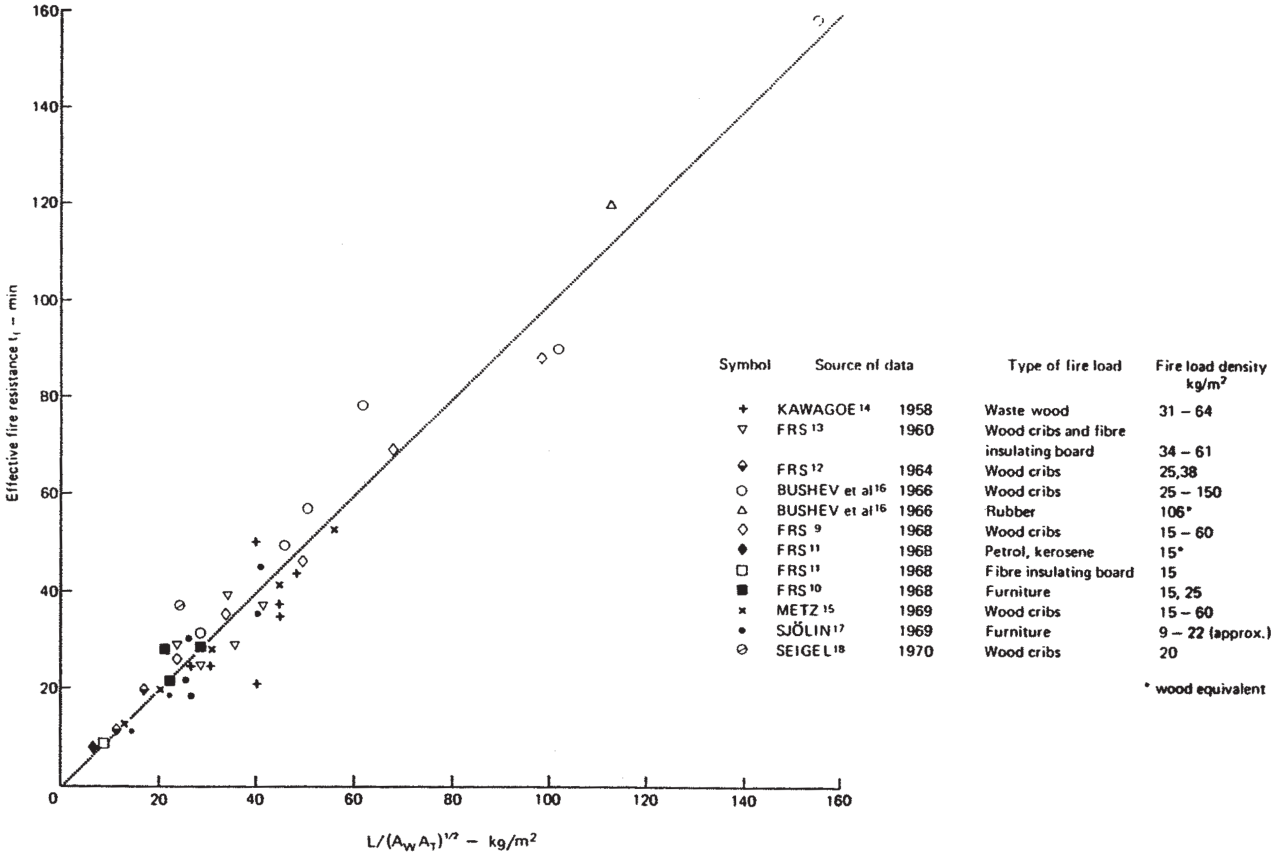


FIG. 2.4 FIRE RESISTANCE REQUIRED FOR PROTECTED STEEL COLUMN IN FIRES IN LARGER-SCALE BRICK AND CONCRETE COMPARTMENTS WITH VARYING TYPES OF FIRE LOAD

where L is the total fire load expressed as the equivalent weight of wood in kg, and A_W and A_T are in m².

The formula may over-estimate t_f for tightly-packed materials, an error which is on the safe side.

We now examine how this result could affect building design.

Use of relationship to estimate fire-resistance requirements for buildings

It is possible to express the term $L/(A_WA_T)^{\frac{1}{2}}$ as follows:

$$\frac{L}{(A_WA_T)^{\frac{1}{2}}} = \frac{L}{A_F} \times \frac{A_F}{(A_WA_T)^{\frac{1}{2}}}$$

where A_F is the floor area.

The first term, L/A_F, is the conventional fire load density and will vary within and between occupancies. The second term, $A_F/(A_WA_T)^{\frac{1}{2}}$ is a geometric one determined by the building design.

Fire load surveys of buildings show that there is considerable variation of L/A_F within the buildings, and histograms such as the one illustrated in Fig. 2.5 can be obtained[19]. Clearly fire resistance based on the highest value of L/A_F measured would give over-design and a representative value needs to be selected. Assessment of risk is discussed elsewhere[20] but we should note here that because there is an element of variability in the size of the fire load we can accept some variability in fire behaviour due to differences in the type and distribution of the fire load.

We now consider the control which can be exercised by the building designer.

As an example, take a compartment of floor area 400 m², 3 m high, with windows on two opposing walls, containing a fire load density of 60 kg/m². The plan shape and window area can be varied. Curve (a) of Fig. 2.6 is for a square plan and shows how t_f varies with window opening expressed as a percentage of the containing wall, increasing the window area from 25 to 100 per cent halves the required fire resistance. Curve (b) shows how t_f varies with depth of compartment when the percentage of window is kept constant: increasing the ratio of depth to width sixteenfold doubles the required fire resistance. Curve (c) shows how t_f varies with depth of compartment when the actual area of window is kept constant: there is very little change.

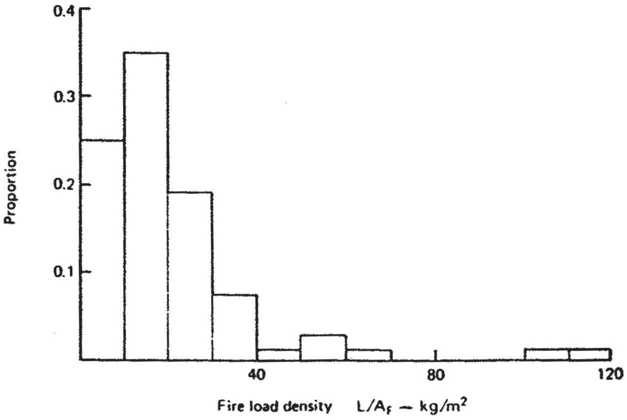


FIG. 2.5 DISTRIBUTION OF FIRE LOAD DENSITY IN ROOMS OF TWO MODERN OFFICE BUILDINGS

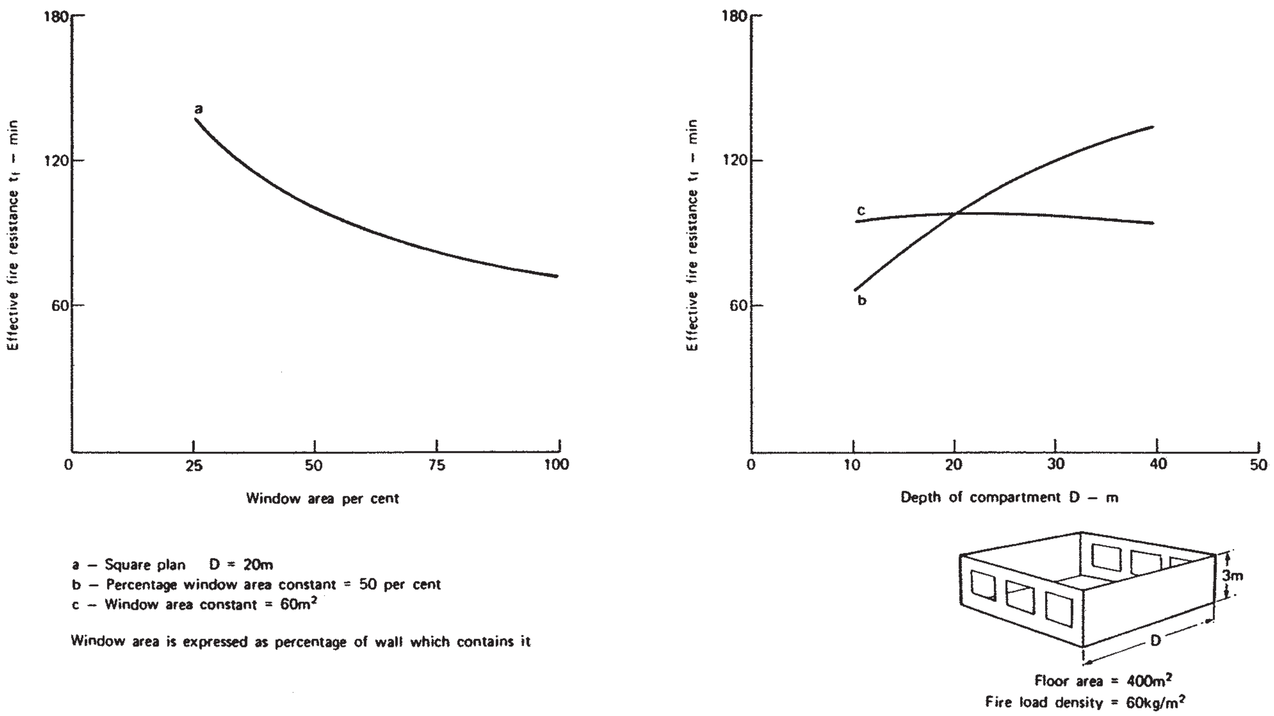


FIG. 2.6 EFFECT OF VARYING WINDOW AREA AND PLAN SHAPE OF COMPARTMENT ON t_f

We can see that for a given floor area the controlling factor is the area of window opening.

As another example, take a compartment like the one above but square on plan, and vary the floor and window areas. Figure 2.7 shows how t_f varies with floor area if the windows are (a) a fixed percentage of the wall area and (b) a fixed percentage of the floor area. This demonstrates that with a fixed window pattern the effective fire resistance increases with compartment area but that if the windows are directly related to the floor area then the effective fire resistance changes very little as the compartment area increases.

The window pattern is clearly important and it is interesting to note that it also has an important effect on the radiation hazard to nearby buildings. Thus although a reduction in window area could lead to an increase in the required fire resistance this might be compensated for, from the fire hazard point of view, by a reduction in the required building separation.

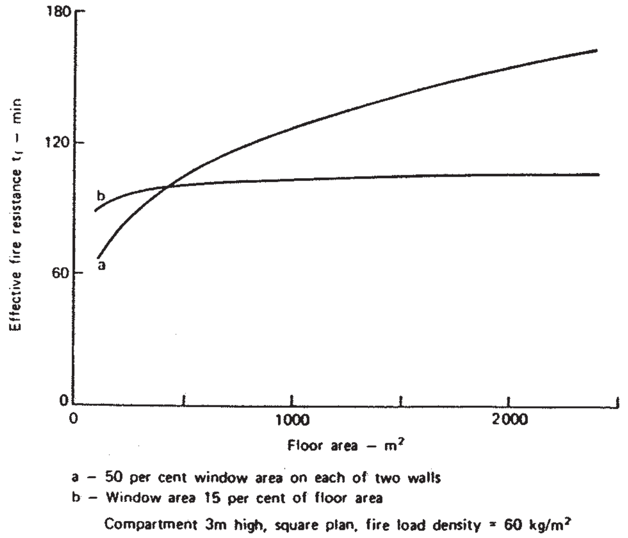


FIG. 2.7 EFFECT OF VARYING FLOOR AREA OF COMPARTMENT ON t_f

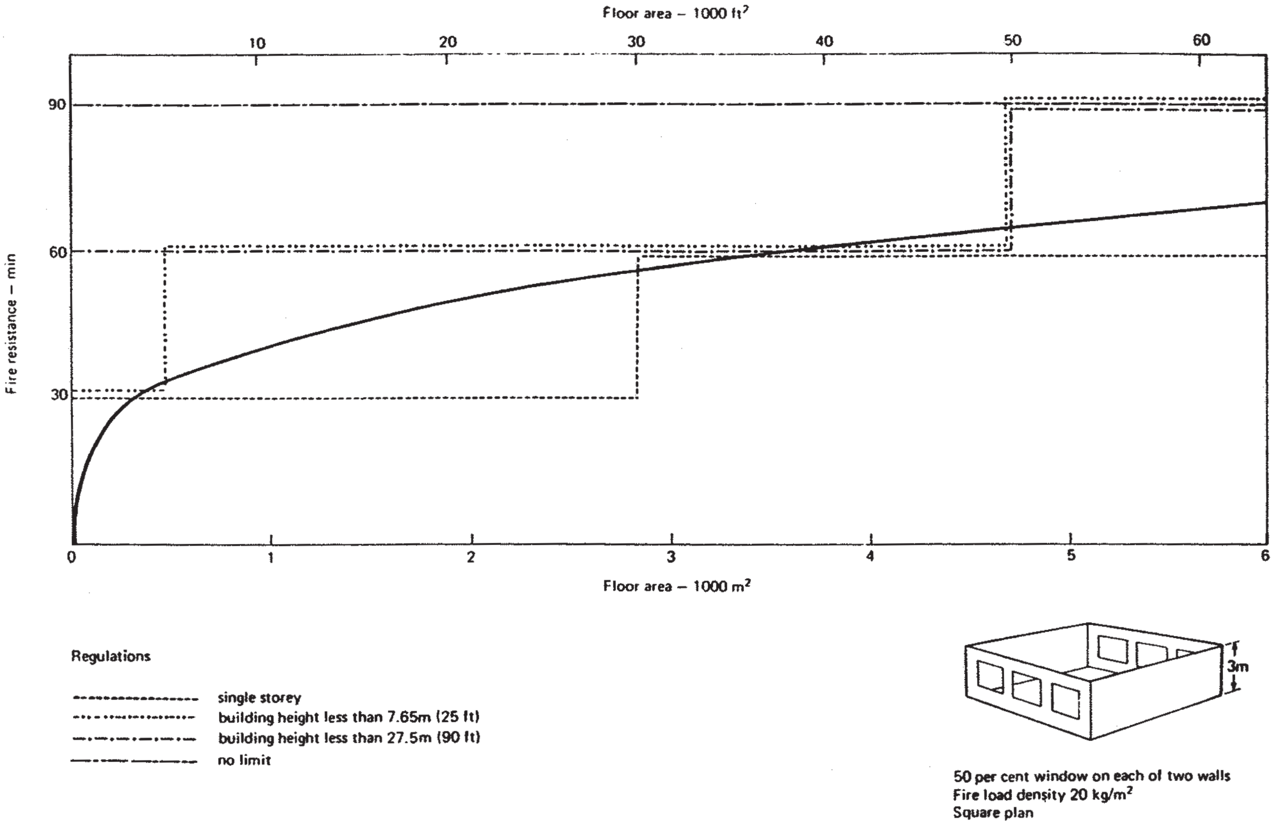
Comparison with existing building regulations

United Kingdom regulations for fire resistance stem[21] from the classic work of Ingberg[22] who related fire resistance to fire load density. Although he did not measure the effect of ventilation, Ingberg noted its importance and it has been possible to show that his deductions are in broad agreement with the results of the CIB data[3,4].

The Building Regulations for England and Wales[23] relate fire resistance not only to Purpose Group, which broadly speaking takes into account fire load density, but also to floor area and cubic capacity, so that some allowance is made for A_T, if not for A_W. Based as they are on experience, the Regulations must also contain allowances in varying degrees, albeit unquantified, for fire brigade activities and life safety.

For illustration we can consider the requirements for compartment walls of a compartment of an office building (Purpose Group IV). The required fire resistance depends on the height of the building containing the compartment as well as on the compartment size itself. Figure 2.8 illustrates this for a compartment height of 3 m. Also shown is the calculated fire resistance of a steel column needed to survive a burn-out of a fire load density of 20 kg/m² (taken as an average value for offices) when there is 50 per cent window opening on each of two walls.

We may note firstly that by selecting an average value of fire load density we introduce an element of risk since there may well be higher values (Fig. 2.5).



50 per cent window on each of two walls
Fire load density 20 kg/m²
Square plan

FIG. 2.8 FIRE RESISTANCE CALCULATED FOR 3m HIGH COMPARTMENT COMPARED WITH REQUIREMENTS OF BUILDING REGULATIONS

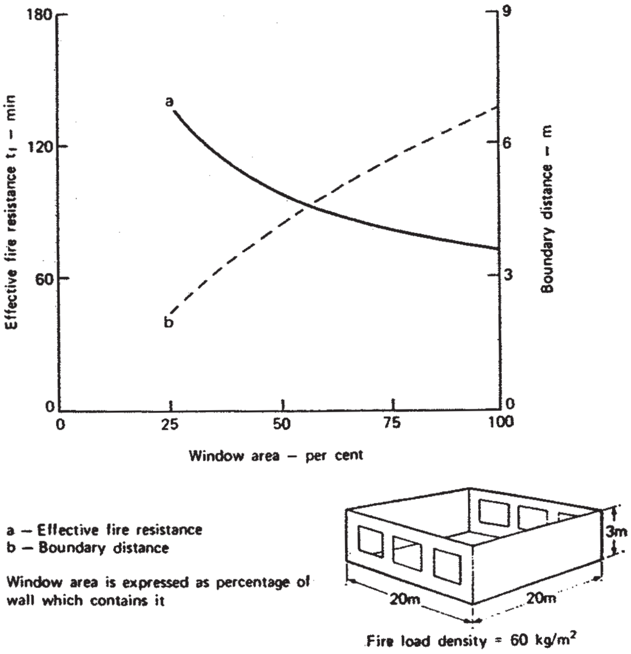
If, however, we choose a much higher value this could lead to over-design.

Secondly, we note that the fire-resistance requirements for identical compartments vary according to the height of the building that contains them and yet if each compartment has been designed to survive a total burn-out, the height of the building should be irrelevant. Insofar as fire-fighting becomes more difficult on the upper storeys of a tall building, we might conclude that fire brigade activities are taken into account in the fire-resistance requirements. However, a fire on the ground floor of a 27·5 m (90 ft) building should present no more fire-fighting problems than one on the ground floor of a 7·5 m (25 ft) building. We might conclude therefore that some extra allowance is made for life safety in a tall building and if this is so, should there be some interaction between requirements for fire resistance and requirements for means of escape?

The assessment of these risks is outside the scope of this paper but the points have been introduced here to set the subject of the paper in context. A fuller discussion is given elsewhere[20].

Although the regulations for fire resistance take no account of A_W, there are important requirements for external walls which do control the area of window openings in relation to boundary distance, the purpose being to reduce the risk of fire spread by radiation to nearby buildings.

For example, we show in Fig. 2.9 the effect on boundary distance of varying the percentage window area. For the building illustrated, a decrease in window area from 100 to 25 per cent gives a threefold decrease in the required boundary distance. This can be compared with a twofold increase in the required fire resistance, as already illustrated by curve (a) in Fig. 2.6.



a – Effective fire resistance
b – Boundary distance

Window area is expressed as percentage of wall which contains it

Fire load density = 60 kg/m²

FIG. 2.9 EFFECT OF VARYING WINDOW AREA ON t_f AND BOUNDARY DISTANCE

Discussion

The concept of effective fire resistance appears to be a useful way of correlating the results of the experimental fires. Earlier work[24] has distinguished between two kinds of fire behaviour – fire load control and ventilation control – but no such distinction is apparent in the values of t_f, which are given by a single correlation. In fire load-controlled fires, those with ample ventilation, the rate of burning is controlled by the thickness and dispersion of the fuel, but because the absolute values of t_f are low, it is probable that the effects of fuel bed design on t_f, real though they may be, are too small to be important.

There are certain circumstances, however, where a more detailed examination of fire behaviour would be valuable. This would be for very low fire load, well-ventilated fires (low $L/(A_W A_T)^{\frac{1}{2}}$) and high fire load, very poorly ventilated fires (high $L/(A_W A_T)^{\frac{1}{2}}$), where the maximum fire temperature might be less than the critical failure temperature for the structure. It must also be realized that real fire temperatures may be higher than in the standard fire and it is possible that some insulating materials will behave differently at these higher temperatures. These reservations are, of course, equally relevant to the existing Building Regulations.

The correlation of t_f with $L/(A_W A_T)^{\frac{1}{2}}$ is novel in that it explicitly recognizes the importance of both ventilation and compartment size. If we examine the existing Building Regulations in Great Britain [23, 25] we see that control of openings in the external wall, based on earlier work of the Fire Research Station [26], gives the building designer flexibility of choice between area of openings, boundary distance and compartment size. Fire-resistance requirements related to area of openings and compartment size would give the designer yet more choice.

The work described in this paper forms one part of a fire-grading 'system'. Statistical information about fire loads, fire spread, fire brigade activities, and random variation in behaviour of both fires and structures is needed to assess risk. What, for example, would be the effect on fire spread if the present fire-resistance requirements were doubled?

If the major objectives of fire resistance can be summed up in the phrase 'fire containment' we may define them as: limiting the size of the fire so that it can be controlled by the fire brigade, preventing fire spread to escape routes and 'places of safety', preventing fire spread to other people's buildings, and preventing fire spread to property within one's own buildings. The fire-resistance requirements might not necessarily be the same for all these objectives.

Conclusions

1. For engineering purposes the fire resistance, t_f, needed by a protected steel column or by reinforced concrete, to survive a total burn-out of a fire in a compartment can be given by:

$$t_f = \frac{L}{A_F} \times \frac{A_F}{(A_W A_T)^{\frac{1}{2}}} \text{ min}$$

where L is the total fire load (wood equiv) – kg
A_F is floor area – m^2
A_W is area of ventilation opening – m^2
A_T is area of enclosing surfaces to which heat is lost (excluding A_W) – m^2
and L/A_F is fire load density – kg/m^2

2. This relationship correlates fires with varied types of fire load including wood cribs, furniture, waste timber, fibre insulating board, petrol, kerosine and rubber. It may over-estimate t_f for tightly-baled paper and cloth.
3. The relationship has been derived from (i) the CIB experimental programme on fully-developed fires in model compartments of various scales, shapes and degrees of ventilation with various amounts and dispersions of fuel in the form of wood cribs and (ii) from results of experiments all over the world in larger-scale brick and concrete compartments, mostly cubical in shape, with varied types of fuel.
4. The relationship explicitly recognizes not only fire load density (L/A_F) which is the traditional basis for regulations, but also ventilation and compartment size, which are both known to have important effects on fire behaviour.
5. The relationship assumes that the maximum fire temperature will exceed a critical value for the steel column and this might not happen for very low values of L/A_F or A_W. In these situations t_f would be over-estimated. It further assumes that the maximum fire temperature, which could exceed the temperature of the standard fire-resistance test, would not produce significantly different changes in the behaviour of the protective material. (These reservations are equally relevant to existing requirements for fire resistance).
6. In the context of fire resistance, the necessity of distinguishing between fire load controlled and ventilation-controlled fires appears to have been removed, probably because in the fire load controlled regime the absolute values of t_f are small. (The distinction would still be necessary for other considerations such as flame height from windows).
7. Examples show the importance of window area and floor area: for one representative compartment an increase in window area from 25 to 100 per cent halves t_f; an increase in floor area from 200 to 2000 m^2 doubles t_f.
8. A comparison of calculated values of t_f with requirements of the existing Building Regulations highlights the value of measuring risk.
9. The existing Building Regulations recognize that openings in external walls can spread fire by radiation to nearby buildings and control A_W in relation to boundary distance. For example, reduction in window area from 100 to 25 per cent could give a threefold decrease in the required boundary distance. On the other hand, as noted above, this could double the required fire resistance.
10. Recognition of the importance of fire load density, ventilation and compartment size in determining both fire-resistance requirements and distance between buildings would give wider choice to the building designer and be a further step in the process of compiling a fire grading 'system'.

Acknowledgements

The author has relied heavily on the work of many of her colleagues; in particular she would like to thank Dr. P. H. Thomas, Mr. A. J. M. Heselden and Mr. R. Baldwin for very helpful discussion and advice.

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Appendix

REINFORCED CONCRETE FAILURE

Because reinforced concrete will fail if the steel reinforcement reaches a critical temperature, the fire resistance normally varies with the depth of the reinforcement from the heated face. The steel temperature can be assumed to be similar to that of the concrete at the same depth, and the concrete temperature can be calculated by assuming that the steel has negligible effect on the heat flow in the concrete[27].

A relationship between the effects of a real fire and the standard fire can be obtained in two steps by:

(i) calculating the maximum depth x at which the critical temperature θ_x would be attained when exposed to the real fire temperature-time curve

(ii) calculating the time t_f to attain the same temperature θ_x at the same depth x when exposed to the standard curve.

Temperature gradients can be calculated by methods of numerical analysis based on the heat conduction equation for one-dimensional heat flow:

$$\frac{d\theta}{dt} = k\frac{d\theta}{dx}$$

where k is the thermal diffusivity.

For the standard curve, these methods show:

$$\frac{\theta_x}{\theta_t} = 1 - \text{erf}\,\frac{x}{1{\cdot}85\,(kt_f)^{\frac{1}{2}}} \qquad (3)$$

where erf denotes the normal error function.

Since θ_t is a prescribed function of t_f, it is possible using equation (3) to obtain a relationship between $x/(k)^{\frac{1}{2}}$ and t_f, for a given value of θ_x. For the real fire curve it is possible to calculate the maximum value of $x/(k)^{\frac{1}{2}}$ at which the temperature θ_x can be attained. Calculations have been made for two values of θ_x, 550°C for reinforced concrete and 400°C for prestressed concrete. The values of t_f which were obtained are shown in Table 2.4, compared with the values of t_f obtained for a protected steel column. These demonstrate that there is little difference in the values and that correlations based on the column will be very similar to ones based on reinforced concrete.

Table 2.4

Calculated valves of t_f for reinforced concrete and protected steel column

Source of data	Effective fire resistance – t_f – min		
	Reinforced concrete		Steel column
	$\theta_x = 550$	$\theta_x = 400$	$\theta_x = 550$
CIB, 441 1·5 m scale	87	95	88
	65	66	62
	99	111	102
	150	160	154
	33	27	25
	68	77	64
	47	44	40
Fire Research Station compartment containing steelwork[8]	18	19·5	24
	33·5	33·5	35
	69	71	69
	18·5	21	20
	53	48	47
	84	91	87

If we write:

$$\frac{x}{1{\cdot}85\,(kt_f)^{\frac{1}{2}}} = \frac{x}{2\,(k \times 0{\cdot}86\,t_f)^{\frac{1}{2}}}$$

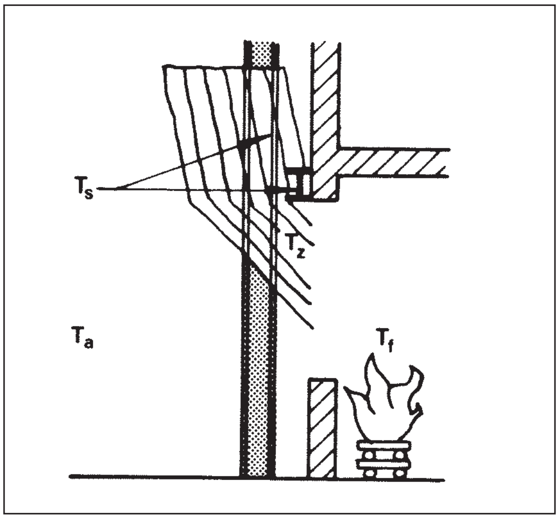
it is interesting to note that equation (3) is equivalent to a constant temperature θ_t applied for a time 0·86 t_f.

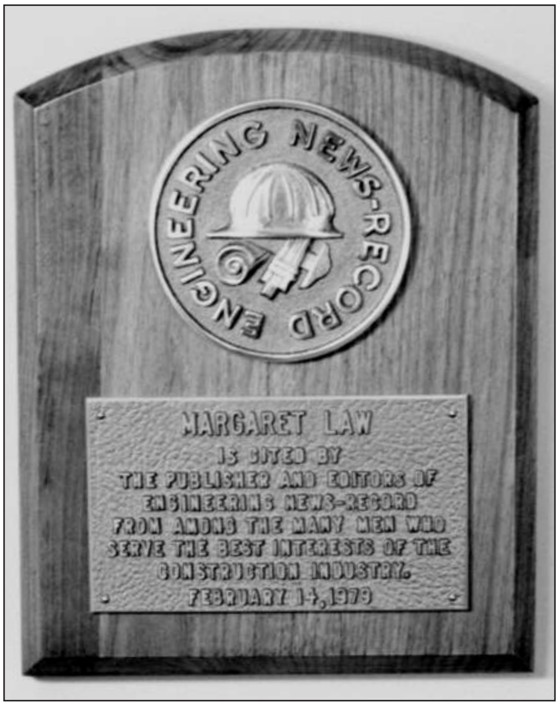
PAPER 7

Fire safety of external building elements - the design approach

Margaret Law, Engineering Journal, Second Quarter, pp 59-74, 1978.
American Institute of Steel Construction (AISC), USA

Figure showing the location of temperatures relevant to the calculation of heat accumulation in bare external steel. The plate shows the plaque presented by Engineering News Record, which designated Margaret Law as a man.





A weathering steel had been developed in the 1960s which, if left unpainted, would acquire a weathered external layer or skin giving protection from rust and corrosion to the steel beneath.
Its use was attractive for bridges and other external structures since it did not need painting. However, when this steel formed the structure on the exterior of a building the benefits were not realised because the by-laws and codes required all elements of building construction, whether inside or out, to have fire cladding. Arup R&D was commissioned jointly by Constrado and the American Iron and Steel Institute to devise an engineering design method to identify locations outside the building where fire cladding was not needed. Turlogh O'Brien, then Leader of Arup R&D, and I produced three reports: the background analysis reproduced here, a state-of-the-art report, and a design manual. The analysis of fire exposure was based on research results obtained in various countries.

The main US Building Codes accepted the method. However, there was general astonishment in the USA to find engineering methods actually being applied to fire safety and I was cited by the journal Engineering News-Record as having 'made marks'. At the annual ENR 'Man of the Year' banquet I was presented with a bronze plaque that categorised me as a man (because that was the only mould they had).

Fire Safety of External Building Elements—The Design Approach

MARGARET LAW

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Fire Safety of External Building Elements—The Design Approach

MARGARET LAW

The adoption of a design approach to fire safety in buildings has gained increasing acceptance as it has become clear that the traditional rules are not always sufficiently flexible or may not be adequate to cope with modern developments in the use and construction of buildings. For elements of structure, building codes have a performance requirement based on a specified exposure period of the element to the standard fire resistance test of ASTM E119, and while it has been recognized that the building fire exposure may not be the same as the standard fire exposure, the tendency has been more to criticize the required period of fire resistance than to question the standard test conditions themselves. However, a major difficulty with the standard test has been encountered when buildings are designed with external structural steel elements. These elements are required by the codes to have the same minimum periods of fire resistance and hence the same cladding as internal elements, even though the external fire exposure conditions are known to be less severe.

Internal elements exposed to fire are surrounded by flames and by the heated surfaces (walls, ceiling, floor) of the enclosing room or compartment. These heating conditions are similar to those of the standard fire resistance test, where the element is enclosed in a furnace. External elements are exposed to radiation from the windows in the facade, the value of the intensity of radiation received varying with the position of the element in relation to the windows. They are exposed to radiation and convection from the outflowing flames and hot gases, the heat flux again varying with position, and they also lose heat to the surroundings at normal ambient temperature. Depending on their size and position and on the behavior of the fully developed fire, external steel elements may be designed so that they do not need any cladding.

Initially, attempts were made in research programs to simulate external exposure by inserting a window in the standard test furnace wall, but this was not really satisfactory, because no matter how long the test is run, the flame exposure is likely to be less severe than that from a real building fire.[1] Accordingly, *ad hoc* experiments have been carried out from time to time with external elements exposed to flames and radiation from "real" fires, the results of these experiments leading to a relaxation of code requirements for individual specific buildings.[2,3] If, instead, a design approach is adopted, it not only obviates the need for these *ad hoc* tests, but also extends to sizes of fire well beyond the limits of size of practical fire tests. The approach is to analyze the external heat transfer to structural elements and to calculate the amount of protection, if any, which would be needed.

For structural steel elements, critical conditions can be defined in terms of a critical steel temperature and, given the heat transfer conditions, calculation of the steel temperature is relatively straightforward. The main problem, then, in adopting the design approach, is to define the external heat transfer.

A large body of data on building fire and flame behavior exists, and the objective of this paper is to show how it may be analyzed and used to estimate external heat transfer for practical designs of buildings. In particular, correlations have been derived not only from model-scale experiments, but also from measurements for a wide range of experimental fires in large-scale building compartments.

Since this work forms the basis of a design guide[4] for the use of bare exterior structural steel, it has been considered necessary to meet the following requirements:

1. The correlations of fire and flame behaviour should be based on parameters which can be readily identified by the designer.
2. The correlations should be explained by relatively simple equations to facilitate calculations.
3. The geometrical model of flame projection should also be simple, to facilitate calculations.

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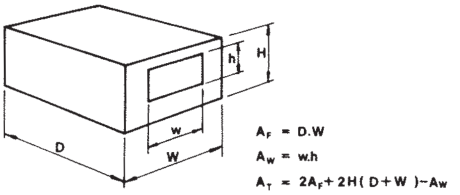

Fig. 1. Simple fire compartment

The parameters which have been adopted are the dimensions of the compartment and its windows, and the fire load per unit floor area, L/A_F. The compartment in its simplest form is illustrated in Fig. 1; in practice, the correlations can be used for a variety of window sizes on one or more walls. The value of L/A_F can be estimated for the particular building under consideration, or obtained from survey data for the type of occupancy. A simple pocket calculator is adequate for the calculations.

This paper has been arranged to give, first, a summary of the main experimental data describing fire and external flame behavior. (The main features of the large-scale experiments are listed in the Appendix.) Correlations based on these data are then derived. The mode of heat transfer to external steel elements is outlined and a heat transfer model has been developed, so that steel temperatures may be estimated.

INTERNAL FIRE BEHAVIOR

A building fire which is allowed to continue until the fuel is exhausted, without intervention of the fire brigade, can be considered to go through three main phases: growth, full development, and decay. Most flaming and most structural damage occur during the fully developed period, and this phase has been studied by a number of workers; a summary is given by Thomas.[5] An analysis of fully developed fire behavior is complex, and the models which have been developed are based on a number of simplifying assumptions, notably that the temperature distribution is uniform throughout the fire compartment and that the fuel burns in a uniform way. Nevertheless, important parameters have been defined, and a substantial data bank exists from which it is possible to show how these parameters interact.

The pioneer worker in this area was Ingberg,[6] whose relationships between fire load density (fire load per unit floor area) and fire severity have formed the basis of fire resistance requirements for elements of structure. The importance of ventilation was quantified by Fujita[7] in terms of area and height of the ventilation opening (usually the window). Later work, carried out in a cooperative research program under the auspices of the Conseil International du Batiment (CIB),[8] has shown how the Fujita relationship is modified by the size and shape of the fire compartment. By using models, it was possible in the CIB program to cover a wide range of these and other factors. On large-scale, an early systematic study of some of the factors was carried out at Borehamwood[9] and later at Maisieres-les-Metz,[10] and there are a number of other large-scale experiments which yield some measurements to compare with the model-scale data.

In experiments, the fire load has usually been cribs of wood sticks, an easily reproducible fuel, or waste wood, but some data are available for furniture. Strictly speaking, the information derived is only applicable to fires involving mainly wood fuel, but it may be assumed to give reasonable correlation with domestic, office, and similar types of fire load. Most experiments have been carried out in still air or light wind conditions, that is, the air flow has been controlled by the fire behavior and compartment dimensions, and this may be termed "natural draft". Some experiments have included an extra air supply and this may be termed "forced draft". The windows have usually been unglazed, the most likely condition once the fire becomes fully developed.

Where external fire exposure is concerned, two of the most important features of the fully developed fire are the rate of burning, which affects flame size and fire duration, and fire temperature, which affects the radiation from the window.

Natural Draft—Continuous weighing of the fire load during actual tests has shown[11] that the rate of weight loss is approximately steady over the fully developed period when the weight falls from 80 to 30% of its initial value. This rate is defined as the average rate of burning, R, and the effective fire duration, τ, is defined by:

$$R = \frac{L}{\tau}$$

where L is the total mass of the fire load.

With ample ventilation—the free burning condition—the value of τ is τ_F, determined by the characteristics of the fire load, thin fuels with large surface areas giving smaller values of τ_F. Thus, for any given type of fuel, R is directly proportional to L and is given by:

$$R = \frac{L}{\tau_F} \qquad (1)$$

Where ventilation is restricted, there is an upper limit to the value of R, however large the fire load, and it has been shown, by considering air flow and a heat balance, that important parameters are the area A_w and height h of the windows, the area A_T of the enclosing surfaces to which heat is lost (excluding the windows), and the ratio of the depth D to width W of the compartment. Thomas[5] gives the correlation of the CIB data shown in Fig. 2, for a range of these parameters, in compartments 1.6, 3.3, and 4.9 ft high. He modifies the Fujita equation:[7]

$$R = 0.6\, A_w h^{1/2}$$

to allow for the compartment dimensions D, W, and A_T. The measurements of R which have been reported for large-scale ventilation-restricted fires,[9,10,12] have been

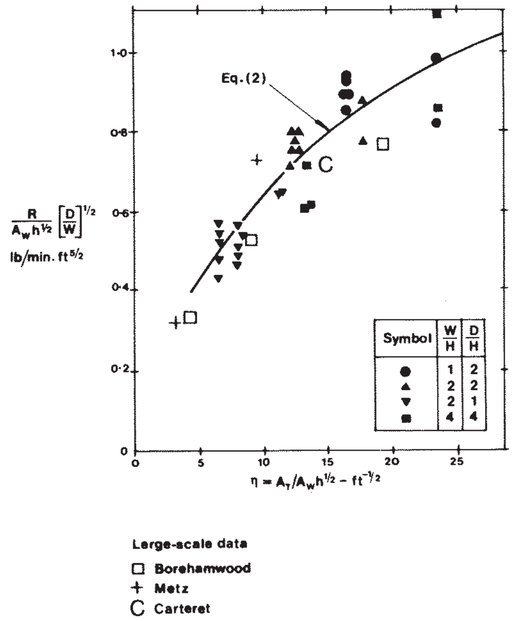

Fig. 2. Variation of $R/A_w h^{1/2}$ with compartment size and ventilation, as given by Thomas for CIB data

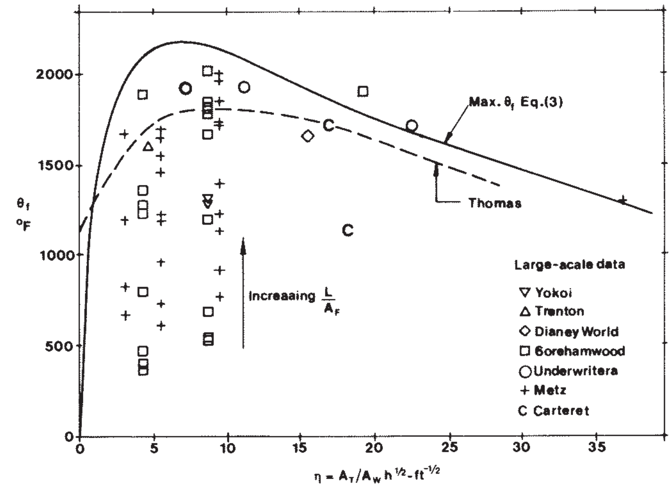

Fig. 3. Variation of average fire temperature rise with compartment size and window area, natural draft

plotted in Fig. 2 and are in reasonable agreement with the CIB data. The line drawn by Thomas is the best one through the points, and can be represented by the following equation:

$$R = \frac{1.22\,(1 - e^{-0.065\eta})}{(D/W)^{1/2}}\,(A_w h^{1/2}) \qquad (2)$$

where
$$\eta = \frac{A_T}{A_w h^{1/2}}$$

For a particular fire load and compartment size, R should be calculated from both Eqs. (1) and (2). If Eq. (2) gives a lower value, there is a ventilation controlled condition.

There is an upper limit to the temperature attained within the fire compartment, depending on the fire load and the compartment dimensions. Thomas[5] gives the correlation of the CIB measurements of average fire temperature rise, θ_f, over the fully developed fire period, as a function of η, as shown in Fig. 3. The major point of interest is that θ_f rises to a maximum for $\eta = 5$ to 10 and then declines. The value of θ_f also depends on the fire load, and this is clearly demonstrated in Fig. 3 where the results for large-scale tests[9,10,12,13–17] with low fire load densities, fall well below the Thomas curve. It is reasonable to assume that there is an "upper limit" or maximum to the value of θ_f for a given value of η; the following equation is proposed:

$$\theta_{f(max)} = 8025\,\frac{(1 - e^{-0.18\eta})}{\eta^{1/2}} \qquad (3)$$

Equation (3) is shown in Fig. 3.

For low values of fire load, the upper limit is not attained and examination of the data indicates that the effect is not simply one of fire load density, but of fire load in relation to ventilation and compartment dimensions. Earlier analysis[18] of both the CIB and large-scale data showed that $\psi = L/(A_w A_T)^{1/2}$ is an important parameter which is related to an equivalent fire resistance. It has been used to modify Eq. (3) for the upper limit, as follows:

$$\frac{\theta_f}{\theta_{f(max)}} = 1 - e^{-0.25\psi} \qquad (4)$$

Figure 4 indicates that this correlates the large-scale data. Combining Eqs. (3) and (4) gives:

$$\theta_f = 8025\,\frac{(1 - e^{-0.18\eta})}{\eta^{1/2}}\,(1 - e^{-0.25\psi}) \qquad (5)$$

Forced Draft—There is not much information available on the effects of forced draft on rate of burning, but observations made during the Underwriters' Laboratories tests[16]

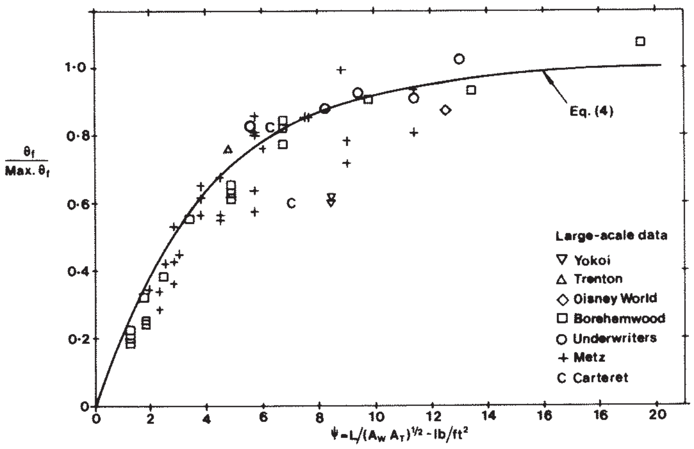

Fig. 4. Variation of average fire temperature rise with fire load, compartment size, and window area, natural draft

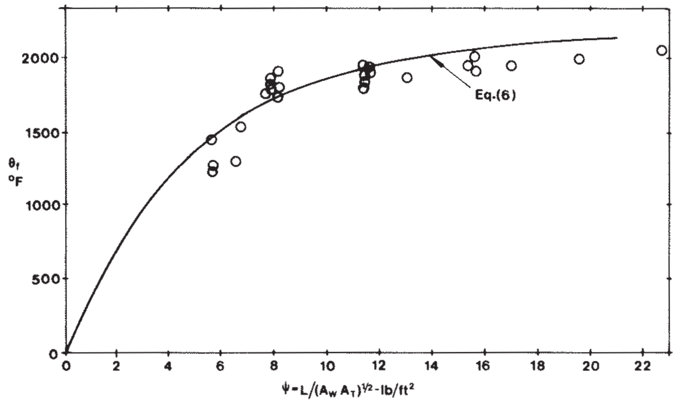

Fig. 5. Variation of average fire temperature rise with fire load, compartment size, and window area, forced draft, Underwriters' Laboratories data

indicate that its maximum effect would be to give the free-burning condition of Eq. (1), i.e., $R = L/\tau_F$.

The data obtained at the Underwriters' Laboratories show no significant variation of temperature with η or air supply, but θ_f can be related to ψ as shown in Fig. 5. The curve has the equation:

$$\theta_f = 2160\ (1 - e^{-0.20\psi}) \qquad (6)$$

It would be expected that θ_f would decrease with increasing air supply, and Eq. (6) may overestimate the fire temperature where there is a strong wind.

EXPERIMENTAL STUDIES OF EXTERNAL FLAME PROJECTION

The first comprehensive study of flame projection from windows was made by Yokoi,[13] who wished to estimate the risk of vertical fire spread. He first derived correlations for temperature and velocity distribution in the plume of hot gases rising above alcohol fires burning in rectangular trays. By treating the upper half of a window as the rectangular heat source, he then derived similar correlations for the plumes rising from various size and shape windows in a 1.3 ft x 1.3 ft x 0.65 ft high model room containing alcohol fires. He demonstrated the effect of a wall above the window and the shape of the window on the temperature distribution and trajectory of the plume. The wall absorbs heat from the plume, but restricts the air entering from the wall side, and the wider the window the closer the plume is to the wall. Yokoi denoted the shape of the window by $n = w/{}^1\!/_2h$, the ratio of the width to the height of the upper half of the window, and derived a series of plume shapes for different values of n. He obtained good agreement between the results of his model tests and four experiments using wood fuel in large-scale concrete buildings, even though, as he points out, theoretically it is necessary to make adjustments for the emissivity of wood flames and for the thermal properties of the wall above the window. He also comments that, where there is restricted ventilation in the room, the outflowing gas will continue to burn after it leaves the window and this will affect the correlation.

Webster et al.[19—21] carried out a series of tests, mostly on model scale, with cubical rooms open on one side, containing wood crib fires. Visual records of flame height were made. Thomas [22] correlated these results by a dimensional analysis essentially the same as that used by Yokoi, derived from the dominant role of buoyancy and considerations of turbulent mixing. By assigning a flame tip temperature of about 1000°F, reasonable agreement could be obtained between these data and those of Yokoi.

Seigel[23] reported some findings derived from the tests at the Underwriters' Laboratories[16] in a large-scale room with various sizes and shapes of window containing wood crib fires. An air supply was connected to this room for most of the experiments, which had the effect of increasing the rate of burning of the cribs to the "well-ventilated" (free-burning) condition.[24] Visual records of flame height and projection were made and the temperature distribution in the emergent plume was recorded. Seigel's correlation treats flames as forced horizontal jets and the projection is defined by a temperature of 1000°F at the flame tip.

In a series of tests[9] at Borehamwood, in a large-scale room with natural ventilation, containing wood crib fires, visual flame heights were recorded, but only as a by-product of the main experiment; thus, these values are rather approximate.

Most of the large-scale experiments[3,12,14,25,26] specifically designed to study flame projection, have been *ad hoc.* The information derived can be generalized by relating them to the correlations described above. This process has at least two important aspects: first, it demonstrates the validity of the correlations obtained by the use of models; secondly, it illustrates the difference between the idealized laboratory environment and "natural" conditions. For example, it has been observed that in practice the fire load may burn unevenly or that flame projection from windows may be asymmetrical.

Figure 6 illustrates the main features of interest for flame projection.

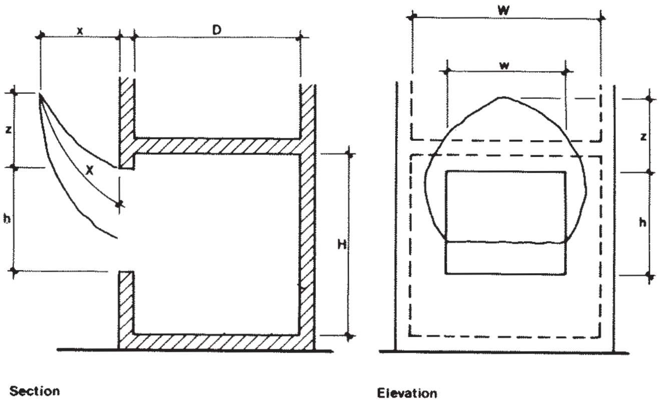

Fig. 6. Dimensions used in calculations of flame projection

EXTERNAL FLAME DIMENSIONS

Natural Draft—Yokoi correlated y/r_o, where y is height above the top of the window and r_o is the effective radius of the upper half of the window, with Θ, a dimensionless term involving temperature rise and rate of heat supply, and obtained a family of curves for different values of n, the ratio of width to height of the upper half of the window. Thomas[22] showed that these curves could be brought together by correlating $n^{1/3}y$ with Θ. Thomas and Law,[27] analyzing the data of Yokoi, Webster et al. and Seigel, proposed the following correlation:

$$\frac{n^{1/3}(z+h)}{r_o} = \frac{2}{\Theta} \tag{7}$$

where $(z + h)$ denotes the height of the flame tip above the base of the window of height h, assuming a temperature at the tip of 1000°F.

Equation (7) may be rearranged to give:

$$\frac{z+h}{h} = 2\pi^{1/3}\left[\frac{R}{A_w\rho_z(gh)^{1/2}}\right]^{2/3}\left[\frac{C^2T_a}{c_z{}^2\theta_z{}^3}\right]^{1/3}$$

or

$$\frac{z+h}{h} = 23.5\left[\frac{R}{A_w\rho_z(gh)^{1/2}}\right]^{2/3} \tag{8}$$

where $C = 6.9 \times 10^3$ Btu/lb, $c_z = 0.24$ Btu/(lb °F), $T_a = 520°\text{F}$, ρ_z is density of hot gas, and g is acceleration due to gravity.

Data for large scale fires[3,9,12–16,25,26] are plotted in Fig. 7, which indicates that Eq. (8) overestimates flame height on large scale and that other factors appear to affect the flame behaviour. A regression analysis of the log values shows that $R/[A_w\rho_z(gh)^{1/2}]$ is nevertheless highly significant, n is significant at the 5% level, and the following equation is obtained:

$$\frac{z+h}{h} = 8.9\left[\frac{R}{A_w\rho_z(gh)^{1/2}}\right]^{0.51} n^{0.12}$$

Much of the scatter of the data is probably random and the power of n is small; accordingly, there seems no strong reason to depart from the general form of Eq. (8), but to use an adjusted coefficient.

The recommended correlation for flame height is:

$$\frac{z+h}{h} = 16\left[\frac{R}{A_w\rho_z(gh)^{1/2}}\right]^{2/3} \tag{9}$$

This may be written:

$$z + h = 3.55\left[\frac{R}{w}\right]^{2/3} \tag{10}$$

where $\rho_z = 0.028$ lb/ft^3 at 1000°F.

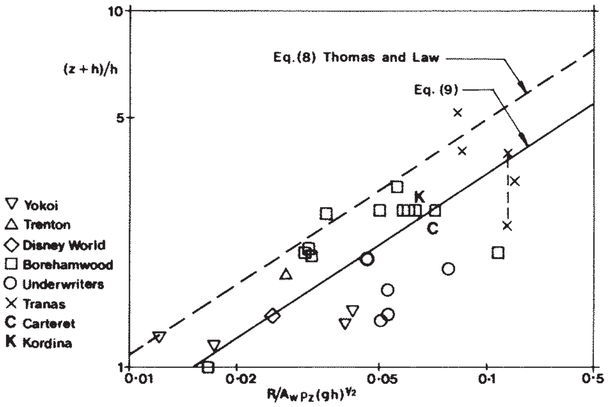

Fig. 7. Flame heights for large-scale tests with natural draft (Note: Range of n: 0.5-18.7)

A similar regression analysis for the projection x of the flame tip gives:

$$\frac{x}{h} = \frac{0.454}{n^{0.53}} \tag{11}$$

with n significant at nearly the 0.1% level and the term $R/[A_w\rho_z(gh)^{1/2}]$ not significant. The data are plotted in Fig. 8. Equation (11) indicates that projection of the flame tip decreases with n, as shown by Yokoi, and is less than half the window height for values of n exceeding unity, which includes most situations. Equation (11) is the recommended correlation for x, provided there is a wall above the window. Yokoi showed that without a wall, the value of x would be independent of n. In the absence of other data, Yokoi's no-wall relationship is recommended. It may be represented by the following equation:

$$\frac{x}{h} = 0.60\left[\frac{z}{h}\right]^{1/3} \tag{12}$$

The measurements at the Underwriters' Laboratories suggest that the maximum width of the emerging flame will be little different from the window width.

Forced Draft—Seigel,[23] treating the flame as a jet,[28] proposed an equation of the form:

$$l \propto R/A_w{}^{1/2}\theta_z$$

where l is the distance along the center line at which the temperature rise is θ_z. For the data obtained by the Un-

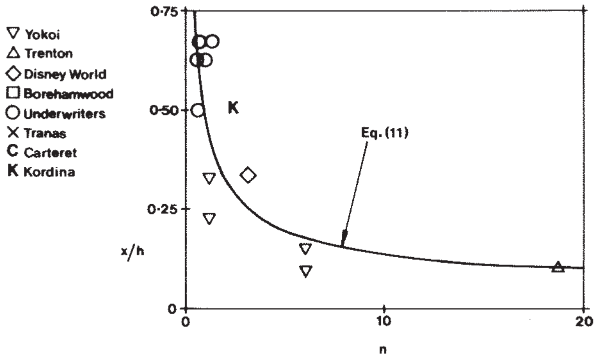

Fig. 8. Horizontal projection of flame tip for large-scale tests with natural draft, wall above

derwriter's Laboratories, he showed that at the flame tip, where $l = X$:

$$X = 0.051 \frac{L}{A_w{}^{1/2}} - 1.28 \tag{13}$$

for fires with "normal" burning. Normal burning was defined as sufficient ventilation for the cribs used as fire load to burn at their maximum rate, that is, as if they were free-burning.

For these cribs, τ_F was 26 min so that Eq. (13) may be written:

$$X = 1.33 \frac{R}{A_w{}^{1/2}} - 1.28 \tag{14}$$

Seigel's correlation is based on the reasonable assumption that the main effect of a forced draught is to increase the rate of burning of a ventilation controlled fire. The effect on "free-burning" fires was insignificant for the range of forced ventilation used. However, for a given rate of burning, a wind may also affect the flame size and direction. For this reason, regression analyses of the data, similar to the ones for natural ventilation, but including a Froude number (u^2/gh) have been carried out, and the following have been obtained, where u is wind velocity:

$$\frac{z+h}{h} = 6.99 \left[\frac{R}{A_w \rho_z (gh)^{1/2}}\right]^{0.784} n^{0.434} \left[\frac{u^2}{gh}\right]^{-0.216} \tag{15}$$

$$\frac{x}{h} = 6.85 \left[\frac{R}{A_w \rho_z (gh)^{1/2}}\right]^{0.760} \times n^{0.444} \left(\frac{u^2}{gh} \text{ not significant}\right) \tag{16}$$

From this it can be deduced that:

$$x \simeq \left[\frac{u^2}{gh}\right]^{0.216} (z+h) \tag{17}$$

Equation (15) may be written:

$$u^{0.432}\,(z+h) = 20.0 \left[\frac{R}{A_w{}^{1/2}}\right]^{0.784} \tag{18}$$

The data for flame height are plotted this way in Fig. 9 and indicate that a correlation of the form proposed by Seigel, with $R/A_w{}^{1/2}$ raised to the power of unity, would be reasonable provided the wind effect is included. The following correlation is proposed:

$$u^{0.43}(z+h) = 12.5 \left[\frac{R}{A_w{}^{1/2}}\right] \tag{19}$$

Note that Eq. (19) agrees with Eq. (14) for u = 180 ft/min, which is the mean value for these experiments.

The data for x are plotted in Fig. 10, showing the following correlation, derived from Eq. (17):

$$x = 0.077 \left[\frac{u^2}{h}\right]^{0.22} (z+h) \tag{20}$$

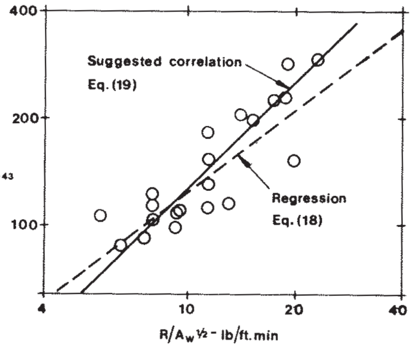

Fig. 9. Flame heights for large-scale tests with forced draft, Underwriters' Laboratories data (Note: Range of u: 100-367 ft/min)

The maximum width, w_z, of the emerging flames usually exceeded the window width. The angle made by the emerging flame, as shown in Fig. 11, does not correlate with any of the dimensionless parameters considered above. The average value of the angle is 11°, giving:

$$\frac{w_z - w}{2x} = 0.194$$

or

$$w_z \simeq w + 0.4x \tag{21}$$

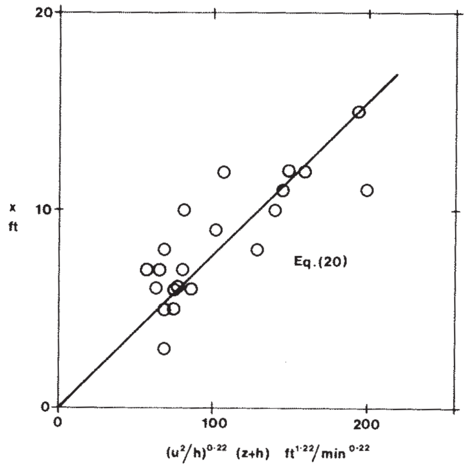

Fig. 10. Horizontal projection of flame tip for large-scale tests with forced draft, Underwriters' Laboratories data (Note: Range of u^2/h: 1000-22,500 ft/min^2)

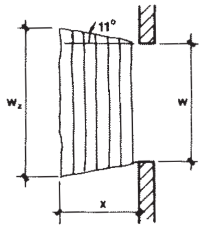

Fig. 11. Plan view of emerging flames with forced draft

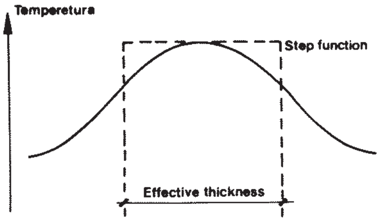

Fig. 12. Temperature distribution across flame section

Effective Flame Boundary—In order to estimate heat transfer to steel structures, the flame boundaries need to be defined. In cross section, the temperature distribution would be as illustrated in Fig. 12, and one approach would be to define the flame boundary by the 1000°F contour (which would be consistent with the definition of the flame tip). However, since radiative transfer will be an integrated effect, which can be made equivalent to a uniform effective temperature, an equivalent step function distribution is proposed. Since radiant transfer is so sensitive to the value of temperature, it is prudent to adopt the axial temperature (maximum) for the step function with a defined effective thickness. The problem is to define this effective thickness, bearing in mind an assumption of maximum temperature throughout.

With natural draft, the flame emerges above the neutral plane from the upper two-thirds of the window. Since flame width varies little with distance from the window, it seems reasonable to assume that the step function remains the same size throughout the trajectory, that is, $w \times 2h/3$. This is illustrated in Fig. 13. As shown later, this assumption is consistent with estimated values of emissivity. A wind could deflect this flame sideways and it will be assumed that, as an average throughout the fire, the deflection would not exceed 45°, as shown in Fig. 13. This seems reasonable, because on average the wind speed will be of the same order as the speed of the outflowing hot gases.

With forced draft, the flame can emerge from the whole window. The width does increase with distance and it is reasonable to assume that the vertical dimension also increases. However, the upper vertical increase is already contained in the value for z. It is therefore proposed that the size should be $h \times w$ at the window, increasing to $h \times (w + 0.4x)$ at the flame tip, as shown in Fig. 13.

TEMPERATURE AT FLAME AXIS

Seigel[24] has analyzed the temperature distribution in flames for the forced draft data and obtained the following correlation, where θ_o is measured at the window:

$$\text{For } \frac{lA_w{}^{1/2}}{R} > 0.52: \quad \frac{\theta_z}{\theta_o} = 0.62\left[\frac{lA_w{}^{1/2}}{R}\right]^{-3/4} \tag{22}$$

$$\text{For } \frac{lA_w{}^{1/2}}{R} < 0.52: \quad \frac{\theta_z}{\theta_o} = 1.0$$

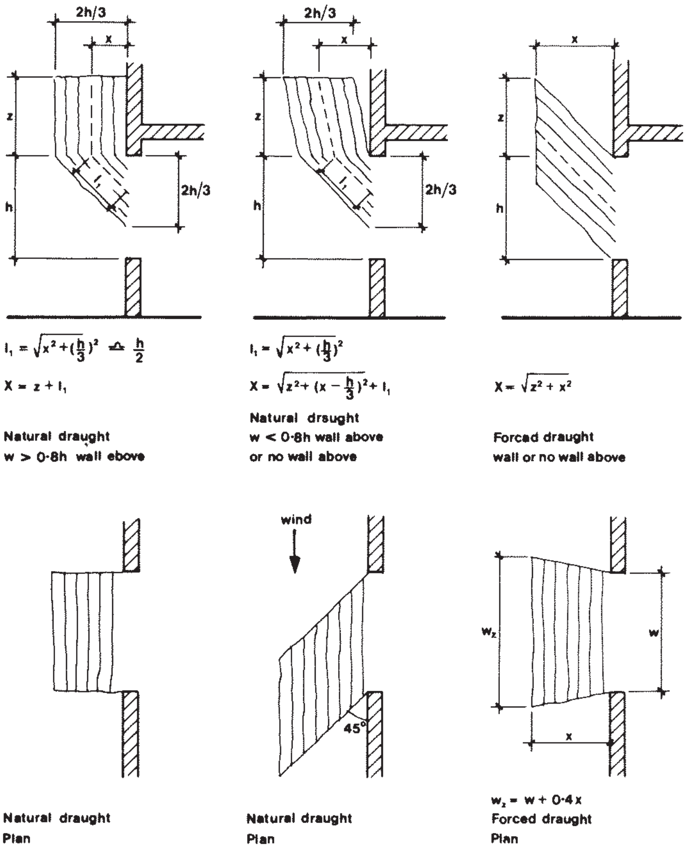

Fig. 13. Assumed trajectories of emerging flames

This follows the temperature distribution pattern found for jets.[28] The data are plotted in Fig. 14. Note that combining Eqs. (14) and (22) gives $(\theta_z/\theta_o) \simeq 0.5$, which is correct at the flame tip.

A similar approach has been adopted to correlate the temperature data for natural draft. These are better correlated in terms of lw/R and the data are shown in Fig. 15. The line has the equation:

$$\frac{\theta_z}{\theta_o} = 1 - 0.33\,\frac{lw}{R} \tag{23}$$

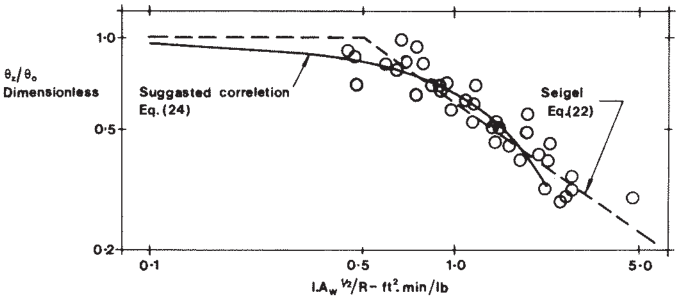

Fig. 14. Flame temperature distribution for large-scale tests with forced draft, Underwriters' Laboratories data

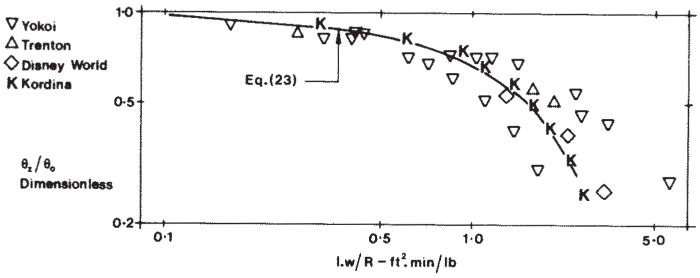

Fig. 15. Flame temperature distribution for large-scale tests with natural draft

A similar correlation for the forced draft data is shown in Fig. 14, and has the advantage, from an analytical point of view, of avoiding a discontinuity. The correlation has the equation:

$$\frac{\theta_z}{\theta_o} = 1 - 0.33\frac{lA_w{}^{1/2}}{R} \qquad (24)$$

The significance of Eqs. (23) and (24) is that the decrease in flame temperature is directly proportional to the distance along the center line of the flame. By substituting θ_z = 940°F (assuming an ambient temperature of 60°F) and $l = X$ in Eqs. (23) and (24), the value of θ_o may be derived. For fires with natural draft, this may give values of θ_o which are greater than the fire temperature θ_f. This result is not unexpected, since substantial amounts of unburnt gas can be emitted from the compartment. For forced draft fires, the values of θ_o may be less than θ_f.

MODEL OF HEAT TRANSFER TO EXTERNAL STEEL SURFACE

In the following equations, the temperatures, T, are on the absolute scale °R, since a major portion of the heat transfer is by radiation, and intensity of radiation is proportional to the fourth power of the absolute temperature. Thus, $T_z = \theta_z + T_a$, $T_s = \theta_s + T_a$, and $T_f = \theta_f + T_a$, where the suffix z refers to the external flames, s to the external steel, f to the fire within the building, and a to the ambient external air. Temperatures at these positions are illustrated in Fig. 16. In the following equations, T_s denotes an average temperature across the section.

If an external steel surface is engulfed by flame and is heated by radiation and convection from flames, and by radiation from the openings of a building on fire, the heat balance for a unit surface area is given by the following equation:

$$\begin{aligned}\alpha_z(T_z - T_s) &+ \epsilon_z\epsilon_s\sigma(T_z{}^4 - T_s{}^4)\\ &+ \epsilon_f(1 - \epsilon_z)\epsilon_s\phi_f\sigma(T_f{}^4 - T_s{}^4)\\ &+ (1 - \epsilon_z)\epsilon_s(1 - \phi_f)\sigma(T_a{}^4 - T_s{}^4)\\ &= \frac{Mc_s}{A_s}\frac{dT_s}{dt} + k \qquad (25)\end{aligned}$$

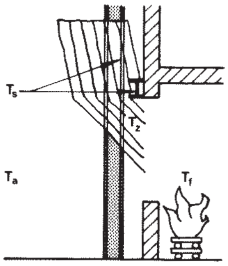

Fig. 16. Location of temperatures

In Eq. (25), $\alpha_z(T_z - T_s)$ represents the net rate of heat transfer by convection from the flame. The value of α_z, the heat transfer coefficient, will depend on the temperature and velocity of the flame and on the geometry of the steel surface. Provided the velocity is known, α_z can be obtained from standard textbooks; α_z may not be known with great accuracy, but since most of the heat is transferred by radiation, the error will be small.

$\epsilon_z\epsilon_s\sigma(T_z{}^4 - T_s{}^4)$ represents the net rate of heat transfer by radiation from the flame. The flame emissivity, ϵ_z, will depend on the flame thickness. The emissivity of the surface of the stanchion, ϵ_s, will be high, of the order of 0.9 and for the purposes of these calculations could be taken as unity (a conservative assumption). The Stefan-Boltzmann constant is denoted by σ. Provided ϵ_z is known, the heat transfer can be estimated.

$\epsilon_f(1 - \epsilon_z)\epsilon_s\phi_f\sigma(T_f{}^4 - T_s{}^4)$ represents the net rate of heat transfer by radiation from the windows and other openings of the building on fire. The emissivity of the fire within the building, ϵ_f, is high and may be taken as unity.[29] Some of the radiation will be absorbed by the flame, the fraction which is transmitted being given by $(1 - \epsilon_z)$. The configuration factor, ϕ_f, of the windows in relation to the surface will depend on the size and shape of the windows and the position of the surface; its calculation is given in standard textbooks. (The factor is the ratio of the intensity of radiation received at the surface to the intensity of radiation emitted; it is inversely proportional to the square of the distance between source and receiver and varies with their relative orientations and areas.) Provided ϵ_z is known, the heat transfer can be estimated.

$(1 - \epsilon_z)\epsilon_s(1 - \phi_f)\sigma(T_a{}^4 - T_s{}^4)$ represents the net rate of heat transfer by radiation from the surroundings at ambient air temperature and, since T_a will be less than T_s, it will be negative.

$(Mc_s/A_s)dT_s/dt$ represents the rate of heat gain per unit surface area. The mass per unit length, M, divided by the perimeter, A_s, gives the mass per unit surface area, and c_s is the specific heat of steel.

k represents the rate of heat loss by conduction away from the heated area but, where engulfed by flame, the temperature gradient is likely to be small and for the purposes of these calculations it will be neglected (a conservative assumption).

$\sigma T_a{}^4$ is small and may be neglected.

Taking account of the assumptions described above, Eq. (25) may be simplified to give:

$$\alpha_z(T_z - T_s) + \epsilon_z\sigma T_z{}^4 + (1 - \epsilon_z)\phi_f\sigma T_f{}^4 - \sigma T_s{}^4 = \frac{Mc_s}{A_s}\frac{dT_s}{dt} \qquad (26)$$

For steady state conditions the right hand side of Eq. (26) is zero ($dT_s/dt = 0$).

If the steel surface is outside the convective stream of flame and hot gases, the heat balance is similarly given by:

$$\epsilon_z\phi_z\sigma T_z{}^4 + \phi_f\sigma T_f{}^4 - \sigma T_s{}^4 - \alpha_s(T_s - T_a) = \frac{Mc_s}{A_s}\frac{dT_s}{dt} \qquad (27)$$

$\epsilon_z\phi_z\sigma T_z{}^4$ represents the heat transfer by radiation from the flame. The configuration factor, ϕ_z, of the flame in relation to the surface will depend on the size and shape of the flame front and the position of the flame in relation to the surface. Since the value of T_z varies along the flame front, an effective value must be estimated.

$\alpha_s(T_s - T_a)$ represents the heat loss by convection to the surroundings and can be taken as $\alpha_z(T_s - T_a)$ for most situations of practical interest.

As before, for steady state conditions, the right hand side of Eq. (27) is zero. In practice, steady-state conditions may not be attained, but if they are assumed, the maximum steel temperature will be calculated and a conservative solution will result. However, when the duration of flaming is short and/or the value of M/A_s is high, there may be transient conditions, and T_s can then be calculated by iterative methods, using Eq. (26) or (27) as appropriate.

Before calculations can be undertaken, it is necessary to estimate the flame velocity to determine α_z for convective transfer, and the emissivity and effective temperature of the flames, to calculate radiative transfer. Measured values of heat transfer from flames in large scale experiments will be examined to help to establish a realistic model.

Convection from Flames and Hot Gases—The convective heat transfer coefficient, α_z, depends on the mass flow per unit area, $u_z\rho_z$, of the hot gases and the size and orientation of the receiving surface; it can be obtained from relationships between the Nusselt number, *Nu,* and the Reynolds number, *Re,* where:

$$Nu = \frac{\alpha_z d}{K_z}$$

$$Re = \frac{u_z\rho_z d}{\mu_z}$$

d = a characteristic length of the surface
K_z = gas thermal conductivity
ρ_z = gas density
μ_z = gas viscosity

The thermal properties of the gas are taken at the "film" temperature, the mean of the temperature of the hot gas and the surface. For flow perpendicular to a tube[30] of diameter d:

$$Nu = 0.24\, Re^{0.6} \qquad (28)$$

For flow at angle of 45° the value of the constant in Eq. (28) is about 0.18, and for parallel flow about 0.12. Equation (28) will normally be appropriate for both columns and beams.

When there is natural draft, a column or beam will only be exposed to convective heat transfer if it is close to the building where the mass flow per unit area can be assumed to be nearly the same as at the window. The mass flow leaving the window depends on the processes by which air is drawn into the fire.[31] For a ventilation controlled fire it is approximately $6.4R$. Since the neutral plane, above which the flames and hot gases leave the compartment, is about $2h/3$ below the top of the window, the mass flow per unit area is given by:

$$u_z\rho_z \simeq 9.6\frac{R}{A_w}$$

and the Reynolds number is:

$$Re = \frac{9.6Rd}{A_w\mu_z} \qquad (29)$$

Equations (28) and (29) can be combined to give:

$$\alpha_z = 0.93\, K_z\left[\frac{R}{\mu_z A_w}\right]^{0.6}\left[\frac{1}{d}\right]^{0.4} \qquad (30)$$

The value of α_z is not very sensitive to film temperature and a representative temperature of 1350°F may be adopted. Equation (30) then becomes:

$$\alpha_z = 0.027\left[\frac{R}{A_w}\right]^{0.6}\left[\frac{1}{d}\right]^{0.4} \qquad (31)$$

For a free-burning fire, Eq. (31) overestimates α_z and its use gives a slightly conservative solution.

Where there is a significant forced draft, the mass flow will include the supplied air and will emerge from the whole window area. Thus Eq. (28) becomes:

$$\alpha_z = 0.24\, K_z\left[\frac{R}{\mu_z A_w} + \frac{u_z\rho_z}{\mu_z}\right]^{0.6}\left[\frac{1}{d}\right]^{0.4}$$

or

$$\alpha_z = 0.0068\left[\frac{R}{A_w} + \frac{u}{13}\right]^{0.6}\left[\frac{1}{d}\right]^{0.4} \qquad (32)$$

When the steel structure is remote from the flame, it loses heat by natural convection:

For columns:

$$\alpha_s = 0.0040\left[\frac{\theta_s}{d}\right]^{0.25} \qquad (33)$$

For beams the coefficient is similar, 0.0037.

When d exceeds 1 ft:

$$\alpha_s = 0.0050\ (\theta_s)^{0.25} \tag{34}$$

Radiation from Flames—The value of flame emissivity ϵ_z depends on flame thickness λ and may be assumed to follow a relationship of the following form:

$$\epsilon_z = 1 - e^{-b\lambda} \tag{35}$$

A value for b of 0.158 ft^{-1} was obtained by Beyreis et al.[32] for flames above wood cribs burning inside an enclosure. This value is somewhat higher than that assumed by Seigel[24] for flames outside the enclosure or by Heselden,[33] who suggests a value of about 0.09 ft^{-1}. Direct measurements of heat flow from emerging flames were made in the large scale experiments at Borehamwood,[9] where a heat flow meter was placed in the wall at a height of 1.8 ft above the top of the window. Denoting the measured value of heat flux by I_z and neglecting convective transfer (small):

$$I_z \simeq \epsilon_z \sigma T_z^{\,4}$$

Values of I_z at 1.8 ft above the window have been calculated according to the methods described and $\sigma T_z^{\,4}$ is plotted against the measurements of I_z in Fig. 17. The slope gives ϵ_z and the value of 0.3 adopted by Seigel is shown to be realistic for these data. To generalize the result, $\lambda = 2h/3$ is substituted in Eq. (35) and gives a value for b of about 0.09 ft, the value suggested by Heselden. Using the value suggested by Beyreis gives $\epsilon_z = 0.47$, which is rather high. Therefore, within the assumptions made here, it is recommended, for flames emerging from windows, that

$$\epsilon_z = 1 - e^{-0.09\lambda} \tag{36}$$

When a surface is engulfed in flame the effective radiating temperature may either be the local flame temperature or an average of a range of flame temperatures according to the circumstances. For example, one surface of a column may "see" a thickness of flame varying from the local temperature T_l to the value T_o at the window, and another surface may see a thickness varying from T_l to T_x at the flame tip. As a conservative assumption, the value of T_z should be taken as the local value or the far value, whichever is the larger.

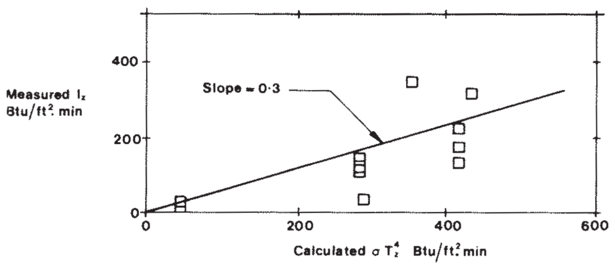

Fig. 17. Heat flow from flames above window in large-scale experiments at Borehamwood compared with calculated heat flux for fully emissive flames

When a surface is not engulfed in flame it "sees" a flame front varying in temperature from T_o at the base to T_x at the tip. At a large distance, the effective radiating temperature T_z would be given by:

$$T_z^{\,4} \simeq \frac{T_o^{\,4} + T_x^{\,4}}{2}$$

Close to the flame front, the effective radiating temperature for the point on the surface receiving the maximum rate of heating would be given by:

$$T_z^{\,4} \simeq T_o^{\,4} \tag{37}$$

Equation (37) is a reasonable approximation for most situations of practical interest for forced draft fires.

For fires with natural draft, the radiation is mainly received from the portion of the flame above the window, the portion below being thinner. Then, at a large distance:

$$T_z^{\,4} \simeq \frac{T_w^{\,4} + T_x^{\,4}}{2}$$

and close,

$$T_z^{\,4} \simeq T_w^{\,4} \tag{38}$$

where T_w is the flame temperature opposite the top of the window.

Equation (38) is a reasonable approximation for most practical situations of interest for fires with natural draft.

Measured values of the sum of fire and flame radiation from fires with natural draft[9] are compared in Fig. 18, with values calculated according to the methods described. The comparison shows that the calculations tend to overestimate the intensity of radiation received, but not by an unacceptable amount.

MEASURED TEMPERATURES OF EXTERNAL ELEMENTS

Using the correlations and heat transfer models described in the previous sections, temperatures of external steel elements have been calculated and compared with measurements made in the large-scale tests, the maximum measured values being selected. In the following graphs, if there were perfect agreement the points would fall on the line. Where points fall above the line, the calculation errs on the safe side.

Elements Engulfed in Flame—Figure 19 shows a comparison for columns engulfed in flame from fires with natural draft. For unshielded columns, Fig. 19(a), the calculated temperatures tend to exceed the measured values except for one of the readings at the Underwriters' Laboratories.* Fig. 19(b) shows results for columns with insulated shields on the flange facing the fire, as illustrated in Fig. 20(a) or (b). (In the calculations it has been assumed that there is no heat transfer on the shielded face.) For these columns, the calculation method appears rather insensitive

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* *See later discussion.*

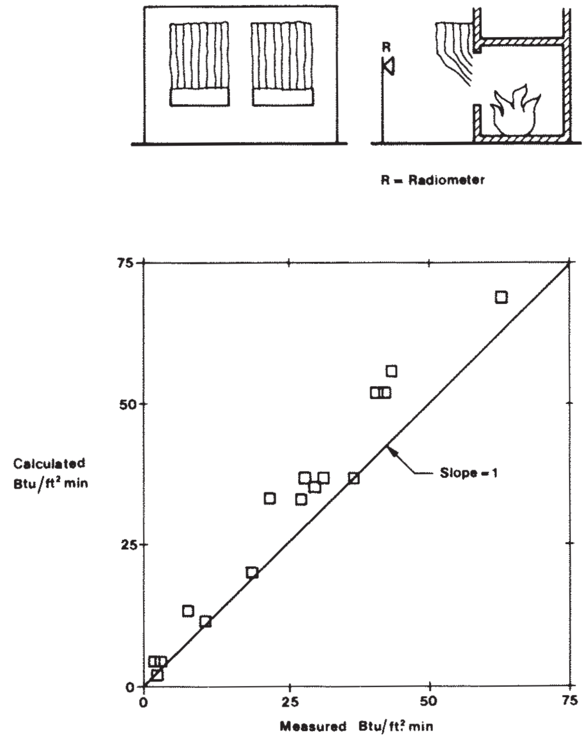


Fig. 18. Sum of window and flame radiation received by radiometer at 15 or 20 ft in large-scale experiments at Borehamwood

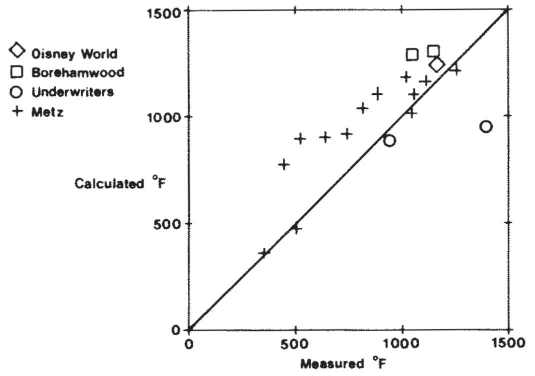
to the effect of shields on temperature attained, but errs on the safe side, except for the readings at the Underwriters' Laboratories.

Comparisons of calculated and measured temperatures of unshielded columns in large-scale fires with forced draft are shown in Fig. 21. The calculated temperatures are in general lower than the measured ones. The significance of this result will be discussed later.

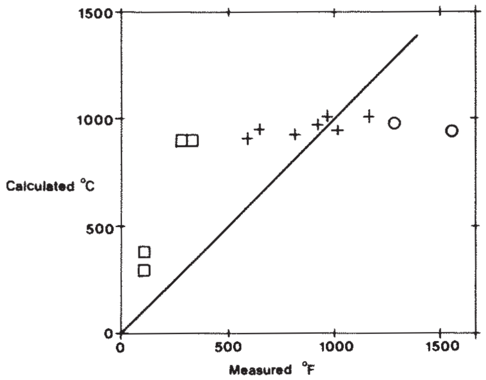
Comparisons of calculated and measured temperatures of spandrel beams in the large scale tests at Borehamwood and Trenton are given in Fig. 22 and show satisfactory agreement. At Trenton the beam was shielded as shown in Fig. 20(c), and in calculations it has been assumed that there is no heat transfer to or from the flanges.

Elements Not Engulfed in Flame—For columns not engulfed in flame, Fig. 23 shows a comparison for fires with natural draft and Fig. 24 for fires with forced draft. There is reasonable agreement, although calculated temperatures tend to be slightly lower than measured ones for the forced draft tests.

For a spandrel beam not engulfed in flame, forced draft fires, Fig. 25 shows a comparison for the Underwriter's tests, in two of which there was an awning which shielded the lower range flange. There is reasonable agreement for both the shielded and unshielded results.



a) Unshielded columns



b) Shielded columns

Fig. 19. Measured and calculated temperatures of steel columns engulfed in flame, from large-scale tests with natural draft

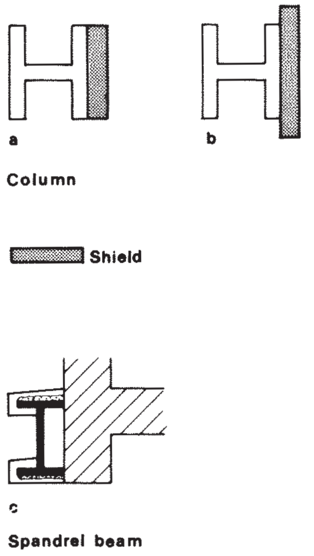


Fig. 20. Shielded elements

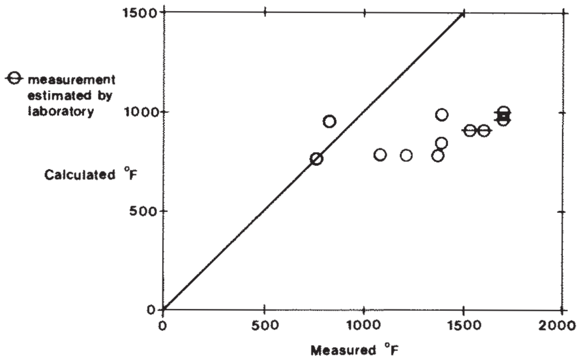


Fig. 21. Measured and calculated temperatures of steel columns engulfed in flame, from large-scale tests with forced draft, Underwriters' Laboratories

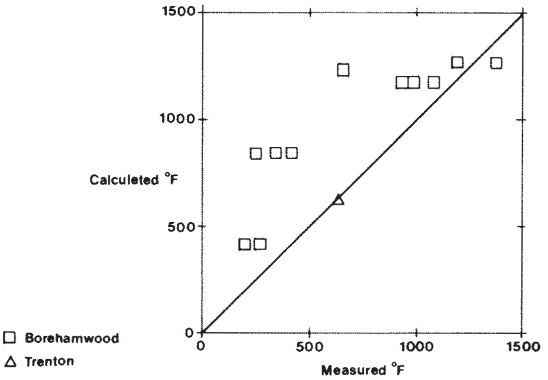


Fig. 22. Measured and calculated temperatures of spandrel beams engulfed in flame, from large-scale tests with natural draft

Discussion of Steel Temperatures—Although the agreement between calculated and measured steel temperatures is in general satisfactory, there are certain results which need further consideration. Some of the calculated temperatures for the Metz columns and the Borehamwood columns are rather high (Fig. 19). For these tests the fire loads were low and it is possible that the duration of external flaming was less than the fire duration. Some of the calculated column temperatures for the Underwriters' Laboratories tests are low (Figs. 19 and 21) and the reasons for this are not clear. The calculated flame temperatures for the engulfed columns in Fig. 21 (forced draft) are certainly not lower than the measured ones. They are high enough to compensate for any error in measurement of the kind discussed in the Underwriters' Report. A very large increase in emissivity would be needed if the heat transfer calculations were to give some of the steel temperatures reported. The satisfactory agreement of the calculation method with the other sets of data, and indeed with some of the Underwriters' data, suggests that the method is not in serious error.

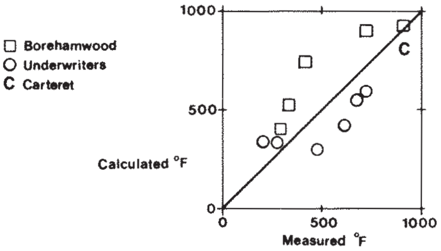


Fig. 23. Measured and calculated temperatures of columns not engulfed in flames, from large-scale tests with natural draft

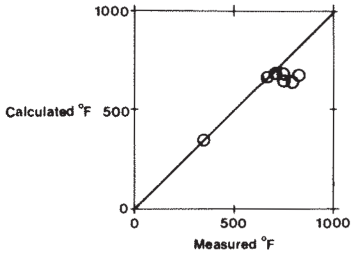


Fig. 24. Measured and calculated temperatures of columns not engulfed in flame, from large-scale tests with forced draft, Underwriters' Laboratories

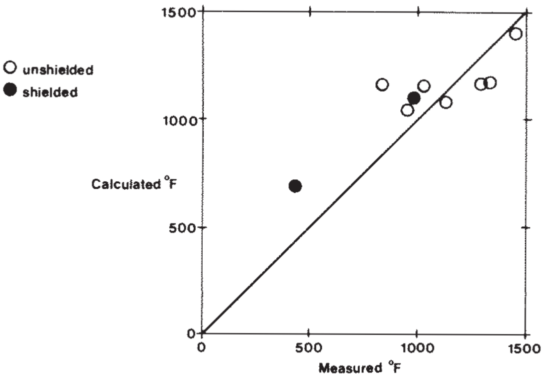


Fig. 25. Measured and calculated temperatures of spandrel beam, from large-scale tests with forced draft, Underwriters' Laboratories (Note: Shield is 2-ft awning)

It will be noted that the comparisons given are for steel temperatures up to values of about 1000°F. The critical temperatures normally adopted in standard fire resistance tests for carbon grades of structural steel are 1000°F for columns and 1100°F for beams. Temperatures much in excess of these values are thus of little interest.

PRACTICAL APPLICATION OF THE CALCULATIONS

Fire and Flame Behavior for Larger Compartments—The correlations for flame and fire behavior show satisfactory agreement between calculation and measurement for the large-scale data, but it will be noted that most of these data are for room size compartments, the largest experiment being at Trenton, where the compartment was 56 ft wide by 24 ft deep. In the calculations, it is assumed that the whole compartment, however large, is involved in fire simultaneously, whereas for very large compartments the fire is likely to be progressive; if so, flame size and fire temperature could be overestimated. On the other hand a progressive fire could last longer, but this is allowed for by assuming steady state heating conditions. It is reasonable, therefore, to assume that the correlations may be used for a large compartment and that errors for large sizes will tend to be on the safe side.

The effective fire duration in the free-burning condition depends on the type, thickness, and spacing of the fire load. Experimental fire loads are usually of wood cribs—an easily reproducible fuel—and there has been considerable study of the effects of crib design on the rate of burning. Less information is available for furniture, but it can be assumed that a fire involving domestic furniture would give similar results to a fire in wood cribs with a free-burning time of 20 min.[34] It is unlikely that the amounts of plastics usually found in furnishings would significantly alter this value. For the type of fire load normally found in residential, office, educational, and hospital buildings, a free burning time of 20 min is recommended. For fire loads which are significantly different, it would be prudent to carry out a supplementary measurement. If significant amounts of combustible materials were used as linings for the walls and ceiling, the time could be very much shorter, (as found in Test S of the Borehamwood experiments), but these are not normally permitted by building codes and should not be used.

Compartment Parameters—In the calculation of R for ventilation controlled fires with natural draft, using Eq. (2), (D/W) represents the ratio of depth of the compartment to the width of the wall which contains the window or windows. If, however, there are windows on more than one wall, (D/W) is effectively reduced. In general, if the wall having the maximum window area is of width W:

$$\left(\frac{D}{W}\right)_{effective} = \frac{(A_w)_1}{A_w}\left(\frac{D}{W}\right)$$

where $(A_w)_1$ = window area on wall of width W
A_w = total window area, all walls

When there is more than one window, the value of A_w used in Eqs. (2), (5), and (30), for fires with natural draft, is the sum of the individual areas:

$$A_w = A_1 + A_2 + A_3 + \ldots \text{ etc.}$$

For forced draught, the value of A_w used in Eqs. (6), (19), and (24) is the sum of the individual areas of the windows through which the flames emerge, or approximately half the sum of all windows when there is a through wind.

The value of w used in Eqs. (10) and (23), for fires with natural draft, is the sum of the individual widths:

$$w = w_1 + w_2 + w_3 + \ldots \text{ etc.}$$

When the windows have different heights, the value of h used in Eqs. (2) and (5), and in n, for fires with natural draft, is as follows:

$$h = \frac{A_1h_1 + A_2h_2 + \ldots}{A_1 + A_2 + \ldots} \text{ etc.}$$

There is one exception to this, in the calculation of n for widely spaced windows. If the space between windows exceeds two window widths, according to Yokoi, the flames from the windows may be assumed to be separate and n should be calculated for the individual window.

Temperature Gradient in Steel—The measurements of column temperatures show that, in general, the maximum value is attained at the level opposite the top of the window, a typical difference between top and bottom window levels being 400°F. The way in which the temperature falls off above the window level will vary with the flame height. There can also be a temperature gradient across the section such that the inner flange facing the fire could be 400°F more than the outer flange, particularly when there is shielding. The calculations described here are not sensitive enough to estimate the size of such gradients, but it should be noted that in practice there can also be large gradients for internal members. Thus, it is reasonable to adopt an average temperature as the criterion, but to reduce the stress in an external structure which the engineer estimates to be particularly sensitive to differential heating.

Relationships Used in Calculations—For convenience, the main relationships used for calculations are summarized in Table 1, given in both U.S. and S.I. units.

CONCLUSIONS

The fire exposure of external structural elements cannot be simulated by the standard fire resistance test, but it can be calculated. The heat transfer to these elements depends on the flame trajectory and temperature, the temperature in the fire compartment, the position of the element, and the cooling of the element to the surroundings. As for internal elements, the structural performance depends on the steel temperature, and a calculation method for estimating the temperature rise can be established. The calculation method is based on comprehensive studies with models and on a number of large-scale experimental fire tests in realistic buildings. The calculated steel temperatures are in satisfactory agreement with values measured in the large-scale experimental fire tests.

External flame and internal fire behavior can be calculated, given the amount and type of fire load, the dimensions of the compartment or room assumed to be on fire, and the dimensions of the windows. The effects of a forced draft, such as a through wind, can also be allowed for. Equations describing the various types of behavior are summarized in Table 1. They can be applied to the sizes of rooms and compartments normally found in buildings.

Contents

Table 1. Summarized Relationships

		U.S. units lb, ft, min, Btu, °R	S.I. units kg, m, s, kJ, °K
Natural Draft			
Flame	$z + h$	$3.55\left(\frac{R}{w}\right)^{2/3}$	$12.8\left(\frac{R}{w}\right)^{2/3}$
	x	$0.45h\left(\frac{1}{n}\right)^{0.53}$	$0.45h\left(\frac{1}{n}\right)^{0.53}$
	x "no-wall"	$0.60h\left(\frac{z}{h}\right)^{1/3}$	$0.60h\left(\frac{z}{h}\right)^{1/3}$
	w_z	w	w
	ϵ_z	$1 - e^{-0.09\lambda}$	$1 - e^{-0.30\lambda}$
	$\frac{\theta_z}{\theta_o}$	$1 - 0.33\frac{lw}{R}$	$1 - 0.027\frac{lw}{R}$
	θ_o	$\frac{940}{(1 - 0.33Xw/R)}$	$\frac{520}{(1 - 0.027Xw/R)}$
	α_z	$0.027\left(\frac{R}{A_w}\right)^{0.6}\left(\frac{1}{d}\right)^{0.4}$	$0.026\left(\frac{R}{A_w}\right)^{0.6}\left(\frac{1}{d}\right)^{0.4}$
Fire	R	$\frac{L}{\tau_F}$ or $1.22\frac{(1 - e^{-0.065\eta})A_w h^{1/2}}{(D/W)^{1/2}}$	$\frac{L}{\tau_F}$ or $0.18\frac{(1 - e^{-0.036\eta})A_w h^{1/2}}{(D/W)^{1/2}}$
	θ_f	$8025\frac{(1 - e^{-0.18\eta})(1 - e^{-0.25\psi})}{\eta^{1/2}}$	$6000\frac{(1 - e^{-0.10\eta})}{\eta^{1/2}}(1 - e^{-0.05\psi})$
Forced Draft[a]			
Flame	$z + h$	$12.5\left(\frac{1}{u}\right)^{0.43}\left(\frac{R}{A_w^{1/2}}\right)$	$16.9\left(\frac{1}{u}\right)^{0.43}\left(\frac{R}{A_w^{1/2}}\right)$
	x	$0.077\left(\frac{u^2}{h}\right)^{0.22}(z + h)$	$0.61\left(\frac{u^2}{h}\right)^{0.22}(z + h)$
	w_z	$w + 0.4x$	$w + 0.4x$
	$\frac{\theta_z}{\theta_o}$	$1 - 0.33\frac{lA_w^{1/2}}{R}$	$1 - 0.027\frac{lA_w^{1/2}}{R}$
	θ_o	$\frac{940}{(1 - 0.33XA_w^{1/2}/R)}$	$\frac{520}{(1 - 0.027XA_w^{1/2}/R)}$
	α_z	$0.0068\left(\frac{R}{A_w} + \frac{u}{13}\right)^{0.6}\left(\frac{1}{d}\right)^{0.4}$	$0.0065\left(\frac{R}{A_w} + 1.3u\right)^{0.6}\left(\frac{1}{d}\right)^{0.4}$
Fire	R	$\frac{L}{\tau_F}$	$\frac{L}{\tau_F}$
	θ_f	$2160(1 - e^{-0.20\psi})$	$1200(1 - e^{-0.04\psi})$
Surroundings			
	T_a	520	293
	α_s	$0.0040\left(\frac{\theta_s}{d}\right)^{1/4}$ or $0.005(\theta_s)^{1/4}$ for $d > 1$	$0.0014\left(\frac{\theta_s}{d}\right)^{1/4}$ or $0.002(\theta_s)^{1/4}$ for $d > 0.3$

[a] A_w denotes window(s) through which flames emerge.

The heat transfer model which has been developed employs simplified flame shapes and effective temperatures, derived from the equations describing flame and fire behavior. It has been used for shielded and unshielded elements, engulfed in flame or not, attaining temperatures up to about 1100°F.

NOMENCLATURE

A_F = floor area ($D \times W$), ft^2
A_s = perimeter of steel, ft
A_T = $2A_F + 2H(D + W) - A_w$, ft^2
A_w = window area, ft^2
b = extinction coefficient, ft^{-1}
C = calorific value, Btu/lb
c = specific heat, Btu/(lb °F)
D = depth of compartment, ft
d = diameter, side of steel, ft
g = acceleration due to gravity, ft/min^2
H = height of compartment, ft
h = height of window, ft
I = heat transfer per unit area, Btu/(ft^2·min)
K = thermal conductivity, Btu/(ft·min·°F)
k = heat loss by conduction, Btu/(ft^2·min)
L = fire load, lbs
l = distance along flame center line from window, ft
M = mass of steel per unit run, lbs/ft
n = $2w/h$, dimensionless
R = rate of burning, lbs/min
r_o = $(A_w/2\pi)^{1/2}$, ft
T = absolute temperature, °R
t = time, min.
u = velocity, ft/min
W = width of compartment, ft
w = width of window, ft
X = center line distance of flame tip from window, ft
x = horizontal distance of flame tip from window, ft
y = vertical distance above top of window, ft
z = vertical distance of flame tip above top of window, ft
α = convective heat transfer coefficient, Btu/(ft^2·min·°F)
ϵ = emissivity, dimensionless
ϕ = configuration factor, dimensionless
μ = viscosity, lb/(ft·min)
Θ = dimensionless flame temperature

$$= \Theta_z \left[\frac{r_0{}^5 c_z{}^2 \rho_z{}^2 y}{R^2 C^2 T_a}\right]^{1/3}$$

θ = $T - T_a$, °F
θ_f = fire temperature rise, °F
ρ = density, lbs/ft^3
σ = Stefan Boltzmann constant, 2.861×10^{-11} Btu/(ft^2·min·°R^4)
τ = fire duration, min
τ_F = free-burning fire duration, min
λ = flame thickness, ft

$$\eta = \frac{A_T}{A_w h^{1/2}}, \text{ ft}^{-1/2}$$

$$\psi = \frac{L}{(A_w A_T)^{1/2}}, \text{ lb/ft}^2$$

The subscripts $a, f, l, o, s, z,$ denote ambient, fire, local, window plane, steel, and flame respectively. Subscripts w and x used with the temperature denote flame temperatures level with the top of the window ($y = 0$) and at the flame tip, respectively.

ACKNOWLEDGMENT

This work was prepared as part of contracts with the American Iron and Steel Institute and the Constructional Steel Research and Development Organization (British Steel Corporation). The author wishes to thank Mr. L. G. Seigel and Dr. P. H. Thomas for very helpful discussions during the course of this work.

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APPENDIX A
DIMENSIONS OF COMPARTMENTS AND TYPES OF FIRE LOAD IN LARGE SCALE EXPERIMENTAL FIRE TESTS

Test	D, ft	W, ft	H, ft	Type of fire load
Yokoi[13]				
1	31.8	43.8	11.5	Timber
2	11.4	14.1	8.1	Timber
3	8.2	16.4	5.5	Timber
4	8.2	16.4	5.5	Timber, plywood linings on walls and ceiling
Trenton[3]	24	56	9	Wood cribs of sticks 1½ in. thick
Disney World[14]	28	14	8.5	Wood cribs of sticks 3½ in. thick with 1 in. spacing
Borehamwood[9,15]	12	25	10.0	Wood cribs of sticks 1¾ in. thick with 1¾ in. spacing Fibre insulating board on walls and ceiling Test S
Tranas[25]				
1[a]	20.7 × 2	21.6	8.4	Mixed furniture
11[a]	20.7 × 2	21.6	8.9	Mixed furniture
Carteret[12]	12	10	8	Wood cribs
Kordina[26]	16.7	11.9	9.0	Office furniture
Webster[21]	8	8	8	Wood cribs of sticks 1 in. thick
Underwriters[16]	12	10	10	Wood cribs of sticks 1½ in. thick
Metz[10,17]	12	11	10	Wood cribs of sticks 2¾ in. × 1¾ in. thick with 1¾ in. spacing

[a] Windows on two opposing (shorter) walls.

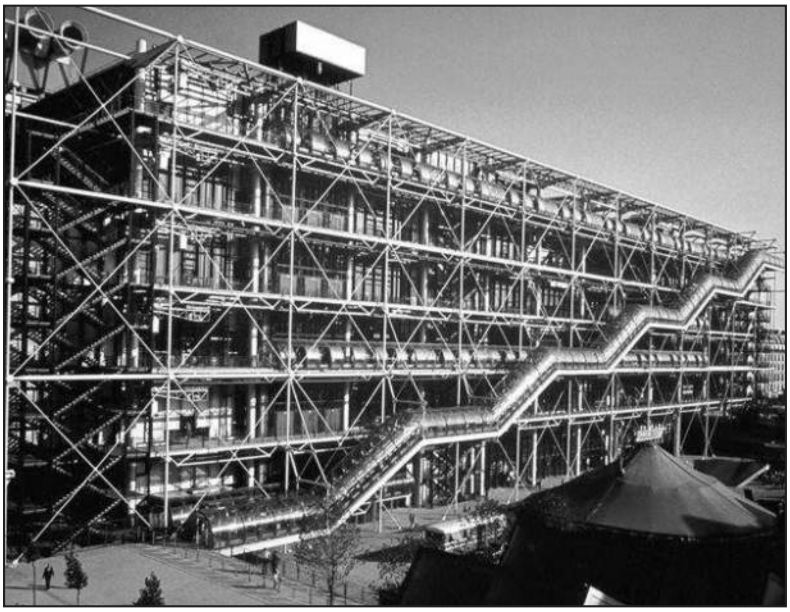
PAPER 8

Designing fire safety for steel - recent work

Margaret Law, ASCE Spring Convention, New York, May 11-15 1981. American Society of Civil Engineers (ASCE), USA

Engineers and architects always find case studies interesting and I aim to show designers how fire safety engineering can help them. This paper contains examples from an international point of view.

Plate showing Centre Pompidou in Paris, one of the four case studies contained in this paper and one of Margaret Law’s earlier projects with Arup.



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DESIGNING FIRE SAFETY FOR STEEL—RECENT WORK

Margaret Law

ASCE New York, New York May 11–15, 1981

DESIGNING FIRE SAFETY FOR STEEL - RECENT WORK[a]

By Margaret Law[1]

INTRODUCTION

The use of calculation methods for the design of structural fire protection is gaining increasing acceptance and these methods can be expected to take their place alongside other fire safety calculation procedures which are already well established in, for example, the design of smoke control systems and the provision of adequate space between buildings. There is also more recognition of the need to identify clearly the objectives of providing fire safety so that building design can be related to the nature of the lives and property at risk and the potential hazards. The desire of architects and engineers to reduce or eliminate the need for cladding on structural steelwork in buildings has meant that these subjects have been of particular interest to the steel industry, which has supported much research in this area. The code authorities are naturally cautious in accepting such methods but it has been possible to introduce new approaches, to a greater or lesser extent, in a number of recent buildings. The purpose of this paper is to review the methods and to illustrate their use in practice by describing some steel building structures completed within the last decade.

STEEL WITHOUT CLADDING

Most unprotected steel elements of construction in common use have a section factor, P/A, of around 250 m^{-1} (75 $ft.^{-1}$) giving a fire resistance of about 15 min when subjected to the standard test (12). The fire resistance varies inversely with P/A, where A is the cross-section area and P the exposed perimeter; it is thus possible to achieve higher values of fire resistance with the smaller values of P/A which can be provided by large solid sections. For example it is estimated that a solid 360 mm (14 in.) square section (P/A = 11 m^{-1} or 3.4 $ft.^{-1}$) could give a fire resistance of order 1 hour (26). Such an estimation must at the moment be based on calculations of structural behaviour related to steel temperature, since fire test furnaces do not have the capacity to fully load these massive sections. These solid sections, however, will rarely be used in buildings. It is more useful to identify the other circumstances where cladding is not needed. These can be listed so far as (a) no requirement for fire resistance (b) low fire exposure (c) water-cooling.

No fire resistance requirement.- In a number of circumstances the loss of a steel structural element or elements may be acceptable:

- A single storey building with adequate means of escape and adequate spacing from other buildings.

- A roof structure where failure does not adversely affect the behaviour of other structural elements required to have fire resistance, the lives of fire-fighters are not endangered, and there is adequate separation from other buildings.

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[a] Presented at the May 11-15, 1981, ASCE Spring Convention, held at New York, New York.

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- Certain elements such as wind bracing, which may be "sacrificed" without endangering the overall stability of the building during the fire.

- Elements where load can be transferred, as in concrete filled hollow sections, and concrete/steel decks with secondary reinforcement.

It is common place for single-storey industrial buildings to be of unprotected steelwork, these being accepted provided that there is no adverse effect on escape routes and there is no undue risk to fire fighters or adjacent buildings. The same approach can sometimes be adopted for structures of more than one storey as described for Building A below. Where property protection is concerned, an automatic extinction system is likely to be the appropriate fire safety measure for the contents. As for the structure, it has been suggested, from probabilistic considerations, that structural fire protection is not economically beneficial for low rise buildings (18), and a study of industrial fires in Sweden has shown that the fire losses were independent of the material of construction, provided it was non-combustible (27).

The designation of certain elements as sacrificial in the event of fire, obviously depends on the structural design of the building and the likely pattern of fire behaviour. An example is given below in the description of Building B.

The use of concrete filling of hollow sections has been the subject of recent research in Europe (11); as the steel section is heated, the load is transferred to the concrete core. Tests have shown that the fire performance of steel ribbed floors with concrete topping can be significantly improved by the incorporation of extra reinforcement in the "cool" portion of the concrete (5).

Low fire exposure.- In certain circumstances the fire exposure may be low and there is a very small probability of the steel reaching cricial temperatures:

- Structural elements in open-sided car parks.

- Elements in other types of building where the fire load is small and calculation or test shows that the temperatures attained will be low.

- External structural elements, free to cool to the ambient air, which are placed at certain positions in relation to the windows and other openings of a building.

It was widely believed for many years, with apparently no supporting evidence, that structures housing parked automobiles needed very high standards of fire resistance. Statistical surveys and experiments (6) (10) finally demonstrated that unprotected steelwork is acceptable for open-sided car parks. No similar analysis has yet been carried out for other types of occupancy. Methods of calculating potential fire exposure, taking into account fire load and ventilation, already exist (14)(22) but have not so far been used generally to demonstrate circumstances where the exposure is low enough to obviate the use of structural fire protection. The method of calculating fire exposure most commonly adopted (22) uses assumptions for rates of burning which are not so directly applicable to the low fire load/high ventilation condition which favours the use of unprotected steelwork.

The fire exposure outside a building - by emerging flames and radiation from the window openings - is not represented by the standard fire resistance test, since the exposure is so sensitive to the position of the exposed structural element. At certain positions the fire exposure is much lower than for the internal elements and cladding is not needed. In order to avoid costly experiments and to give general guidance to engineers on the use of external steel, a technical study was commissioned by the American Iron and Steel Institute (AISI) and Constrado (21) (15). The basis of the calculation has already been accepted by the main US codes. A design manual has been published by AISI (2) and one by Constrado is in preparation (17). In more recent years, the results of some experiments in an apartment building at Lehrte have been reported (24) which are consistent with the assumptions for fire and flame behaviour contained in the design method, and a study of the structural behaviour of fire exposed external steel assemblies has been carried out (13).

It has also been suggested that where automatic sprinkler systems are installed, structural fire protection may be reduced or eliminated. There is certainly a case to be argued on probabilistic grounds. However if a sprinkler system does not control a fire, the fire severity will be as great as if the system had not been installed - there is no partial protection - while a loadbearing element of construction with passive protection, however substandard it may be, is likely to have some degree of fire resistance. Passive fire protection tends to be most unreliable for walls and floors designed as barriers to fire spread which are often breached by open fire doors or by unsealed openings provided for the passage of services. Thus sprinklers may be more valuable as an alternative way of providing fire containment rather than as reducing the standard of protection for loadbearing capacity.

Water cooling.- The heat-absorbing capacity of water can be exploited by water filling hollow structural sections and, given a constant supply, the cooling effect on the steel can be extended indefinitely. With its high latent heat the cooling is particularly marked when water is converted to steam. An early example of the use of water cooled hollow sections is the U.S. Steel building in Pittsburgh (25).

For effective cooling the objective is to ensure that water is always in contact with any fire-exposed steel that is acting structurally and the problems are, first, the removal, separation and release of steam without too much loss of water and, second, the avoidance of stagnant areas which would allow the formation of steam traps. There are a variety of systems in use, some circulating the water and others not (16). A guide to water-cooling has been published by Constrado (4).

Water cooling as a method of keeping steel below critical temperatures has mainly been used for exterior hollow elements, as illustrated by Buildings B and C below, although in principle it should be acceptable for interior elements as well. Water circulation can be promoted by natural convection or by pumps. The expense of water storage tanks can be avoided by interconnection of a large number of hollow elements not all fire exposed, by connection to the water main, or by using simply filled, non-replenished columns where the fire resistance requirement is low.

Cooling of steel structures by water spray or drenchers has been used in aircraft hangars and for industrial storage tanks but has not generally been used for the protection of building elements.

STEEL WITH CLADDING

Standard test.- The amount of cladding required for various elements of structure is defined in terms of a specified survival time in the standard fire resistance test. The test is essentially a way of measuring the thickness of cladding required and, because of the size of the specimen, it can take into account cracks, variations in thickness, effects of expansion, and behaviour of joints and fixings, in a way which a laboratory test on a small sample could not.

However this test has been criticised for a number of reasons:

- The standard temperature-time curve is different from the temperature-time exposure likely to be encountered in real fires which will depend on the amount and type of fire load, the ventilation, size and shape of the building and the activities of the fire brigade. However, it can be said that, given the thermal impedance of a protected steel element, the temperature rise at critical points is not very sensitive to the shape of the temperature-time curve. For many interior building fires, the heating conditions are not greatly different from those in the furnace. It is the required duration of the test which is more open to criticism. As mentioned earlier, external exposure from building fires is not represented by the standard test.

- The loading and end conditions are not well defined.

- The structural properties of the test specimen at room temperature are not defined. If the nominal guaranteed values are used to estimate the change in properties during a standard fire test, the calculated critical steel temperatures will normally be lower than those measured (23).

In these circumstances, methods of calculating the fire resistance of elements of structure should be more readily accepted. Such a method has been adopted in France (7) and is about to be published by the European Convention for Constructional Steelwork (9).

Design for compartment fires.- It has been suggested that, rather than meeting the requirements of regulations for a certain arbitrary value of fire resistance, the element should be designed to withstand the assumed 'natural' fire conditions. A temperature-time curve for a compartment fire is calculated, assuming burn-out of a certain amount of fire load and taking into account the ventilation, size, shape and thermal properties of the bounding compartment. The amount of cladding can then be calculated directly, or the compartment fire can be given an equivalent or effective fire duration meaning that it would give the same effect at a critical point in a structure as that duration of a standard test. This approach could be of benefit for steel structures where it can be demonstrated that because of low fire loads or large heat losses from the compartment, little fire resistance would be needed to withstand the effects of the compartment fire.

Calculated temperature time curves are already accepted in Swedish Codes (22) and a similar approach has been published in France (7). A simple relationship for effective fire resistance, t_f, has been derived (14):

$$t_f = k \frac{L}{\sqrt{A_w \cdot A_T}} \quad \text{min}$$

where L = fire load in wood equivalent - kg (lb)

A_w = window area - m^2 (sq.ft.)

A_T = area of floor, ceiling, walls (excluding A_w) - m^2 (sq.ft.)

$k \simeq 1$ ($\simeq 5$)

The design method for exterior steel (2) can also be used to calculate the fire exposure of protected external members, as illustrated for Building D below.

Analytical approach.- An analytical approach, in which the steel temperature is calculated, can have advantages, whether the standard fire or compartment fire is assumed. These are:

- Extrapolation of the results of standard test by scaling methods.

- Estimation of the effects of varying the load acting on the element.

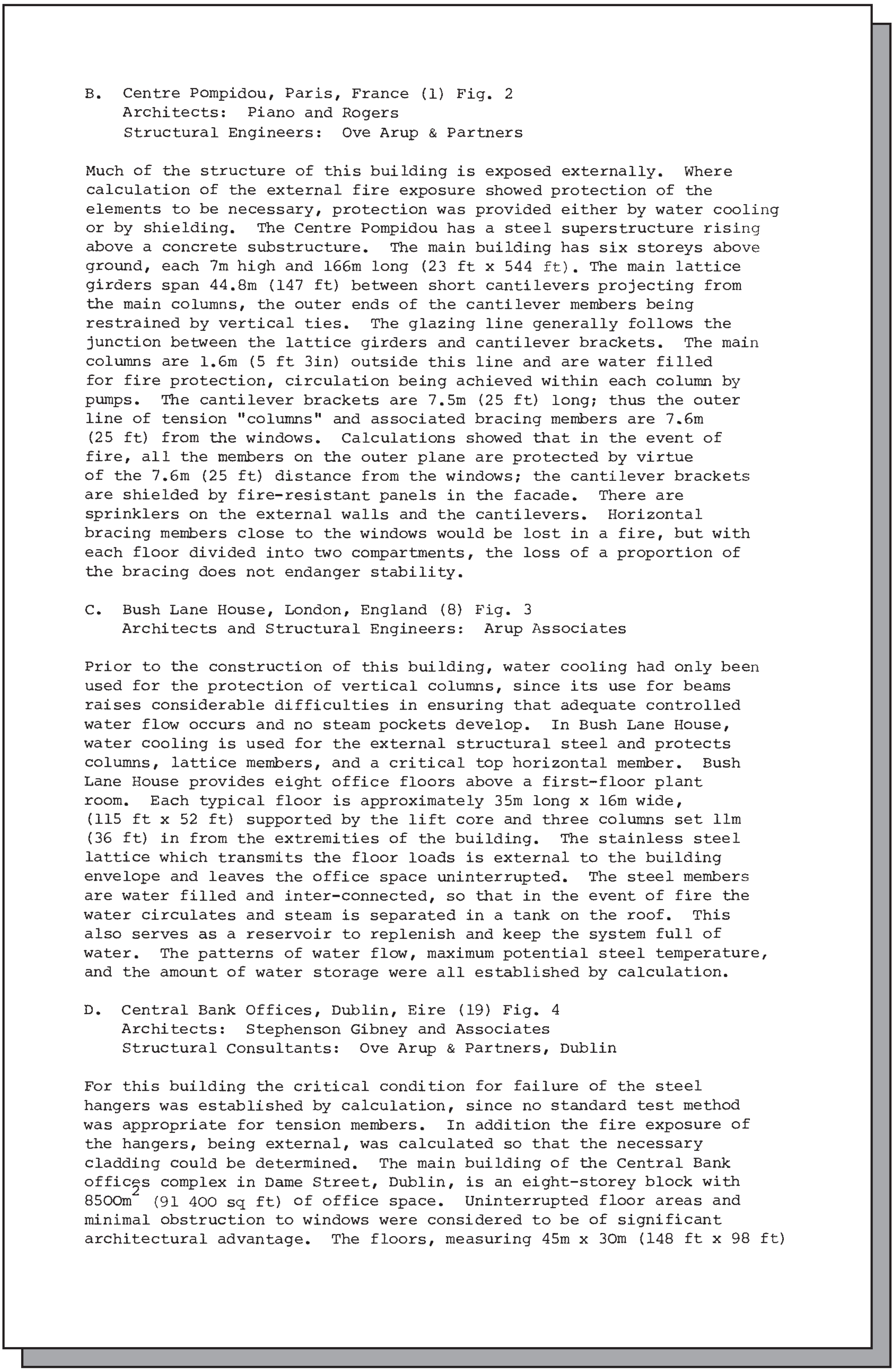
- Estimation of the effects of varying the duration of the standard fire.

- Saving the considerable expense of a conventional fire resistance test.

EXAMPLES OF THE DESIGN APPROACH AND THE USE OF WATER FILLING FOR STRUCTURAL FIRE PROTECTION

A. The Royal Exchange Theatre, Manchester, England (20) Fig. 1.
Architects: Levitt Bernstein Associates
Structural Engineers: Ove Arup & Partners

For this building, a fire engineering appraisal was used to demonstrate that cladding of the steel was not essential for the purposes of building regulations. The Royal Exchange Theatre is a concentric auditorium standing within the Great Hall of the Manchester Royal Exchange - formerly used for trading in cotton. There is an open-stage auditorium, seven-sided in plan with stage and seating for 450 at the level of the Exchange floor and two galleries above, each of which seats a further 150 people. The theatre is clad with toughened glass and roofed with metal decking. It was imperative to develop as light a structure as possible and this, taken together with the desire to achieve a high degree of transparency, led to a system of tubular steel trusses from which the galleries are suspended, the trusses being supported by existing brick piers. A full fire engineering appraisal was carried out, in cooperation with the city authorities, and this led to an agreement that the steelwork could remain unprotected, thus avoiding the cost and additional weight and bulk of fire cladding. The appraisal included an examination of means of escape, the smoke generation and crowd movements being carefully analysed, and a generous number of exits was provided. It was established that should the fire remain unchecked after evacuation, the floor of the Exchange could survive collapse of the structure and consequently there would be no additional hazard to fire fighters. Non-combustible or low flammability materials are used throughout, and arrangements have been made to ensure detection of a fire and for surveillance by the theatre staff whenever the public is present.



B. Centre Pompidou, Paris, France (1) Fig. 2
Architects: Piano and Rogers
Structural Engineers: Ove Arup & Partners

Much of the structure of this building is exposed externally. Where calculation of the external fire exposure showed protection of the elements to be necessary, protection was provided either by water cooling or by shielding. The Centre Pompidou has a steel superstructure rising above a concrete substructure. The main building has six storeys above ground, each 7m high and 166m long (23 ft x 544 ft). The main lattice girders span 44.8m (147 ft) between short cantilevers projecting from the main columns, the outer ends of the cantilever members being restrained by vertical ties. The glazing line generally follows the junction between the lattice girders and cantilever brackets. The main columns are 1.6m (5 ft 3in) outside this line and are water filled for fire protection, circulation being achieved within each column by pumps. The cantilever brackets are 7.5m (25 ft) long; thus the outer line of tension "columns" and associated bracing members are 7.6m (25 ft) from the windows. Calculations showed that in the event of fire, all the members on the outer plane are protected by virtue of the 7.6m (25 ft) distance from the windows; the cantilever brackets are shielded by fire-resistant panels in the facade. There are sprinklers on the external walls and the cantilevers. Horizontal bracing members close to the windows would be lost in a fire, but with each floor divided into two compartments, the loss of a proportion of the bracing does not endanger stability.

C. Bush Lane House, London, England (8) Fig. 3
Architects and Structural Engineers: Arup Associates

Prior to the construction of this building, water cooling had only been used for the protection of vertical columns, since its use for beams raises considerable difficulties in ensuring that adequate controlled water flow occurs and no steam pockets develop. In Bush Lane House, water cooling is used for the external structural steel and protects columns, lattice members, and a critical top horizontal member. Bush Lane House provides eight office floors above a first-floor plant room. Each typical floor is approximately 35m long x 16m wide, (115 ft x 52 ft) supported by the lift core and three columns set 11m (36 ft) in from the extremities of the building. The stainless steel lattice which transmits the floor loads is external to the building envelope and leaves the office space uninterrupted. The steel members are water filled and inter-connected, so that in the event of fire the water circulates and steam is separated in a tank on the roof. This also serves as a reservoir to replenish and keep the system full of water. The patterns of water flow, maximum potential steel temperature, and the amount of water storage were all established by calculation.

D. Central Bank Offices, Dublin, Eire (19) Fig. 4
Architects: Stephenson Gibney and Associates
Structural Consultants: Ove Arup & Partners, Dublin

For this building the critical condition for failure of the steel hangers was established by calculation, since no standard test method was appropriate for tension members. In addition the fire exposure of the hangers, being external, was calculated so that the necessary cladding could be determined. The main building of the Central Bank offices complex in Dame Street, Dublin, is an eight-storey block with $8500m^2$ (91 400 sq ft) of office space. Uninterrupted floor areas and minimal obstruction to windows were considered to be of significant architectural advantage. The floors, measuring 45m x 30m (148 ft x 98 ft) are supported at 12 hanger points around the perimeter and on twin reinforced concrete cores. From the hanger points the loads are transmitted directly to roof level through pairs of high tensile Macalloy steel bars. Cantilever frames transmit the vertical reactions to the cores. The fire protection of the Macalloy bar hangers presented a somewhat unusual problem. They were to be exposed on the facade of the building and it was of considerable architectural importance that they be expressed as separate bars. It was essential therefore to provide a fire cladding which would give adequate protection without being very thick, since each 40mm bar (1.57 in) was to be encased in an aluminium tube not exceeding 120mm (4.72 in) diameter. A research programme was necessary to establish the Macalloy steel characteristics, thus leading to a definition of the critical condition for the structure under fire exposure. Fire engineering calculations, based on the method in (21), established that the bars would be less severely exposed than internal members and the cladding finally adopted was 20mm (0.79 in) thick Marinite machined to form interlocking sections round the bars.

CONCLUDING REMARKS

A recent study (3) has identified four broad subject areas which need further attention if the use of steel is to be exploited:

- A more precise definition, by the authorities responsible for building regulations, of the objectives of providing structural fire protection. This would help engineers to determine more clearly the level of protection needed, if any, and the effect on this level of employing alternative protection measures such as automatic sprinklers.

- The development of calculation methods for the fire safety of structures which could be incorporated into the methods for structural design at normal temperatures.

- Calculation manuals for the fire behaviour of structural steelwork giving methods to engineers which could be accepted by the authorities.

- Design guides for architects and engineers which explain when structural fire protection is needed and give information on the methods available for protection of steelwork and their relative costs.

Some of the work already carried out has been described and illustrated in this paper. It is to be hoped this type of work will be followed by general acceptance of the design approach to providing fire safety in buildings.

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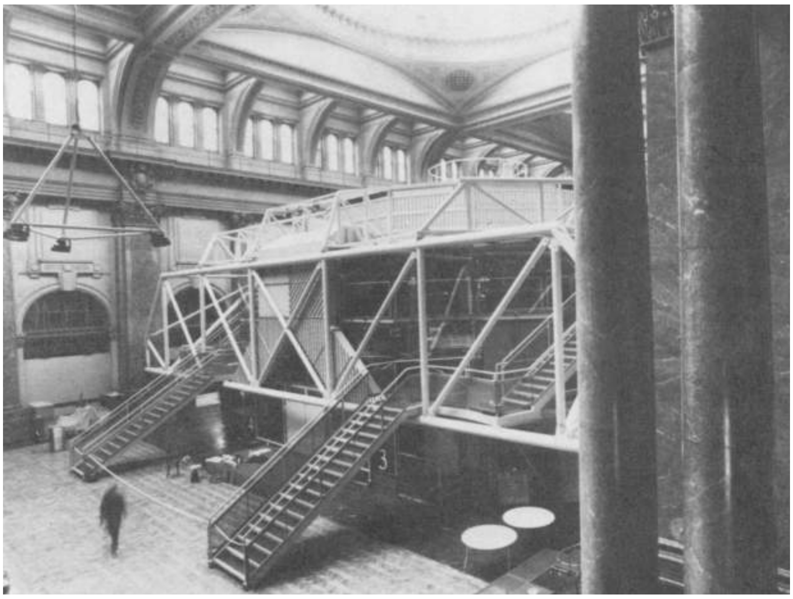

Fig. 1 The Royal Exchange Theatre, Manchester

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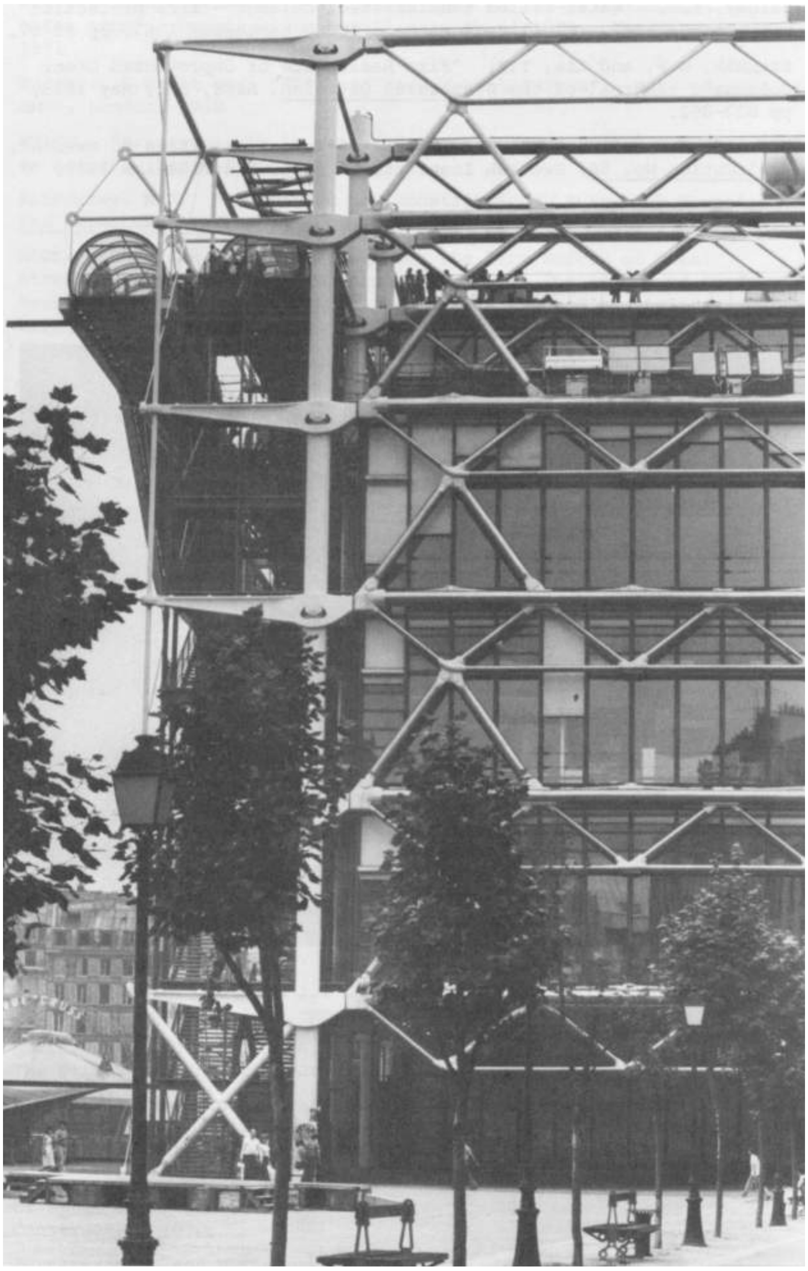

Fig. 2 Centre Pompidou, Paris (side view)

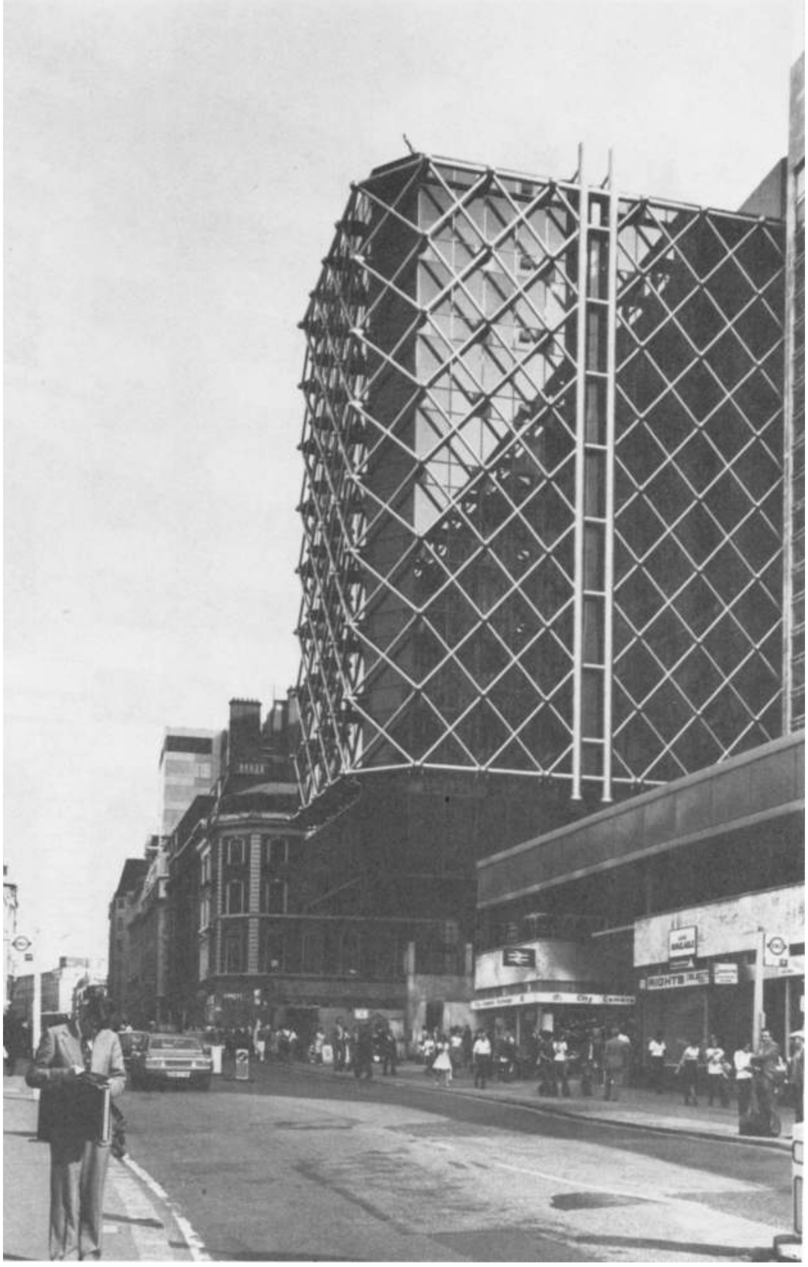

Fig. 3 Bush Lane House, London

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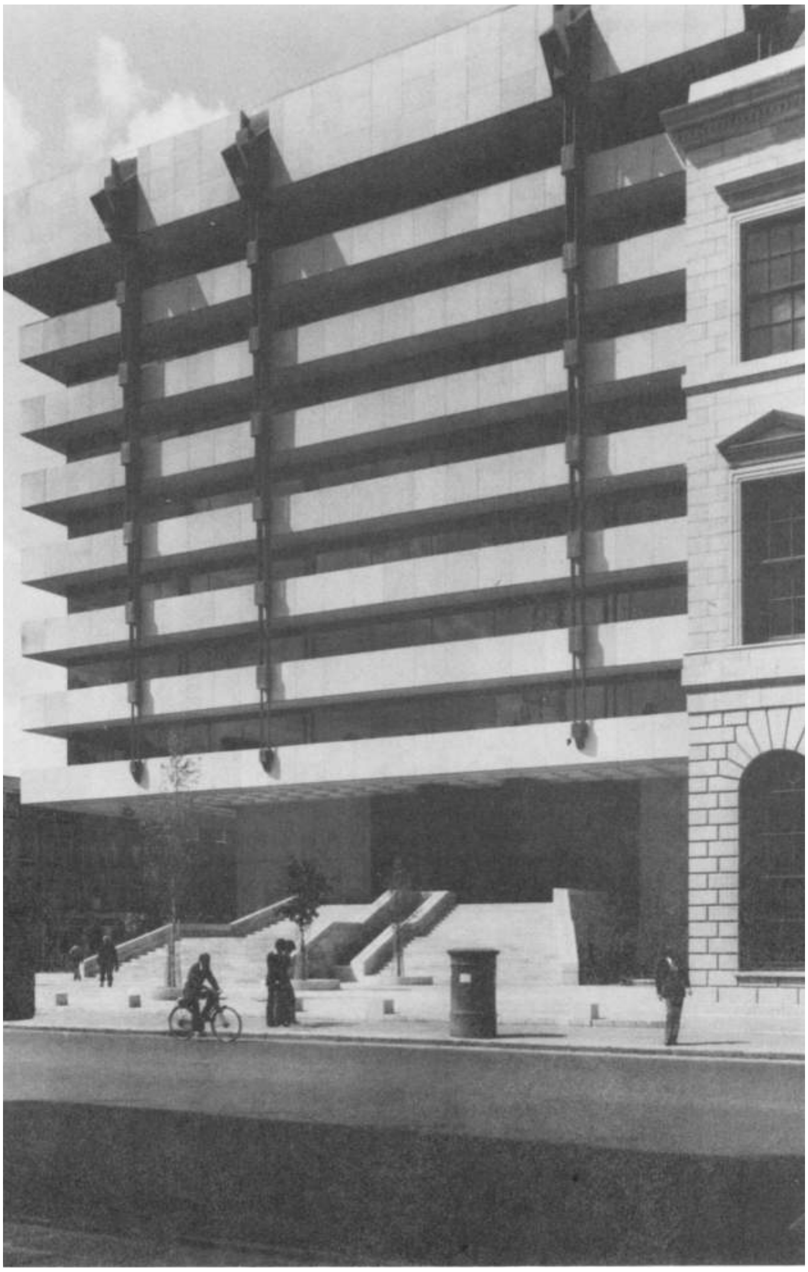

Fig. 4 Central Bank Offices, Dublin

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PAPER 9

Notes on the external fire exposure measured at Lehrte

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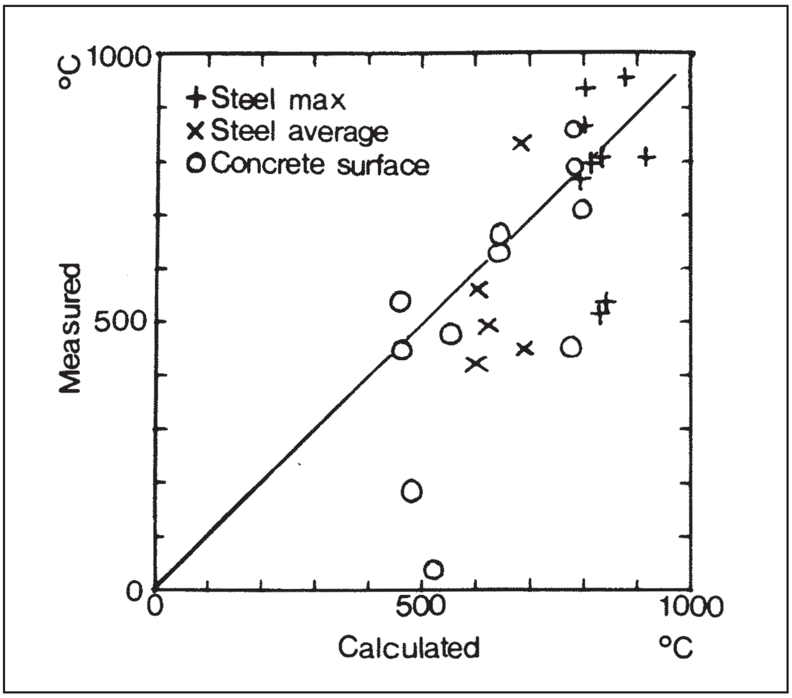
In 1978 a large experimental programme of compartment fires was carried out in Germany, set in a block of flats. Structurally speaking, the main interest was the fire exposure of external steel. Unprotected elements were placed in the zone of maximum flaming and, not surprisingly, reached high temperatures. Nevertheless, the measurements of fire behaviour were valuable, so in this paper I analysed them and compared them with the analysis in Paper No 7.

Figure comparing the calculated and measured temperatures of columns placed outside the windows of burning rooms.



Notes on the External Fire Exposure Measured at Lehrte

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SUMMARY

Temperature measurements of external flames and of external columns made during the experiments at Lehrte are compared with correlations of earlier data and shown to be in broad agreement.

INTRODUCTION

The results of a series of fire experiments carried out in a block of flats at Lehrte were published in 1978 [1]. In these experiments fires were started in one or more rooms containing varying types and amounts of fire load (wood cribs, domestic furniture, and office furniture ranging in fire load density from 10 to 90 kg/m^2). The numerous measurements included gas temperatures, both inside and outside the burning rooms, and the temperatures of external steel and concrete columns. It is the purpose of this note to compare these measurements with the method of calculating the fire exposure of external building elements contained in a report presented to the American Iron and Steel Institute and Constrado in 1977 [2, 3]. This method forms the basis of manuals for calculating the temperature rise of external steel elements without fire cladding [4, 5]. In these manuals, if the calculated temperature of the element does not attain a critical value it is considered to be safe.

The results of the experiments at Lehrte cannot be used directly to determine the safe position of external steel columns without fire cladding since, in these experiments, they were placed in the worst position, that is they were opposite mid-window and enveloped in flame where, as shown in earlier experiments [6], they would be expected to reach unacceptably high temperatures. However, the calculation method can still be used to calculate the column temperatures at these unsafe positions for comparison with the measured temperatures.

FLAME BEHAVIOUR

The Lehrte report gives a number of diagrams showing the temperature distribution along the flame axis outside the window of the burning rooms. The earlier work indicated that the distribution would be linear and this is confirmed. Some typical results are illustrated in Fig. 1. Extrapolation of the lines to $l = 0$, where l is the distance along the axis measured from the window, gives a value θ_0 and the earlier correlation indicated that

$$\frac{\theta_l}{\theta_0} = 1 - 0.027\frac{lw}{R} \qquad (1)$$

where θ_l is the temperature rise on the flame axis at distance l (°C), w the window width (m), and R is the rate of burning (kg/s).

The rate of burning was not measured but it can be assumed that the fires were ventilation controlled. Using the results of the CIB experiments [7, 3] the value of R has been calculated from:

$$R = kA_W\sqrt{h} \text{ (kg/s)}$$

where

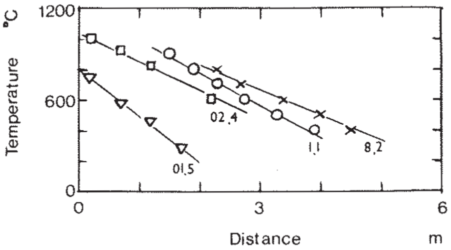

Fig. 1. Variation of temperature with distance along flame axis from window — some typical results. Note: 01, 5 denotes Test 01, Room 5.

$$k = 0.18[1 - \exp(-0.036\eta)]\sqrt{\frac{W}{D}}$$

and

$$\eta = \frac{A_\mathrm{T}}{A_\mathrm{W}\sqrt{h}}$$

where A_W is the window area (m^2), h the window height (m), A_T the area of the enclosing surfaces minus A_W (m^2), W the width of the compartment (m), and D is the depth of the compartment (m).

The variation of θ_l/θ_0 with lw/R is shown in Fig. 2 and the results are in good agreement with eqn. (1).

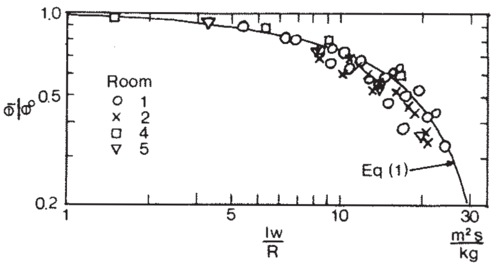

Fig. 2. Correlation of temperature distribution along flame axis with distance, window width, and rate of burning.

The flame tip can be defined as the point where the temperature is 540 °C. Using this criterion the height of the flame tip above the window, z, has been deduced from the measurements. The earlier correlation was as follows:

$$z + h = 12.8\left(\frac{R}{w}\right)^{2/3}. \tag{2}$$

The variation of $(z + h)$ with R/w is shown in Fig. 3. For Room 2, the values of $(z + h)$ have been adjusted to allow for deflection by the balcony above.

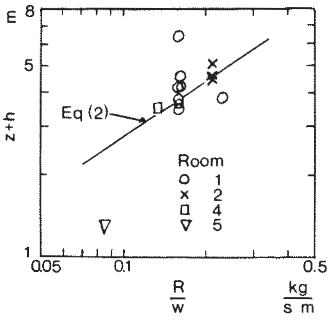

Fig. 3. Correlation of flame height above top of window with rate of burning and window width.

There is considerable scatter, but it has not been possible so far to find any systematic variation with such factors as wind speed and direction or with fire load (see Table 1).

COLUMN TEMPERATURES

The exposed columns varied from test to test both in type and location. They included two I-section bare steel sections, a bare, rectangular hollow section (RHS) and a concrete filled RHS. The calculation model has been used to calculate the maximum steady state surface temperatures and the maximum average temperatures for the steel sections and these are compared with the measurements in Fig. 4. In view of the difficulties to be expected in predicting temperatures so close to the windows, the agreement in Fig. 4 is remarkably good.

FIRE BEHAVIOUR

A brief review of the temperatures within the rooms has been made (see Table 1). In general, the temperatures do not increase with fire load as much as expected from earlier tests. Neither does the "equivalent fire resistance" increase as much with fire load as expected. This was measured by a test piece and has also been calculated by the author of this note from the temperature–time curves for the rooms. The calculation gives the fire resistance of a protected steel column which would attain a maximum temperature of 550 °C during the fire [8].

CONCLUSION

While further analysis of the results will be of interest, it is already clear that the experiments tend to support earlier conclusions regarding the use of external steel without cladding. It is to be regretted that no steel elements were placed in what are deemed to be safe positions — to the side of the window for example — since there was wind gusting during some of the tests and the resulting effect on column temperature would have

TABLE 1

Measurements for rooms 1 and 2

Room	Fire load density (kg/m^2)	Wind		Flame height (m)	Max. fire temperature (°C)	Equivalent fire resistance*		Test
		Speed (m/s)	Direction			A (min)	B (min)	
1	30	0.5	S	2.1	890	49	34	1
	30	4.5 - 5.0	E - S	2.2 - 2.7	940	41	34	5
	30	1.5	W		980	43	39	6′
	32	1.5	SW	1.8	850		27	2
	39	2.0 - 4.0	SW	3.1 - 4.9	855	38	30	3
	60	0.5	SW	2.7	960		60	7
	60	1.0	W		890		45	6
1b	30	1.0	NW	2.3	690		26	4
	90	2.5	W		760	37	45	8
2	26	2.5	SW		980		40	2
	30	1.0	NW		800	55	41	4
	30	1.5	W	2.3	860	38	33	6′
	30	1.5	W		850			8′
	52	1.0	SW	1.8	830		37	3
	60	4.5 - 5.0	E - S		890		43	5
	60	1.0	W	4.6**	840		45	6
	60	0.5	SW		880		54	7
	90	2.5	W	1.7	940	37	66	8

*A, test piece in compartment; B, calculated by author from temperature — time curve in compartment.
**Crib on balcony above ignited.

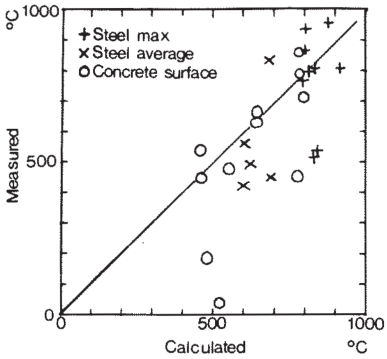

Fig. 4. Calculated and measured temperatures of columns placed outside windows of burning rooms.

been of interest. The calculation model assumes a steady 45° deflection of flames, where this would give a more severe exposure, and it is not known how conservative is this assumption.

NOMENCLATURE

A_T	Area of enclosing surfaces of compartment minus A_W (m^2)
A_W	Window area (m^2)
D	Compartment depth (m)
R	Rate of burning (kg/s)
W	Compartment width (m)
h	Window height (m)
l	Distance along axis of flame from window plane (m)
w	Window width (m)
z	Flame height above top of window (m)
η	$A_T/A_W\sqrt{h}$ (m$^{-1/2}$)
θ_l	Temperature rise on flame axis at distance l (m)
θ_0	Temperature rise on flame axis at $l = 0$ (m)

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PAPER 10

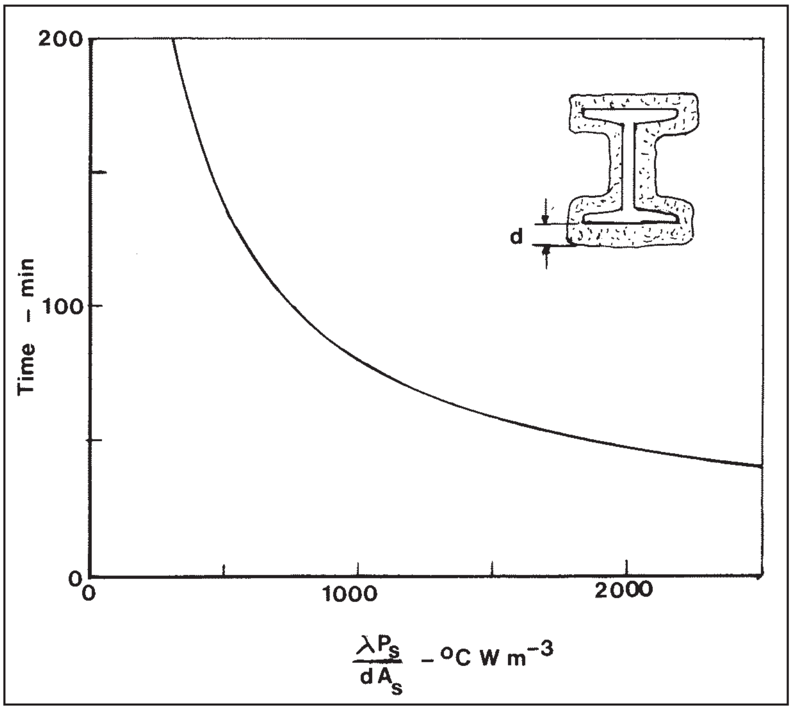
A basis for the design of fire protection of building structures

Margaret Law, BSc, FIFireE, Ove Arup & Partners, The Structural Engineer, Vol. 61A, No.1 January 1983. Institution of Structural Engineers (I Struct E), UK

Reprinted from Fire Safety Journal, Vol.4 No.4, Notes on the external fire exposure measured at Lehrte, pp 243-246, Copyright 1981/82 with permission from Elsevier.

In the early 1980s there was very little scope for introducing fire safety engineering into structural fire design. It was important to engage the structural engineers in order to make progress. This paper was designed to show how much information was already available that could be applied to practical design. It was presented at an ordinary meeting of the Institution of Structural Engineers and subsequently received the Institution's Oscar Faber Award.

Figure showing the relationship between time for the average temperature of protected steel to reach 550°C in the standard fire resistance test and the physical properties of the insulating material, together with the perimeter and cross-sectional area of the steel.



Contents

A basis for the design of fire protection of building structures

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Margaret Law is a Technical Director of Ove Arup Partnership, providing specialist advice on all aspects of fire safety in buildings. She worked at the Fire Research Station, Borehamwood, for a number of years, carrying out research into many aspects of fire behaviour and its effects on building materials and structures and also became involved in the application of research results to Building Regulations, Codes of Practice, and design guides. After a period in the Directorate of Research Requirements of the DoE, assessing research priorities in the field of building and construction, she joined the Research and Development Group of the Partnership in 1974.

Synopsis

The present system for grading the fire resistance of structural elements gives little scope for engineering design, and the current regulatory requirements give only a broad indication of the fire safety objectives. Methods of quantifying fire exposure and structural behaviour in building fires for design purposes are reviewed, and it is suggested they could form part of a new approach to designing structural safety. Such an approach would be more selective and would take into account the beneficial effects of fire safety measures which are increasingly required for life safety. It is necessary for public authorities to identify clearly the fire safety objectives of the regulations, while structural engineers should propose a formulation of performance requirements which would give design methods compatible with structural Codes and would help to facilitate cost-effective design.

Introduction

Fires affect the structural performance of buildings because they change the physical and mechanical properties of the materials of construction. By defining the importance of these changes, which can be related to the estimated fire exposure, a structural Code could provide methods of designing a structure to give the prescribed performance in a building fire. At present, however, performance is defined by the authorities (regulatory and insurance) as the minimum time for which each element would survive if it were subjected to a standard test, and this test provides an arbitrary fire exposure, an arbitrary load, and arbitrary restraint. Therefore, at the moment, the Codes contain little scope for design and are constrained to describe ways of achieving the required results in the standard test. It is the purpose of this paper to review the information available that could form the basis of an alternative method of design for the fire protection of building structures and to discuss ways in which a more selective approach could be adopted to meet the requirements of both the public and the private sectors for the protection of life and property.

This review is concerned primarily with the safety of the building structure. In order to provide adequate protection for the occupants, for the movable contents, and for nearby buildings, other measures are needed in addition—notably, control of smoke movement in a building and access for fire fighting.

The relevance of structural fire protection in the overall fire safety plan is discussed later. Structural fire protection is a passive measure, in that it is deemed to be 'always there', unlike active measures, such as automatic detection and alarm systems, which are designed to operate only when a fire starts. The importance of this distinction is also discussed later.

Quantification

A fire engineering design system needs to quantify the fire exposure and the effects of that exposure on structural behaviour. Certain critical conditions for loss of loadbearing capacity, excessive deflection, or excessive heat conduction, can be defined in terms of the attainment of a critical temperature or a given amount of degradation.

The quantification of fire exposure for design purposes is based on the study of so-called compartment fires. These can be considered to be more representative of the potential exposure in a real fire than the standard fire resistance test because they take account more directly of fire load, compartment size, and ventilation.

Fire exposure

A building fire that is serious enough to need the attention of the fire brigade can be said to go though three main phases—ignition and growth, full development, and decay. Detectors, alarms, and automatic extinction systems, are designed to operate during the growth stage, while the fire is still small, before the structure is at risk. Large flames, high rates of heating, and most structural damage, occur during the fully developed period. The decay period begins when the fire is brought under control or when the fuel (fire load) is exhausted.

In this paper the term 'real fire' denotes a fire that occurs in real life in a building, i.e. not an experimental fire. Laboratory experiments with representative buildings or structures are constrained in one or more ways even when they contain realistic fire loads, and they simulate only certain aspects of a real fire. These fires can therefore be called simulated and form one type of experimental fire. (The term 'natural fire' is often used for what is really a simulated fire.) In general, an experimental fire may be more or less realistic, in terms of scale, fire load, enclosure, mode of ignition, and means of extinction (if any). For example, the experimental fires in enclosures are usually designed to develop very quickly and the windows are left unglazed. In a real fire the windows would break when and if the fire becomes large, and the growth period could be very long.

The term 'compartment fire' is commonly used for the design concept of a defined enclosure containing a fully developed fire extending throughout the defined space (which may be a room, a compartment, or a whole building). The method of calculating the behaviour of a compartment fire is based on measurements in experimental fires using mainly wood cribs as the fuel.

The standard fire is the one used in standard fire resistance tests and is provided by a furnace usually gas-fired or oil-fired, controlled in a standard way.

Compartment fires

For structural engineers the fully developed period of a fire is of major importance. It has been studied by a number of workers and a summary is given by Thomas[1]. An analysis of fully-developed fire behaviour is complex, and the models that have been developed are based on a number of simplifying assumptions, notably that the temperature distribution is uniform throughout a fire compartment and that the fuel burns in a uniform way. Nevertheless, important parameters have been defined and a substantial data bank exists from which it is possible to show how these parameters interact.

Fire temperature

When the combustible materials are heated and decompose in a fire, the heat released by the burning volatiles is absorbed by the enclosing surfaces of the compartment and any other structural surfaces, by the surface of the unburnt fuel and by the incoming air. Heat is lost to the exterior in the flames and hot gases that emerge from the windows and by radiation through the windows. The rate of heat generation and the way it is distributed has been measured experimentally. An example of a heat balance measured in a small compartment is given in Table 1[2]. For this compartment, unglazed windows provided ventilation from the start of the fire.

TABLE 1—Heat balance measured in experimental fires in a compartment of 29m^2 floor area with a fire load of wood cribs

Fire load (kg)	Window area (m^2)	Heat release* (kcal/s)	Heat loss from gases (%) Effluent gas	Structural surfaces	Feedback to fuel	Window radiation
877	11·2	1900	65	15	11	9
	5·6	1900	52	26	11	11
1744	11·2	3200	61	15	11	13
	5·6	2300	53	26	12	9
	2·6	1600	47	30	16	7

*From rate of burning (rate of weight loss of fuel)

The table illustrates the significant amount of heat loss in the effluent gases and shows that, with decreasing window area, a larger proportion of the heat released will enter the enclosing structure. The total heat released, assuming a complete burnout, is directly proportional to the size of the fire load but the *rate* of heat release may be controlled by the ventilation. In this example, with the lower fire load, both window areas give sufficient ventilation for the fuel to burn at its maximum (free-burning) rate but, with the doubled fire load, the burning rate is not doubled because the window area restricts the ventilation needed. This ventilation effect has been described as follows[3]:

$$R = 0\cdot 1\, A \sqrt{h} \qquad \ldots .(1)$$

where
R is the rate of burning (kg/s)
A is the window area (m^2)
h is the window height (m)

The outflow of hot gases is also proportioned to $A \sqrt{h}$. The area of structural surfaces to which heat is lost is expressed by $(A_t - A)$ where A_t is the area of the planes enclosing the compartment (walls, ceiling, floor). For a given fire load, compartments with different values of A_t, A, and h, will have a different heat balance, and thus the temperature in the compartment will vary. This is illustrated in Fig 1 which shows how temperature varies with $\eta = (A_t - A)/A\sqrt{h}$. For low values of η (i.e. high ventilation areas), the rate of heat release is at a maximum but the heat loss from the window is also large and the resultant temperature is low. For high values of η (i.e. low ventilation areas), there is little heat loss to the outside but the rate of heat release is also small and the resultant temperature is again low.

The curve in Fig 1 has been derived from many experimental fires[4]. For design purposes, it has been defined as follows[5,6]:

$$\text{max. } T_f = \frac{6000\,(1 - e^{-0\cdot 1\eta})}{\sqrt{\eta}} \quad (^\circ\text{C}) \qquad \ldots .(2)$$

This represents an upper limit of fire temperature for a given η. However, if the fire load is low, this value may not be attained. The importance of the fire load effect depends on A and A_t also, and it can be allowed for as follows[5]:

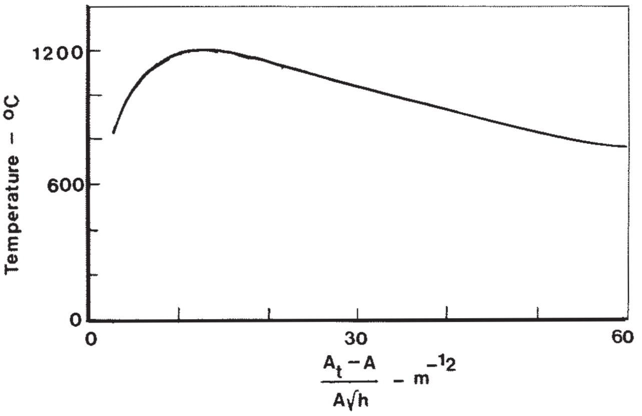

Fig 1. Average temperature during fully developed period measured in experimental fires in compartments[1] (A_t is the area of walls, ceiling, floor; A is the window area; h is the window height)

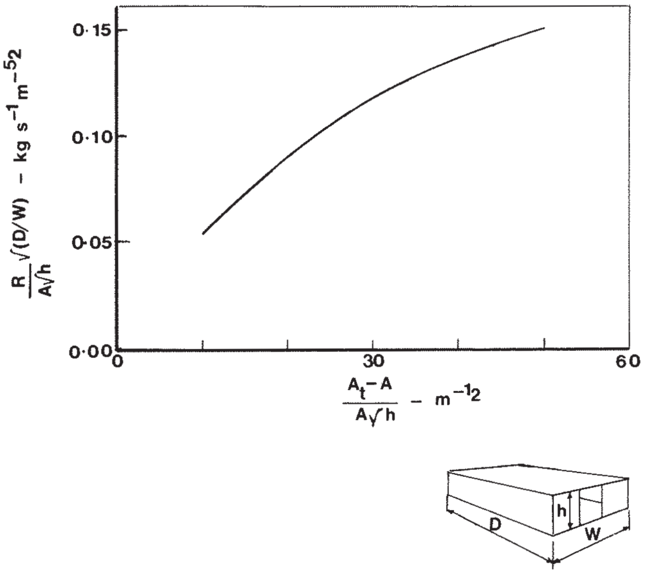

Fig 2. Variation of rate of burning during fully developed period measured in experimental fires in compartments[1] (R is the rate of burning; A_t is the area of walls, ceiling floor; A is the window area)

$$T_f = \text{max. } T_f \; (1 - e^{-0\cdot 05\,\psi}) \qquad ^\circ\text{C} \ldots .(3)$$

where $\psi = \dfrac{L}{\sqrt{A(A_t - A)}}$ (kg/m^2)

and L is the fire load (wood) (kg)

The effect of the fire on the structure depends not only on the value of T_f but also on the duration of heating. The effective fire duration, τ, is given by.

$$\tau = \frac{L}{R} \quad (\text{s}) \qquad \ldots .(4)$$

Equation (1) suggests that the smaller the value of $A\sqrt{h}$ the lower the rate of burning and the longer the duration. Assuming a complete burnout, therefore, the effect on the structure tends to be more severe for large values of η (small $A\sqrt{h}$)

Rate of burning

Because R defines not only the rate of heat release but also the fire duration, it has been the subject of much study.

Later work[4] based on many experiments showed equation (1) to be only approximate and demonstrated that R was not simply proportional to $A\sqrt{h}$ but also depended on A_t and the ratio of depth D to width W of the compartment, as illustrated in Fig 2. For design purposes the following equation has been derived[5]:

$$R = 0{\cdot}18\,A\sqrt{h}\sqrt{(W/D)}\,(1\text{-}e\ -\ 0{\cdot}036\eta) \qquad \ldots.(5)$$

This equation is for ventilation-controlled fires. When there is ample ventilation, so that the fuel is free burning, the value of R depends on L and the type of fuel. For example, domestic furniture has a free-burning fire duration[7] of about 20 min, giving $\tau = 1200$s and $R = L/1200$

Temperature-time curves
The temperatures discussed above are the average measured during the fully developed period of the fire. It is possible to calculate a complete temperature-time curve using the heat balance model, and the most comprehensive work has been done in Sweden[8]. This work assumes that all fires are ventilation controlled, with the simple relationship for rate of burning given by equation (1), and it is assumed that combustion of 1 kg of wood releases 18·8 MJ. Fig 3 shows some typical curves. (In this method the fire load is expressed in relation to A_t as $q = 18{\cdot}8L/A_t$ MJ/m^2.) The curves are calculated for walls, floor and ceiling materials with 'normal' thermal properties, but it is possible to adapt the method to enclosures with thermally different properties.

Fire loads
The amounts of combustible material in buildings have been measured in a number of surveys[8,9,10]. The traditional way of describing fire load is as weight or heat units per unit floor area (although, in Sweden, it is related to A_t). Usually these materials burn in a similar way to wood, so that, when weight is given, it is the amount of wood that is deemed to give an equivalent amount of heat.

Standard fire

The standard fire exposure is defined as[11]

$$T - T_o = 345\log_{10}(8t + 1) \qquad (°\text{C})$$

where
t is the time (min)
T is the furnace temperature at time t
T_o is the initial furnace temperature

The furnace is controlled so that the temperature of thermocouples adjacent to the exposed surface of the element of construction undergoing a fire resistance test follows the standard curve shown in Fig 4. The curve is virtually the same throughout the world, but heat transfer to the element can vary according to the fuel and the furnace design. The significance of these effects is discussed later.

The British report on fire grading of buildings (1946)[12] gives the broad relationship between standard fire exposure and fire load shown in Table 2. It takes into account American measurements of simulated fires in offices and a comparison of the area under the measured temperature – time curve with the area under the standard curve.

Real fires

There are many uncertainties in real fires which are not taken into account in the compartment fire model:
- —the time taken to reach full development may be much longer;
- —the temperature distribution is not likely to be uniform, particularly in large spaces, so that there may be local rates of heating significantly different from the average;
- —the fire may be progressive, so that only part of the structure is exposed to the fully developed fire at any one time;
- —the fire brigade tackles the fire before all the fuel is consumed;
- —the fuel itself may not behave like wood.

Such uncertainties do not rule out the use of a design method, and they exist with the present grading system, but they are matters that should not be forgotten by the engineer.

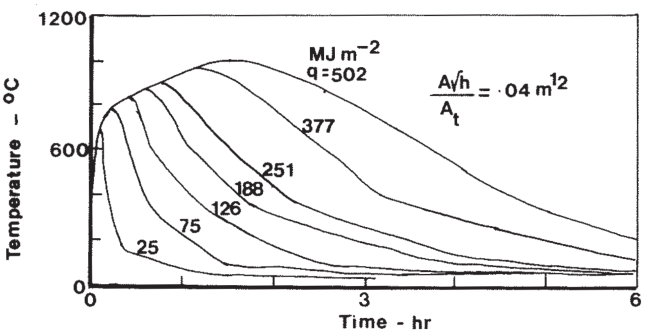

Fig 3. Calculated temperature-time curves for compartment fires with different fire loads (from reference 8) ($q = 18{\cdot}8\ L/A_t$; L is the fire load; A_t is the area of walls, ceiling floor; A is the window area; h is the window height)

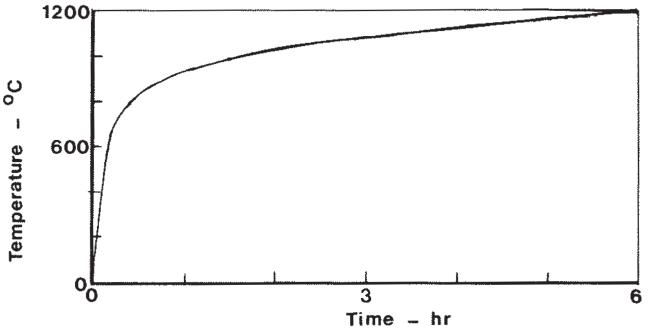

Fig 4. Standard temperature-time curve specified for the fire resistance test[11]

TABLE 2—Assumed equivalent severities of building fires (from *Postwar building studies no. 20)*

Fire load* (kg/m^2)	Equivalent severity of fire in standard test (min)
Less than 60, i.e. low fire load	60
60-120 i.e. moderate fire load	120
120-240 i.e. high fire load	240

*Assuming approx. 8000 Btu/lb for wood

The measurements available from real building fires are mainly statistical, based on fire brigades' reports. The information includes an estimate of the fire duration and the area damaged by fire. In large buildings the fires are progressive and tend to grow exponentially:

$$A_f = A_o \exp(\alpha t)$$

where
A_f is the floor area damaged in time t
A_o is the floor area originally ignited
α is the fire growth parameter

A general value of 4 min ($\alpha = 0{\cdot}0029\ \text{s}^{-1}$) for doubling time has been suggested[13], while a special study of fires in the textile industry[14] gives a value of 11 min for A_f to double in size. ($\alpha = 0{\cdot}00105\ \text{s}^{-1}$.) This exponential type of fire growth means that, if the fire is not tackled early enough, it may be too big to be controlled and extinguished by the fire brigade and it will continue to burn until virtually all the fuel is exhausted. Such fires may last considerably longer than calculated for compartment fires, and the discrepancy can be accounted for partly by the progressive nature of large fires and partly by the cooling effect of fire hoses which prolongs the burning time. Since this cooling effect is likely to be beneficial for the structure, a design based on the compartment fire model would tend to be conservative.

Special studies of industrial fires have provided useful estimates of burning rates and heat output per unit fire area for a variety of contents[15]. These confirm that the wood cribs used in experimental fires give fires that are realistic and constitute a fuel of reasonably severe hazard. Most of the fires studied were well ventilated and free burning, but one building had a very high value for η, of about $230\mathrm{m}^{-1/2}$, which meant that the airflow was insufficient to maintain flaming combustion throughout the building. However, there was sufficient heat generated during more than 1 h to heat up the entire building and its contents, so that when, eventually, air was admitted, fire flashed over the whole interior and produced a minor explosion which coincided with the arrival of the fire brigade.

The fire duration τ_f for these industrial fires correlated with fire load per unit floor area as follows.

$$\tau_f = 590\left(\frac{L}{A_F}\right)0{\cdot}30\mathrm{s} \quad \text{(correlation coefficient} = 0{\cdot}62)$$

where A_F is the floor area (m^2)

A better correlation was with fire load per unit fire area

$$\tau_f = 126\left(\frac{L}{A_f}\right)0{\cdot}48\mathrm{s} \quad \text{(correlation coefficient} = 0{\cdot}70)$$

where A_f is the fire area (m^2)

Rate of burning per unit fire area correlated with bulk density of fuel as follows:

$$\frac{R}{A_f} = 0{\cdot}11\varrho^{-0{\cdot}34}\ (\mathrm{kg/m^2.s})$$

where ϱ is the bulk density $= L/(A_f \times \text{fuel height})\ (\mathrm{kg/m^3})$

Studies such as these indicate that it is possible to postulate design fire exposures which would correlate reasonably well with experience of real fires.

External fire exposure

It has been known for a long time that structural elements placed outside the façade are likely to receive lower fire exposure than internal elements because, although they can be heated by radiation and convection from the emerging flames and by radiation from the windows, they are free to cool to the ambient air. No satisfactory relationship with the standard fire exposure can be established and therefore this is an aspect of structural fire safety that has been an obvious candidate for a design approach.

The discussion earlier of heat balance showed the importance of heat loss in the emerging flames and hot gases and the window radiation. Since it is the internal fire that controls the external fire exposure, the heat balance approach is equally relevant. It has been shown[5] that the height z of the flame tip of the emerging flame above the top of the window is given by

$$z + h = 12{\cdot}8\left(\frac{R}{w}\right)^{2/3}$$

where w is the total width of windows

The temperature at the flame tip is about 540°C. The temperature distribution along the flame axis is linear and given by:

$$\frac{T_l - T_a}{T_{lo} - T_a} = 1 - \frac{0{\cdot}027lw}{R}$$

where

l is the distance along flame axis from window plane (m)

T is the temperature at distance l (°c)

T_{lo} is the temperature rise at $l = 0$ (°C)

Since $T_l - T_a = 520°\mathrm{C}$ at the flame tip, T_{lo} can be derived. Design manuals have been published[16, 17] which show how to estimate the rates of heating at different positions within and adjacent to the emerging flames.

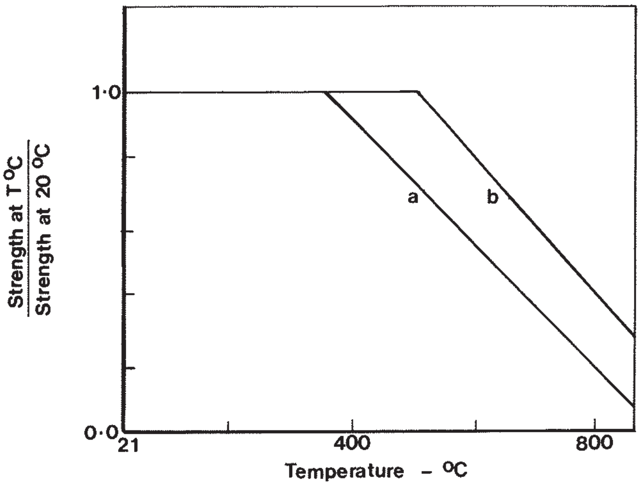

Fig 5. Design curves for variation of concrete strength with temperature[20] (a) *Dense concrete* (b) *Lightweight aggregate concrete*

Material properties

The effects of temperature on the thermal and mechanical properties of structural materials have been published in a range of papers, and wide-ranging summaries are available[18,19]. For design purposes, simplified relationships have been devised.

Concrete

For concrete, the compressive strength varies not only with temperature but also with a number of other factors including the rate and duration of heating, whether the specimen was loaded or not, the type and size of aggregate, percentage of cement paste, and the water/cement ratio. In general, it may be said that concrete heated above 300°C loses some compressive strength. For design purposes, compressive strength as a proportion of strength at normal temperature has been codified as illustrated in Fig 5.

The elastic modulus also decreases with temperature; for design, it has been suggested that the reduced value at 700°C can be taken as 40% of the normal temperature value for lightweight concrete and 10% for other concretes. Creep becomes significant at quite low temperatures, but, for the short-duration transient heating normally experienced in building fires, is not taken into account in design. The coefficient of thermal expansion is of order $10^{-5}/°\mathrm{C}$ and varies with aggregate. Design values and methods of estimating thermal deformation are given in references 20. 21, and 22.

For transient heating, an important thermal property is the thermal diffusivity k where

$$k = \frac{\lambda}{\varrho c} \quad (\mathrm{m^2/s})$$

λ is the thermal conductivity (W/m°C)

ϱ is the density (kg/m^3)

C is the specific heat (J/kg°C)

The value of k depends on the aggregate, porosity, and moisture content. For gravel aggregate concrete, it varies from about 10^{-6} m^2/s at normal temperatures to about 4×10^{-7} m^2/s at 700°C. For lightweight concrete, it varies from about 7×10^{-7} to 3×10^{-7} over the same temperature range[20]. These low values of diffusivity mean that, in building fires, the 300°C contour, beyond which the concrete retains virtually all its strength, may be at only a small depth below the heated face.

Steel

The effect of temperature on yield strength varies with the type of steel. For mild steel, it is reduced to half at about 500°C. A design curve for effective yield stress of mild steel is shown in Fig 6[23]. Similar curves are available for various reinforcing and prestressing steels[20]. The stress-induced strains of steel start to be affected by creep at temperatures over about 450°C. However, for the heating rates normally encountered in building fires, these design curves can be assumed to include the effect of creep. Thus it is not normally necessary to take into account the stress and temperature history of the structure. The elastic modulus decreases with temperature; because at elevated temperatures the stress-strain relationship follows a curve, the recommended values for design apply to the tangent modulus at infinitely small stress[23]. The coefficient of thermal expansion varies with temperature, but an approximate value can be taken as $1 \cdot 4 \times 10^{-5}$/°C, which is similar to the value for concrete.

The thermal diffusivity of steel is significantly greater than that for concrete and, except for very massive sections, unprotected steel rapidly heats up in a fire. The specific heat is a function of temperature but an approximate value can be taken as 520 J/kg°C, which is about half the value for concrete.

Masonry
The thermal properties of concrete bricks and blocks are similar to those of concrete having similar constituents and mix design[19]. The properties of clay bricks are not available in such detail as for concrete. A rise in temperature gives a decrease in compressive strength and causes expansion. Values of thermal conductivity depend on density and increase somewhat with temperature. For example, for brick of density 2100 kg/m^3, the conductivity increases from 0·93 W/m°C at normal temperature to 1·07 W/m°C at 700°C[18]. Specific heat varies with temperature but an approximate value is 1000 J/Kg °C, similar to the value for concrete.

Wood
The tensile and compressive strengths of wood also depend on its temperature. However, because of the insulation provided by the charred surface layers, the uncharred portion of wood in a building fire may be assumed to retain virtually all its normal temperature strength. For design, a nominal reduction of 10% in the strength of the uncharred section has been suggested[19]. The rate of charring, which is the major feature of interest, depends to some extent on species but mainly on the rate of heating[24]. For rates of heating, I, between 20-3300 kW/m^2, the charring rate[25] has been found to be $3 \cdot 67 \times 10^{-4} I$ mm/s. Measurements of char depths in timber beams subjected to the standard fire resistance test showed a char depth of 18mm after 30 min exposure which suggests there was a heating rate of about 30 kW/m^2 in these standard furnace tests[26]. Notional charring rates can be used to design for standard fire resistance ratings[27].

Heat transmission
The heat transfer from the fire to the structure can be calculated as follows:

$$I = (\alpha_c + \alpha_r)(T_t - T_s) \quad (\mathrm{W/m^2})$$

where
T_t is the ambient gas temperature at time t (°C)
T_s is the surface temperature at time t (°C)
α_c is the heat transfer coefficient for convection (W/m^2°C)
α_r id the heat transfer coefficient for radiation (W/m ^{2}°C)

and $$\alpha_r = \frac{5 \cdot 7\, \varepsilon_r}{(T_t - T_s)} \left[\left(\frac{T_t + 273}{100}^{4} \right) - \left(\frac{T_s + 273}{100}^{4} \right) \right] (\mathrm{W/m^2{}^\circ C}$$

and ε_r is the resultant emissivity of flames, combustion gases

where $$\varepsilon_r = \frac{1}{1/\varepsilon_t + 1/\varepsilon_s - 1}$$

where ε_t is the emissivity of the flame and ε_s is the emissivity of the surface

T_t can be taken from the temperature-time curve. Values of 25 W/m^2°C for α_c and 0·85 for ε_t have been suggested for compartment fires, while α_c = 25 W/m^2°C and ε_t = 0·57 are suggested for standard fire resistance tests[8]. As a conservative approximation, it can be assumed that the surface temperature of the exposed structure follows the temperature-time curve for the fire.

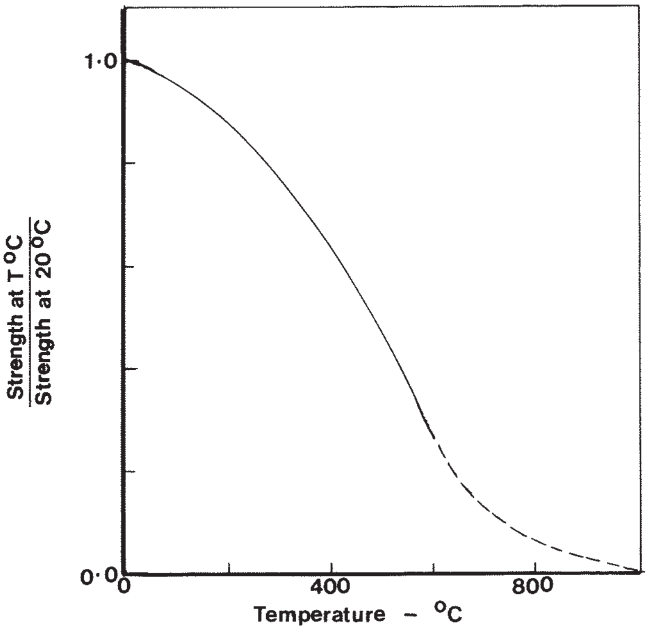

Fig 6. Design curve for variation of effective steel strength with temperature[23]

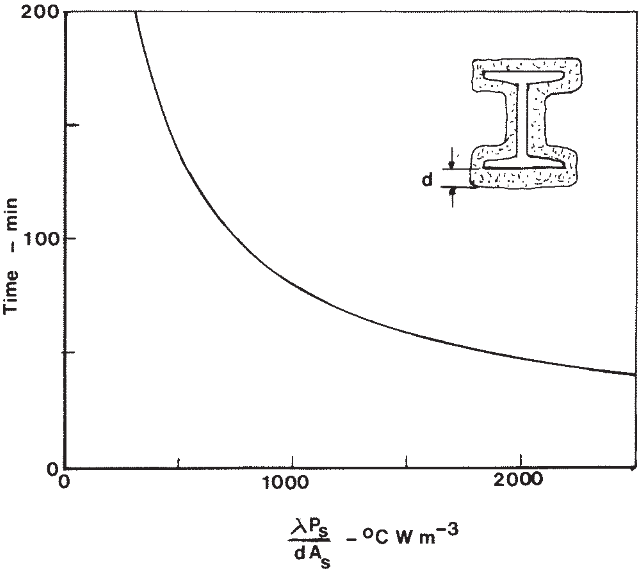

Fig 7. Time for average temperature of protected steel to reach 550°C in the standard fire resistance test (derived from reference 23) (λ is the thermal conductivity of insulating material; d is the thickness of insulating material; P_s is the perimeter of steel; A_s is the cross-sectional area of steel)

Heat transfer within the structure can be calculated using standard heat conduction equations and certain simplifying assumptions. With concrete, for example, where the critical condition is usually the temperature of the reinforcement, it can be assumed that the steel is of the same temperature as the adjacent concrete. Temperature gradients within the concrete can be calculated or, for heating in fire resistance tests, obtained from charts[20]. With steel elements, it is assumed that the steel temperature is uniform across the section, so that the steel is acting purely as a thermal capacity, while the insulating material is acting as the thermal resistance. Equations and charts have been devised for the standard fire resistance test and for compartment fires[8, 28] which take into account the mass and exposed surface area of the steel sections as well as the fire exposure. Fig 7 illustrates this approach.

A relationship between the fire exposure in the standard fire resistance test and in compartment fires has been developed in terms of attainment of a certain critical temperature within an element of structure. For protected steel elements and reinforced concrete elements, where failure is due to the steel reaching a critical temperature, the relationship is given by[29]:

$$t_e = K \frac{L}{\sqrt{A(A_t - A)}} \quad \text{(min)} \qquad \ldots.(6)$$

where t_e is the equivalent fire exposure in the standard test and K depends on the furnace design and is of order unity.

Thus the temperature attained at a critical part of an element exposed to a compartment fire can be assessed where measurements are available from a standard test of duration t_e on the same element.

A design method for the estimation of heat transfer to external fire exposed elements is also available[16,17].

Mechanical behaviour

Most of the information that has been available to measure the mechanical behaviour of structures exposed to fire is provided by the results of standard fire resistance tests of elements of construction. It is important, therefore, to understand how the test is carried out and what is measured.

Fire resistance tests

A loadbearing element of construction can fail in a standard test under any one of three criteria

—stability
—integrity
—insulation

Stability failure is failure to support the test load or, for floors, flat roofs, and beams, a deflection exceeding span/30. Integrity failure for floors and walls is the formation of significant cracks or other openings through which flame or hot gases pass. Insulation failure for floors and walls, is an average temperature rise of 140°C on the unexposed face or a local temperature rise of 180°C. The fire resistance is the duration of the test period or the time to failure under one of these criteria, whichever is shorter, except that, for stability, the fire resistance is reduced by 20% if the element fails to support the load 24 h later. (This 'reload' test is not applied in other countries.) It is interesting to note that a wall or floor could fail on insulation or integrity while still supporting the load.

These particular criteria for failure have been in existence for some time. The possibility of changes to the deflection criterion is frequently discussed, some support being voiced for a limiting rate of deflection rather than a limiting deflection, while it has been suggested that, for some constructions, a deflection of as much as span/20 would be acceptable. The insulation criterion is rarely discussed, although its origins are obscure; it may have been intended to prevent fire spreading by conduction to papers. The author has not been able to find an example of a real fire where there was fire spread by conduction through a fire-resistant wall.

The load applied is required to produce 'stresses of the same nature and of the same order of magnitude as would be produced at normal temperatures in the full-size element by the maximum permissible loads which the element is capable of carrying when designed in accordance with the requirements of the appropriate British Standards or Codes of Practice; loads other than these may be applied only by agreement between the sponsor of the test and the testing laboratory. The load shall be maintained constant throughout the test period'. Thus it is the reserves of strength designed to withstand extreme loads at normal temperature that are exploited for fire safety. The vertical edges of loadbearing walls are tested free from restraint. Floors, roofs, and beams, are supported and restrained in ways that 'as far as possible are similar to those which would be applied in service'; when these cannot be defined, the elements are tested simply supported.

There is some variation in results between test houses, thought to be due to variations in modes of heating, loading, and support conditions. Great efforts are being made to achieve more uniform results, although it might seem more useful to attempt to define what is being measured. However, the purpose of the test is to form the basis of the grading system used by regulators; it is not intended to be used by engineers for design purposes. Thus, the initial properties of the structural materials are not measured; the changes that take place when the temperatures within the element increase, are not monitored in a way to give design information; the desire to satisfy the reload test means that the test may be terminated before the mode of failure becomes clear. Therefore, at present, the design engineer needs to postulate a model for structural behaviour in fire and use the results of fire resistance tests, such as they are, plus whatever research data are available, to check his assumptions.

Design guidance is mainly confined to ways of passing fire resistance tests; since these are carried out on single elements, there is much less guidance for assessing the behaviour of frameworks and multistorey structures. Guidance for frameworks has been based mainly on calculations. However, there is a particular difficulty in calculating fire resistance in this country because the conditions for the reload test are not defined: there is not a prescribed cooling curve (timber elements are hosed down to prevent further charring but the other elements are not). For practical reasons, the load is maintained on some elements through the 24-h cooling period, while it is removed from other elements at the end of the test and reapplied 24 h later. It has not been found possible to measure the usefulness of this test, which is probably why it is not used in other countries.

Design guidance

Interim guidance[20] for concrete construction stresses the importance of good detailing of elements which, together with suitable proportioning of the members, will meet the objectives of satisfactory performance for up to 2-h fire resistance without being unduly sensitive to the actual rates of heating that might be encountered in a real fire.

For larger periods of fire resistance, it can be worthwhile using a method of analysis based on limit state principles, taking into account the effects of temperature rise on the material properties. Methods of analysis have been developed for flexural members (beams and slabs) where the mode of failure may be in flexure, shear, or combined flexure and shear. Analysis is carried out after the temperature of the tensile steel and the average temperature of the concrete has been estimated and the corresponding reductions in strength have been determined. Methods of analysis are available for statically determinate members (rare in practice but forming a basis for analytical treatment), for members monolithically built into supporting structures but not fully continuous (the most likely condition for members designed as simply supported), and for continuous structures. There are certain circumstances when the flexural action of a beam or slab can be replaced by membrane action, and it has been suggested that a deflection of span/20 may be acceptable[30]. Up to now, there has been less success in devising analytical methods for the design of compression members—walls and columns—and reliance must be based on experience from fire resistance tests and good detailing. The majority of methods developed so far are directed towards achieving certain levels of fire resistance but, in principle, the same approach could be adopted for compartment fire exposure and extended to frameworks and multistorey structures[30].

No discussion of concrete behaviour in fire is complete without a mention of spalling. The usual approach is to detail the element to avoid spalling but there is is no doubt that, if design rules could be established that showed that the element would perform adequately even if spalling occurred, this would be a great improvement.

Design rules for steel elements have been devised for estimating the critical steel temperature for columns and beams[23], and the heat transfer to the steel for both the standard fire and compartment fire can be determined[8, 23]. Calculating the fire resistance generally gives conservative results: one reason is that characteristic values of initial steel strength are used in calculations, whereas the test element is a random sample. However, correction factors have been devised[31]. Some information is available for frameworks and a special study of fire-exposed portal frames has been published[32].

Guidance for timber is mainly related to good detailing and nominal rates of charring[27], while for masonry the information is mainly in the form of tables of constructions deemed-to-satisfy the various fire resistance requirements.

Behaviour in real fires

The most familiar structural failures are those experienced in single-storey unprotected steel-framed buildings subjected to severe or moderately severe fires—a not unexpected result, since unprotected steel generally has a low fire-resistance. However, once designed to provide a given period of fire resistance, all structural materials appear to perform equally well during real fires. It is rare that a properly detailed building structure, built to comply with the regulations, suffers a major collapse during a real fire, although of course it may need extensive repair or even replacement if the fire has been very severe. A concrete structure may suffer extensive spalling and some deflection but still serves its purpose during the fire.

The effects of expansion may cause serious damage (e.g. in some long-lasting fires where concrete slabs have been heated to a significant depth and caused damage remote from the area where the fire occurred[33]) but major failure due to expansion of a fire-protected structure is rare while the fire is in progress. In general, the performance of building structures as loadbearing elements and barriers to fire spread is good. (Where fire breaches a wall or floor designed as a fire barrier, it is usually through gaps such as open doors or unprotected ducts.) This would suggest that the current fire grading regulations may be about right but are probably conservative.

Fire safety measures

Structural fire protection is only one part of the package of fire safety measures used in a building. There are two broad groups of measures:

- —fire prevention, designed to reduce the chance of a fire occurring;
- —fire protection, designed to mitigate the effects of a fire should it nevertheless occur.

Fire protection measures may be passive or active. Passive measures include structural fire protection, layout of escape routes, fire brigade access routes, and control of combustible materials of construction. Active measures include detection and alarm, fire extinction, and smoke control, all of which may be operated manually or automatically. When deciding what structural performance is needed, it would seem reasonable to take into account special measures designed to reduce the chance of a fire occurring, or measures designed to reduce the fire severity.

Early detection leading to early fire-fighting decreases the risk that there will be a large fire. Automatic detection and extinction measures decrease the risk that there will be a large fire. Although such automatic devices were developed originally to protect building contents, they indirectly protect the structure as well. In recent years, the combination of automatic sprinklers and a designed smoke-control system has been used to protect people escaping from fire in large buildings[34]. Since there are methods and data available for assessing the effectiveness of automatic fire detectors and sprinklers[14, 35, 36], there is scope for explicitly recognising their beneficial effects in the determination of the level of structural fire protection needed.

At present in regulations the limit of 7000m^3 compartment size for shops is doubled when there is an automatic sprinkler installation. This is a recognition that sprinklers provide fire containment. In London, all large buildings other than flats and maisonettes are required to have automatic sprinkler installations, except for very small compartments, and in return some relaxation of smoke-control measures and of water pressure in rising mains may be accepted[37]. There is, as yet, no explicit recognition that extra structural safety could be provided by active measures as a substitute for an increase in structural fire protection. It is interesting to note that, from a national point of view, a Home Office study shows that some 90% of industrial floor space could be cost-effectively covered by sprinklers and 25% by automatic detectors. Sprinklers should be cost effective in the larger shops, but not in hospitals, offices, schools, public houses, and restaurants, or in all but the largest storage buildings (because the probability of fire occurring is low)[38]. For the individual owner, of course, there may be benefits but, from a regulatory point of view, where there is no benefit in relation to fire losses, it would seem that requirements for sprinklers should be justified either because they are needed for life safety or because they result in savings elsewhere.

Fire grading

The present regulatory system is based on grading of elements in the standard fire-resistance test. This test does not represent the fire exposure, the loading (floor loads, structure, wind, etc.) or the restraints experienced in real fires, but this is not necessarily a drawback if it can be assumed that the test ranks performance of the elements in the same order and degree as their performance in a real fire when they form part of the building structure. A regulatory system can then select the grading needed according to the circumstances and the objectives. It is the lack of definition of the circumstances and the objectives that provides much of the dissatisfaction with the present system.

Objectives of the regulations

The level of fire risk to an individual person is fortunately low compared with other risks, as illustrated in Table 3[39, 40, 41].

TABLE 3—Some comparative risks of fatality

Activity	Fatal accident rate* person 10^8h exposure
Staying at home-average (excluding sickness)	3
Total for able-bodied person	1
Travelling by car (UK)	57
Travelling by car (USA)	95
Motor cycling (UK)	660
Fires in hotels (UK)	1
Fires in dwellings (UK)	0.1
Scheduled flights aviation (USA)	240
Average for disease (USA)	110
Natural disaster	0.01

*In these units a mean lifetime of 70 years corresponds to 160.
70 years = $6{\cdot}1 \times 10^5$h. $10^8/6{\cdot}1 \times 10^5 = 160$

Most of the life loss caused by fire involves few people in any one incident, and these losses occur mainly in dwellings. However, in a large building the potential for large life-loss is greater. Therefore, to maintain public confidence the national authorities have two main objectives:

- —maintenance of a low average risk per person, which means paying attention to dwelling fires;
- —reduction of the risk of fire disasters that will cause large life-loss or economic loss, or both[42].

Recent studies indicate that, because so high a proportion of fire casualties in dwellings results from personal incapacity or behavioural factors, there is little scope for addition to the Building Regulations that could further influence life safety in dwellings. In the case of other occupied buildings, the number of casualties by type of building is too few to enable firm conclusions to be drawn[38].

If we examine the origins of regulations for structural fire protection and control of building materials, we see that the regulatory requirements have arisen from the need to allay public concern, and this is done by reducing the risk of major fire spread in cities and by protecting a person and his property from the foolish acts of his neighbours. Thus the requirements are essentially designed to provide fire containment—by compartmentation and wide streets—and also to provide stability of major structural components. The insurance companies, concerned to reduce the maximum likely loss of a building structure or a building's contents, or both, also require containment and structural stability. In addition, they have placed major emphasis on the use of fire extinction measures: many of the public fire brigades were originally established by the insurance companies, who also pioneered the use of automatic detectors and sprinkler systems for property protection.

It is difficult to justify many of the existing regulations on the grounds that they save life but they do have the effect of reducing property loss.

Levels of grading

The level of fire protection required depends on a number of factors that are not all stated explicitly. The 1946 *Report on fire grading of buildings*[12] formed the starting point for current regulations. It considered fire load to be an important factor, as illustrated by Table 2. This relationship, in terms of fire exposure, can be expressed as:

$$t_e = \frac{L}{A_f} \qquad \text{(min)}$$

whereas, from the studies of compartment fires, equation (6) suggests:

$$t_e = \frac{L}{\sqrt{A(A_t - A)}} \qquad \text{(min)}$$

The level of grading chosen is not necessarily the equivalent fire exposure, however, because it also includes allowances for uncertainties and the consequences of failure. Another matter of concern in the report was the need to reduce property loss, and this resulted in recommended limits to compartment size.

The selection of three levels of fire load, as in Table 2, can be discerned in the current regulations where residential, office and assembly fall in the low group, shop and factory in the moderate group, storage and general in the high. In addition, the detailed grading and compartmentation requirements vary according to the height, area and volume of the building and vary again according to the building's use. It is not easy to explain the reasons behind all of these differences, although some guesses can be made.

It would seem reasonable for grading to increase with height in order to have increased structural safety for tall buildings, when the consequences of failure could be serious. There are also requirements that are related to the height of a fire brigade ladder, since, apparently, it was assumed that above this height a person could not be rescued and needed extra protection. However, since escape routes must now be designed so that people can escape unaided, some reappraisal may be needed.

The increase of fire grading with volume is presumably intended to take account of fire severity increasing with compartment size, but it can give anomalies because, for a given floor area, the designer can be penalised for providing a high ceiling. This enclosure of extra space does not add to the fire load and, indeed, from heat balance considerations, an increase in wall surface area could cool the fire. The floor area would be a better guide to the size of the fire load and the number of people who could be in the building.

The need to protect fire-fighters may be taken into account, but it is not clear how this is done in the fire gradings required.

The regulations make a distinction between dwellings or institutions, where there is a so-called sleeping risk or there are disabled people, and buildings where people work or play and can be expected to be able bodied. Thus, extra protection is given to people who do not escape because they are asleep or disabled and may have to stay in the building until the fire is exhausted.

The categorisation of buildings according to fire load is a reasonable approach, based on the total burnout principle; in practice, the treatment is broad brush, grouping together, for example, carparks with a low fire load and warehouses that may have a very high fire load under the heading of storage.

At the moment, there are three sets of regulations in Great Britain with the same broad objectives but with the requirements differing in detail. Thus, it ought to be possible to calibrate one set of regulations against another and assess the importance of the various rules. However, there is no evidence available that buildings in England and Wales, or London or Scotland, perform significantly differently in real fires. It is likely, therefore, that all the regulations are on the conservative side. This is encouraging, since it indicates that there is scope for change and that a more analytical approach would yield some benefit without prejudice to meeting the fire safety objectives. In any new approach, however, the fire safety objectives need to be stated explicitly.

New approach to fire safety

During recent decades, it has become clear that the tradional approach to fire safety is not enough on its own. With the higher standards of living in the developed countries come demands, by the consumer, for higher standards of personal safety. The changes in furnishings, the increased numbers of high-rise buildings and large assembly buildings, have directed the attention of the public authorities to life safety provisions, in particular to automatic detection and extinction systems, smoke control systems, control of furnishings, and efforts to improve fire prevention.

These changes in approach to the design of fire safety have at least three major implications for building structures:

—If life safety is assured by other measures, in what circumstances should structural fire protection also be provided?
—If measures are installed that reduce the chance of a large fire occurring, can the present levels of structural fire protection be reduced or eliminated?
—What is being spent on fire protection? Which combination of measures will give the optimum return on investment in terms of life and property saved?

If questions such as these are to be answered fully (whether by engineers or politicians), the risks, the benefits, the potential fire exposure, and the effectiveness of the safety measures, must be quantified. Much information is available, but even if these factors cannot all be quantified as yet, it is still important that the questions be asked.

On the assumption that a physical model for assessing fire exposure and structural behaviour exists, the designer then needs a definition of the performance required. While it is the responsibility of the authorities to set the levels required, these levels should be expressed in a way that is suited to a design approach and gives design methods that are compatible with the structural Codes. Thus the structural engineer needs to take the initiative if the changes are to be to his benefit.

Whether the performance is defined on a probabilistic basis, by various limit states, or by a modification of the present grading system, there are certain aspects to be included which would involve a more selective approach and, formulated properly, would give a system more responsive to changes in fire behaviour and building uses in the future.

A definition of objectives could include one or more of the following:

—protection of people while they escape
—protection of people who cannot escape readily
—protection of property within buildings
—protection of access for fire-fighters
—protection of adjacent buildings from fire spread
—protection of adjacent buildings from structural collapse

It would then be possible to define which elements need to have structural fire protection to meet these objectives and to be selective about the performance required. It might be that only the escape route structure needs protection. For a tall building, once people had escaped, the sole objective might be to prevent collapse of the building on to its neighbours; thus the loadbearing capacity of the walls and floors could be of more importance than their compartment properties and a reduced standard of insulation and integrity would be acceptable.

On the basis of the work described, a burnout fire could be defined, using agreed values of fire load per unit floor area and the compartment characteristics. Small buildings and single-storey buildings would not necessarily need to withstand a burnout, but for many larger buildings it might be thought necessary to have a notional value of fire resistance to give some protection, even if all other safety measures fail. For these buildings it would probably be considered that the main elements of construction should be able to at least withstand a notional burnout and that, in tall or important buildings, they should survive by a comfortable margin. Once the building had been designed to survive a burnout, the extra margin of safety would not necessarily be provided by increasing the structural fire protection; other protection measures, such as automatic sprinklers or automatic detectors, could be used. The benefits of such active measures would therefore need to be quantified.

The present grades of fire resistance required by the regulatory authorities must include, though not explicitly, allowances for uncertainties in loading, material properties, fire behaviour, fire-fighting and fire resistance testing. Such uncertainties remained unquestioned until attempts were made to introduce calculation methods. Defining all the uncertainties may be difficult, but there is scope for using the statistical data available and, as a first step, statistical models could be calibrated against the existing grading system. The standard fire resistance test itself, if it is to be extended to be a design tool, should be studied by engineers and modified as necessary.

There are advantages in a more selective approach not only to the designer and client but also to the authorities. By having defined fire loads for different uses, for example, the building design can respond more quickly than at present to significant changes in amount and type of fire load and the introduction of new hazards (or the withdrawal of old ones). The definition of objectives and the performance needed would encourage the production of buildings that are more fit for the purpose of fire safety. The protection needed for the fire-fighters would be identified more clearly and their major role as protectors of property would be recognised[13].

It is often suggested that a structural fire protection Code should include design for repairability. This would be, in principle, a departure from the usual approach, which is to design for an ultimate limit state, and it is difficult to see how it would be done in practice. A separate Code for the assessment and repair of fire-damaged buildings would, however, be very useful.

Conclusions

There is sufficient information available to produce design models for structural behaviour in building fires. The definition of performance requirement depends on a clear definition of the fire safety objectives and quantification of the safety levels required. Although this identification and quantification is ultimately the responsibility of the public authorities, the engineer should take the initiative so that any changes in the present system facilitate methods of design that are compatible with structural Codes and give cost-effective solutions. If, as seems likely, the standard fire resistance test is to be retained, it should be modified to give more design information to the engineer.

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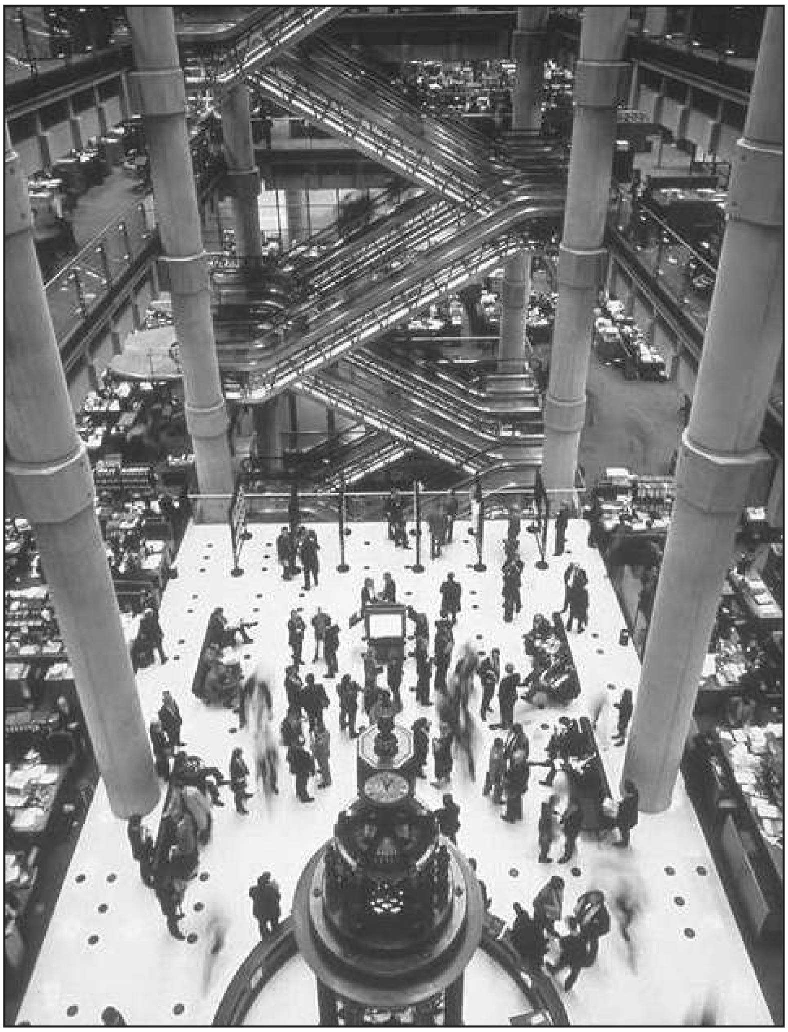
PAPER 11

Fire safety systems in tall buildings

Margaret Law, Technical Director, Ove Arup & Partners and DA Whittleton, Director, Ove Arup & Partners HK Ltd, International Conference on Tall Buildings, No. 3, Hong Kong & Guangzhou, 10-15 December 1984. Proceedings pp 522-526. Editors Cheung, YK & Lee, PKK. Organising Committee of the International Conference on Tall Buildings, Council on Tall Buildings and Urban Habitat, USA

Plate showing the atrium in the Lloyds Building, London. This is a significant example of Margaret Law's work at Arup where she applied engineering principles to fire safety design.



The design approach to fire safety was usually discussed in relation to structural fire protection and compartmentation, because they were major components of building regulations. Nevertheless, the design approach was also being adopted in relation to smoke management and means of escape and the measures that were used depended on building systems. The aim of this paper was to explain how fire safety could be incorporated into buildings, using these systems, and to illustrate what had been done in some recently constructed tall buildings.

This paper was presented first in Hong Kong and then in Guangzhou. At that time I think that fire safety engineering was not so familiar in the Republic of China and our discussions were very interesting…

Contents

FIRE SAFETY SYSTEMS IN TALL BUILDINGS

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SUMMARY

In addition to the well-established and traditional fire safety measures - structural fire protection, compartmentation, fire brigade activities - a design approach is being adopted for measures such as smoke management and escape design in tall buildings. These are discussed and their application to some recent tall buildings reviewed.

INTRODUCTION

In the design of fire safety for a tall building there are certain aspects which are specifically related to height:

- Most of the occupants will need to remain in the building for a significant period of time after the start of a fire. Instant evacuation is not practical, and rescue by fire brigade ladder is not possible.
- The major services essential for the functioning of tall buildings such as lifts, service risers and ventilation ducts, can provide paths for fire and smoke apread.
- Architectural features such as atriums and light-wells, which are desirable in deep buildings, can increase the risk of fire and smoke spread.
- The fire brigade must enter the building to fight the fire and the access routes, horizontal and vertical, must be protected.
- Structural collapse would cause major life and property loss.

In order to deal with these aspects, the traditional fire safety measures, in particular compartmentation and structural fire protection, are supplemented by active measures - automatic detection, alarm and extinction systems and control of smoke movement. Many of these systems have been well-tried and tested in various forms over the years. What is new is their incorporation into a design solution tailored to fit a specific building.

This paper discusses some of the less traditional measures, notably the management of smoke movement and the new ideas on escape route design and human behaviour. These reinforce the traditional measures which are still of vital importance, in particular, structural fire protection, compartmentation, control of the use of combustible materials, access and facilities for the fire brigade, fire prevention and good housekeeping.

SMOKE MANAGEMENT

It has been estimated that one person in ten will refuse to move through smoke if the visibility is reduced to 8m, and the combustion products from burning only 1kg of wood, when dispersed in a volume of 1000m^3, can reduce the visibility to this value (1). Near to the fire source, the smoke will be hot and will tend to form a layer under the ceiling, above head level. As the smoke moves away and cools, it can fill corridors down to floor level, and may enter rooms remote from the fire. This smoke movement is caused initially by expansion and buoyancy of the heated gases from the fire; subsequently it can be significantly affected not only by the ventilating and air conditioning systems within the building but also by pressure differences caused by stack effect and wind. Stack effect, when the external air is at a lower temperature than the air in the building, promotes upward flow of air through shafts in the building. Reverse stack effect when the external air is at a higher temperature, promotes downward flow. If a fire occurs below the neutral pressure plane then, in a building with normal stack effect, the smoke will tend to move with the air flow in the building up the shafts and out into the upper floors above the neutral plane. If the floors are reasonably well-sealed, then the floors below the neutral plane, other than the fire floor, will remain free of smoke. If the fire occurs above the neutral plane, smoke will tend to move out of openings in the facade of the fire floor, and with well-sealed floors, only the fire floor will be smoke-affected. However, floor openings will allow considerable smoke logging of the levels above the fire. It can be assumed that reverse stack effect will act on cool smoke in a similar way to normal stack effect but in reverse; however, if the smoke is hot, its buoyancy can overcome the downward air flows.

For standard atmospheric pressure the presure difference due to stack effect is given by (2):

$$\Delta P = 3460h\left[\frac{1}{T_0} - \frac{1}{T_1}\right]$$

Where ΔP = pressure difference (Pa)

T_0 = outside air temperature (K)

T_1 = shaft air temperature (K)

h = height above neutral plane (m)

The level of the neutral plane is given by (3):

$$\frac{h_2}{h_1} = \left(\frac{A_1}{A_2}\right)^2 \frac{T_1}{T_0}$$

Where h_2 and h_1 are shaft heights, and A_2 and A_1 are leakage areas in the facade, above and below the netural plane respectively.

The effect of wind on air movement within well-sealed buildings will not be great but, once a window is broken by fire, the wind can promote smoke movement within the building.

The wind pressure can be expressed as (2):

$$P = 0.6\ C\ V^2$$

Where P = wind pressure (Pa)

V = wind velocity (m/s)

C = pressure coefficient

Values of C and V are published in standard works on wind engineering and data for the calculation of air infiltration rates are available (4).

The traditional methods of smoke management - physical barriers and natural ventilation openings in protected routes - have been found inadequate for those tall buildings which are subject to the air flows and pressure effects described above. Alternative methods have therefore been developed.

SMOKE CONTROL

The term smoke control is normally used to describe the method which establishes favourable pressure differences across barriers using mechanical pressurisation. The spaces selected to be pressurised are usually the protected escape routes, that is the staircases, the lobbies and on occassions a corridor. The system is designed by identifying the size and location of the leakage paths and calculating the air flow that will be needed to maintain the required pressure differential.

The flow through cracks round a door or window is given by :

$$Q = 0.83A\ (\Delta P)^{1/N}$$

Where Q = air flow (m^3/s)

A = crack area (m^2)

N = index between 1 and 2

For large cracks N is taken as 2, for narrow cracks as 1.6 (5).

The total air supply needed to maintain a given level of pressurisation in a space is estimated by taking into account all the leakage paths from the space, both in series and in parallel. The design can, and should take into account the effect of some exit doors being open. Data for estimating crack areas and calculation methods are given in references (2) and (5). Reference (2) gives a computer programme which is specifically written for the purpose.

The advantages of this kind of active smoke control are that escape stairs and lobbies need not be on external walls; leakage in barriers can be allowed for; the stack, buoyancy and wind effects can be taken into account; exit doors propped open do not let in as much smoke as those in a traditionally designed building.

SMOKE EXTRACT

An early example of smoke extract design is the stack over the stage of a theatre. The roof vent of the stack is sized so that all air flow is from the auditorium to the stage, the neutral plane being at the level of the top of the proscenium (6). Another example is the design of automatic roof vents for industrial buildings which provide a clear layer of air at ground level so that the fire brigade may enter to tackle the fire (7). These are examples of natural venting, which relies entirely on buoyancy. Mechanical smoke extract is also possible, but is normally only practical for evacuating smoke from small fires. This can be explained as follows:

The smoke plume from a fire entrains air as it rises, and increases in size; the mass flow entrained above the fire is given by (7):

$$M = 0.2\ P_f\ y^{3/2}$$

Where M = mass flow (kg/s)

P_f = fire perimeter (m)

y = height above the fire (m)

For a fire of area $9m^2$ (ie $P_f \simeq 12m$) the mass flow at 3m above the fire is 12.5kg/s. A fire involving a typical office fire load would generate about $300kW/m^2$, so that the temperature rise at this level would be 215 K and the volume flow $17.5m^3/s$. This illustrates that in order to keep the smoke from even a small fire above people's heads, very high extract rates are needed. Furthermore, when smoke flows from the room down a corridor or round a balcony, the air entrainment rate can be doubled, so that the volume flow of smokey air becomes very large indeed. It may be concluded that mechanical extract of smoke is unlikely to be practical unless the size of the fire can be controlled, by automatic sprinklers, and the smoke plume kept as compact as possible to reduce entrainment.

The use of automatic sprinklers, to control fire size, and automatic venting (natural or mechanical) to keep smoke at a safe level above people's heads is a standard requirement in the UK for large covered shopping malls (8). The same approach can be adopted for other types of buildings, particularly those with atriums.

ATRIUM

An atrium in a tall building is an increasingly popular architectural feature and a method of admitting light into a deep building. However, the modern atrium, being roofed, can increase the risk of heat and smoke spread through the building. If the floors overlooking the atrium are glazed, then the risk of fire spread from floor to floor via the atrium is not likely to be greater than via the external facade, and with automatic sprinklers installed, the chance of vertical fire spread is low (either within the atrium or along the facade). However, even with sprinklers there is a chance of smoke entering the atrium, thus putting the other floors at risk, unless positive smoke management measures are adopted. The two approaches favoured are either to extract the smoke from the fire before it enters the atrium or to allow the smoke to enter and then vent it safely at roof level. For the venting to be successful, fresh air must be supplied, and if natural leakage is not sufficient then automatically opening inlets will be needed. It is the combination of automatic sprinklers and smoke extract which provides the best protection; for most atriums one measure on its own will not be adequate. A review of fire safety in atrium buildings has recently been published (9) and a code for use in North America is available (10). It is generally considered that even when a satisfactory smoke management system is provided, an atrium space should not be relied upon as the sole route of access to an escape stair or exit at upper levels.

DETECTION AND ALARM

In a tall building, heavy reliance must be placed on automatic detection systems, and there are inevitably conflicts between the desire for greater sensitivity and the need to avoid false alarms. Much improvement has been achieved in this area, although the importance of selecting the appropriate type of detector, installing it properly, and maintaining it regularly needs to be emphasised. In recent years, along with improvements in 'conventional' heat and smoke detectors, new systems have been developed such as continuous monitoring by air sampling and beam detectors. However, a person on the spot when a fire begins is still just as efficient as a detector (11) and therefore manual call points should always be readily available.

After the alarm has been raised, it is generally recognised that people want to know more than that the fire alarm has sounded. Methods of giving information and instructions over a public address system have been recommended (3), and have been requested by the FSD in Hong Kong under certain circumstances. An alternative method giving visual instructions on a digital display panel has also been proposed (12). It is interesting to note that the evidence available indicates that people do not panic in disasters provided they believe they are taking a useful course of action (3)(13), so that positive information should not only promote efficient escape but also reduce a tendency to panic.

ESCAPE

Escape codes differ in detail from country to country. However, they do share some common approaches: a person confronted by a fire should be able to turn away and find an exit to a protected route in the other direction, which means there should be at least 2 exits from any floor; there should be a limit on travel distance to the exit; once having entered a protected route, (usually a staircase) the person must be protected until a place of safety is reached. The place of safety is ultimately the open air at ground level, but in a tall building may initially be a designated refuge zone. In Hong Kong, the authorities do not at present actually require the inclusion of refuge floors in tall buildings, although the Fire Services Department does have recommendations on the subject. Many recent buildings do incorporate refuge floors, but in the absence of clear direction from the authorities their application will continue to be inconsistent.

Measurements have been made of crowd movement along corridors and on staircases, notably in Japan, Britain and Canada (14)(15). A formula for total evacuation time of a tall building has been proposed (14), and for a building with the same population on each floor and uniform staircase width the formula gives a typical evacuation time as the larger of the following:

$$T = \frac{nQ}{1.1b} + 16 \qquad (s)$$

$$T = \frac{Q}{1.1b} + 16n \qquad (s)$$

Where Q = population on one floor
b = staircase width
n = number of floors

This formula gives the evacuation time once people have reached the exit stairs. It is usually assumed that people should reach the exit within 2.5 minutes. It was originally thought that people would panic if a longer evacuation time were permitted, and lengths of routes to exits were defined accordingly. At the moment there is little scope in the escape codes for varying the travel distance according to the smoke management design, the exit widths, the space available, or the actual behaviour of people, and this subject merits further study.

PRACTICAL EXPERIENCE

Pressurization as a method of keeping escape routes free of smoke became well established in the UK once the British Standard was published. Although the principles will not change, it is likely that the standard will be revised and extended in the light of practical experience. In the early days, it had been considered necessary to test the assumptions on a larger scale than was possible in the laboratory. To this end, fire tests were carried out in the United States on two buildings scheduled for demolition, a 22 storey office building in New York and a 14-storey hotel in Atlanta. Both tests demonstrated that pressurization could give satisfactory smoke protection of the stairways. In Hamburg, a system designed for a brand new office building was tested by fire and proved satisfactory (16). Fortunately, it is not considered necessary nowadays to subject every new system to this ordeal. Commissioning of the system is carried out by making pressure measurements at all the relevant locations. This is essential because the leakage areas actually available in the building may not be the same as those assumed for design purposes. Because the system must be designed to work when doors are opened, pressure relief flaps may be needed to avoid excessive pressures when all doors are shut.

Although the principle of pressurization is simple, the solutions can become complicated. A recent example in London is the Trocadero Entertainment Complex, for up to 10,000 people, with a 21,000M^3 atrium, eight service cores and 27 individual pressurization systems.

In Hong Kong, staircase pressurisation is recommended by the Fire Services Department, but is not yet a requirement. As a result, some buildings are being provided with pressurisation systems and some are not. Where systems are provided, the British Standard is generally being used as the basis of design.

Modern atriums are relatively new in the UK, and initially the fire authorities were very conservative. Whereas fire resistant glazing to the atrium was considered essential at one time, it is not usually required these days. Drenchers are now considered to be of doubtful benefit in preserving glazing, and they can interfere with smoke venting. It is becoming recognised that each building poses its own problems and requires its own solution: for example experience has shown that smoke ventilation should not be defined as an arbitrary number of air changes per hour or be related simply to floor area. The use of the building in terms of people and contents is also an important factor.

Tall buildings are not common in the UK, and a number of the existing atriums are in relatively low-rise buildings. An early example in London is Coutts Bank, strand, constructed within an existing facade with a 4-storey garden court covered by a glazed roof of 50M span. Fire resistant glazing was required for the areas overlooking the court. Taller buildings in London include Lloyds Chambers, Goodmans Yard, a structural steel frame office building with a 50M high atrium: buildings nearing completion are Finsbury Avenue, Finsbury and Lloyd's redevelopment, Lime Street. The Lloyds's building has the tallest atrium in the UK. At its base is a double height underwriting room. There are 12 gallery levels above, and initially the first two levels will be open with the other levels glazed. Special attention has been paid to the sprinkler system and the provisions for smoke ventilation. Up

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to now, high rise hotels with atriums have not been constructed in the UK but as confidence grows they will undoubtedly appear.

In Hong Kong, atriums have become very popular in recent years and are now a feature of many major shopping centres and hotels. The tallest atrium is at the Royal Garden Hotel in Tsimshatsui, where hotel rooms lead on to corridors overlooking a ten storey atrium with a glazed roof. Most of these recent atria are designed with sprinkler protection and smoke management systems, usually incorporating high level extract and low-level fresh air make up via automatically opening vents. There are at present no regulations specifically covering the design of smoke control systems but draft legislation, covering the design objectives rather than the means of achieving them, is currently under consideration.

CONCLUDING REMARKS

Fire safety in buildings generally, and in tall buildings in particular, has been the subject of considerable research, and methods are being developed to deal with problems which traditional precautions and approaches are unable to cope with. Whilst the updating of existing legislation and codes is essential and is to be welcomed, it is important to recognise that although many modern tall buildings have much in common, each building will have its own problems and should be considered individually. The objectives of design for fire are clear; the detailed means of achieving those objectives will vary.

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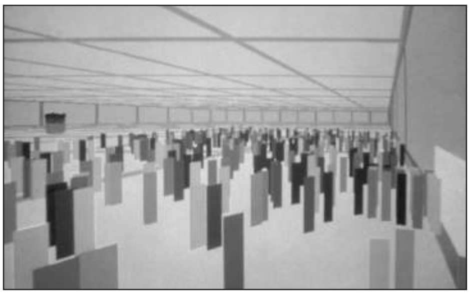
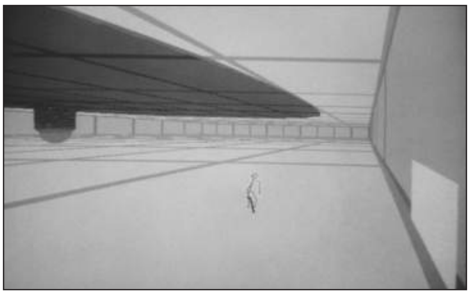
PAPER 12

Fire protection in terminal buildings

Margaret Law, Ove Arup Partnership, London, Paper in Building Services For Airports, Symposium at Gatwick, UK, 6-7 November 1985. Reprinted with kind permission from The Chartered Institution of Building Services Engineers (CIBSE), UK

Plate showing an internal view of Stansted Airport and computer graphics showing the combined results of computational fluid dynamics for smoke movement and evacuation modelling. The last man out with a walking stick is now recognised in Airport escape design as representative of the demographic change in the population. Margaret's work on Stansted Airport formed the basis of Arup's fire safety design at several International Airports (see Paper 18).





In 1984 I was asked to provide a paper for a Symposium on 'Building Services for Airports' organised by the Chartered Institution of Building Services Engineers (CIBSE). It seemed to me that since CIBSE members were used to installing fire protection systems in buildings, they would probably be interested to have a measure of how useful they had been in practice. Not long before, the British Airports Authority had commissioned Arup R&D to prepare a review of the fire design of a new airport terminal. One important issue was the need for large compartment volumes, not permitted under Building Regulations without obtaining a relaxation. This involved our collecting a range of data from experiments, surveys, and fire statistics, to illustrate how various measures could compensate for lack of compartmentation. I was pleased to have the opportunity to provide this collection of data and other information to a wider audience. It was also useful to have the design aspects on record. The paper was awarded the CIBSE Bronze Medal.

FIRE PROTECTION IN TERMINAL BUILDINGS

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The fire protection of passengers, visitors and staff must be of a high standard and disruption of passenger services must be minimised. In passenger terminals, the compartment sizes conventionally required for assembly buildings are usually exceeded but safety standards can be maintained by alternative measures including active protection systems. Fire and smoke loads have been surveyed and can be used in the design of smoke management systems. Walking speeds of passengers in a terminal have been measured.

INTRODUCTION

An airport passenger terminal is an important public building which can at times hold a great many people. The fire protection of the passengers, visitors and staff must be of a high standard yet there is little official guidance on the methods of maintaining public safety in the special conditions of a passenger terminal. Thus in addition to safeguarding the terminal in order to minimise the risk of disruption to passenger services and the risk of damage to structure and contents caused by fire, the airport authority has a major responsibility in setting its own standards of public safety. For example, the British Airports Authority has its own fire safety codes and has commissioned special studies. The building regulations form a starting-off point but their limits on compartment size may interfere with the efficient operation of the terminal. Conventional codes of practice for design of means of escape may also be inappropriate. It is the purpose of this report to discuss the ways in which equivalent levels of safety can be provided by alternative measures, in particular active protection systems, and to include some of the design data collected by the British Airports Authority and others.

OCCUPANCY CLASSIFICATION

The main use of the Terminal would bring it into the occupancy class "Assembly". In addition to the main public areas there are sub-occupancies, such as ancillary offices, plant rooms and the baggage loading hall, which are normally in separate compartments. In the public areas there will be a number of activities, including check in, customs, duty free shops, cafes, bars, baggage reclaim, which are additional to the main purpose of channelling passengers through the terminal to and from the aircraft.

The non-public areas can generally be dealt with under the building regulations and the codes of practice. The public areas, with their mixed uses, need special appraisal.

PEOPLE USING THE PUBLIC AREAS

The passengers will range from babes-in-arms through adults to very elderly people, most of them unfamiliar with their surroundings. In an international airport a significant proportion may not understand broadcast or televised messages. Since in normal circumstances passengers need to cover some distance before they finally reach the aircraft, it can be assumed that they will be mobile; the airlines arrange transportation for those passengers unable to walk.

Staff will be adult, mobile and generally familiar with their surroundings. As far as possible it would be hoped they could carry out first aid fire fighting - some might receive special training - and assist passengers towards an exit.

There is also the contribution made by the airport's on-site fire brigade. The normal standard would be a requirement for such a brigade to attend the scene of a fire within 3 minutes of the alarm being given.

CHANCE OF A FIRE OCCURRING

There are no separate statistics available for fires occurring in air terminals in the U.K. but the record appears to be good.

It is likely that the chance of a fire occurring in the shops, cafes etc. in the public areas would be similar to that in shops and cafes elsewhere, although the standard of 'house keeping' may be of a higher standard than in some high street shops.

From statistics of fires attended by local authority fire brigades, the annual probability of a fire occurring in a shop is estimated to be 6.6×10^{-5} x floor area (m^2) and for places of public assembly, including public houses, restaurants, cafe's* non-residential clubs etc. a value of 7.5×10^{-5} x floor area (m^2) has been suggested by Rutstein(1). No data are available which would be relevant to the check-in, circulation areas and lounge areas of a terminal.

Fire prevention measures can be designed to reduce the chance of a fire occurring. They include paying particular attention to the design of services, the use of non-combustible or Class 0 finishes wherever practicable, furnishings and fittings which are non-combustible or do not ignite easily and a high standard of "good housekeeping".

By such means the chance of a fire occurring in the public areas would be kept as low as possible.

CHANCE OF A FIRE BECOMING LARGE

Various measures can be used to reduce the chance of a fire becoming large:

Attendance time

The potential benefits of reduced attendance times by local authority fire brigades have been assessed by the Home Office(2). The conclusion was that the factor most likely to contribute to the development of fires into large loss fires is delay in the discovery of the fire, rather than the speed and weight of initial attack. Some provisional estimates for 1978 indicated that for occupied buildings other than dwellings, when fires were discovered within 5 min of ignition only about 5% spread beyond the room of origin, whereas 17% did so when discovery was later.

Detection

As a result of a survey of industrial fires by Rutstein(3) it was concluded that where people are present in a room at the time of ignition, they are at least as efficient at reducing the chance of a fire becoming large as automatic detectors would be in an unoccupied building. When people were not in the room at the time of ignition a general estimate of the potential benefits of automatic detection is that they give on average a reduction of damage in shops of 85% with direct line alarm and 40% with local alarm. For pubs, restaurants and similar the figures were 55% and 40% respectively. On average detectors resulted in a 50% reduction in damage. Earlier work by Dunn and Fry(4) indicated that on average they reduce the chance of a large fire by a factor 2, but for terminals the factor is probably less, because much of the floor area is devoted to low fire load activities. Nevertheless, for large terminals it would be prudent to install automatic detectors in all public areas, except where it can be established that people will be present at all times.

Automatic sprinklers

The benefit to be obtained from automatic sprinklers depends on the use of the building. In industrial buildings they can reduce the chance of a large loss fire by a factor of about 6(4) but in shops Roger(5) gives the factor as 2. For terminals, it would probably be less than 2, again because of the low fire load activities in a large proportion of the public areas.

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* Some of these would be defined as 'Shop' in Building Regulations.

Fire brigade reports include an assessment of the floor area damaged by fire. Statistics for shops from Morgan and Chandler(6) indicate that for large fires, that is ones of $10m^2$ area or more, the proportion of fires P(%) exceeding an area A_f (m^2) is given by

$$P = 62\ A_f^{-0.95} \text{ for sprinklered shops ....} \quad (1)$$

$$P = 107\ A_f^{-0.77} \text{ for non-sprinklered shops} \quad (2)$$

Similar statistics given by Morgan and Hansell(7) for large fires in offices can be arranged to give

$$P = 60\ A_f^{-0.63} \text{ for sprinklered offices} \quad (3)$$

$$P = 180\ A_f^{-0.78} \text{ for non-sprinklered offices} \quad (4)$$

However the non-sprinklered data for 'daytime' fires in offices are significantly different from those for 'night time'.

$$P=130\ A_f^{-0.78} \text{ day} \quad (5)$$

$$P=340\ A_f^{-0.78} \text{ night} \quad (6)$$

This illustrates the value of people being present. If they are, then sprinklers in offices would reduce the chance of a large fire by a factor of about 1.5. If they are not, then by a factor of about 4.

The data for offices, with their relatively low fire loads, suggest that in those areas of a terminal with even lower fire loads - the circulation areas, for example - automatic sprinklers would not add much extra benefit to the reduction of the chance of a fire becoming large, particularly while these areas are full of people.

Dispersion of fire load

It is suggested by Marchant(8) that in some areas there may be a significant separation of fuel "packages" and this would reduce the fire severity.

Taking this concept further one approach is to consider the main concourse areas as places of relative safety and to treat selectively those 'fuel packages' such as shops which constitute higher fire loads and/or higher fire risks. For example, a duty free shop could be considered as a partial compartment, and be fitted with automatic sprinklers designed to control or extinguish a fire starting in that area. Such an approach would reduce the chance of a fire becoming large. However, before operation of the sprinklers, considerable smoke and hot gases could nevertheless be produced and it is necessary to consider what effect this might have on escape from the concourse areas.

SMOKE PRODUCTION

Estimates of smoke production become important when people have long distances to travel before they reach an exit, as in covered shopping centres for example (see Hinkley(9)).

Building fires produce smoke, toxic products and heat. Smoke reduces visibility. Toxic products produce injury, unconsciousness and death. Heat spreads the fire and warms the air so that it expands, becomes buoyant and transports the smoke and toxic products (At a later stage heat attacks the structure).

Most people are reluctant to move through smoke. About one person in 10 will turn back if the visibility is less than 8m and in a $1000m^3$ space the products from burning 1kg of wood can reduce the visibility to 8m (see (9) and Butcher and Parnell (10)). In the same space the products from burning 10kg of wood would produce a dangerous concentration of toxic products for the period of exposure likely to be experienced by escaping people. Thus, in general, loss of visibility becomes a problem before toxicity and if people are to escape, then the smoke concentration must be low.

People in the vicinity of the fire will of course be exposed to some smoke, but during the initial stages, the hot smoky gases will tend to form a layer at ceiling level, leaving a relatively clear space below. The speed of layering can be calculated using estimates of the rate of decomposition of building fires and entrainment equations for the smoke plume.

The amount of heat and smoke produced depends on the amount and type of fire load and the rate of burning. Traditionally, fire load has been defined in terms of weight of wood per unit floor area and studies have shown that in terms of heat output this is a reasonable approach for most buildings, even today.

Fire load density can be defined as the weight of fire load, in wood equivalent, per unit floor area. Some values measured in terminals are shown below

TABLE 1 - Fire load density measurements (kg/m²) in terminals

Occupancy	Fire load density (range) Drysdale et al (11)	Kirby(12)	Suggested for design
(a) average values			
Lounge		6.7 (2.9-9.7)	10
VIP Lounge	40 (25-46*)	17.2	20 if non-combustible finish
Restaurant/buffet	16.2 (15-17)	11.2 (10.9-11.8)	30
Control	-	5.5 (1.5-8.3)	10
Duty free store	38.4 (2-77)	-	120
(b) single values			
Duty free shop	28	-	50
Duty free gift shop	20	-	30
Baggage reclaim	4	1 excluding baggage	1 plus $\frac{15N}{A_f}$
Check-in Hall	-	5.6 excluding baggage	6 plus $\frac{15N}{A_f}$

* cork tiles on the wall

N.B. Kirby assumes each piece of baggage is 15 kg of wood equivalent. It is reasonable to assume, on average, 1 piece of baggage per member of the public, which gives a total baggage weight of 15N kg where N is the number of people in the area concerned.

The suggested design value for the duty free shop has been increased significantly over that measured because it is likely that the fire loads are increasing.

The rate of burning R (kg/s) of a fire load L(kg) on an area A_f(m²) is given by

$$R = \frac{L}{A_f} \times \frac{A_f}{60T} \qquad (7)$$

where $\frac{L}{A_f}$ = fire load density (kg/m²)

T = burning time (min)

For furniture freely burning, work by Theobald and Heselden(13) shows that a burning time of 20 minutes is reasonable. The effective calorific value for wood is 13MJ/kg, thus giving the total heat output of a fire Q(MW) as

$$Q = \frac{L}{A_f} \times \frac{A_f}{60\times 20} \times 13 = .011 \frac{L}{A_f} \times A_f \qquad (8)$$

For a fire load density of 10 kg/m² the heat output would thus be 0.11 MW/m² and for a fire load density of 50kg/m² (the duty free shop) it would be 0.55MW/m².

It is necessary to assume a fire of a certain floor area which may be increasing with time. When the fire is controlled by sprinklers. statistical data for sprinklered shops indicate that a reasonable maximum fire area for design purposes is 9m²(6). How can the design fire area be estimated for non-sprinklered shops or for other types of use?

Until the fire is controlled by sprinklers or fire fighting it is likely to increase exponentially. A doubling time of 4 minutes has been suggested by Baldwin and North(14), that is, the fire area doubles in size every 4 minutes(14). On this assumption the fire area could be as follows:

$$A_f = 3.0e^{.003t} \quad m^2 \qquad (9)$$

where t = time s

and $A_f = 3.0$ m² at $t = 0$

After 2½ min = 150s, A_f would be 4.7m², after 5 min it would be 7.4m².

We can compare this equation with one measured by Ramachandran(15) for the textile industry from actual fire incidents:

$$A_f = 4.69e^{.00105t} \quad m^2 \qquad (10)$$

Here the doubling time is 11 minutes (660s). At 2½ min A_f is 5.5m², after 5 min it is 6.4m². It may be that equation (9) is somewhat conservative.

Calculations of entrainment of air into the smoke plume from a growing fire indicate that very large volumes of smoke can be produced, some 10 to 100m³/s. If escape times are longer than normal, then either a large smoke reservoir or a designed smoke extract will be needed, if the space is to be maintained relatively safe while the people are escaping.

The amount of smoke to be handled can be limited by sprinklers and this is the accepted Home Office(16) approach for covered shopping centres. Where there is a very large space available it is worth computing smoke movement without smoke extract in order to estimate the time available before smoke provides a hazard to the occupants. Field model computations as described by Cox and Kumar(17) can be applied to solve the flow equations in large enclosures. The results of such a computation for an enclosure measuring 300mx180m on plan, with a height to the roof of 12m is illustrated in Fig. 1. The postulated fire was specified according to equations (8) and (9), assuming a fire load density of 20 kg/m² and no control by sprinklers. This would represent a worst case condition for a lounge area.

ESCAPE PROVISIONS

In general escape routes are designed so that should a person be confronted by a fire he can turn away and move unaided to an exit. Thus there should be at least 2 exits available in substantially different directions. The exits lead either directly or via a protected route (usually a staircase) to a place of safety which is normally the open air at ground level. A separate compartment (also provided with escape routes) is sometimes used as part of the protected route. The number of exits needed is usually controlled by the travel distances (see below), but may also be related to the number of people. The width of exits depends on the number of people to be evacuated and is calculated on the basis of one unit of exit width of about 0.5m accepting 100 people in 2.5min. The total exit width is calculated on the assumption that one exit will be blocked by fire.

In general, the codes set a limit of 45m travel distance to the nearest exit. When the floor layout is not known they set a limit of 30m distance drawn on plan to the nearest exit.

The practical consequence of the code requirement for limited travel distance to an exit is that where the diameter of the floor exceeds about 60m (area about 2000m²) it is not possible to meet the travel limits if all the exits are at the perimeter. Exits leading to protected corridors or shafts must be introduced within the floor space. It can be undesirable or impractical to lead people into tunnels and the Greater London Council Code (18) does give limited scope for increased travel distance over large floor areas, although it gives no technical basis for this allowance.

However, the major difficulty with the code approach first became apparent with the building of covered shopping centres. It was recognised that people leaving the shops when the fire alarm was raised would naturally use the covered malls to reach an exit from the centre and it was not practicable to limit the total travel distances to 45m. It was therefore decided instead to control the smoke hazard. (16) and Morgan (19).

All shops are fitted with sprinklers. Smoke which flows into the mall is collected in a ceiling reservoir above people's heads and then vented to the outside (naturally or mechanically). Alternatively, smoke is collected in a ceiling reservoir in the shop and is extracted mechanically so that it does not enter the mall.

It would seem equally valid to permit longer travel distances in a terminal, if smoke conditions are tolerable for a sufficient time.

The code assumption that it takes 2.5 minutes to travel 45m, i.e. 0.3m/s, gives a very slow walking speed and represents movement down a crowded corridor with less than $0.2m^2$ floor area per person. However, in open space, people move more quickly. A table prepared by Marchant is shown below, with added data provided in a memorandum to the Scottish Building Regulations.

TABLE 2 - Variation of horizontal walking speed at different population densities

Density N/m^2		< 1	1	2	3	
Investigator						
Miliniskii	(20)	-	1.6-0.6	0.9-04	0.6-0.32	*
Fruin	(21)	1.3	1.0	0.55	-	
Pauls	(22)	0.6	0.4	0.27	0.14	**
Hankin & Wright	(23)	1.08-1.3	0.7	0.6	0.42	
Togawa	(24)	1.3	0.9	0.46	0.3-0.5	
Scotland	(25)	1.3	1.0	0.62	0.45	

*Range of values given by different values of threat (more threat gives greater speed)
**Modified staircase values.

Fruin (21) observes that in normal situations the carrying of hand baggage does not alter gait or travel speed significantly. Measurements have been made, by courtesy of the British Airports Authority, of walking speed in a crowded baggage reclaim hall. The median speed for individuals was found by Butt (26) to be 0.9m/s and for groups was 0.7 m/s. As a conservative estimate it has been suggested that a person plus baggage passing through an exit is equal to 2 persons without baggage.

In estimating the time needed for escape from a terminal other aspects are important such as separation of families while waiting in a departure lounge and unfamiliarity with the language. A designed smoke management system can provide extra time for these aspects. Once they have been allowed for, the maximum distance to an exit could be determined from the remaining time available, and the walking speed appropriate to the population density.

COMPARTMENT SIZE

Compartment size

Compartment walls and floors are required to separate areas in a building with substantially different uses and to reduce the maximum likely size of fire.

Most regulations set limits on compartment area or volume for certain occupancy classifications. For Assembly, the following have been listed (8):

TABLE 3 - Volumetric limits for Assembly Buildings

Regulation for:	Volume/Area Limits
England and Wales (27)	7,000 m^3
Scotland (28)	No Limit
Canada (29)	372 m^2 to no limit [a]
New Zealand (30)	930 m^2 to 2790m^2 [b]
USA (31)	410 m^2 to no limit [c]

[a] 372 m^2 for a combustible building to no limit for non combustible construction.

[b] 930 m^2 when building is 2 storeys with a combustible intermediate floor. 2790 m^2 for a single storey building of a high fire resistance construction: intermediate allowable areas for combustible construction, i.e. similar to Canadian Code.

[c] 410 m^2 per floor for a two storey building of heavy timber combustible construction. 557 m^2 for a single storey combustible building with a population of not more than 300 persons.
No limit for a fire-resistive construction.
All similar to the Canadian Code.

Only the Regulations for England and Wales have an upper limit for volume and this limit is not practical for most terminals. Nor is it consistent with the limits set for other types of occupancy in England and Wales.

It can be concluded that the limitation is an administrative device to ensure that any large public building is appraised at Departmental level through the relaxation procedure.

In these circumstances the grounds for relaxation would undoubtedly include measures to reduce fire and smoke spread and to provide adequate means of escape.

CONCLUDING REMARKS

Building services can make a major contribution to fire safety in terminals, but they should be used selectively in order to relate the type of protection they can provide to the needs of the passengers and staff in the special conditions of a passenger terminal.

Automatic detection is of most value when an area is likely to be unoccupied for any significant period. Where automatic detectors are installed, experience shows that direct-line alarms are better at reducing the chance of a fire becoming large.

Automatic sprinklers offer the most benefit, in terms of reducing the chance of a large fire, where there are high values of fire load. Thus they are more obviously beneficial in shops and duty-free areas than in main circulation areas, where the fire load can be maintained at a low level. There is thus a case for partial sprinklering, when the fire loads are contained in well separated "packages" surrounded by 'sterile' areas with low fire load.

The large uninterrupted floor areas which are desirable for efficient circulation of people in the terminal can give rise to longer-than- normal travel distances to a fire exit. In compensation, the speed of movement will generally be two to three times greater than normally assumed for people escaping down corridors. However, separation of families, unfamiliarity with layout and language, and possible hampering of exits by baggage may mean that extra time for escape is needed. Smoke extract can be designed to give this extra time, taking into account the geometry of the enclosure, the fire loads in the space and the likely size of fire. Alternatively, it may be possible to exploit the volume available in a larger enclosure to provide a smoke reservoir.

The operation of automatic smoke extract systems will depend on signals from automatic detectors. The extract may rely on natural buoyancy or it may be mechanical. Mechanical extract is needed when there could be adverse wind effects. Automatic opening of doors or louvres for inlet air may also be required so that the extract can work efficiently.

It appears that it is only in England and Wales that the Regulations impose such a low limit on compartment size for Assembly Buildings. Experience suggests that a successful case for relaxation can be based on provision of good fire prevention and good housekeeping, early detection and alarm, speedy first aid fire fighting, automatic extinction systems in selected areas and smoke management designed to give people time to reach a protected escape route or an exit to the open air.

SYMBOLS USED

A_f = floor area (m^2)

L = fire load in wood equivalent (kg)

N = number of people (-)

P = proportion (%)

Q = heat output (MW)

R = rate of burning (kg/s)

T = burning time (min)

t = time since start of fire (s)

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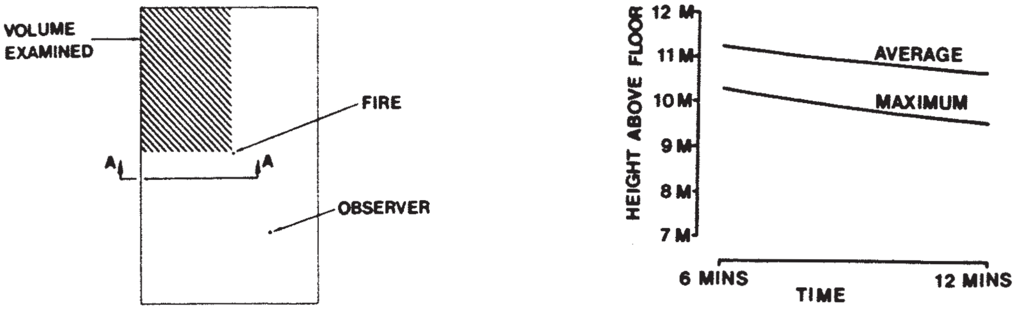
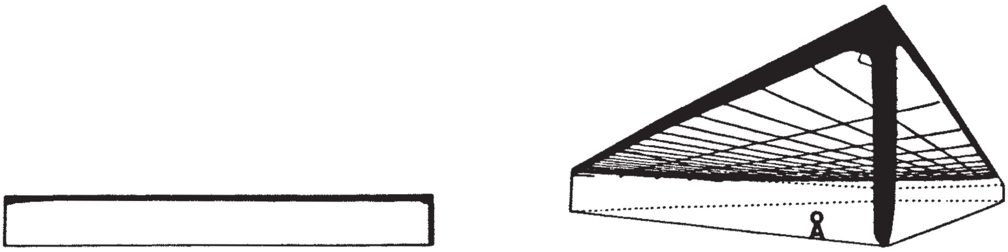
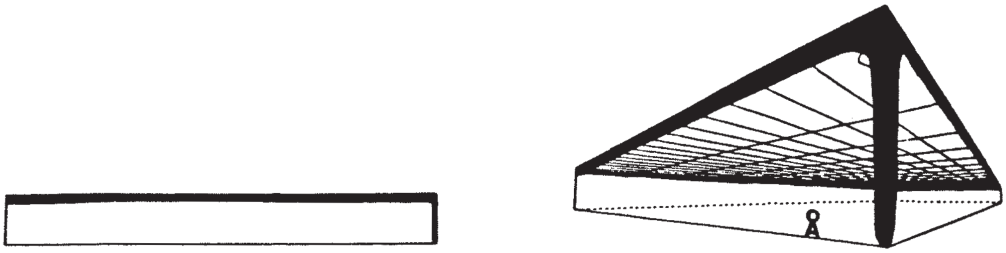


a. PLAN VIEW

b. SMOKE LAYER DEPTH



c. SMOKE AFTER 6 MINUTES



d. SMOKE AFTER 12 MINUTES

FIRE SIMULATION

FIGURE 1

PAPER 13

Translation of research into practice - building design

Margaret Law, Ove Arup Partnership, London, Fire Safety Science - International Symposium No 1 Gaithersburg, Maryland, 7 - 11 October 1985. Proceedings, pp 603-609. Editors Grant, C & Pagni, P. Taylor & Francis, USA

Plate showing the concourse at Liverpool Street Station, London. Furniture calorimeter tests on passenger rolling stock were commissioned by Arup to enable us to estimate the peak heat release rate for the carriages using this station. The resultant fire dynamics model was then used on other rail stations in the U.K.(see Paper 15).

When I am asked to contribute a paper to a meeting I normally agree if it fits a specific purpose or purposes. It may be to force myself to make some sense of ideas floating around in my head, or it may be to set down for the record some interesting design aspects of a specific project. Sometimes it aims to spread propaganda about fire safety engineering. It goes without saying that one should try to tailor the paper to the audience - and the most difficult people to engage in an audience are researchers. They think that consultants treat their work in a cavalier way – which of course we do – and we think that researchers take a ridiculously narrow view of our work with no sense of proportion – which of course they do. Therefore this paper had two purposes, one to sort out ideas and the other to show why consultants are supporters of fire research.

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Translation of Research into Practice: Building Design

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ABSTRACT

Progress towards 'fire engineering by design' will be slow unless researchers can demonstrate to the public authorities and the engineering community that the objectives of fire precautions can be achieved more effectively than at present. Research can give methods of quantifying and defining the requirements for public safety. It is then possible for the building designer to adopt the fire protection measures appropriate to the use of the building and its importance in terms of people and property. Practical examples of applying fire engineering design methods are given.

INTRODUCTION

It is over ten years since I joined a large engineering practice, with the broad brief to "provide fire engineering by design". The results of fire research must be a major input, because most of our regulations and code of practice cannot be applied directly to innovative buildings. Working with creative architects and engineers to find a practical solution is a challenge. The fire engineering advice must be soundly based and respect the needs and aspirations of the designers and users of the building. Fortunately the fire research is of a high standard, but the administrative procedures and bureaucratic attitudes we must work with can be frustrating. It is in changing these attitudes that I believe research should make a major impact. Except perhaps in North America, the relatively small numbers of professional fire engineers exert little influence at a national level; they are certainly not as influential as the structural engineers, for example. In this paper I would like to explore this theme but first, as the French say, a little history.

THE LAST FOUR DECADES

Forty years ago the UK government published a report on 'Fire Grading of Buildings'(1). The objectives of fire precautions were stated to be 'to safeguard life and property' and to this end fire precautions should aim 'to reduce the number of outbreaks of fire' and, in relation to fire grading, should 'limit the development and spread of a fire in the event of an outbreak and......provide for safe exit of occupants'. It was considered that a rational and economic combination of passive and active defence measures was the ideal, but was difficult to achieve in the absence of a coordinated body of fire statistics.

Shortly after publication of the Report, the systematic collection of fire statistics was initiated. In 1980 the UK Home Office published a consultative document on 'Future Fire Policy'(2) which summarised the results of a study started in 1976 to review and measure the total cost of fire to the community and submit proposals as to the range and level of measures which should desirably be taken to have the optimum effect in mitigating losses. The fire statistics provided a major input. Some brief extracts from the report are given here.

The current numbers of annual deaths and injuries in the UK are 900 and 6000 respectively and the casualty problem which exists 'derives essentially from a number of small fires, mostly in dwellings, affecting just one person, normally close to the source of ignition'. In discussing Building Regulations and life safety the report suggests that 'because so high a proportion of fire casualties in dwellings results from personal incapacity or behavioural factors, there is little scope for additions to the Regulations which could further influence life-safety. In the case of other occupied buildings, the number of casualties by type of building is too few to enable firm conclusions to be drawn'. The report draws attention to the high fire protection costs in large buildings to which the public are admitted and suggests they are expensive compared with those for other areas of public safety.

This report confirms that the UK fire grading requirements of the Regulations have been broadly successful in relation to life safety and structural stability. This is generally true for the other developed countries. Whether the requirements are rational and economic is a topic which is not really addressed in the report although there are some interesting assessments of the economic benefits to the community of installing active fire protection measures in various sectors.

DEVELOPMENTS IN RESEARCH AND PRACTICE

Research and Regulations

With the background of buildings being relatively successful in surviving fires, research has been devoted more to the behaviour of the contents. In relation to life safety, the areas of research interest have been domestic dwellings and institutions. In relation to property safety, the major research interest has been in the contents of industrial and storage buildings. However, in practical building design the major constraints and the increased expenditure on fire safety, needed to comply with regulations, are incurred in quite different areas. For life safety, it is the buildings which contain large numbers of the public which are the major concern, while for property, the standards of protection, both active and passive, are being increased in buildings which are not particularly valuable, either in structure or in contents.

Why should this have happened? One reason is that the building authorities perceive - quite rightly in my view - that the larger the number of people exposed to risk, which means the more serious the consequences of failure, the higher the standard of public safety should be. However there is no agreed definition of this standard and no assessment of whether the measures required are effective and make the best use of resources. The fire authorities are only just beginning to admit that such an assessment is desirable but they believe it is not possible to do one. Research should show that it is possible and how it can be done.

The authorities also perceive that the public can become alarmed by a large property loss, even when there are no deaths or injuries. What is the critical size of loss and how does it vary with sector?

How much should public regulations mandate the safety of private property? Mandatory automatic sprinkler protection is increasing while at the same time the standards of structural fire protection, at least in the UK, are being raised.

The improvement in structural protection is being achieved not by changing the regulations, but by re-writing the rules for the design of elements to achieve a specified grade of fire resistance. Structural engineers protest that buildings designed to the old rules did not fall down in fires, so why is it necessary to increase the standard of protection? The grading should be reduced to maintain the status quo. The dilemma for the authorities is both political - if the required levels of grading are reduced it will appear that safety is being decreased - and technical - what reduction can be accepted and does it apply to all structural materials? If the beneficial effect of sprinklers can be recognised how is it quantified?

A further problem identified is the change in methods of structural design at normal temperatures: if there are smaller margins of safety in modern buildings, then past performance in fire cannot be relied on as a guide to their performance in the future. It is difficult to resolve these problems because although there have been many standard fire resistance tests carried out on single elements of construction, there has been much less study of the ways of assessing levels of safety or fire performance of building structures.

Research and Testing

Standard testing of materials and components is an important part of the procedure needed for compliance with the requirements of the authorities, but too many tests are administrative tools, not design tools. Tests become part of a regulation and are only incidentally fire safety measures. Any test method should at least define what is being measured and there should be an attempt to establish its relevance to practical conditions. The research people should be quite firm about this; if the authorities want a test they should say why it is wanted and what they hope to achieve. If they will not say this, then the research people should not be involved.

It is important that the authorities take into account the costs and benefits of the tests and regulations they impose. However, they should be clear about where their responsibilities end and the commercial market takes over. For example, our UK standard for fire resistance tests is currently undergoing extensive revision, in an attempt to obtain more uniform test results from the various commercial laboratories. The differences in results can be important in commercial terms to the manufacturers and the laboratories but if, as I suspect, they have little practical significance in relation to public safety then why involve the state-funded researchers and administrators? As far as I am aware, the authorities have not even asked the question - do these differences affect public safety?

FIRE ENGINEERING BY DESIGN - SOME PRACTICAL EXAMPLES

Covered Shopping Centres

The covered shopping development, where the old style open street is replaced by a covered pedestrian mall, is familiar around the world. When they began to appear in the UK, the authorities perceived that they would break the rules on compartment size and therefore automatic sprinklers were required in all the shops, as an alternative method of reducing the chance of a fire becoming large. The safety of people escaping was then considered and it was realised that smoke protection of the malls would be needed so that there would be time for the people to reach the open air outside the development. The amount of smoke generated by a fire during the escape phase would determine the amount of smoke venting needed, but this was difficult to quantify. Instead, it was observed from statistics of sprinkler operation that most fires in shops were controlled by very few sprinkler heads, and it was decided that the final fire size was not likely to exceed a 3m x 3m plan area. This size was therefore adopted for smoke design and assuming a heat output of about 0.5 MW/m^2, a total size of 5MW was formulated. It is now part of the UK mythology. The Fire Research Station produced design guidance for smoke venting the $9m^2$, 5 MW fire, in a form which could be used by engineers; as a consequence, with new developments, the negotiations with the authorities are relatively straightforward.

As might be expected, the older shopping centres with open malls have become less popular and many are being refurbished and covered. With the temperate climate of the UK, all that may be required is a fairly basic shelter from the wind and the rain and some simple measures to alleviate the effects of solar gain.

The first such scheme we became involved in was Basildon Town Square. Here, shops border all four sides of a pedestrianized square which measures 200m long by 36m wide. A translucent fabric roof varying in height from 11.5-15m was proposed, to cover the whole Square. The enclosed space would not be conditioned, but would be naturally ventilated to be in balance with the exterior. With the Square being enclosed the authorities immediately asked for sprinklers to be installed in all the shops. They were not concerned about an increased risk of fire spread but about smoke being contained and hampering escape from the Square. Unfortunately the cost of the sprinkler systems and even more important, the costs of compensation for disruption of trading ruled out the sprinkler option.

The architects' view was that the enclosed space was so large that people could escape before smoke from a non-sprinklered fire became a problem. The national experts advised them however, that without sprinklers to control a fire it was not possible to establish the fire size as a basis for determining if the people would be safe. Not being convinced, the architects came to see me, and I suggested that we tried some scenarios, assuming a fire which was growing.

Most experimental studies of fire growth were of single artefacts burning in small rooms. These studies were the wrong scale for our problem. Fire statistics for actual fires in industrial buildings showed an exponential form of spread for fire-damaged area. There were no comparable data available for shops but we thought they were likely to be exponential too. Eventually, by using as a starting point the largest non-sprinklered shop permitted by regulations without smoke venting, we evolved a model which said that the fire area was initially $3m^2$ and doubled in size every 4 minutes. (Recent analysis of statistics for shops indicates that 4 minutes is conservative).

The convective heat output per unit fire area was taken as 0.5 MW/m^2 as before and we assumed this all flowed into the Square. The entrainment into the plume and the subsequent smoke layering under the roof were calculated using the Fire Research Station methods, and we were able to estimate a time for the smoke to descend. This time had to be compared with the time taken for people to escape.

People needed time to move from a shop into the Square and then to walk across the Square to an exit. Some of the distances were quite large compared with those in our codes. Our escape codes are based on travel distances and exit widths which will give evacuation within a notional 2½ minutes. A direct distance on plan to an exit from a shop is limited to 30m, and the fire authority will therefore quote a walking speed of 12m/min. This speed actually relates to a crowd of people lining up in a corridor in order to move through an exit. In less crowded conditions people can move more quickly and can certainly cover a greater distance than 30m in 2½ minutes. We allowed for this in assessing the time needed to evacuate the people in the Square, and the people emerging from the surrounding shops. The fire authorities did not like this approach; they were, and are, very reluctant to accept increased travel distances, whatever the circumstances. In the end an extra exit was provided by sacrificing a shop unit. We did not think this extra exit was really needed but we were able to exploit it as a protected access point for the Fire Brigade.

Finally, we had to assess the effect of wind on the efficiency of the natural smoke venting. Mechanical extract was of course quite impractical because of the volumes involved. Wind tunnel tests were carried out to determine the location of the wind sensors and the sequence of operation of the vents.

Basildon Town Square was the first of many refurbishment projects we have worked on. Most of the shopping projects have been smaller than Basildon Town Square. Most of them are also without sprinklers, but for these we have not used the fire growth scenario. Instead, we have adopted an 18m^2 area 10MW fire for smoke venting design, on the assumption that a higher standard of smoke extract is needed where sprinklers are not installed. Statistics of fires in shops attended by fire brigades indicate that the chance that a fire in a sprinklered shop will exceed 9m^2 area is about the same as the chance that a fire in a non-sprinklered shop will exceed 18m^2. This comparison may not be directly relevant to the initial escape period of the fire but at least the risks appear comparable. On escape times we find that for a given population, in most circumstances the controlling factor is the width of the exits from the malls, rather than the distance travelled to reach the exits. We also think that automatic detection systems and a public address system are important safety features, if early evacuation is to be achieved. The smoke extract may be mechanical but more often natural venting is used. Wind tunnel tests may be needed if there are adjacent tall buildings.

We use what research data we can to solve our problems; clearly, a great deal of research information is available for direct use, if only it can be presented in the right way. What is difficult to present is a sense of proportion. It seems wasteful to apply the same standards to all covered shopping centres whatever their size. Some single storey centres are smaller in area than one floor of a department store. Others are multi-storey and hold many people. Hand in hand with our fire and escape scenarios there should be some more explicit relationship between the level of safety and the number of people at risk.

Transport Terminals

In the 19th century, the age of steam, large covered railway stations were built, with just enough vents in them to make them tolerable for the passengers. In the 20th century we build large air terminals, without the steam and without the vents. These vast enclosures break the usual limits on compartment size in order to function efficiently. However, they are specifically designed to move people and we ought to be able to exploit this aspect for escape purposes. Our approach has been to categorise the public areas into two types of use. These are first, the concourse and waiting areas, with very low fire loads, which are places of relative safety and second the shop and catering areas with significant fire loads, which must be protected selectively. This we can do with automatic sprinklers and powered smoke extract designed to prevent smoke entering the concourse.

For terminals, as for shopping centres, we think the code limits on travel distance to an exit are not realistic. The assumption during normal working conditions in a terminal is that people move on average at about 1 m/s. Why should it be slower in fire conditions? We are obtaining measurements of the walking speed of people with baggage trolleys, as this is likely to be the critical value, and it does appear to be of the order of 1 m/s.

One terminal we are working on is a very large single-storey space, about 300m long by 180m wide by 12m high. We would prefer people to escape directly to open air through exits on the perimeter, but this would mean their travelling longer distances than normal. The authorities want people to go down into a tunnel in order to limit the distance to an exit. We have therefore estimated the rate of smoke generation and movement in this large space and involved one of our environmental physicists to do the calculations using computer programs, in conjunction with the Fire Research Station at Borehamwood. In large buildings such as this and in large atrium buildings a fire can be considered initially as a local injection of hot air into the building environment. The effect of building physics becomes an important aspect of fire safety design.

Atriums

We have followed the fashion from the USA, and atriums are now very popular architectural features. For fire safety reasons, our authorities have ensured that many atriums are rather sterile spaces, with not much more fire load than a few plants, and they are mainly confined to office buildings. There is much confusion about the fire safety measures which should be adopted. For acoustic reasons there is usually glazing between the atrium and the surrounding accommodation. Drenchers may be required on the glazing as well as arbitrary smoke venting provisions. Some people have adopted the mythical 5 MW fire as a basis for smoke design although there is no obvious reason why offices and covered shopping centres should be treated in the same way. There is no explicit recognition that the rules should take into account the number of people at risk and the nature of the risk. The rules that we may well be saddled with are likely to be dominated once again by the needs of the bureaucrats to pass or fail a building, and not by the need to design fire safety for buildings that people want. We need the intellectual rigour of the researcher to question such rules and provide an alternative rational framework.

Structural Fire Protection

The use of the fire resistance test for the grading of structures is not often questioned by engineers, although it is perceived as irrational. They would like an alternative 'compartment fire', approach to be available for those occasions where it can be demonstrated that because of the nature and disposition of the building contents the fire exposure is different from that normally assumed. The detailing of structural assemblies is perceived as an important area which has not been studied sufficiently while the development and acceptance of calculation methods for fire resistance proceeds rather too slowly.

WHAT THE DESIGNER NEEDS

For many simple, run-of-the-mill buildings, the architect and engineer will prefer to have simple, if arbitrary, rules. For more complex buildings, the designers need to have flexibility if they are to provide a cost-effective building which meets the needs of the client and the people who use the building.

There are many constraints on the design of a building; fire safety is one important, but small aspect which cannot be allowed to dominate. What is needed is a choice of measures which in combination can achieve a required level of safety. Physical limitations may preclude the use of an extra escape route, or an element of a given fire resistance rating. What compensatory measures could be acceptable? We need a rational framework and agreed numbers.

I believe that we have enough information available to produce the rational framework. If we are successful then the practitioners and administrators will start to ask the right questions - which will benefit us all.

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PAPER 14

A note on smoke plumes from fires in multi-level shopping malls

Margaret Law, Ove Arup Partnership, 13 Fitzroy Street, London, W1T 4BQ (UK), Fire Safety Journal, 10 (1986) pp 197-202. Elsevier Science, UK

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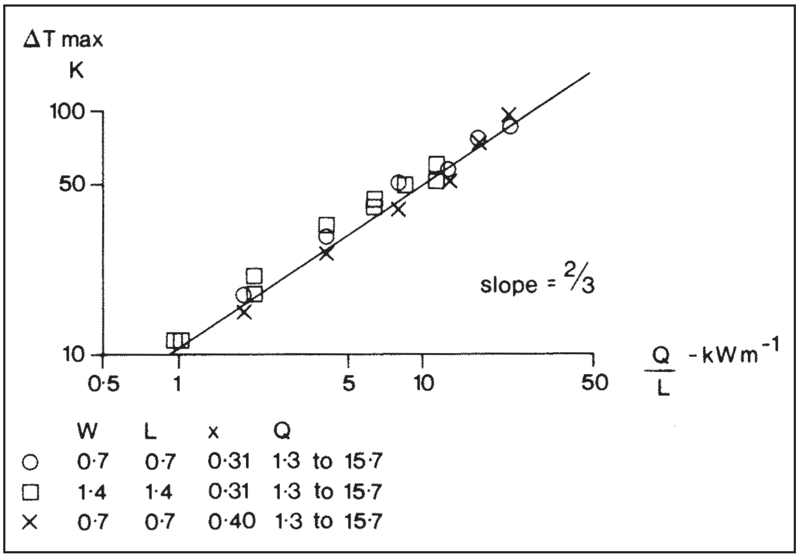
With the growth of fire safety engineering as a discipline, it was inevitable that informed discussion in the UK would extend beyond the walls of the Building Research Establishment. The SFSE (Society of Fire Safety Engineers, later the Institute of Fire Safety, now merged with the Institution of Fire Engineers) organised a Technical Seminar ‘Flow through openings’ to bring together views on this topic. My paper shows measurements collected from various experimental programmes –including some from the United States – and compares them with various models of fire and smoke behaviour.

Figure showing the temperature rise on the axis of the smoke plume at height, x, above the balcony and with varying plume heat content and widths. This work allowed designers to vary the heat output, Q, but use it in a way consistent with other plume equations.



Contents

A Note on Smoke Plumes from Fires in Multi-level Shopping Malls

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(Received September 16, 1985; accepted in final form February 14, 1986)

SUMMARY

It is shown that the experimental data obtained for plume flow in model-scale shopping malls can be correlated using equations similar to those developed by Yokoi. Further analysis is needed to establish the effective source of the plumes and the range of validity of the correlations developed. An alternative method of calculating mass flow above a balcony is suggested for interim use, until further analysis has been carried out.

1. INTRODUCTION

In a multi-level shopping mall, smoke from a fire in a low-level shop can flow upwards to form a layer under the roof. The purpose of smoke venting is to maintain the base of this smoke layer at a safe height above the upper level walkway or balcony. The mass flow of vented gases from the roof reservoir must therefore balance the mass flow of smoky gases as they enter the base of the smoke layer.

Morgan, in his guide to smoke control in shopping centres [1], gives values of mass flow for 5 MW fires, based on results of tests with models. In order to generalise the data, for fires of other than 5 MW, the test results are re-analysed here. These results relate to 1/10 scale models, measuring 0.5 m high and 0.5 m deep, where a plume of hot air emerges from a shop and flows round a balcony or through an opening in a deck.

2. SMOKE PLUME ANALYSIS

The flow of gases from the balcony aperture can be considered to resemble the flow of fire gases from a window aperture, as studied by Yokoi [2], who measured plume temperatures above rectangular heat sources.

Yokoi distinguished three zones, one close to the fire, one remote from the fire and an intermediate zone which, as shown later, is relevant here:

$$\Delta T = \frac{1.764}{n^{1/3}}\left(\frac{r_0}{z}\right)\left(\frac{Q^2 T_i}{g C_p{}^2 \rho^2 r_0{}^5}\right)^{1/3} \qquad (1)$$

where

ΔT = temperature rise on the plume axis (K)
Q = heat output (kW)
T_i = ambient temperature $\simeq$ 290 (K)
g = 9.81 (m/s^2)
C_p = specific heat of air $\simeq$ 1 (kJ/kgK)
ρ = density of gases in plume (kg/m^3)
$\pi r_0{}^2 = na \times a$ (m^2)
$na \times a$ = area of rectangular heat source (m^2)
z = height above heat source (m)

The equation reduces to

$$\Delta T = \frac{7.99}{\rho^{2/3} z}\left(\frac{Q}{na}\right)^{2/3} \qquad (2)$$

3. TESTS WITH MODEL MALLS

3.1. Morgan and Marshall 1975 [3]

In these experiments the shops were either 0.7 m or 1.4 m wide. A 0.4 m-deep balcony extended along the full width: see Fig. 1. In some of the experiments the shop had a 0.16 m-deep fascia but this had little effect on the results. The heat source was methylated spirits in a 0.2 m × 0.2 m tray and the heat output was varied by varying the fuel flow rate. The heated plume from the shops emerged freely into the laboratory, having been channelled under the balcony by screens each side of the front opening. The gas

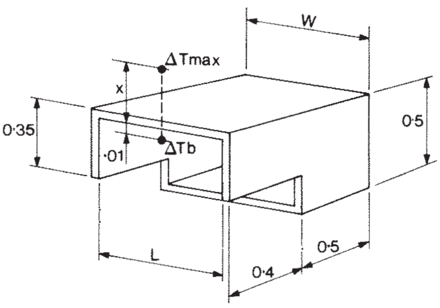

Fig. 1. Fire compartment.

temperature rise 10 mm below the underside of the balcony, ΔT_b, and the maximum temperature rise at a height x above the underside of the balcony, ΔT_{max}, were measured. In most experiments x was 0.31 m, but in a few experiments x was 0.40 m.

Putting $L = na$, where L = distance between channelling screens, eqn. (2) can be written

$$\Delta T_{max} = \frac{7.99}{\rho^{2/3} z}\left(\frac{Q}{L}\right)^{2/3} \tag{3}$$

and for $\rho \simeq \rho_i = 1.25$, where ρ_i = density of gases at ambient temperature

$$\Delta T_{max} = \frac{6.89}{z}\left(\frac{Q}{L}\right)^{2/3} \tag{4}$$

Figure 2 shows ΔT_{max} plotted against Q/L, on log scale, and the points fall on lines with a slope of two-thirds as predicted by eqn. (1). There is very little difference between the lines for $x = 0.31$ m and $x = 0.40$ m.

$$\Delta T_{max} \simeq 10.5\left(\frac{Q}{L}\right)^{2/3}$$

for $x = 0.31$ and $x = 0.40$

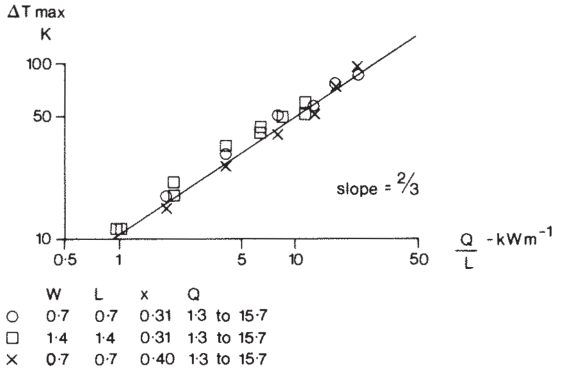

Fig. 2. Temperature rise on axis of plume at height x above balcony.

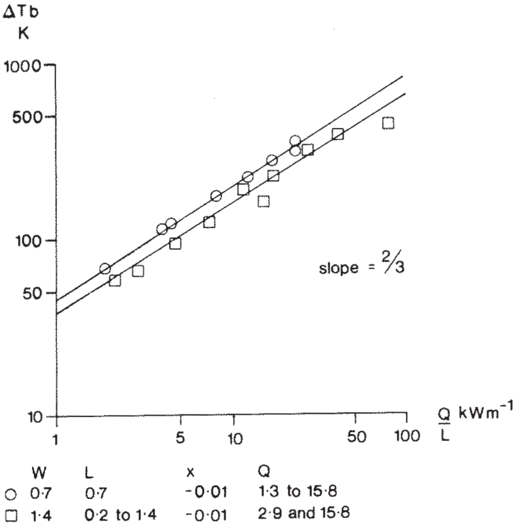

Fig. 3. Temperature rise beneath balcony.

Combining this equation with eqn. (4) gives $z = x + 0.26$ to 0.35, i.e.,

$$z \simeq x + 2H/3 \tag{5}$$

where H = opening height = 0.5 m.

It has been suggested [4] that Yokoi's results can be correlated using $z = (x + H)$, but for these data the effective source of the plume appears to be less than H below the balcony.

Figure 3 shows ΔT_b plotted against Q/L and the points again fall on lines at a slope of two-thirds, except for the smallest value of L (0.2 m) where ΔT_b is lower. Values of ΔT_b for the 0.7 m-wide shop are slightly higher than for the 1.4 m-wide shop; Morgan and Marshall were not able to account for this difference.

For the 0.7 m shop:

$$\Delta T_b = 40\left(\frac{Q}{L}\right)^{2/3} \tag{6}$$

The value 40 is about double that given by the correlation of Yokoi's data [4], and suggests that the effective source is about $H/2$ below the balcony.

If, following Morgan and Marshall, it is assumed that the gas layer under the balcony is at a uniform temperature, then by conservation of heat the mass flow M_b is given by

$$M_b \times \Delta T_b \times C_p = Q \tag{7}$$

and substituting for ΔT_b from eqn. (6)

$$M_b = 0.025(QL^2)^{1/3} \tag{8}$$

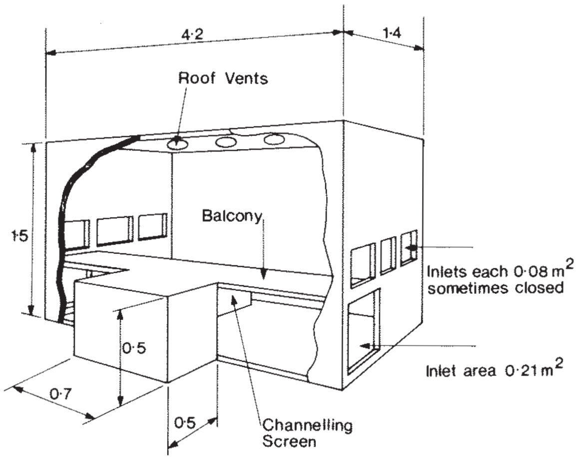

Fig. 4. Experimental arrangement with compartment opening into a ventilated box.

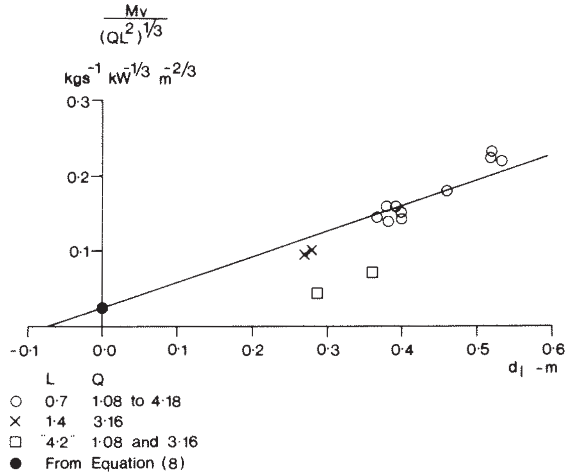

Fig. 5. Mass flow above balcony in vented box. Note that L = "4.2" means there were no screens.

Above the balcony, at any given plume height z, the temperature will not be uniform. However, by analogy with eqn. (7) the mass flow M would be expected to follow this relationship:

$$M \times \Delta T_{\max} \propto Q$$

and hence, using eqn. (4)

$$M \propto (QL^2)^{1/3} z \tag{9}$$

3.2. Morgan and Marshall 1979 [5]

In these experiments only the 0.7 m shop was used. It was arranged so that the heated plume entered a large box: see Fig. 4. The gas layer which formed beneath the roof of the box was extracted mechanically at an approximately constant rate. The heat source was electric convector heaters and the thickness of the layer was changed mainly by varying Q, from 1.08 kW to 4.18 kW; in most experiments L was 0.7 m, in two experiments it was 1.4 m and in two experiments there were no screens. The plume temperature itself was not measured, but the above-balcony temperature distribution was measured outside the plume in order to determine the thickness of the ceiling layer. This temperature was uniform at ΔT_c above ambient, for a depth of about 0.3 m and then gradually decreased so that there was no clear demarcation of the base of the layer. An effective layer depth was determined, therefore, by integrating the temperature-height curve, i.e.,

$$d_b = \frac{T_c}{\Delta T_c} \int_{0.0}^{1.0} \frac{\Delta T}{T} \, dh \tag{10}$$

where

h = height above balcony

1.0 = height of ceiling above balcony (m)

T_c = temperature of layer near ceiling (K).

The height of the clear layer above the balcony, d_l, was given by $d_l = 1.0 - d_b$. When smoke was added to the plume, the value of d_l agreed with visual measurements.

The paper gives values of M_v, the mass flow of vented gases and Fig. 5 shows $M_v/(QL^2)^{1/3}$ plotted against d_l. The value of 0.025 at $d_l = 0$, ($M_v = M_b$) given by eqn. (8), is also shown. When there were no screens, the value of L was indeterminate. Putting $L = 4.2$, the total width of the box, gives points well below the others; Morgan and Marshall say the plume extended the full width of the balcony but their diagram suggests it was not of uniform thickness; there may be a limit to the effective spread of the plume under the balcony, and the results suggest a maximum width of approximately 1.5 m in these experiments, which is the width of the compartment opening plus 1.5 H.

The point given by eqn. (8) is shown in Fig. 5. Assuming a linear temperature distribution along the plume axis [6], it has been included on the line shown, which has the equation:

$$M_v = 0.34(QL^2)^{1/3}(d_l + 0.075) \tag{12}$$

The intercept $d_1 = -0.075$ is equivalent to 0.15 H. This suggests that the effective source of the plume is only a small distance below the balcony.

For comparison with Morgan's design summary, assume that eqn. (12) can be generalised as follows:

$$M_v = 0.34(QL^2)^{1/3}(d_1 + 0.15H) \qquad (13)$$

In his Fig. 20 [1], Morgan gives for a 5 MW fire the mass flow above the balcony at various heights, for various values of screen separation. This figure is the same as Fig. 11 of CP11/79, based on a scaled-up version of the experiments (ten times the linear scale). However, in these figures, the concept of effective height of layer, d_1', is introduced, i.e., M_v is related to d_1' rather than d_1 where

$$d_1' = h_v - 1.26d_b$$

and h_v is the height of vents above the balcony.

Morgan and Marshall introduced the empirical correction factor of 1.26 to the value of d_b in order to obtain agreement between their calculated values of M and the values of M_v measured. Thus their mass flow depends on both d_1 and h. In order to compare eqn. (13) with Fig. 20, a value of $d_1 = 3.5$ m will be selected, since this is the value recommended by Morgan. For $Q =$ 5000 kW, $H = 5.0$ m, the variation of M_v with L is shown in Fig. 6, calculated from eqn. (13); it is compared with the values obtained from Morgan's Fig. 20 for three values of h_v, the height of the ceiling vents above the balcony. Equation (13) agrees most closely for $h_v = 10$ m, as would be expected. For a fixed plume height, the sensitivity of M_v to changes in h_v, (due to applying the correction factor) seems rather large. This correction factor of 1.26 was derived empirically for only one value of h_v (1.0 m on model scale) and the mass flow calculation method used by Morgan and Marshall [3] itself contains another empirical factor. Therefore, in view of these uncertainties it is suggested that eqn. (13) could be used for the general relationship and also as an alternative to Fig. 20, until further analysis is available.

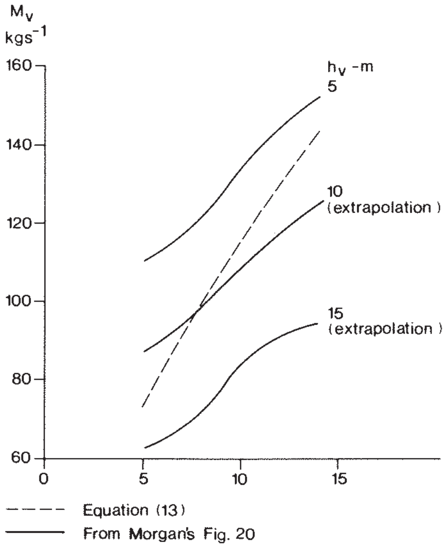

Fig. 6. Calculated mass flow for $d_1 = 3.5$ m, $Q =$ 5000 kW, $H = 5.0$ m.

3.3. Morgan, Marshall and Goldstone 1976 [7]

In these experiments the 0.7-m-wide shop was used again, with the plume flowing into the box but with the balcony replaced by a deck across the whole width and depth of the box. The deck contained two apertures, one 1.0 m × 0.6 m, the other one either 1.0 × 0.6 m or 0.5 m × 0.6 m. Smoke curtains 1.76 m apart were used in all but two experiments to contain the smoke so that it flowed only through the latter aperture. These curtains extended to the full depth of the deck. The gas was vented naturally from up to eight vents in the roof, each of 0.06 m^2 area. The inlets below the deck gave 0.42 m^2 area and above the deck 0.48 m^2 area. The heat output Q was a constant 3 kW and the value of d_1 was altered by varying the areas of the inlets and vents.

The mass flow through the vents was calculated using the following equation

$$M_v = \frac{C_v A_v \rho_i (2g d_b \Delta T_c T_i)^{1/2}}{T_c^{1/2}\left(T_c + \frac{A_v^2}{A_i^2} T_i\right)^{1/2}} \qquad (14)$$

where

A_v = vent area (m^2)
A_i = inlet area (m^2)
C_v = discharge coefficient = 0.6

If L is replaced by na in eqn. (9):

$$M \propto (Qn^2a^2)^{1/3}z \qquad (15)$$

then $M_v/(Qn^2a^2)^{1/3}$ should vary linearly with d_1; Fig. 7 shows the relationship is indeed

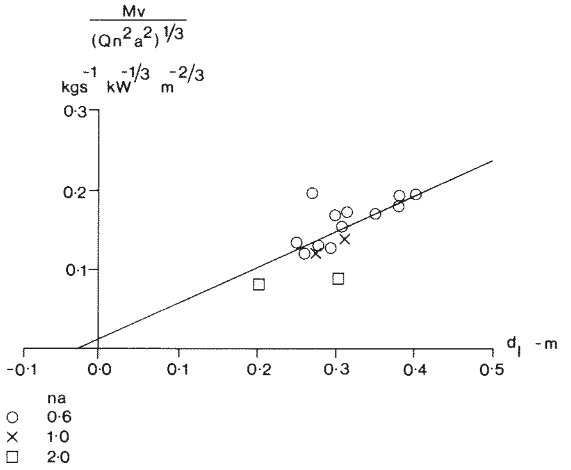

Fig. 7. Mass flow above rectangular apertures in deck of ventilated box.

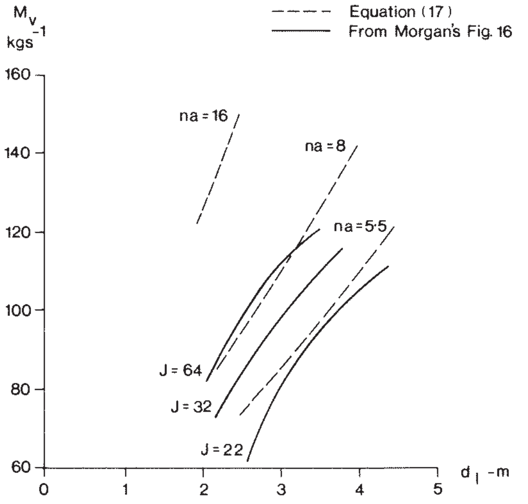

Fig. 8. Calculated mass flow above deck for Q = 5000 kW, H = 5.0 m. J = perimeter of aperture (m) and $na = J/4$.

linear for all but two values. One result for na = 0.6 m is probably a rogue value; the other, for na = 2.0 m, may be a real result, but there are not enough results for this size of aperture to confirm this.

Omitting these two results gives:

$$\frac{M_v}{(Qn^2a^2)^{1/3}} = 0.46(d_l + 0.03) \qquad (16)$$

which implies that the effective origin of the plume is only just below the deck, about $H/10$, so that

$$M = 0.46(Qn^2a^2)^{1/3}(d_l + 0.1H) \qquad (17)$$

In his design summary, Morgan gives values of M_v for various aperture perimeters, J, for Q = 5000 kW. These are compared with eqn. (17), assuming H = 5 m and $na = J/4$, as shown in Fig. 8. Equation (17) gives higher values, particularly for the largest aperture, J = 64, which corresponds to na = 16 in Fig. 7. It is necessary to have further analysis of the results.

It should be noted that the values of M_v and ΔT_c given in the report indicate that only some 70% of the heat was contained in the vented gases. Morgan has explained [8] that there was minimal heat loss from the rising plume but the heat loss from the layer under the ceiling to the walls and roof was large, and these values of ΔT_c are not expected to be the same in practice.

4. CONCLUSIONS

(1) When the heated plume from a fire in the model shop flows round a balcony, the temperature rise on the axis, ΔT_{max}, at a given height is proportional to $(Q/L)^{2/3}$ where Q (kW) is the heat output of the fire and L (m) the width of the plume under the balcony.

(2) The temperature rise ΔT_b beneath the balcony is also proportional to $(Q/L)^{2/3}$.

(3) The experimental results for mass flow from a vented roof reservoir, M_v, when the visible smoke layer is at a height d_l above the base of the balcony are correlated by the general equation

$$M_v = 0.34(QL^2)^{1/3}(d_l + z_0) \qquad \text{(kg/s)}$$

where z_0 (m) is the depth of the effective source below the balcony. This correlation suggests that $z_0 = 0.15\ H$ where H is the height of the balcony above the fire. This equation may overestimate M_v for values of L greater than twice the width of the shop opening, and further analysis is needed to establish its validity.

(4) The temperature rise correlations suggest z_0 is 0.5 H - 0.7 H.

(5) If the balcony is replaced by a deck with a rectangular aperture, most of the values of M_v are correlated by

$$M_v = 0.46(Qn^2a^2)^{1/3}(d_l + 0.10H) \qquad \text{(kg/s)}$$

where $na \times a$ (m²) is the area of the aperture. Further analysis of the results is needed.

(6) These equations for M_v are based on 1/10 scale experiments with roof vents 1.0 m above the balcony or deck, i.e., 10 m high on full scale. It is possible that a different ratio of vent height to balcony height or smoke height would give different results.

(7) The temperature of the gas layer under the roof in these experiments would not be the same on full scale. In fact the design summary of Morgan assumes conservation of heat in the vented gases, whereas in the experiments they contained only some 70% of the heat from the fire. This affects the volume flow of the vented gases, which is higher if the heat is conserved.

(8) Additional analysis is desirable, to establish the range of validity of the correction factors obtained by Morgan and Marshall.

LIST OF SYMBOLS

a	short side of rectangular heat source (m)
A_v	vent area (m^2)
A_i	inlet area (m^2)
C_v	discharge coefficient (m^2)
C_p	specific heat of air (kJ/kgK)
d_b	effective depth of hot layer beneath ceiling (m)
d_l	effective height of clear layer above balcony (m)
g	gravitational acceleration = 9.81 (m/s^2)
h	height above balcony (m)
h_v	height of vents above balcony (m)
H	height of soffit of balcony above fire (m)
J	perimeter of aperture (m)
L	distance between channelling screens (m)
M	mass flow in plume (kg/s)
M_b	mass flow of gases beneath balcony (kg/s)
M_v	mass flow of gases through vents (kg/s)
n	ratio of long side to short side of rectangular heat source
Q	heat output (kW)
r_0	effective radius of heat source (m)
T	temperature on plume axis (K)
T_b	temperature beneath balcony (K)
T_c	temperature beneath ceiling (K)
T_i	ambient temperature (K)
ΔT	temperature rise on plume axis (K)
ΔT_{max}	temperature rise on plume axis at height x (K)
x	height above soffit of balcony (m)
z	height above effective source of plume (m)
ρ	density of hot gases (kg/m^3)
ρ_i	ambient temperature density of gases (kg/m^3)

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PAPER 15

Design formulae for hot gas flow from narrow openings- points for consideration

Margaret Law, Arup Research and Development, Paper 2 in Technical Seminar, “Flow through openings”, SFSE meeting 13 June 1989, Fire Research Station, Borehamwood. Society of Fire Safety Engineers, UK

Figure showing how the mass flow of smoke above narrow openings varies with heat output, total width of opening and height above the base of the opening. This work was used directly in the design of a smoke extract system for St Paul’s Thameslink Station, shown in the plate, where mass flow of smoke from above the carriage windows was important.

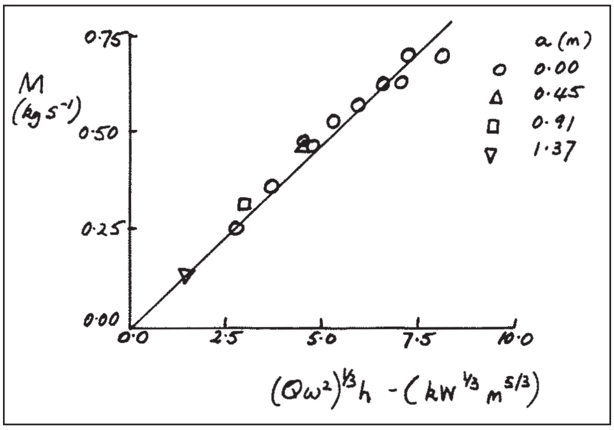

Figure showing how the mass flow of smoke above narrow openings varies with heat output, total width of opening and height above the base of the opening. This work was used directly in the design of a smoke extract system for St Paul’s Thameslink Station, shown in the plate, where mass flow of smoke from above the carriage windows was important.

Contents

DESIGN FORMULAE FOR HOT GAS FLOW FROM NARROW OPENINGS - POINTS FOR CONSIDERATION

Margaret Law, Arup Research and Development

1. INTRODUCTION

Morgan and Hansell have proposed design formulae for the flow of hot gases from wide openings bordering an atrium. (1) It would also be useful to have formulae for a narrow opening, such as a doorway or a small window. Several sets of experiments yield relevant data.

Table 1 lists the main features of these experiments.

2. CORRELATION OF EXPERIMENTAL DATA

Examination of the data shows that simple correlations for the mass flow from the opening, M, can be obtained as follows.

$$M = K\,(Qw^2)^{1/3}h \qquad (1)$$

where Q = heat output

w = width of opening

h = height of opening

and K varies with the experimental conditions.

A typical correlation of data in reference (2) is shown in Fig. 2. The slope, K, is 0.095. These results are for a methane burner 30 cm diameter, fitted flush into the floor and at the centre of the compartment. With the burner moved to the mid-back of the compartment a similar correlation is obtained but with K = 0.085. With the burner at the corner back, K = 0.072. The perimeter, P, of the source and the depth of the downstand, b, were not varied in these experiments. The variation in the value of a, the height of the upstand, appears to be accounted for by the change in h, the height of the aperture; this suggests that it is the level of the base of the aperture which is more significant than the level of the base of the fire. Table 2 shows the effect of raising the fire source 30 cm above the floor.

Experiments reported in reference (3) were in the same compartment as reference (2) but the methane source was a line burner at the back of the compartment. The length of the burner, P_L, varied from 0.46 m to 1.84 m. A very similar correlation to Fig. 2 was obtained, one for each value of P_L. This is illustrated in Fig 3.The values of K are listed in Table 3. It is interesting to note that K = .084 for P_L = 0.92, compared with K = 0.085 for the mid back burner (P = 0.94) in the earlier experiments.

For the experiments reported in reference (4) there were two types of fuel, wood cribs and polyurethane cribs. For each fuel, there is a very good correlation with $(Rw^2)^{1/3}$ where R is the rate of weight loss of the fuel. The wood results are shown in Fig. 4. The values of h, b and a were constant. Adopting the values suggested by the authors of 15 kJ/g for wood and 23 kJ/g for polyurethane, values for K are 0.058 for the wood cribs and 0.053 for the polyurethane cribs. Once R is taken into account there appears to be no "P" effect, but the two are correlated since R increases with the number of cribs.

The authors of the three sets of experiments discussed above have carried out detailed and successful correlations of the results, which can be found in the references given.

The next two sets of experiments are also interesting, because the value of b was varied, and the presence of a deep downstand is significant in Morgan and Hansell's formula. In the experiments reported in reference (5) the fuel was methylated spirits. The value of P was constant. Hot gases flowed out of the compartment opening and under a 0.5 m high balcony. The gas temperature rise under the balcony, ΔTb, is reported for the with downstand condition (h = 0.36, b = 0.16). Following the authors suggestion of a uniform temperature distribution in the layer the following is obtained (7):

$$M_b = K_1 (Qw^2)^{1/3} \qquad (2)$$

where K_1 = 0.025 for W = 0.7 m
K_1 = 0.029 for W = 1.4 m
and W = compartment width

These are illustrated in Fig 5. In the context of this paper we would expect that $K = K_1 h$, but it is not clear whether the relevant h is the height of the opening or the height of the balcony and reference (5) gives no values of ΔT_b for the without-downstand condition (h = 0.5). However the temperatures in the plume above the balcony are given for both with-and without-downstand and they are not significantly different. This suggests that the balcony height (0.5m) is the relevant h, in which case K becomes 0.050 for the 0.7m wide compartment and 0.058 for the 1.4m wide compartment. Some of the openings might be described as wide since they were up to 1.4m. These are discussed later (Section 3). The authors of this report noted the compartment effect but did not find a complete explanation. Their main interest was flow in the plume above the balcony.

The experiments in reference (6) were designed to simulate a shopping mall and perhaps the opening could be described as wide, since it was 3m wide by either 1.6m or 2.5m high (b = 1.2 or 0.3). The fuel was either wood cribs or kerosene. The opening width was constant, but both Q and P were varied. Fig. 6 shows M plotted against $(Qw^2)^{1/3}h$ and it appears there could be some downstand effect, in addition to the effect of height of opening. However in view of the small number of experiments and the different fuel sources, it would be rash to draw any firm conclusions. Taking the results together, the value of K is 0.041.

The values of mass flow in the mall are also given in reference (6). A correlation has been suggested as follows (8):

$$M = 0.4\ Py^{3/2} \tag{3}$$

where y is height above the floor of the mall. (The value of y has been defined as a critical dimension for the design of smoke extract in shopping malls (8)). The results from reference (6) are plotted against $Py^{3/2}$ in Fig. 7, where y is the average smoke layer height in the mall, excluding the local depth at the opening. There is no significant correlation. Accordingly the results have been plotted against $(Qw^2)^{1/3}y$ as shown in Fig. 8. This is a more significant correlation. Again, there appears to be some downstand effect. Taking the results together, the slope is 0.094 which is consistent with the doubling effect noted by the authors (6). There was little variation in y and it is not possible to confirm a linear relationship or a $y^{3/2}$ relationship from these results. The inconclusive nature of the results may indeed explain why they were not discussed in reference (1).

3. COMPARISON WITH THE FORMULAE FOR WIDE OPENINGS

3.1 Fuel-bed control (FBC)

The wide opening formula for fuel-bed control (1) is given, in the notation of this report, as follows:

$$M = \frac{0.188Pw(h+a)^{3/2}}{\left[w^{2/3} + \left(\frac{7.27P}{\gamma}\right)^{2/3}\right]^{3/2}} \tag{4}$$

where γ = 36 with a deep downstand
and γ = 78 without downstand

In the experiments of reference (2) P and (h + a) were constant; thus equation (4) would suggest that the only significant variable was w. It would, for $\gamma = 36$, give values of M ranging from 0.17 to 0.28, whereas those measured range from 0.13 to 0.70 (see Fig. 9). Equation (4) would therefore give unsatisfactory correlation of these results and indeed of most of the others discussed.

The model-scale experiment of reference (5) had relatively the widest openings. For W = 0.7m, w = 0.7m (w/h = 1.4) and Q ranging from 1.3 to 15.8 kW the estimated mass flow ranged from 0.019 to 0.047 kg/s. Equation (4) with (h+a) = 0.5, $\gamma = 78$, P = 0.8 and w = 0.7 gives M = 0.039 over the whole range. For W = 1.4, w = 1.4, (w/h = 2.8) and Q = 2.9 or 15.8 the estimated mass flow was 0.051 or 0.082 kg/s respectively. Equation (4) gives M = 0.044 for both. The effect of Q, not taken into account in equation (4), was significant for all the widths in these experiments.

The shopping mall opening (6) is also near to being "wide". With the largest source of heat, the fires would be described in reference (1) as fully involved.

3.2. Fully involved compartment with large openings (FILO)

The formula for a compartment fully involved with fire but not ventilation controlled (1) is given, in the notation of this report, as follows:

$$M = 0.12wh^{3/2} \quad \text{for } \gamma = 36 \tag{5}$$

$$M = 0.14\ wh^{3/2} \quad \text{for } \gamma = 78 \tag{6}$$

For the shopping mall experiments, equation (5) gives 0.7 kg/s for h = 1.6 and 1.4 kg/s for h = 2.5, Fig. 10 shows the values of M predicted by equations (4) and (5) compared with the experimental values. The correlation is poor.

3.3 Ventilation control (VC)

The formula for a compartment with a ventilation controlled fire (1) is given, in the notation of this report, as follows:

$$M = 0.50\ wh^{3/2} \tag{7}$$

Measurements of M for these fires are not readily available.

3.4 Heat flux - Q_w

For FBC, it is assumed in reference (1) that some 55 to 60% of the heat from the fire flows from the opening. Here we assume, in the notation of this report, that for FBC:

$$Q_w = 0.55Q \tag{8}$$

For FILO, from (1)

$$Q_w = 109wh^{3/2} \quad \text{for } \gamma = 36 \tag{9}$$

$$Q_w = 128wh^{3/2} \quad \text{for } \gamma = 78 \tag{10}$$

For VC, from (1)

$$Q_w = 456wh^{3/2} \tag{11}$$

Fig. 11 shows some experimental values for Q_w, from a compartment with two openings, where w/h was either 1.7 or 3.3 (9). Predicted values of Q_w, using equations (8)(9) and (11) are also shown. Prediction is best for the FBC fires.

3.5 Temperature above ambient - θ_w

The temperature above ambient of the gases flowing from the opening is given in (1) as;

For FBC:

$$\theta_w = \frac{Q_w}{MC_p} \tag{12}$$

wher C_p = specific heat of gases

For FILO and VC:

$$\theta_w = 912 \qquad (13)$$

Fig 12 shows experimental values in reference (6) and Fig. 13 shows experimental values in reference (9).

4. DISCUSSION

In any empirical approach it is important to recognise that the data may be in a range where some significant effects fortuitously cancel each other out. With this caution in mind, some conclusions may nevertheless be drawn:

It appears that a simple design formula for mass flow from narrow openings could be adopted but further consideration should be given to various effects. The location, type and geometry of the source, and the geometry of the compartment can have significant effects in addition to the heat output of the source and the geometry of the opening. A method for codifying these effects is desirable. One way forward would be to adopt the analytical approach of reference (2), for example, to assess the magnitude of such effects for a variety of compartments and sources.

For most conditions, the interest of the designer will be mainly in the behaviour of the plume after it leaves the opening, and it may be that same of the effects discussed above are less significant in this zone. The ideal would be to have some experiments designed to assess the effects both at the opening and in the subsequent plume.

The wide-opening formula is easy to use because the compartment and source effects are not taken into account, at least explicitly. It may be indeed that they are not significant for wide openings. However, for the experimental conditions reviewed in his paper, the wide-opening formula does not give satisfactory correlations. A definition of wide is thus of some importance, and is considered in reference (1) which, in its Table 3, gives examples of flows out of compartment openings. For fuel bed controlled fires the values of w/h range from 1.05 to 15.0, which would suggest that an opening wider than square is "wide". However, the definition given for wide is:

$w \gg d$
where d = depth of layer of gases at the opening
if $d \simeq 0.5h$
then $w/h \gg 0.5$

This would suggest an opening significantly wider than square.

5. CONCLUSIONS

5.1 For various openings a simple formula for mass flow can be derived as $M = K\,(Qw^2)^{1/3}\,h$.

5.2 K varies with the geometry of the compartment and the type, location and geometry of the source. For the experiments analysed it varied from .041 to .092.

5.3 Further analysis is needed to establish design values for K.

5.4 The experiments analysed had openings mainly narrower than square but some were wider.

5.5 The wide-opening formulae of Morgan and Hansell do not correlate the results of these experiments satisfactorily. It is suggested therefore that designers should make a more detailed analysis for narrow openings such as doorways, or windows which are approximately square.

5.6 Some of the effects discussed may be less significant for mass flow in the plume once it is outside the opening. Further experiments are needed to validate the models proposed.

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List of Symbols

A_f = Fuel Area (m^2)
a = Height of upstand to opening (m)
b = Depth of downstand to opening (m)
C_p = Specific heat of gases leaving opening (KJ/KgK)
D = Depth of compartment (m)
d = Depth of gas layer leaving opening (m)
H = Height of compartment (m)
h = Height of opening (m)
K = Slope of line correlating M with $(Qw^2)^{1/3}h$
K_1 = Slope of line correlating M_b with $(Qw^2)^{1/3}$
M = Mass flow of hot gases (kg/s)
M_b = Mass flow of hot gases beneath balcony (kg/s)
P = Perimeter of fire (m)
P_L = Length of line fire (m)
Q = Heat output of fire (kW)
Q_W = Heat in gas layer leaving opening (RW)
R = Rate of burning (g/s)
ΔT_b = Temperature above ambient of gases beneath balcony (K)
W = Width of compartment (m)
w = Width of opening (m)
y = Height above mall (m)
γ = Numerical factor in layer mass flow formulae
θ_W = Temperature above ambient of gas layer leaving opening (K)

Table 1

Main features of experiments considered

Reference	H	D	W	h	w	b	a	Fuel	A_f	P	Q
(2)	2.18	2.8	2.8	1.83	0.24 to 0.99	0.35	0.0	Methane circle	0.071	0.94	3.2 to 158
				1.38	0.74	0.35	0.45				63
				0.92	0.74	0.35	0.91				63
				0.46	0.74	0.35	1.37				63
(3)	2.18	2.8	2.8	1.83 to 0.46	0.23 to 0.99	0.35	0.0 to 1.37	Methane line		0.46* to 1.84	30 to 120
(4)	2.41	2.18	2.18	1.83	0.19 to 0.79	0.58	0.0	Wood cribs	0.06 to 0.36	0.98 to 2.4	77 to 430
								Polyurethane cribs	0.06	0.98	136 to 812
									0.14	1.63	
									0.23	2.40	
									0.36	2.40	
(5)	0.5	0.5	0.7	0.34	0.7	0.16	0.0	Meths burner	0.04	0.8	1.3 to 15.7
			1.4	0.34	0.2 to 1.4	0.16	0.0				2.9 and 15.8
(6)	2.8	7.5	3.75	1.6	3.0	1.2	0.0	Kerosene	1.65	5.2	3200
				2.5	3.0	0.3	0.0		1.65	5.2	3200
				2.5	3.0	0.3	0.0		0.58	3.15	1100
				1.6	3.0	1.2	0.0	Wood cribs	1.08	4.80	600
(9)	3.05	3.71	7.70	1.83	3.05 and 6.10	0.3	0.8	Wood cribs	28.6	22	2500 to 13400

*P_L

Table 2

Effect of raising the source (2)

Location of source	Mass flow-kg/s Flush	 Raised
Centre	0.57	0.52
Mid-back	0.50	0.48
Corner-back	0.44	0.47

NB $Q = 63$, $h = 1.83$, $w = 0.74$

Table 3

Variation of K with length of source. Data from reference (3)

P_L	K
0.46	0.078
0.92	0.084
1.38	0.087
1.84	0.091

Table 1

Main features of experiments considered

Table 2

Effect of raising the source$^{(2)}$

Table 3

Variation of K with length of source

Fig. 1 Diagram of a fire compartment.

Fig. 2 Mass flow for 30 cm diameter burner at centre of compartment. Data from reference (2).

Fig. 3 Mass flow for line burner at rear of compartment $P_L = 0.46$m. Data from reference (3).

Fig. 4 Mass flow for wood cribs. Data from reference (4).

Fig. 5. Mass flow under balcony. Data from reference (5).

Fig. 6 Mass flow from a shop front. Data from reference (6).

Fig. 7 Mass flow in a shopping mall and equation (3). Data from reference (6)

Fig. 8 Mass flow in a shopping mall. Alternative correlation.

Fig. 9 Mass flow from a compartment (2) and equation (4).

Fig. 10 Mass flow from a shop front (6) and equations (4) and (5).

Fig. 11 Heat flow from a compartment (9) and equations (8), (9) and (11).

Fig. 12 Temperature above ambient of out flowing gases and equations (12) and (13), for a shop front (6).

Fig. 13 Temperature above ambient of out flowing gasis and equations (12) and (13), for a fire compartment (9).

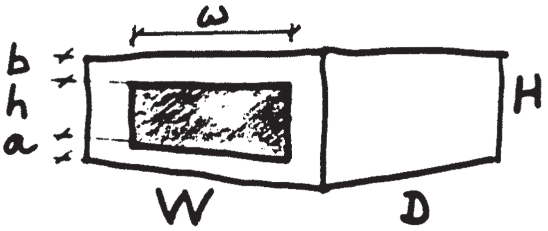

Fig. 1 Diagram of a fire compartment.

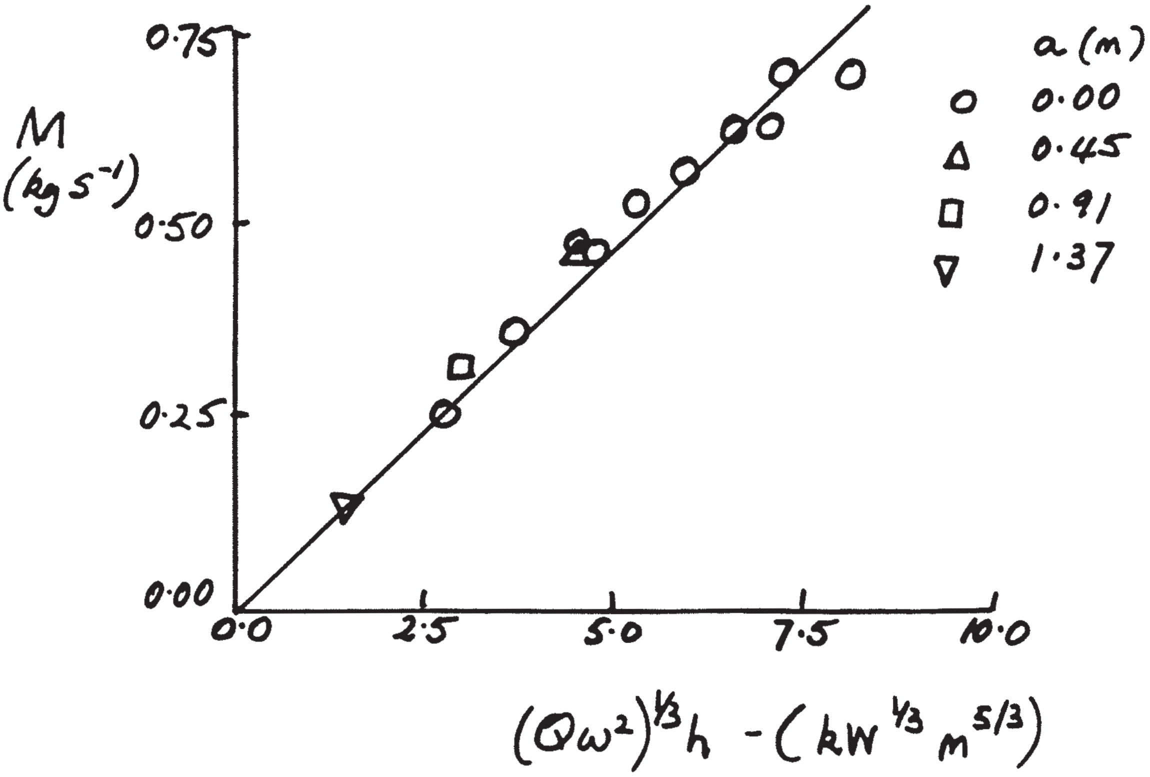

Fig. 2 Mass flow for 30 cm diameter burner at centre of compartment. Data from reference (2).

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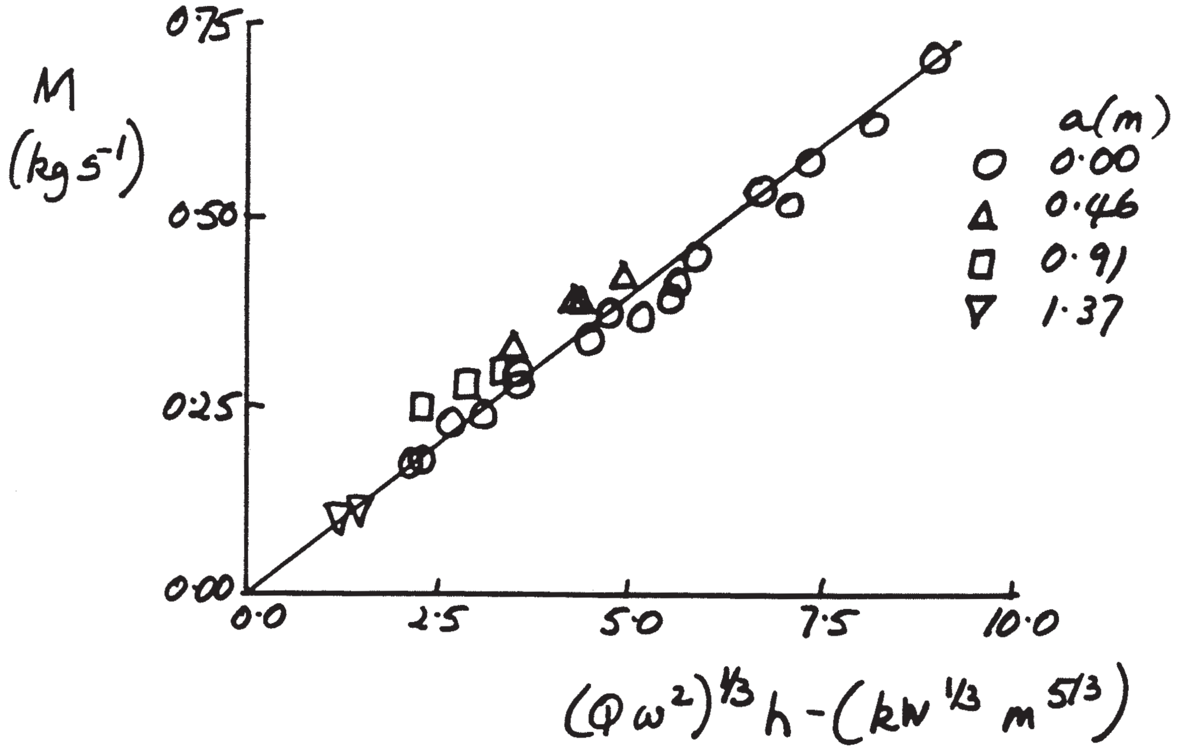

Fig. 3 Mass flow for line burner at rear of compartment P_L = 0.46m. Data from reference (3).

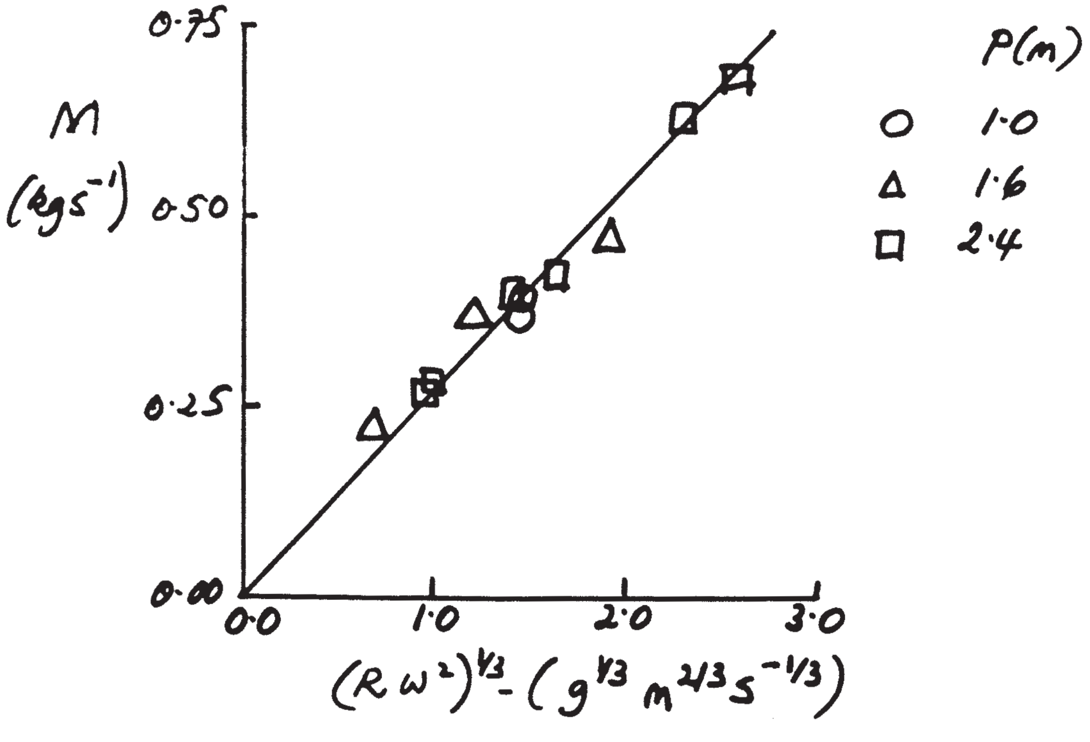

Fig. 4 Mass flow for wood cribs. Data from reference (4).

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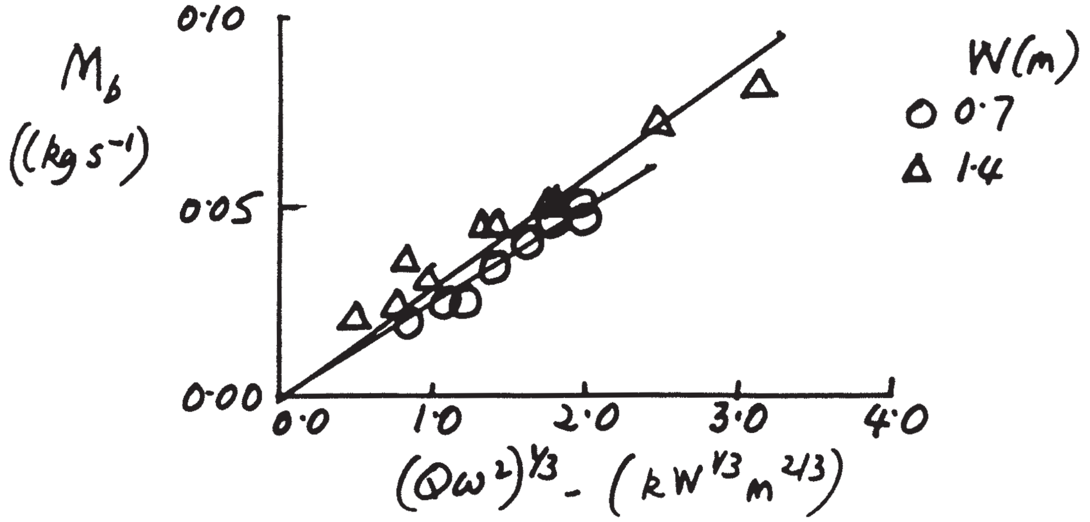

Fig. 5. Mass flow under balcony. Data from reference (5).

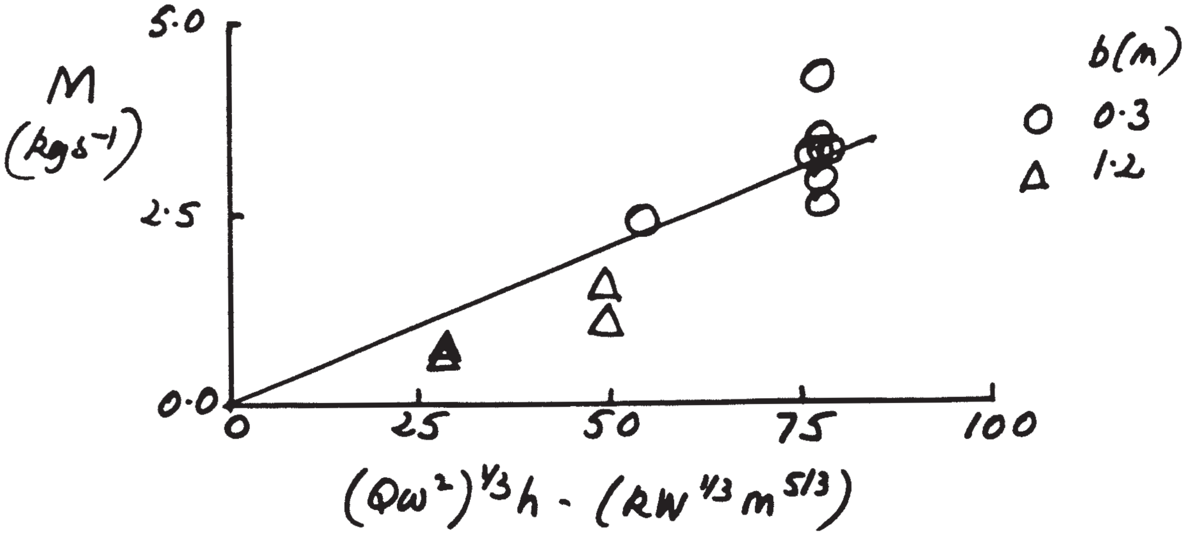

Fig. 6 Mass flow from a shop front. Data from reference (6).

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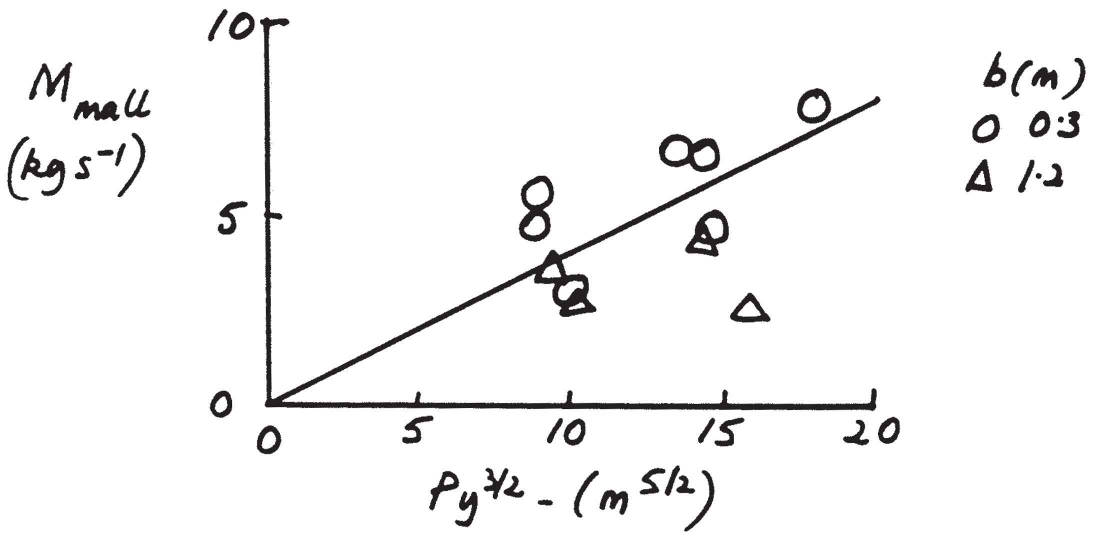

Fig. 7 Mass flow in a shopping mall and equation (3). Data from reference (6)

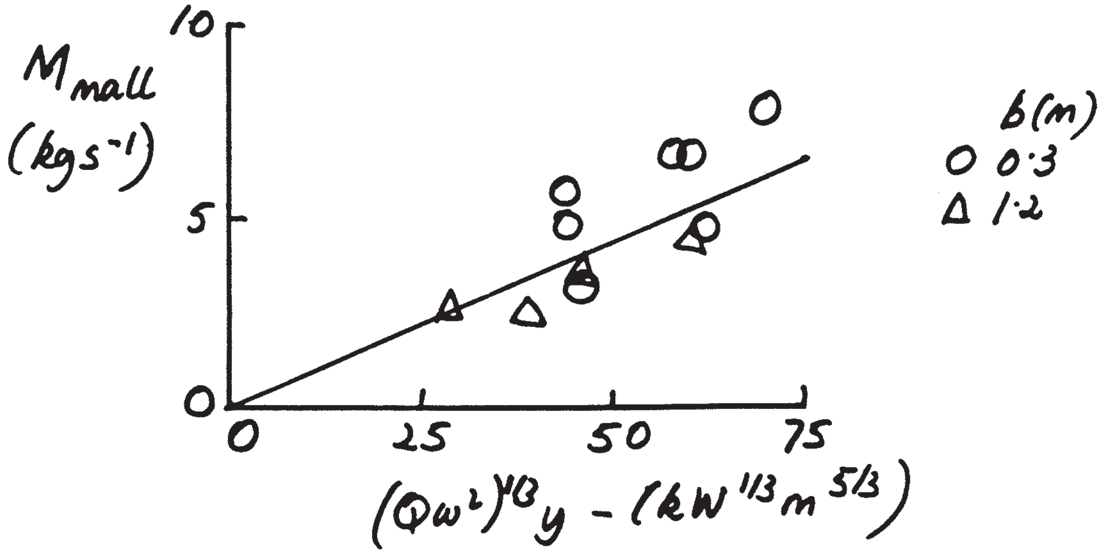

Fig. 8 Mass flow in a shopping mall. Alternative correlation.

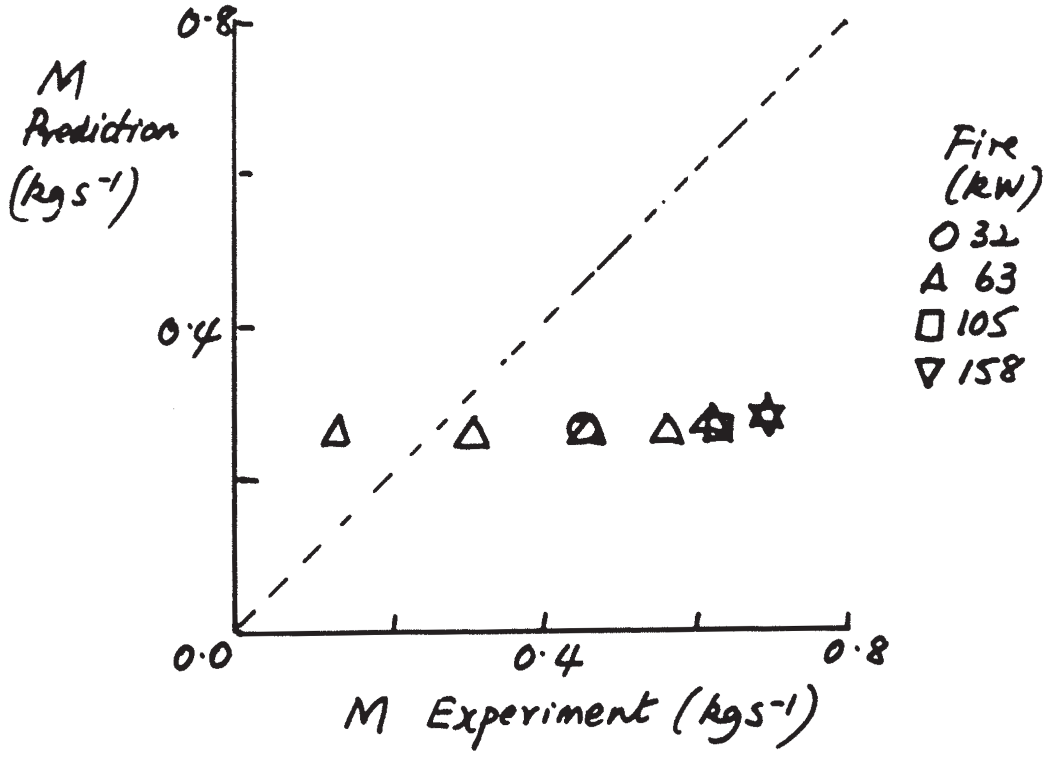

Fig. 9 Mass flow from a compartment (2) and equation (4).

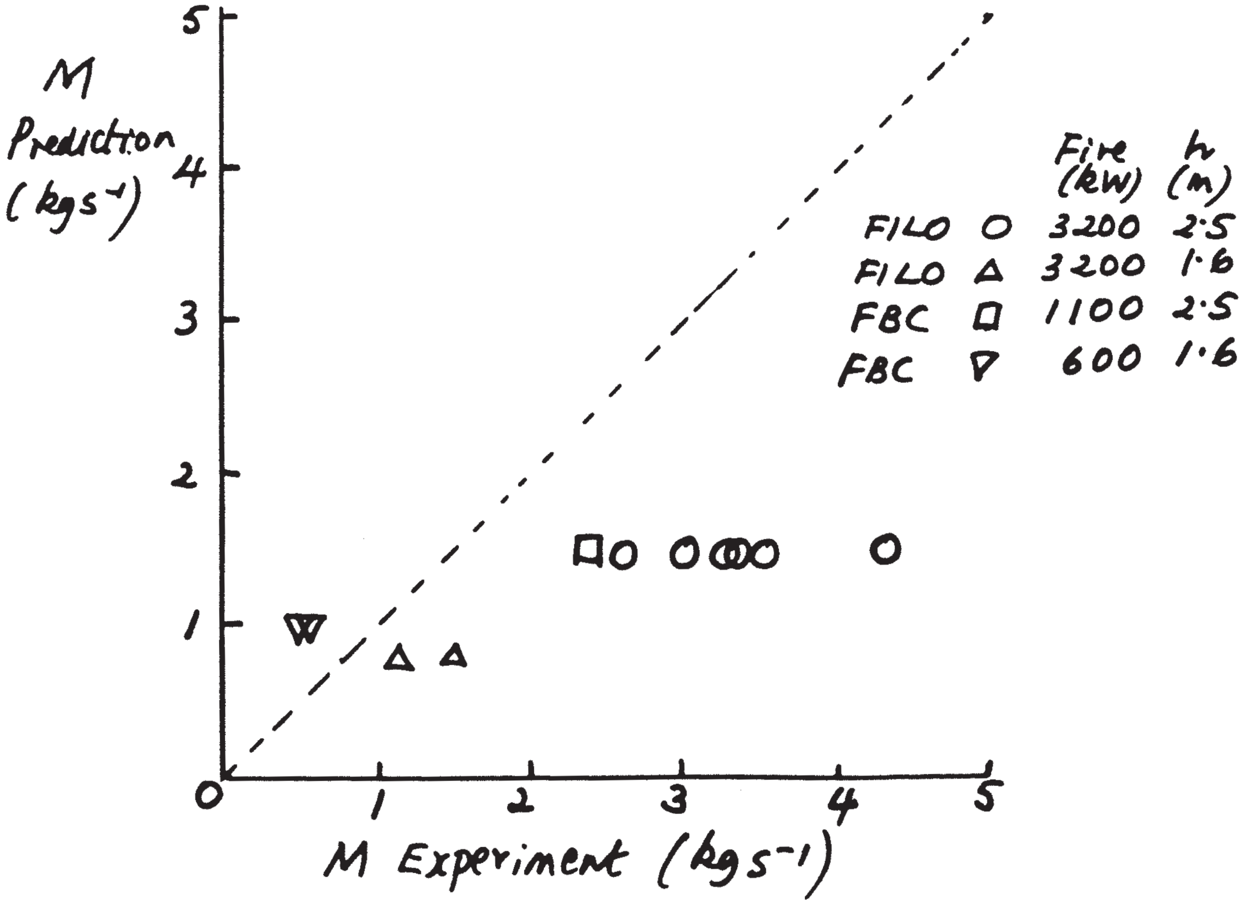

Fig. 10 Mass flow from a shop front (6) and equations (4) and (5).

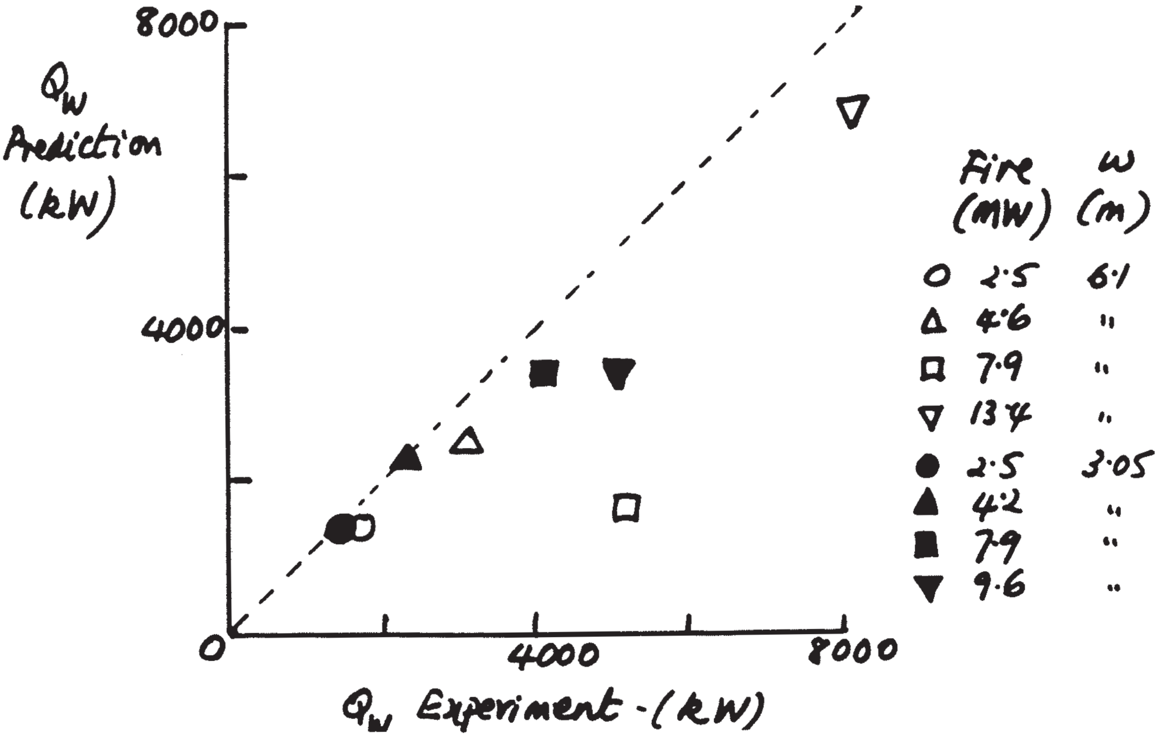

Fig. 11 Heat flow from a compartment (9) and equations (8), (9) and (11).

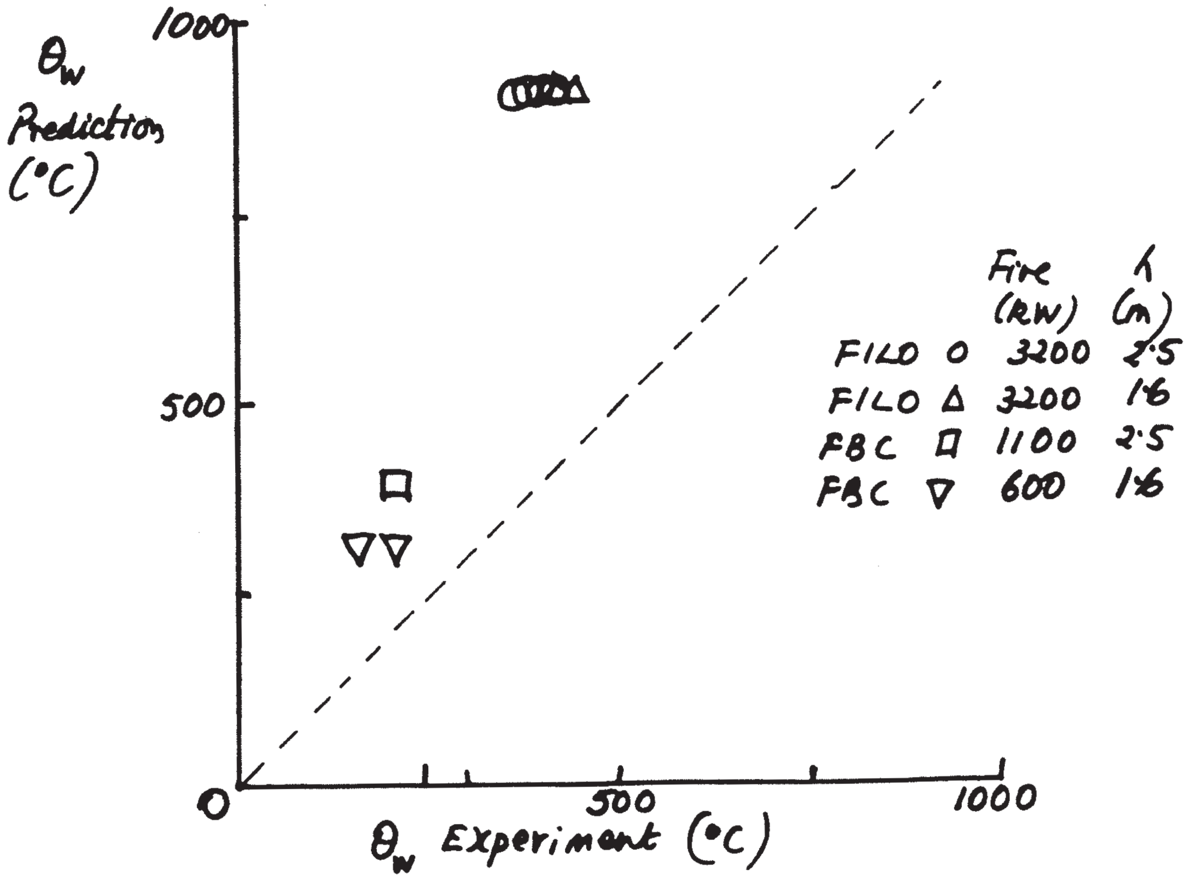

Fig. 12 Temperature above ambient of out flowing gases and equations (12) and (13), for a shop front (6).

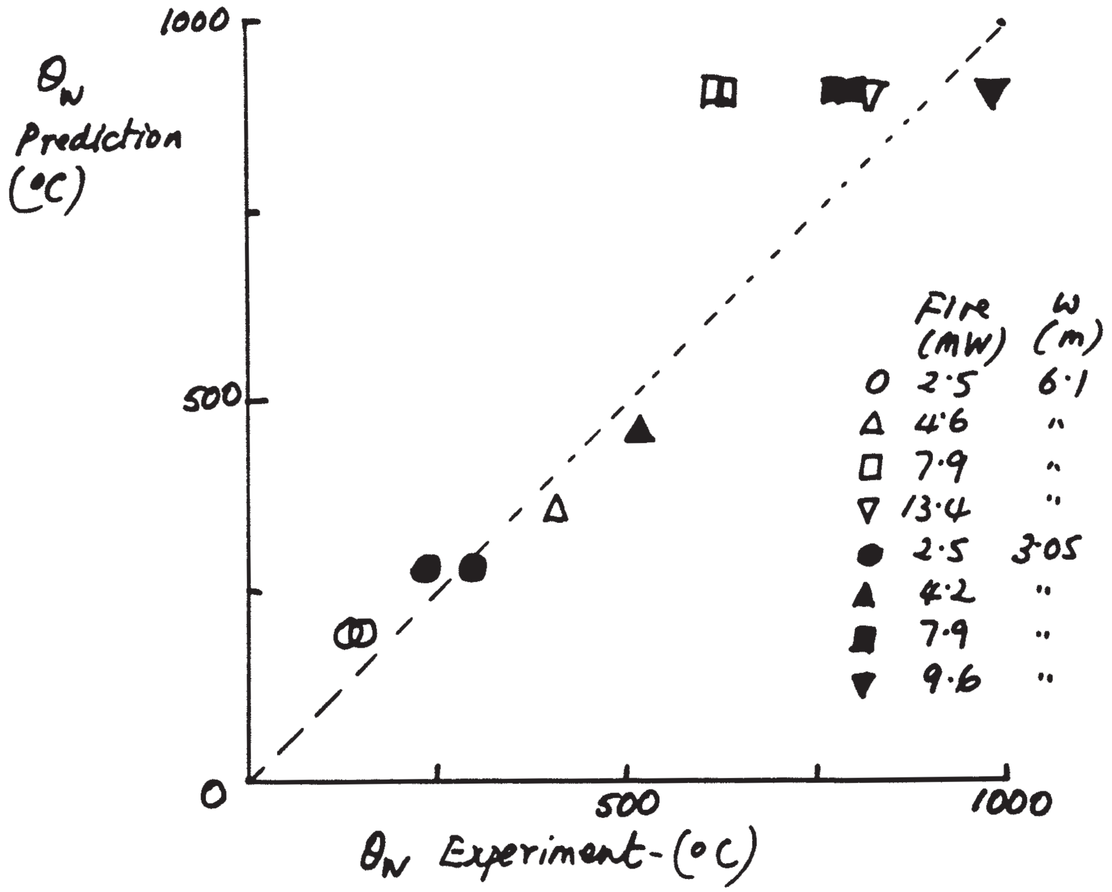

Fig. 13 Temperature above ambient of out flowing gas s and equations (12) and (13), for a fire compartment (9).

PAPER 16

What is a fire engineer?

Margaret Law, BSc, FIFireE, MSFSE, MSFPE, Arup Research and Development, London, UK, Journal of Applied Fire Science, 1 (1) 3-6 1990-1. Baywood Publishing Company Inc, USA

I was originally asked, as a consultant, to write a paper on ‘What is a Fire Engineer?’ as an introduction to a BRE forum on ‘Future Demand for Fire Safety Engineers’. It was clearly a poisoned chalice. This contribution developed eventually into ‘a paper to sort out my ideas’, which I found quite interesting to do.

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WHAT IS A FIRE ENGINEER?*

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It seems rash to agree to come to a meeting such as this to explain to the audience what a fire engineer is or ought to be.

At at recent meeting I attended, the view was expressed that a fire *safety* engineer, a term I will use rather than *fire engineer*, is just another sort of engineer. By that was meant a *professional* engineer and that is one shorthand description of how a fire safety engineer is perceived. However, if that is all there is to it, then how is it possible to fill in a half-hour slot in this program? I believe we can expand a little on this simple statement.

You may know that I work in a large engineering and architectural consultancy and have the benefit of meeting a very wide range of specialists and some generalists—not exactly the C.P. Snow definition—but including economics, financial, legal people and so on. One of the things that was decided about a year ago was to hold a series of lunch-time seminars open to all nontechnical staff to explain what Arup engineers were doing.

These seminars have been extremely popular. The first one was given by a retired director. It was called, *What Is an Engineer*. He said to me, 'You know, Margaret, I have presented many technical papers in my time but this one was the most difficult I had to do.'

PREREQUISITES

Background

It does seem to me that whatever their specialty, be it structural, mechanical, acoustic, chemical, for example, all engineers have certain assumptions and background knowledge in common. They can discuss concepts across the frontiers of their

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*This article is based on an address given by the author at the meeting "Forum-Future Demand for Fire Safety Engineers in the U.K. and Their Training and Education" in Borehamwood, U.K. on June 29, 1989.

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specialty. The concept of flow, for example, whether it is water down a pipe, people down a corridor, electrical charge and so on—these can be discussed, directly or by analogy, with ease. The physical and mechanical behavior of materials and structures can be understood and discussed in a broad way. Engineers, and architects too, by their education and training have these concepts built into them and discuss matters accordingly. It is much more difficult to discuss technical matters with people who have not had that background of professional education, however intelligent they may be. In my own field of building fire safety, for example, I know that there is this blank, when members of the design team try to understand the concerns of the fire service, and vice versa. They come from different worlds, just as Basil, our Arups Director who talked to our nontechnical staff had to realize they came from different worlds. He was forced to rethink his presentation from scratch.

My first point therefore is that a fire safety engineer must have built into his education and training the basic engineering assumptions and understandings. He must be in the engineers' world.

Knowledge of Measurement and Quantification

A characteristic of engineering design is that it is based on the best understanding available of the physical and chemical processes and *measurement*. Measurement and quantification are fundamental to any proper engineering design. It is sad that so many people are reluctant to measure things: presumably this might cast doubts on what they know to be right. Because fire danger and the effects of fire can generate deep emotions, the proposal to reduce such matters to cold numbers seems to be callous and not a proper response to the imponderable forces of nature. Yet decisions have to be made.

We have to design for wind effects, earthquakes, moving loads on bridges and so on and in the end it comes to numbers. The phrase 'taking a calculated risk' is normally used in a pejorative sense, but a responsible engineer must always calculate, measure and quantify as best he can. Of course, judgment comes into it, which is part of experience.

My second point therefore is that a fire safety engineer must understand how to measure and quantify fire phenomena and fire safety.

Awareness

Fire safety engineering is an important component of most activities and no one person could hope to be an expert across the board. Nevertheless, the fire safety engineer should have an awareness of the various aspects, an ability to identify potential problem areas and where to go to find an answer. For example, when my colleagues were doing a survey of a very large bakery—the biggest in Europe incidentally—they obviously needed to take into account fire safety and consulted me about the structural fire protection. I also knew, of course, about the hazard of

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dust explosions and said, 'Well I'm not knowledgeable on this subject—but with all that flour around you ought to see an industrial consultant. Try Burgoyne and Partners,' which they did.

Now there are some people working at this research station who I would not call fire safety engineers. They are doing very valuable studies of chemical aspects of extinction or physical aspects of toxicity, but they are scientists who happen to be studying a fire phenomenon, almost independently of others. Awareness is not a quality which is required of them (although it is of their seniors) and they are scientists, not fire safety engineers.

Experience

The third point therefore is that a fire safety engineer should have an awareness of fire phenomena in general.

Awareness is part of experience. Experience, as well as academic training, is recognized as an essential part of engineering training and is just as important for fire safety engineers—experience of: What will happen? not What ought to happen?; What is practical in the circumstances?; What is trivial? and What is significant?; What contributes to safety and What is value for money?; and What must be done to meet the rules?

Research and Development

The fourth point therefore, is that the fire safety engineer should have the opportunity to gain practical experience.

Over the career of a fire safety engineer there will be many changes—in technology, life style and knowledge—which need to be recognized and understood. For example, one of the major changes in the past two decades has been the general acceptance of the importance of identifying potential smoke problems and the ways of controlling smoke flow and crowd movement. This has happened because there are now so many large buildings opened up to all types of public activities.

The guidelines are being developed almost on the hoof. For many aspects of fire safety there is not yet the basis of an engineering design approach or enough accumulated practice on which a code of good practice can be based. Therefore it is particularly important that the fire safety engineer keeps ahead of the latest research and development.

The fifth point therefore, is the need to keep informed on latest developments.

Toughness

Finally, the fire safety engineer needs a certain toughness—and I am referring to intellectual toughness. By this I mean that the engineer must be able to be tested and challenged and deal with matters in a rigorous, analytical and, above all, honest way. He must be aware of the rules but not use them as a shield.

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Designs and projects should be tested and assessed in all the quantifiable ways possible. With all respect to Mr. Fennell [1], it is unacceptable to say ‘fire is unpredictable’ or ‘people will panic’ and use that as an excuse to avoid doing any calculations or measurements. That is sloppy thinking and should not be allowed where public safety is concerned.

Of course, not all the information will be available. The engineer must be strong enough to admit honestly what is not known as well as insisting that what we do know is taken into account. All information is an aid to judgment. The largest collection of unread masterpieces must be PhD theses. But, the sheer effort of getting the thesis together into a consistent whole and then justifying it to a group of academics who, intellectually at least, are usually quite ruthless, should and does toughen up most graduates who go through this process.

My sixth point therefore is that the fire safety engineer must be tough enough to stand up to a good deal of questioning and in his turn to be able to push other people in the same way: justify what you are saying if you want to be taken seriously.

This article lists six points: It seems to me that there are training or education aspects of them all. What makes this list different from other aspects of engineering? Nothing: Only that with fire safety engineering we have to spell it out. It is not yet taken for granted.

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1. D. Fennell, *Investigation into the King's Cross Underground Fire*, Her Majesty's Stationery Office, The Departmenl of Transport, London, 1988.

PAPER 17

Quantifying fire safety for tall buildings

Margaret Law, Ove Arup Partnership, London, UK, Tall Buildings: 2000 and Beyond, Fourth World Congress, 5-9 November 1990, Hong Kong. Not published in Proceedings.

This paper brings together various assessments from statistical data that could be incorporated in a risk-based code for tall buildings. The idea was to give a lot of information in a very simple way, so as to engage the interest of all engineers, not just fire safety engineers.

Plate showing the Hong Kong and Shanghai Bank, Hong Kong. Arup were the consulting engineers and Margaret Law developed a fire safety engineering approach for the Building. Although this paper is targeted at tall buildings it presents a probabilistic approach that can be applied to most buildings.

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QUANTIFYING FIRE SAFETY FOR TALL BUILDINGS

Margaret Law, Ove Arup Partnership, London, UK

INTRODUCTION

The design of fire safety for tall buildings has been based on adopting a comprehensive package of measures: structural fire protection, compartmentation, automatic detection and alarm, automatic and manual fire fighting, smoke control. Although it is considered that the resultant design gives adequate safety, this has not been quantified. With much taller buildings being proposed than we have now, it is important that we try and establish explicitly that the probability of failure is very low.

This paper reviews some of the information available for the measurement of fire safety in buildings.

OBJECTIVES

It is suggested here that fire safety should be achieved by design, rather than by following the prescriptive approach of most building regulations or codes. For low-rise and medium-rise buildings the prescriptive approach is probably adequate and could be used as an alternative to a design approach. However, it is considered that for very tall buildings it is desirable to adopt a design approach.

QUANTIFY

In order to assess whether the design achieves an adequate level of safety it is necessary to quantify fire phenomena and fire safety. Both these aspects will be discussed in terms of fire models and safety models.

FIRE MODELS

- Fire and fire spread can be modelled in terms of the rate of heat output, temperature, the mode of heat transfer by convection, conduction and radiation.
- Smoke can be modelled in terms of the smoke particles, toxic products, volume, temperature, velocity.
- Structural behaviour can be modelled in terms of the physical and mechanical changes which occur when the structural materials are heated.
- Material behaviour can be modelled in terms of reaction to fire, ignitability, heat output and flame spread.
- Evacuation of buildings can be modelled in terms of the movement of people and their motivation to escape.
- Extinction of fires can be modelled for manual and automatic measures.

SAFETY MODELS

- Life safety has been measured for a variety of buildings and the acceptable life loss by fire, for single and multiple deaths has been estimated.
- The acceptable property loss for the individual is different from that for the nation. For example, loss of a factory may be a disaster for the owner but at a national level it may be perceived that the lost business can be taken up by other factories with spare capacity.
- Disasters are the events which have led to most safety regulations and can be considered as events which society thinks to be unacceptable.
- For design purposes we need to devise tests which prove the adequacy of the design. We are not attempting to predict what might actually happen but to ensure that our design has a low probability of failure.

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LOSS OF PROPERTY BY FIRE

It is difficult to model property loss in terms of money because with inflation the face value does not reflect the real value. Likewise, when making international comparisons the exchange rates used may mean that like losses are not being compared. However, broadly speaking, large losses correlate with extensive fire spread; fire-damaged area is a universal statistic, being independent of assumed monetary values, and can indicate loss.

A large fire is defined by UK fire brigades as one which needs five or more jets to fight the fire and it corresponds on average to a fire area exceeding about 120m² *(Melinek, Baldwin and Thomas 1970)*. It has been shown that this is consistent with an insurance survey of fire losses *(Law, 1989)*.

CRITICAL FIRE AREA

Once the fire has reached a certain size it is too large for the fire brigade to extinguish because of the large amount of heat produced. In these circumstances the fire is likely to be a complete burn-out. Estimates of the critical size of fire for control by the fire brigade vary. The NFPA suggests 230m², the National Bureau of Standards, (USA) and the Fire Research Station, (UK) suggest about an order less *(Baldwin 1970)*.

A broad criterion is that a large fire leading to a burn-out will exceed 100m² and that a large loss fire will also exceed 100m².

PROBABILITY OF A LARGE FIRE

Once a fire has occurred, the probability P_L of a large fire depends on P_S the probability of spread beyond the room of origin *(Baldwin 1970)*.

$$P_L = 1.23\ P_S^{3.2}$$

A small reduction in P_S gives a large reduction in P_L.

METHODS OF REDUCING PROBABILITY OF SPREAD

- Fire spread can be opposed by barriers, either partitions or compartment walls and floors.

- Early detection alerts fire fighters and protective systems while the fire is small enough to be controlled or extinguished. Extinction measures assist in arresting fire spread.

BARRIER FAILURE

In a recent paper *Ramachandran (1990)* discusses target probabilities for barrier failure, with and without sprinklers in the room of origin.

AUTOMATIC DETECTION

The value of early detection in reducing fire spread is illustrated below, from statistical data in occupied buildings in the UK other than dwellings *(Home Office 1980)*:

Discovery time min.	**Spread %**
up to 5	5
over 5	17

The value of automatic detection in reducing damage is given below *(Rutstein 1979a, Ramachandran 1980)* for the UK.

Alarm System	**Reduction in damage %**	
	Shops	Textile industry
Direct line	85	72
Local	40	63

AUTOMATIC SPRINKLERS

Automatic sprinklers are efficient at controlling fires and reducing the chance that there will be a large loss fire as illustrated below: *(Thor and Sedin 1979, Morgan and Chandler 1981, Law 1985).*

Reduction of large loss

Use	Factor
Shops	2 - 4
Industry	1.3- 6
Offices	1.5

The factor for industry depends on the amount of fire load. Where there is a low fire load, sprinklers do not offer so much benefit.

PROBABILITY OF A FIRE

The annual probability P_f of a fire occurring (to which the fire brigade is called) has been estimated for the UK *(Ramachandran 1979/80)*:

$$P_f = K A_B^{\alpha}$$

A_B is the floor area at risk (m²)

For all fires the average value of K is 0.0019 and α is 0.5 *(Rutstein and Clarke 1979)* but there are variations according to the use of the building *(Rutstein 1979, CIB 1983).*

FIRE SPREAD

Fire spread can be modelled in terms of the spread of fire damaged area. A doubling time can be deduced from fire statistics, that is the time period for the area to double *(Ramachandran 1980)*

$$A(T) = A(0)\ \exp\ (\Theta T)$$

A(T) is the area at time T. For the textile industry A(0) is approximately 4.7 m^2 and Θ is approximately 0.063 min^{-1}. This corresponds to a doubling time of 11 minutes. For all risks an average value of 4 minutes for doubling time has been derived from sprinkler statistics *(Baldwin and North 1971)*.

Initially the fire spread being small, the fire is localised and the fire has not flashed over to involve the whole room. Pre-flashover is of particular interest in relation to escape, detection and automatic extinction.

FIRE GROWTH - PRE-FLASHOVER

Fire growth in relation to detection systems is characterised by heat output Q(kW) and for design purposes may be taken as proportional to the square of time t(s), or it has exponential growth as shown below *(NFPA 1984)*:

$$Q = kt^2$$

$$Q = Q_o \exp[\alpha(t - t_o)]$$

The doubling time may be as low as ½ minute for polyurethane foam or 4 minutes for cartons on pallets *(Friedman 1978)*.

Prediction of the heat output needed to cause flashover is difficult but it is not likely to happen unless flames reach the ceiling.

FULLY DEVELOPED FIRE

The fully developed fire attacks the structure, and may spread fire to adjacent buildings. A heat balance can calculate both internal and external exposure. The rate of burning determines the rate of heat generation and, for a given fire load, the duration of the complete burn-out fire. On average, with ventilation control the rate of burning R (kg/s) is given by

$$R = 0.09\, A\, h^{1/2}$$

Where A is area (m²) and h is height (m) of the ventilation opening. An improved relationship takes into account the area of enclosing surface A_t, the depth D and width W of the compartment. *(Thomas 1974).*

FIRE GRADING

Most building regulations grade fire resistance for elements of structure using the relationship developed by *Ingberg (1928)*

$$t_e = K_1 \frac{L}{A_{floor}}$$

With fire resistance t_e in minutes, fuel load L in kg and A_{floor} in m², the value of K_1 is about unity.

A relationship developed by *Law (1971)* is as follows:

$$t_e = K_2 \frac{L}{[A(A_t - A)]^{1/2}}$$

The value of K_2 is about unity.

The *CIB W14 Workshop (1983)* adopted a similar approach to *Law*. With conservative assumptions for the thermal properties of the walls and a global value for ventilation the following was derived.

$$t_e = 2.8 m_i \frac{L}{A_{floor}}$$

Here m_i represents the fraction of the total fuel load which would be burnt. For offices, m_i has a value of 0.7 or less.

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LIFE SAFETY

The beneficial effects of detectors and sprinklers on life safety are not easy to assess. Most people are killed by small fires.

How much should be spent to save a life? Expenditure varies according to the type of hazard. An accounting method for the value of human life is not popular. An alternative approach is to estimate the critical number of deaths which constitute a fire disaster. It appears to be between 5 and 10 deaths in a single incident. Estimates of target probabilities by *Rasbash (1984)* are shown below:

Annual probability of death by fire

Number of fatalities	Target probability
5 or more	10^{-6}
100 or more	10^{-7} to 10^{-8}

Individual and societal risks are discussed by the UK *Health and Safety Executive (1989)*.

ASSESSMENT OF SAFETY

There are various assessment models in use; none of them are fully probabilistic:

- Points systems take into account factors which cause a risk, or make it worse and the factors which mitigate the risk or improve the safety. They essentially give flexibility within our existing rules, for example the Gretener system *(Burgi 1973)*.

- Evaluation systems have been developed for specific occupancies such as health care buildings *(Nelson and Shibe 1978)*. Statistics and judgement may be used.

- Ranking studies the risks in a qualitative way.
- Fault trees are presented as logic diagrams; currently they rely on some statistics and much judgement. *(Watts 1979).*
- Cost benefit analysis gives the optimum expenditure on fire safety where the sum of the costs and losses is a minimum.
- Expected risk to life and fire cost evaluation have been inferred from existing rules *(Beck and Poon 1988).*

CONCLUSIONS

There exists sufficient information to enable a new type of code to be developed which could be aimed at achieving a low probability of failure of a tall building. Where existing rules do not achieve this it will be possible to increase safety by, for example, more redundancy in the design.

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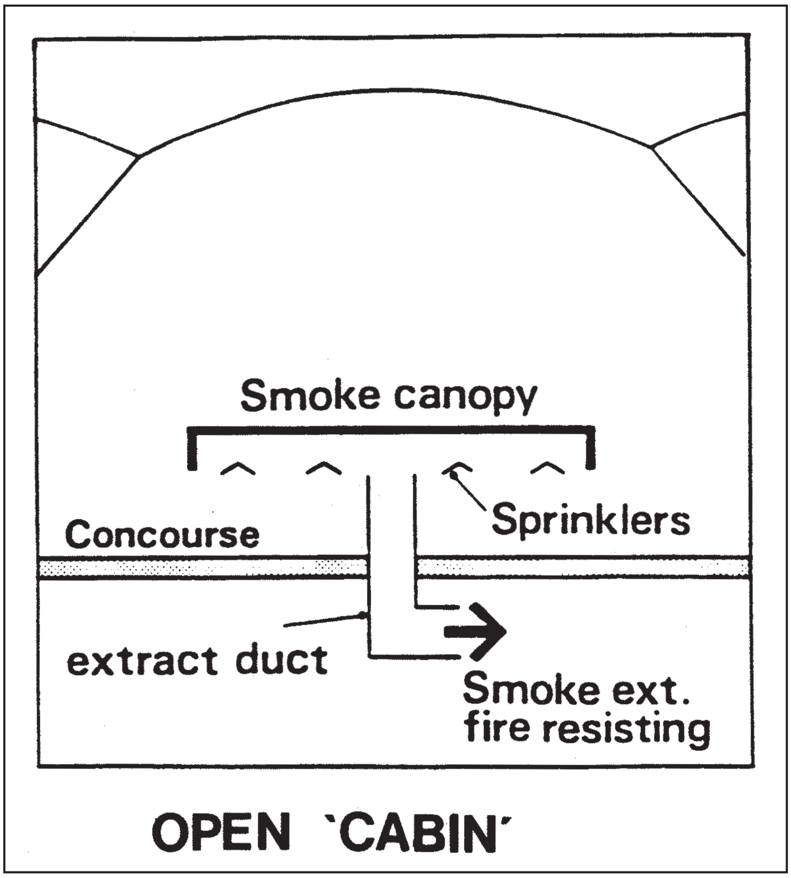
PAPER 18

Fire and smoke models - their use in the design of some large buildings

M. Law, Paper 90-10-3, ASHRAE Transactions, Vol 96 Part 1, pp 963-971, 1990. American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.(ASHRAE), USA

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and CIBSE decided to hold a joint Annual Meeting in 1990, at Atlanta. I was asked to support the British contingent with a paper about fire safety. This paper contains various engineering relationships with case studies to illustrate how they have been used. I also set down for the record some assessments from various projects. I was particularly pleased with the furniture correlation giving maximum rate of heat release against total mass of combustibles, which extended over three orders of magnitude. This paper received the ASHRAE Best Paper Award 1990.

Figure showing a simple schematic of the ‘open cabin’ for Stansted Airport. This was developed by Margaret Law to allow large undivided concourses, free from fire compartment limits, which architects needed in order to realise their ambitions for modern airports. The ‘open cabin’ allowed such a fundamental change in airport design that Arup used this technique on many other International Airports including Kansai, Japan and Chep Lap Kok, Hong Kong. It was also adapted for use on large rail stations including the new MTRC stations in Hong Kong.



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FIRE AND SMOKE MODELS—THEIR USE IN THE DESIGN OF SOME LARGE BUILDINGS

M. Law

ABSTRACT

Movement of smoke and hot gases produced by fires can be a significant part of fire safety design for the occupants of large buildings. A number of models have been developed for calculation of fire dynamics and plume entrainment. Smoke accumulation can be estimated using simple zone models or more detailed field models. For practical application, it is necessary to take into account many matters, including the nature of combustible materials present, the type of people using the building, the time needed for escape, the beneficial effects of automatic and manual fire protection systems, the influence of the internal and external environment, and the overall standard of management and maintenance of the building. Case studies are described.

INTRODUCTION

Building fires produce heat, smoke particles, and toxic gases. The air heated by the fire expands and is buoyant, thereby moving outward and upward. The heated air carries with it the particles and toxic products, and it is this contaminated cloud of warm air that is referred to as smoke. From an engineering point of view, calculation of the warm air movement will indicate where there is smoke and, unless it is very diluted with clean air, all heated air is considered to be undesirable smoke. Therefore, fire engineers usually characterize the fire in terms of its heat output, and then they estimate the degree of entrainment of ambient air into the fire plume. This entrainment cools the smoke and increases its volume.

Extensive studies have been made of the development of fire and smoke spread in small rooms, since most fire fatalities occur in dwellings. However, there is a disaster potential in large buildings, such as shopping malls, high-rise atrium buildings, and passenger terminals, and therefore an understanding of smoke movement in large spaces is also important. In small rooms, the fire is large in relation to the space and controls the dynamics, but in a large building, the physics of the space may control the smoke movement, at least during the initial stages of the fire. Since it is necessary to understand the building environment during normal (nonfire) conditions, it appears possible to extend this understanding to early fire conditions, where an injection of warm smoke can be considered as a local perturbation of the environment. Nowadays, it is common practice to install automatic sprinklers in large buildings; in these circumstances, it may well be assumed that the fire is always small in relation to the space and ameliorative measures are designed accordingly. Methods of assessment are in the developmental phase at the moment.

When a fire becomes large in relation to the space, it must be assumed that any occupants have not survived. The main concern is then to prevent its spread to other parts of the building, either by using physical barriers or by directing the flow of the heat and combustion products away from the vulnerable areas for the time specified.

The time dimension is of major importance in fire engineering. Nearly all conditions are transient, even though for design purposes steady-state conditions may sometimes be assumed. The fire duration is finite, limited by the amount of fuel or the extinction measures. The time needed for escape must always be considered: able-bodied adults at work are very mobile; infirm or confined people may be unable to escape without assistance. A large space remains tenable for a longer time than a small space. The rate of generation of heat and smoke varies according to the type and arrangement of fire load (combustible material) and the ventilation available. For design, these phenomena must be codified.

FIRE MODELS

During the ignition and growth phase of a fire, it is assumed that there is sufficient ventilation for the fire load to burn freely. This phase is of major interest in the design of automatic detection. Most growing fires can be idealized as follows:

$$Q = at^2 \tag{1}$$

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where Q is heat output in Btu/s (kW) and t is time (sec).

The value of a is 0.0277 (0.0293) for a slow fire and 0.0444 (0.0469) for a fast fire (NFPA 1984). An exponential growth rate is often adopted as an alternative:

$$Q = Q_o \exp b\,(t - t_o) \qquad (2)$$

where Q_o is initial heat output at time t_o, with a typical value being 10 Btu/s (10 kW). The value of b can range from 0.33 s^{-1} for PU foam to 0.0029 s^{-1} for cartons on pallets (Friedman 1978).

The above models are based on measurements of rates of heat release from various artifacts, made in laboratory conditions. Fire brigade statistics have also been used to estimate the rate of fire spread in buildings. From records of fire-damaged floor area and times of ignition and control, the following model has been developed by Ramachandran (1980):

$$A(T) = A\,(0) \exp \theta T \qquad (3)$$

where $A(T)$ is the area damaged in T minutes after zero time, $A(0)$ is the area originally ignited, and θ is a growth parameter. For the textile industry, $\theta = 0.0632$ and $A(0) = 50.36$ (4.6852). By imputing a heat output per unit area of floor according to the type of fire load, fire spread can be expressed in terms of heat output.

The plume of hot gases from the fire is deflected horizontally when it reaches ceiling level and a layer of hot gases forms under the ceiling. The time at which this layer causes operation of an automatic heat detector can be considered as one definition of zero time, where escape is concerned. The time of operation of an automatic sprinkler—which, of course, is also an automatic heat detector—can be considered as a time during which fire growth is slowed down or arrested. It has been the convention, for design purposes, to assume that sprinklers halt the spread of the fire but do not limit its heat output or extinguish it. However, heat transfer from the hot gases to the sprinkler spray is sometimes taken into account, a 50% heat loss being suggested (Morgan and Hansell 1985).

Once a significant layer of hot gases forms under the ceiling, downward radiation to the unburnt fire load accelerates the fire spread and can lead to "flashover," when all combustibles are involved and the room is filled with fire. Flashover does not occur when the fire is small in relation to the space. Therefore, where the fire load is small in relation to the space, or automatic sprinklers are installed, flashover is not expected.

If flashover occurs, the heat output will be controlled by the fire load itself, where there is ample ventilation. For restricted ventilation, the rate of weight loss of fuel is given by

$$R = k\,Ah^{1/2} \qquad (4)$$

where A is the area in ft² (m²) and h is the height in ft (m) of the windows or doorways giving ventilation. When R is in lb/s (kg/s), k is approximately 0.01 (0.09). Equation 4 can be used for mainly wood-type fire loads and for most "normal" occupancies even though they contain some plastics. A value of 5.6 Btu/lb (13 MJ/kg) can be assumed for effective heat output.

For small rooms, the heat output needed to produce flashover, based on a hot layer temperature of 900°F (500 K) above ambient, is given by McCaffrey et al. (1981):

$$Q_{fo} = k_1\,(h_k\,A_t\,Ah^{1/2})^{1/2} \qquad (5)$$

where h_k is a heat transfer coefficient in Btu/ft²•s•°F (kW/m²•K), A_t is the internal surface area of the room in ft² (m²), and A and h are defined above. When Q_{fo} is in Btu/s (kW), k_1 is 4210 (610). The value of h_k ranges from 2×10^{-3} (41×10^{-3}) for brick to 0.015×10^{-3} (0.3×10^{-3}) for EPS. In a large building, the prediction of flashover is of interest when the fire is in a small room, such as an office, which communicates with a large space, such as an atrium.

PLUME MODELS

Freestanding Fires

The plume flow above the fire in the room is usually described as axisymmetric, with a virtual point source located above or below the base of the fire, according to the fuel. Mass flow due to air entrainment is usually much greater than the fuel flow, so the latter may be neglected.

Above flame height, the equation for mass flow for stack fires (i.e., not pool fires) takes the form:

$$M = k_2\,Q^{1/3}\,y^{5/3} \qquad (6)$$

where M is mass flow in lb/s (kg/s), Q is heat output in Btu/s (kW), and y is height above base of fire in ft (m). A representative value of k_2 is 0.021 (0.068) (Zukoski 1978).

The axial temperature is given by

$$T_A - T_o = k_3\,Q^{2/3} / y^{5/3} \qquad (7)$$

where T_A is the axial temperature and T_o is the ambient temperature in °F (°C). The value of k_3 is approximately 324 (24) (Zukoski 1978).

The average plume temperature is given by conservation of heat as:

$$T_p - T_o = Q / MC_p \qquad (8)$$

where T_p is the average temperature in °F (°C) and C_p is the specific heat of air in Btu/lb•°F (kJ/kg•K).

For a fire of base dimension, D, the flame height, z, above the floor for a timber fire is given by Thomas et al. (1961):

$$\frac{z}{D} = k_4\,(Q^2 / D^5)^{1/3} \qquad (9)$$

where D is in ft (m), Q is in Btu/s (kW), and k_4 is 0.24 (0.032), for $Q^2 / D^5 = 8 \times 10^2$ to 8×10^4 (3.4×10^5 to 3.4×10^7).

For a liquid pool fire, the flame height is given by Heskestad (1982):

$$\frac{z}{D} = -1.02 + k_5\,(Q^2 / D^5)^{1/5} \qquad (10)$$

where k_5 is 0.77 (0.23) for $Q^2/D^5 = 3.3 \times 10^1$ to 3.3×10^{11} (1.4×10^4 to 1.4×10^{14}).

For an extended area, an alternative equation for mass flow, at heights comparable with the flame, is given by Thomas et al. (1963):

$$M = k_6\,P\,y^{3/2} \qquad (11)$$

where P is the perimeter of the fire in ft (m) and y is measured above the base of the fire. The value of k_6 is 0.0213 (0.188).

Occasionally, a line source is more appropriate and mass flow is given by

$$M = k_7\,(QL^2)^{1/3}y \qquad (12)$$

where L is the length of the source in ft (m) and y is height above the source. The value of k_7 is 0.059 (0.19) (Zukoski 1978).

Flow from an Aperture

Flow from an aperture can be treated as if the upper half of the aperture were the source of an axisymmetric fire or an extended area fire, an approach initially adopted by Yokoi (1960) in his classic study. He gives the axial temperature for the "intermediate plume," i.e., away from the aperture, as

$$T_a - T_o = (k_8/z)\,(QT/w)^{2/3} \qquad (13)$$

where z is the height above the top of the aperture in ft (m), T is the absolute temperature of the plume in °R (K), and w is the aperture width (m). The value of k_8 is 1.5 (0.16).

A recent analysis of flow leaving an aperture (Law 1989) gives the following:

$$M = k_9\,(Qw^2)^{1/3}h \qquad (14)$$

Here w is the width and h the height of the aperture in ft (m). The value of k depends on the geometry and location of the source and the type of compartment. For these experiments—in small rooms with open doors or windows—the value of k_9 varied between 0.013 and 0.029 (0.041 and 0.092). From a recent set of data with larger fires (Porter 1989), a value of 0.025 (0.08) can be deduced for k_9. For flow away from the opening, the following can be deduced from these larger experiments:

$$M = k_{10}\,(Qw^2)^{1/3}y \qquad (15)$$

Here y is measured above the base of the opening. The value of k_{10} is 0.043 (0.14). It will be noted that Equations 14 and 15 are of the same form as Equation 12 for a line source.

For aperture flow that runs under a balcony and then rises, experimental data have been interpreted as coming from a line source as follows (Law 1986):

$$M = k_{11}\,(QL^2)^{1/3}\,(y - 0.85H) \qquad (16)$$

Here L is the width of the plume, as it rounds the balcony, in ft (m); H is the height of the balcony soffit above the base of the opening in ft (m); and y is the smoke height above the base of the opening in ft (m). The value of k_{11} is 0.11 (0.34). An end correction to the plume by Thomas (1987) gives the following amendment to Equation 16:

$$M = k_{12}\,[Q\,(L + 0.22y)^2]^{2/3}\,(y - 0.5H) \qquad (17)$$

The value of k_{12} is 0.065 (0.21).

Equation 16 postulates a virtual source at a little distance below the balcony, and Equation 17 postulates a virtual source halfway below.

The heat content of the plume outside the aperture is less than Q from the fire:

$$Q_p = k_{13}Q \qquad (18)$$

Here Q_p is the heat content in the plume in Btu/s (kW). The value of k_{13} is suggested to be as low as 0.55 (Morgan and Hansell 1987) and 0.67 is probably a conservative value.

Flame height above the base of the opening is given by Law (1978) as

$$z + h = k_{14}\,(R/w)^{2/3} \qquad (19)$$

where z is the height above the top of the aperture of height h and width w in ft (m), R is the rate of burning in lb/s (kg/s), and k_{14} is 54.7 (12.8).

SMOKE MODELS

Zone Models

The most common smoke model, first used extensively for the design of automatic smoke vents (Thomas et al. 1963), postulates a high-level zone of warm, smoke-contaminated air and a low-level zone of cool, clear air. The smoke zone is assumed to have a uniformly distributed temperature and heat is conserved. It is relatively easy to calculate the location of the base of the smoke layer and the temperature of the layer.

The rate of change in clear layer height in the room is given by:

$$\frac{-dy}{dt} = [(M/d_o) + (Q/d_o \cdot T_o)]/S \qquad (20)$$

Here y is the height of the smoke layer base, d_o is ambient air density, T_o is the absolute temperature of the ambient air, and S is the floor area of the room. Equation 20 can be integrated for the appropriate mass flow and heat flow models. Some solutions are given by Zukoski (1978).

Cooper (1983) has used this type of model to compare the time required to reach the critical layer height and/or temperature with the time needed for people to make a successful evacuation of the room. He suggests a critical blackbody temperature of 361°F (183°C) for smoke layer heights exceeding 5 ft (1.5 m). For heights below 5 ft (1.5 m), he suggests a critical temperature of 199°F (93°C) and a critical CO concentration of 2000 ppm.

Cooling to the ceiling by radiation and convection and to the floor by radiation can be significant, and eventually it leads to loss of buoyancy. In ceiling flow, horizontal entrainment is negligible, but radiative and convective cooling will occur; in some tunnel experiments, a clear distinction could be made between the smoke layer and clear air for a smoke temperature difference as small as 10°F (5 K) (Heselden 1970). These experiments yield a value for the effective heat transfer coefficient of 0.64 Btu/ft^2•s•°F (13 kW/m^2•°C) (Gardiner 1989) from the smoke layer to the ambient surroundings.

In large buildings it seems necessary to take into account the cooling effects explicitly at the moment. Later, it may be possible, for design purposes, to revert to the simplest type of zone model by adopting a suitable value for the design fire.

Field Models

In field models the space is divided into a large number of interconnecting cells, and flow, heat, and mass equations are solved in every cell, including buoyancy, radiation, and turbulence. In principle, the field model can give a precise representation of smoke flow. In practice, it must be used carefully because it relies on certain input assumptions that may have limited validity. It also takes up much computer time. Nevertheless, it has been successful in reproducing smoke movement where the input conditions were known (Markatos and Cox 1984).

SMOKE MANAGEMENT

Automatic Roof Vents in Industrial Buildings

In this method, vents open automatically when smoke is detected and horizontal smoke flow is limited by smoke curtains, which may be permanent or drop-down. The smoke flows out due to buoyancy, and the vent area is sized so that the mass flow of smoke into the ceiling layer is balanced by the mass flow out, for a predetermined fire size and critical smoke height (above the edge of the curtains). Fresh air must be introduced either at a low level or from other, nonaffected, roof vents. The main purpose of the venting is to assist fire fighting by keeping the low levels smoke-free and it is used extensively for large, uncompartmented spaces in industrial buildings (Thomas et al. 1963).

When these buildings are protected by automatic sprinklers, some engineers have suggested that operation of a vent may delay the sprinkler operation significantly. The debate rages and has not yet been resolved.

Pressurization

In this method, a favorable pressure difference is established across a barrier, such as a door to a protected corridor, lobby, or staircase; the flow is designed to overcome the flow of smoke into the protected space. Its primary purpose is to protect people while they escape from the building; it is also a protection for fire fighters gaining access to the upper floors.

Extensive design advice has been published (Klote and Fothergill 1983; BSI 1978), and in this method it is not necessary to define the size of the fire. The main practical difficulty is in predicting the flow paths in the building, and much adjustment is needed during commissioning. If there is too much overdesign to compensate for uncertainties, then it may become difficult for people to open doors in the building in practice.

Mechanical Smoke Extract with Sprinklers

For many buildings it is practical to use the building mechanical system to extract smoke from the floor of fire origin, when the fire is small. Thus this method is practical when an automatic sprinkler system is installed. It can be designed to keep other parts of the building free of smoke and assists the fire brigade in "searching" the building.

Figure 1 *Royal Exchange Theater, Manchester*

Atrium Buildings

An atrium provides a path for flow of heat and smoke throughout the building. However, a large atrium can give a beneficial dispersion of combustion products, which could, if confined, be a threat to life.

When the atrium enclosure is glazed, occupants of the overlooking stories can be shielded from the atrium smoke if its temperature is below the breaking temperature of glass, a conservative value being 200°F (95°C). Sufficient cool air can be introduced to cool the smoke, according to the design size fire.

In very large atriums, if the fire is maintained small, the dilution may be such that the smoke is not a threat to life. Otherwise, it may be necessary to maintain a clear layer above the fire. Where a system of natural ventilation is used to modify the atrium environment, it can often be exploited for smoke removal.

Another method, already described, is to extract smoke from the floor of fire origin using the building's mechanical system to keep the atrium smoke free.

An automatic sprinkler system is an effective measure for protecting the building from vertical fire spread via the enclosures (external and internal).

External Effects

In most smoke management systems, it is necessary

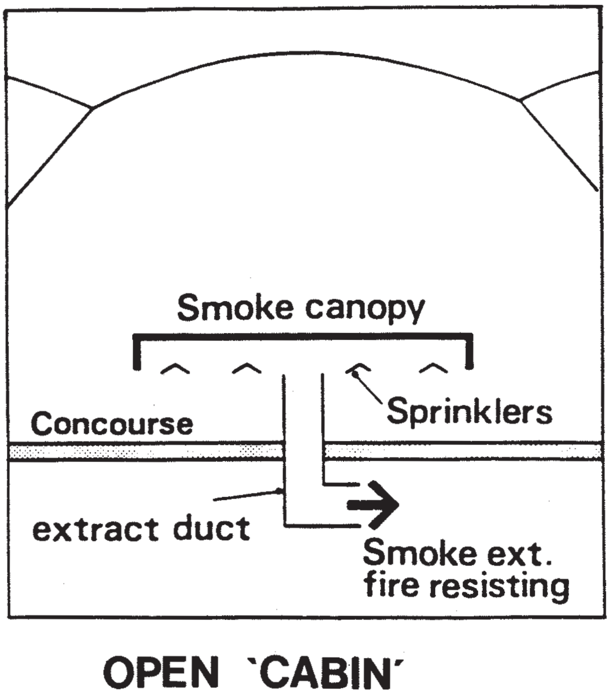

***Figure 2** Stansted Airport passenger terminal*

to consider how sensitive they will be to the environment, wind, and stack effects.

CASE STUDIES

Royal Exchange Theater, Manchester, UK

This theater-in-the-round stands inside the Great Hall of the Victorian Cotton Exchange in Manchester. The theater has an open structure enclosed in glass that has no fire resistance, so that heat and smoke from a fire in the theater could enter the Hall and vice versa. It holds 700 people, about 400 at floor level and 150 in each of two galleries (see Figure 1).

The volume of the theater is about 120,000 ft^3 (3500 m^3) and the volume of the Hall is about 1.8 million ft^3 (50,000 m^3). Despite its large size, the Hall was not considered to be a safe place in the event of fire, and it was decided to estimate whether there would be sufficient time for people to escape from the theater and then from the Hall before smoke became a threat.

It was estimated that the worst fire would be on the stage, involving 1000 kg of mixed furniture and canvas, etc., burning freely, with a burnout time of 20 minutes. The calculated maximum value of Q was 11.0×10^3 Btu/s (11.6×10^3 kW) on an area of 270 ft^2 (25 m^2). An earlier, slightly modified version of Equation 6 was used to estimate mass flow into the domes, and a simple zone model was adopted to define the position of the smoke layer base at various times. By assuming no growth period, i.e., Q was instantaneously at its maximum value, the time for the smoke to descend to 3 m above floor level was 10 minutes. Using Equation 11, applicable only where the hot gases are close to the fire, the time was calculated as 5 minutes. It was considered that when allowance was made for the growth period of the fire, it was reasonable to assume that smoke would not reach head level until at least 5 minutes after full fire development on the stage.

The calculations of exit time were based on the following criteria, which were the basis for the regulatory escape code.

a) A unit of exit width measures 21 in. (535 mm).

b) For exit widths above 3 ft, 6 in. (1070 mm), each increment of 3 in. (75 mm) gives a proportionate increase in the exit width.

c) For unit exit width, an exit discharges 40 people/min.

d) A column of people on an escape route normally moves at 40 ft/min (0.2 m/s).

e) When the people discharge into a short passageway or open space, they move at 60 ft/min (0.3 m/s) and the rate of flow on a unit width is 52 people/min.

f) When the concentration (area per person) exceeds 2.3 ft^2/person (0.12 m^2/person), the walking speed exceeds 60 ft/min (0.3 m/s).

g) The walking speed in an open space is 260 ft/min (1.3 m/s).

h) The rate of flow of people on a unit width of staircase is 40 people/min.

j) A moving column on a staircase occupies one unit width of stairway on every alternate tread and 3 ft^2 (0.28 m^2)/person on the landings.

It was shown that the total evacuation time would not exceed 2½ minutes.

It is believed that at that time, 1974, this was the first project in the UK to gain approval based on an analysis of both smoke movement and evacuation of people. Since that time, calculations of smoke movement have been widely adopted, but, sadly, escape models have not received the same attention.

Airport Passenger Terminal

The new airport terminal at Stansted, Essex, UK, consists of a single-story public concourse some 340,000 ft^2 (32,000 m^2) in area with all services contained in an undercroft. The roof is 43 ft (13 m) above the concourse. The aim is to keep the public circulation areas "safe," that is, free from heat and smoke that could endanger the passengers. It is not practical to have physical separation of many of the areas that contain significant amounts of fire load—duty-free shops and restaurants, for example—therefore, they are in open-sided "cabins" fitted with automatic sprinklers and automatic smoke extract (see Figure 2). Cabins not accessible to the public are fully enclosed. However, it was recognized that fire could still occur in the concourse areas (in the seating, for example) and calculations of heat generation and smoke movement were carried out.

The design fire was assumed to involve a wood-type fire load at a density per floor area of 4 lb/ft^2 (20 kg/m^2) with a burning time of 20 minutes and a convective heat output of 5600 Btu/lb (13 MJ/kg). The initial fire area, $A(O)$, was taken as 32 ft^2 (3 m^2) and the fire area was assumed to double every four minutes. Thus Equation 3 became:

$$A(T) = 32 \exp[0.173T] \quad \text{ft}^2$$

For a heat output of 18.7 Btu/ft^2•s (212 kW/m^2) and T in minutes, Equation 2 gives

$$Q = 598 \exp[0.173(T - T_o)] \quad \text{Btu/s}$$

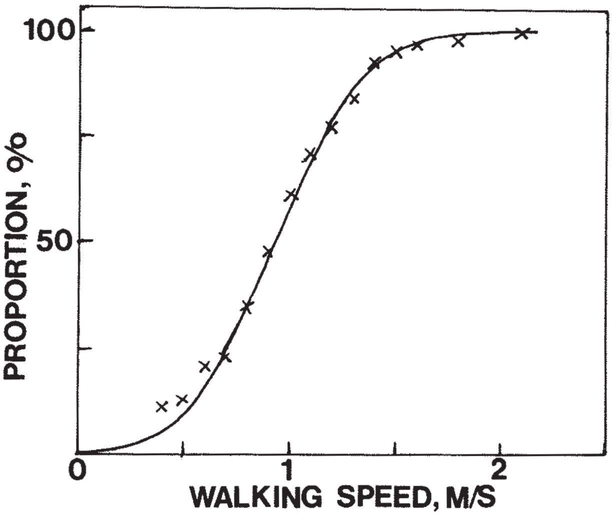

Figure 3 *Distribution of walking speeds in a reclaim area*

TABLE 1
Clear Layer Height in Terminal, Stansted

Scenario	Time min	Clear layer height– ft(m) Minimum	Average
1	6	31 (9.6)	34 (10.4)
	12	25 (7.7)	29 (9.0)
2	6	33 (10.2)	37 (11.3)
	12	32 (9.7)	35 (10.8)

When t is in seconds:

$$Q = 598 \exp [0.00288 (t - t_o)] \quad \text{Btu/s}$$

In a second scenario, it was assumed that the fire growth would be limited to 100 ft² (9 m²) by fire-fighting action.

Using field modeling (Waters 1989) and placing the fire at the center of the floor, it was found that the smoke edge reached the longer wall at T = 4 to 6 minutes. It reached the shorter wall at T = 10 minutes in the first scenario—no fire-fighting action—and at T = 12 minutes in the second scenario, where the fire spread was halted at 100 ft². The height of the smoke layer base, defined by a temperature of 7°F (4°C) above ambient, was lowest adjacent to the fire. The minimum clear layer height and the average clear layer height are shown in Table 1. The calculations indicate that, even with unlimited fire growth, the smoke layer would be well above head height after 12 minutes.

Measurements of walking speed were made in a crowded baggage reclaim area in an existing airport terminal. The walking speed was calculated using the distance actually traveled by a person with baggage from the carousel to the exit, divided by the time taken. The nominal speed was calculated using the most direct distance to the exit divided by the time taken. The time to gather up bags also was measured. The median values were 3.0 ft/s (0.92 m/s) for walking speed, 2.8 ft/s (0.85 m/s) for nominal speed, and 39 s for gathering time. Figure 3 shows the cumulative distribution of walking speeds.

These data were used to estimate the time needed to evacuate the terminal, the speed being assigned randomly according to the distribution described above. A pause time of 30 seconds after detection was assumed. A number of scenarios were tried, from which it was concluded that evacuation would be completed within five minutes (about twice the design escape time in UK codes). Table 1 indicates that smoke would not be expected to threaten the passengers while they are escaping from the terminal.

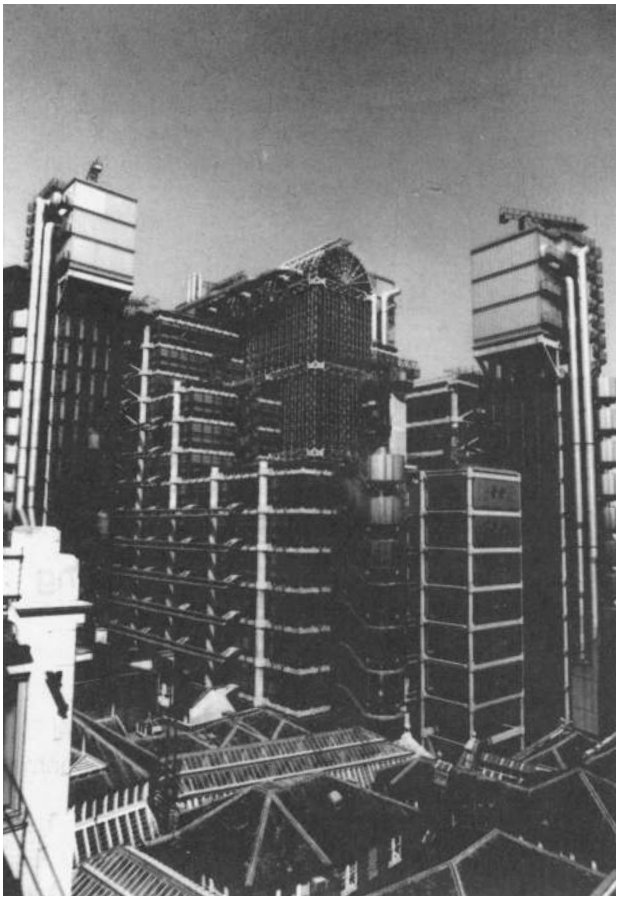

Figure 4 *Lloyd's building, London*

Office Building with Atrium

The Lloyd's building in London, UK, has an atrium approximately 110 ft by 36 ft (34 m by 11 m) on plan and 236 ft (72 m) high. It is overlooked by a double height "room," three open galleries, and nine enclosed, glazed galleries. The top six galleries are cut back to some extent for light to adjacent buildings (see Figure 4). Field models were used to predict air movement patterns for winter and summer conditions, and subsequent monitoring in the completed building gave similar patterns (Waters 1989). Therefore, field modeling of smoke patterns appears feasible as well.

The atrium is equipped at roof level with extract fans to give six air changes per hour, and doors open automatically at low level to provide fresh make-up air when smoke is detected.

For our calculations, the fire growth model was that suggested by Cooper (1984) based on measurements from fires in various commodities. At time t = 0, the heat output is 9.5 Btu/s (10 kW) and using Equation 2:

Contents

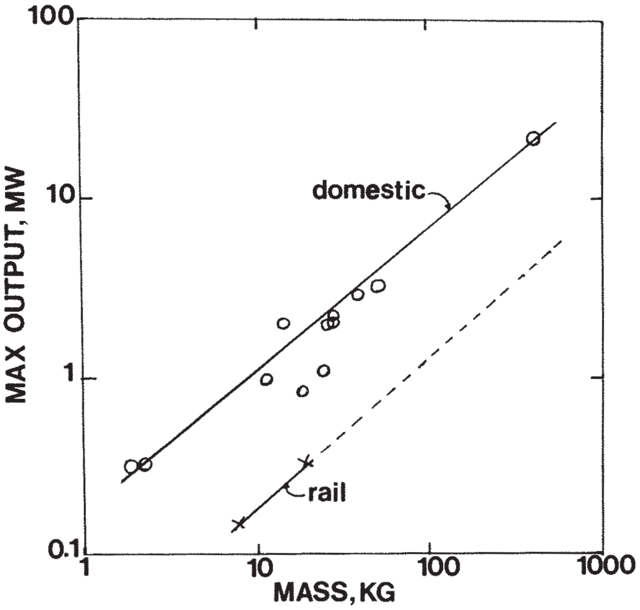

Figure 5 *Heat release rates from furnishings*

$$Q = 9.5 \exp[0.025t] \text{ for } t < 148$$
$$Q = 380 \exp[0.010\,(t - 148)] \text{ for } t < 349$$
$$Q = 2850 \exp[0.005\,(t - 349)] \text{ for } t > 349$$

An axisymmetric flame model was assumed, as given by Zukoski et al. (1981). A linear temperature gradient in the atrium was assumed, with 73°F (23°C) at floor level and 109°F (43°C) at the top. Before ignition, the air was assumed to be stationary. For the field model calculations, the atrium was simulated as a cylinder of 72 ft (22 m) diameter and 236 ft (72 m) height. At 40 seconds the calculations showed that very thin smoke, 65 to 100 ft (20 to 30 m) visibility, would rise some 65 ft (20 m). At three minutes, the thin smoke would be some 100 ft (30 m) high and stratified. As the atrium filled with smoke, it was found that warm air was being entrained back into the plume, so equations that assume the air entrained is at local ambient temperature can give misleading answers. It is intended to repeat these calculations, taking into account typical pre-fire air movements.

Sub-Surface Railway Stations

Some new mainline railway stations are being constructed "sub-surface" and some existing railway stations are becoming effectively sub-surface because the air rights have been sold and the platforms are now covered by rafts. It has been necessary to estimate if there is time for people to escape before smoke from a train on fire puts them at risk. In small stations, or in stations with long evacuation times, it may be advisable to provide smoke extract.

It is first necessary to establish a fire model. The fire scenario presented to us was a fire inside a passenger rail car. A seat would have been ignited (by an arsonist) at a previous station, and the fire would be well developed by the time it reached the station under consideration. All car doors on the platform side would be opened. It could be assumed, because of its construction, that the fire would be contained within one car.

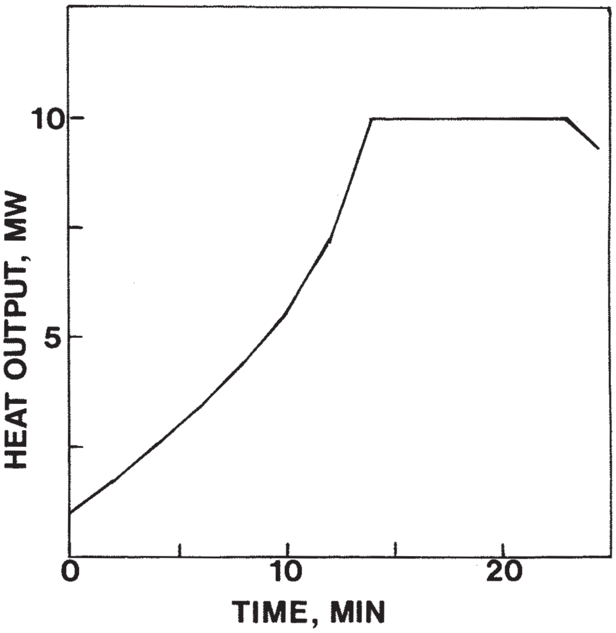

Figure 6 *Design fire for railway carriage*

TABLE 2
Maximum Heat Release Rate from Train Seats

Test	Mass lb (kg)	Q_{max} Btu/s (kW)	Time min
1	17 (7.6)	132 (139)	31
2	43 (19.6)	308 (325)	19

Because of the variety of rolling stock that might use the station, it was difficult to identify the type of seating. Initially, the heat output from domestic seating of mixed materials was examined. It was found that the maximum rate of heat release, Q_{max}, could be correlated with the total mass of combustibles, as shown in Figure 5, given by the following equation:

$$Q_{max} = k_{15} W^{0.8}$$

where Q_{max} is in Btu/s (kW), W is in lb (kg), and k_{15} is 85 (170). A single seat reached its peak output about four minutes after ignition and was burned out eight minutes after ignition. Our first fire model was based on this information. However, we were informed that railway seating burned more slowly, and measurements confirmed this, as shown in Table 2. These results are shown in Figure 5. They could be generalized as follows:

$$Q_{max} = k_{16} W^{0.91}$$

where Q_{max} is in Btu/s (kW), W is in lb (kg), and k_{16} is 10 (22). This equation was used to estimate the maximum heat output possible, with all seats in the carriage burning freely, and yielded 9500 Btu/s (10,000 kW) for a total mass of 1800 lb (820 kg).

The growth curve for Test 2, one seat, could be described by:

$$Q = k_{17} t^{1.63}$$

where Q is in Btu/s (kW), t is in seconds, and k_{17} is 0.00387 (0.00408). This curve is similar to the idealized square law form of Equation 1.

The heat output needed for flashover in the car was calculated using Equation 5, and the time to reach flashover was estimated to be 34 minutes after ignition.

TABLE 3
Smoke Behavior above Platform

Extract Rate	Average Height at 4 minutes	Time for Smoke Logging
ft^3/s (m^3/s)	ft (m)	min
0 (0)	7.9 (2.4)	12
175 (5)	8.9 (2.7)	14
350 (10)	9.5 (2.9)	17

After flashover, it was assumed that all windows would be broken, thus providing ample ventilation and, from experimental evidence, it was concluded that the maximum heat output would be achieved 14 minutes after flashover and that it would stay at that value for 9 minutes and then decay (see Figure 6). Equation 15 was used to estimate mass flow of smoke above the carriage, treating the carriage as a line source and adopting a value of 0.093 (0.20) for k_{10}. Equation 18 was used to estimate the heat content of the smoke, with k_{13} taken as 0.60.

In a new, small station with a ceiling area of approximately 53,000 ft^2 (4900 m^2), it was concluded from tunnel experiments that a smoke layer would cover the platform area within the evacuation time of four minutes. The height from platform level to ceiling level was 3.7 m. Using a simple zone model and Equation 20, the values in Table 3 were obtained.

The average smoke layer temperature at four minutes was 81 °F (45 °C) above ambient. It was concluded that some mechanical extract should be provided, together with downstand screens below the ceiling, to prevent smoke flow up the escalators and escape stairs.

A more detailed zone model, allowing for cooling to the surroundings, is being used for an existing main line station to assess the need, if any, for smoke management under the rafted area. The fire model is the same as before, but the evacuation time is 10 minutes.

CONCLUDING REMARKS

It is hoped that general guidelines for the design of smoke management can be evolved, with application to a wide range of building uses and escape strategies. Such an engineering approach can lead not only to better fire safety, but to more flexible building design.

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DISCUSSION

D. Elovitz, P.E., Energy Economics, Inc., Natick, MA: Do you recall the floor areas for the Exchange building and the Stansted Airport?

M. Law: The floor area of the Great Hall is approximately 22,500 ft^2 (2100 m^2). For Stansted Airport the floor area used in calculations was approximately 340,000 ft^2 (32,000 m^2).

A.S. Vener, Vener Consulting Engineers, Houston, TX: What is the actual fire experience in the U.K. of atrium smoke management systems in actual fires and what is the role of the sprinkler?

Law: We are not aware of any significant fire in a modern atrium building in the U.K. This is not surprising when one takes into account that most atriums are in office buildings, and the safety record in offices has in general been good. It is considered that, when escape is easy, it is not essential to have sprinklers. For high-rise buildings, shopping centers, and the public areas of hotels, it is normal practice to install sprinklers for life safety. However, many buildings in the U.K. would be considered low-rise, particularly by North American standards, and would only be sprinkler-protected where property is considered to be at risk.

F. Mills, Building Design Partnership, Manchester, England: Architects have recently been interested in the use of "tented" roof structures. However, these materials introduce concerns about the use of toxic materials. Will fire- and smoke-modeling techniques help to resolve these issues?

Law: Concern has been expressed about the potential toxicity of PTFE-coated membranes because, in a particular laboratory test (the "Potts Pot" test), very toxic combustion products were obtained. It is not clear that they would be encountered in real building fires. At the moment, it is necessary to demonstrate by fire engineering methods that such fumes, if produced, would not be hazardous to people in the particular conditions of use: for example, if they disperse to the open air at high levels. Alternatively, the membrane itself can be shielded or removed from any potential heat source.

R. Sheng, Senior Engineer, University of Manitoba, Winnipeg, Canada: I was surprised to see a modern theater looking like a space module built inside the Great Hall, a gothic building of historical value. The enclosure and stairs of the modern theater didn't seem to facilitate the escape of spectators and other occupants.

Law: The theater is very popular with the citizens of Manchester. The means of escape from the theater are very good and everyone can be out of the theater and the Great Hall within two and a half minutes. This was proven by measurement.

B. Sun, Flack & Kurtz, San Francisco, CA: Was any type of smoke extraction/relief system used for the theater? The Lloyd's of London atrium building did have a mechanical fan system at the top of the atrium. How was it sized? How was make-up air provided for the atrium?

Law: It was not possible to ventilate the Great Hall for removal of smoke from the theater because the glass domes were protected by legislation for historic buildings; therefore, we had to show there was a large enough reservoir without ventilation. The extract capacity for the atrium of Lloyd's was based on our assessment of what was reasonable, and it was judged acceptable by the building authorities because they were able to relate it to their usual criterion of six air changes per hour. Make-up air is provided by doors at low level that open automatically when smoke is detected in the atrium.

PAPER 19

Fire safety design practices in the UK - new building regulations

Margaret Law, Ove Arup Partnership, London, UK, Conference on Fire Safety Design in the 21st Century, Worcester, Massachusetts, USA, 8-10 May 1991, Proceedings pp 228-235. Worcester Polytechnic Institute, USA

Professor David Lucht of Worcester Polytechnic Institute decided to open discussions in the USA on the design of fire safety. He started the proceedings by inviting overseas speakers to describe recent developments in their own countries. The Building Regulations for England and Wales that were introduced in 1985 were completely new, because the old rulebook was thrown away and replaced by a few simple functional statements. My description of this change had already excited great interest at the annual meeting of the Architectural Association of Japan in 1987. By 1991, UK engineers had experience of working under the new regulations. Although the change applied to all forms of engineering in buildings, it was particularly opportune for the relatively new discipline of fire safety engineering. The American participants liked what they heard about the international developments, voting for the Australian approach as their favourite option.

Plate showing the three overseas speakers, Vaughan R Beck, Australia; Margaret Law, U.K.; Yngve Anderberg, Sweden.

Fire Safety Design Practices in the United Kingdom - New Building Regulations

Margaret Law, Ove Arup Partnership, London, UK.

ABSTRACT

There are three sets of Building Regulations in the UK, for Scotland, Northern Ireland, and England and Wales (together). The first two are of the prescriptive type, the third, established in 1985, gives simple Functional Requirements. Experience with the latter is covered in this paper and the political and technical background to the change is described. The Government also wished to introduce competition in Building Control and proof of compliance can be checked by the Local Building Control Officer or an Approved Person. Practical experience of fire safety design and the changed attitudes of public officials is given.

Key words: Building; Regulations; Fire Safety.

INTRODUCTION

Most building regulations have developed because of disasters such as the collapse of large structures, spread of disease and spread of fire. In London the most significant fire disaster in relation to building regulations was the Great Fire of 1666, when the major part of the capital city was destroyed. The pattern of fire regulations and other building regulations adopted by London in the succeeding centuries was followed broadly by the rest of the country. Despite attempts at consolidation and rationalisation, the resultant conglomeration of rules, regulations and local Acts of Parliament became very difficult to administer and provoked general dissatisfaction. Accordingly, a new approach to regulations has been adopted and "The Building Regulations 1985" brought into force. They cover England and Wales, including London. (For legal and administrative reasons they do not cover Scotland and Northern Ireland). The new regulations represent a radical change in approach.

The reasons for change

It was generally agreed that the rules embodied in the regulations were too rigid and in particular that they were not suited to modern building design. As they were legal documents, the regulations could not include equations, graphs or diagrams. It was considered that the public authorities interpreted the regulations in a very restrictive way, thus stifling innovation, and finally, it was thought that too many subjects were covered. It was argued that some of the rules were not of national interest but were a matter of personal choice.

The final push for change came when the general dissatisfaction which had developed in the 1970s was recognised by the incoming Conservative Government. The Government's view was that, subject to maintaining health and safety, regulations should not interfere with enterprise and that as far as possible market forces should rule. It was also considered desirable to transfer administration from the public to the private sector.

Background

The history of the rebuilding of London after the fire is probably more interesting than the account of the fire itself.(1) There was little life loss, and the rules for rebuilding London were directed towards reducing the spread of fire between buildings. Commissioners appointed to draw up the rules included the architect Dr Christopher Wren, then better known as the Sarilian Professor of Astronomy, and Robert Hooke, the distinguished scientist. Controls were placed on materials of construction - brick and stone for outside walls instead of timber - on the thickness of walls, and on the width of street according to the sort of building. The new sorts of building were rigidly prescribed, as illustrated in Figure 1 and limited to four storeys maximum, except for houses of the 'greater sort'. In addition it was enacted that *'The City shall elect one or more discreet and intelligent person or persons knowledgeable in the art of building to see the said rules well and truly observed'* (This description of the forebear or forebears of our modern Building Control Officers is thought by some people to represent the triumph of hope over experience). In the 19th century, after disastrous industrial fires killed fire fighters and gave major financial losses, further regulations were developed. In the 20th century, experiences of fires during the second world war were incorporated in the regulations of the 1950s. These regulations did not relate to the changes in building technology - new building materials, new construction methods, greater use of building services and the use of factory made components. Amendments were made and by 1976 the Regulations occupied 307 pages; they were very prescriptive and understood mainly by lawyers.

Aims and purposes of the new Regulations

The aims of the new Regulations were to increase flexibility in design, to produce a more intelligent system and to remove constraints, as far as possible, on the putting up of buildings. Competition in Building Control was also desired. The purposes of the Regulations were chiefly for the protection of Health and Safety although two non-traditional subjects were to be included: Energy conservation and Facilities for disabled people. However, protection of property, consumer protection and improved standards of comfort or design were not purposes to be covered by the Regulations. This can be explained by the desire to reduce the effort involved in administration and compliance. It was considered that some desirable objectives might only be achieved, if at all, by using very complex regulations and procedures, with the benefits outweighed by the effort. This explains the concentration on health and safety matters.

The new Regulations

The Regulations issued in 1985 occupy 23 pages. They cover requirements for Structure; Fire; Site preparation and resistance to moisture; Toxic substances; Resistance to the passage of sound; Ventilation, Hygiene; Drainage and waste disposal; Heat producing appliances; Stairways, lamps and guards; Conservation of fuel and power; Facilities for disabled people. The requirements are for adequate and reasonable measures. As an example, these are the requirements of the Regulations for resistance to weather and ground moisture:

> "C4 The walls, floor and roof of the building shall adequately resist the passage of moisture to the inside of the building".

The requirements for stairways and ramps are:

> "K1 Stairways and ramps shall be such as to afford safe passage for the users of the building".

The requirements for fire safety are reproduced in Figure 2.

Compliance with the Regulations

The building designer can use any method to demonstrate compliance, but will probably rely on so-called Approved Documents to argue his case. The main set of Approved Documents consists essentially of user-friendly versions of the old regulations, but other publications, including British Standards, or parts of then, can be Approved Documents as well. Normally, people use the Approved Documents because acceptance is virtually automatic, but alternative documents can be used if there is a case to be argued. Acceptance is then possible but not automatic.

Procedures

The local building authority must be satisfied that the building complies with the requirements; inspection may be by the Local Authority itself or by an Approved Inspector. To date only one Approved Inspector has applied and been appointed: the National House Builders Council (NHBC). This private body sets standards and guarantees for new housing; an NHBC certificate is normally essential for obtaining a mortgage. As this is a lucrative area, the local authorities see NHBC as a competitor and have responded accordingly. Proof of compliance can be based on reports from the designer, which are checked by the Local Authority, or on a Certificate from an "Approved Person". These Persons need to be approved by a professional body such as the Institution of Structural Engineers or the Royal Institute of British Architects. Where there is disagreement, an appeal can be made to the Secretary of State for the Environment (the Government Minister at national level) or there can be a hearing at the Magistrates Court.

General experience so far

The system is working reasonably well. On the whole, architects and engineers find it difficult to believe that they have so much more freedom and still prefer to stick closely to the Approved Documents. The progress in Approved Documents is disappointing; it was originally thought that there would be a stream of new documents but the resources, and the enthusiasm, are limited. Most of the difficulties with the Approved Documents relate to Fire, Energy conservation, Facilities for disabled people. It is interesting that these three all contain aspects which are not strictly related to health and safety. Appointments of Approved Inspectors and Approved Persons have been delayed by Insurance problems. In particular, for fire safety, there is as yet no formal machinery for the approval of fire safety engineers.

Personal experience

My own experience is that the Building Control Officers prefer the new Regulations. The old system imposed constraints and they enjoy the new freedom to use their judgement. In relation to fire safety there is more recognition of calculation methods, of rational design and trade off. A major reason for this positive attitude is the educational standard of the modern Building Control Officers. At one time, only the major cities employed professional architects and engineers. Now, education by the Institute of Building Control is available to all. Some building control officers even refer to architects and builders as their customers. To quote *"Gone are the days of "bicycle-clipped building inspector" who seemed to delight in finding as many things wrong with the deposited plans as he could. The aim of most local authority building control operations is to approve whether conditionally or not, every application. No longer does the building control* *surveyor gain any satisfaction from rejecting plans".*(2) This sounds a bit too good to be true, and it is, but it does illustrate the current attitude of the local authority and its aim to be "part of the team".

Developments in the European Community

Preparations are in hand to form a single market within the twelve countries of the European Community by 1992. These preparations include the production of Eurocodes for structural design, the certification of products and the establishment of tests which will be used to demonstrate that the products meet the Essential Requirements of the Construction Products Directive.

The Essential Requirements deal with Health and Safety and consist of simple functional statements. For Safety in Case of Fire the Directive states:

> "The construction works must be designed and built in such a way that in the event of an outbreak of fire:
>
> - The load bearing capacity of the construction can be assumed for a specific period of time.
> - The generation and spread of fire and smoke within the works are limited.
> - The spread of fire to neighbouring construction works is limited.
> - Occupants can leave the works or be rescued by other means.
> - The safety of rescue teams is taken into consideration."

It will be noted that the Directive is similar in approach to the British regulations.

To assist the European standards body, which will specify tests for classification, documents are being prepared to interpret the functional statements. These so-called Interpretative Documents are being prepared by bureaucrats and engineers representing the 12 member countries and in order to make progress they have been forced to sit down and undertake fundamental discussions about design and function.

The future

The aim must be to achieve better buildings, which incorporate good safety design. It is my hope that in the future there will be more Approved Documents written for technical people, because rules designed for lawyers and bureaucrats will not work so well as design guides. In our own field of fire safety engineering, there is enough information available to form the basis of these guides but it takes effort to provide it in a form suitable for practising designers. By changing from prescriptive rules to functional statements we can give encouragement to safety by design.

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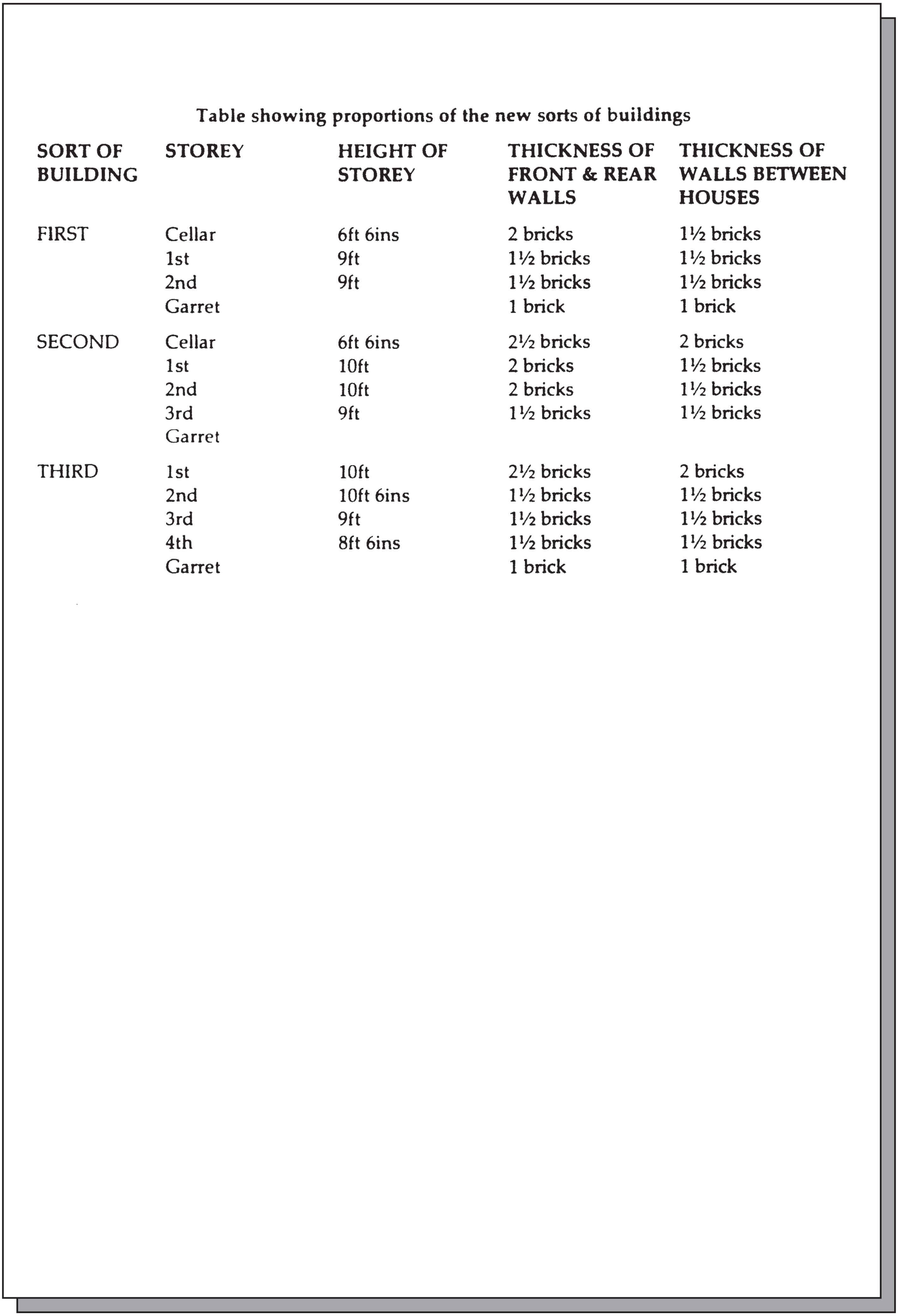

Table showing proportions of the new sorts of buildings

SORT OF BUILDING	STOREY	HEIGHT OF STOREY	THICKNESS OF FRONT & REAR WALLS	THICKNESS OF WALLS BETWEEN HOUSES
FIRST	Cellar	6ft 6ins	2 bricks	1½ bricks
	1st	9ft	1½ bricks	1½ bricks
	2nd	9ft	1½ bricks	1½ bricks
	Garret		1 brick	1 brick
SECOND	Cellar	6ft 6ins	2½ bricks	2 bricks
	1st	10ft	2 bricks	1½ bricks
	2nd	10ft	2 bricks	1½ bricks
	3rd	9ft	1½ bricks	1½ bricks
	Garret			
THIRD	1st	10ft	2½ bricks	2 bricks
	2nd	10ft 6ins	1½ bricks	1½ bricks
	3rd	9ft	1½ bricks	1½ bricks
	4th	8ft 6ins	1½ bricks	1½ bricks
	Garret		1 brick	1 brick

	Requirement	Limits on application
	Internal fire spread (surfaces)	
Internal walls: ceilings.	B2. In order to inhibit the spread of fire within the building, surfaces of materials used on walls and ceilings— *(a)* shall offer adequate resistance to the spread of flame over their surfaces; and *(b)* shall have, if ignited, a rate of heat release which is reasonable in the circumstances.	
	Internal fire spread (structure)	
Structure.	B3. – (1) The building shall be so constructed that, in the event of fire, its stability will be maintained for a reasonable period. (2) The building, or the building as extended, shall be sub-divided into compartments where this is necessary to inhibit the spread of fire within the building. (3) Concealed spaces in the structure or fabric of the building, or the building as extended, shall be sealed and sub-divided where this is necessary to inhibit the unseen spread of fire and smoke. (4) A wall common to two or more buildings shall offer adequate resistance to the spread of fire and smoke. (5) For the purposes of sub-paragraph (4) a house in a terrace and a semi-detached house are each to be treated as being a separate building.	
	External fire spread	
External walls: roofs.	B4. – (1) The external walls of the building shall offer adequate resistance to the spread of fire over the walls and from one building to another, having regard to the height, use and position of the building. (2) The roof of the building shall offer adequate resistance to the spread of fire over the roof and from one building to another, having regard to the use and position of the building.	

PAPER 20

Challenges in design

Paper presented at "Fire Safety by Design: a Framework for the Future", Borehamwood, November 1993. Margaret Law, Consultant, Arup Fire, 13 Fitzroy Street, London, W1T 4BQ, UK, Fire Safety Journal, 23 (1994), pp 115-122. Elsevier Science, UK

Two of the themes introduced in this paper are, firstly, the need for scientific consistency and measurement in engineering design and, secondly, the need to understand the concerns of those professionals who are asked to accept new design approaches.

Plate showing a structural detail at Kansai International Airport; a project on which Margaret Law worked and helped others at Arup Fire to develop and build on her original ideas.

Challenges in Design*

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ABSTRACT

This paper discusses the challenge of integrating fire safety measures into the overall design of a project. The fire safety strategy must take into account the ways in which the building or installation is to be used, thereby aiming to achieve not only a good standard of fire safety but also better buildings. The need for agreement on fire safety objectives and the search for more quantified approaches to design, based on engineering relationships and measurement, are reviewed.

INTRODUCTION

Fire safety design is based on a mixture of science, measurement and judgement. Many people consider that the present mixture needs to be improved, even if it can be considered reasonably successful. The major drawback is perceived to be a lack of flexibility in our regulations which leads to poor architectural design and wasted resources. Property losses are also perceived to be too high. The word 'perceived' is used here, to imply that the evidence is not necessarily available to support these views.

A successful framework for fire safety design must include a recognition of the 'natural laws' of physics, chemistry and mechanics. This must be complemented by measurement, to develop design relationships and to assess safety. The final judgement is then essentially political, where public safety is concerned, or commercial, for

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* This paper was presented at "Fire Safety by Design: a Framework for the Future", Borehamwood, November 1993.

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property safety. What has often happened in the past, and still happens, is that the rule makers or code makers correctly identify that there is a problem, but they concentrate on writing the rules, not always taking into account science and measurement. There is a general tendency, not just in the field of fire safety, to reject measurements and calculations and it is, of course, true that such information should be used as an aid to judgement, not a substitute for it. Nevertheless, it should be recognized that it is more responsible to try to calculate a risk before making a rule.

In order to open the discussion, I will suggest that the people directly concerned with fire safety design might be divided into the three groups, according to their objectives:

Rule makers:	in government and insurance,
Researchers:	in universities, government laboratories and research associations,
Designers and practitioners:	in consultancies, fire brigades and commercial organizations (products).

For rule making, the aim is to ensure that the standard of safety achieved at a national level is tolerable, as required by Parliament or the Insurance Companies, but without over-burdening the Consumer. For research the aim is to understand the various fire phenomena and how they interact: to be able to predict what might happen in a particular set of circumstances. For design, the aim is to provide measures which will give a tolerable standard of safety in an efficient way.

THE RULE MAKERS

National authorities are not primarily interested in what happens to individual buildings or enterprises but in what the overall fire damage is, year by year. The regulatory framework caters for the generality of buildings so that the total number of failures is at an acceptably low level. To achieve this, rules are introduced which very often are written from the point of view of the administrator who has to check on whether a scheme complies with the fire regulations. They may be arbitrary, if it is considered that ‘engineers want to have simple rules’. A simple rule may defy scientific logic but is defended if it ‘gives the right answer’. In practice, however, a regulatory system which makes sense to the checking authority and the practitioner is easier to administer and is likely to result in fewer mistakes. That is why a framework based on science and measurement ought to be attractive to the administrator.

At a national level, the *minimum* aim is to limit the number of deaths and injuries by fire to present levels, and to avoid disasters. Occasionally, major changes are introduced: for example, some 25 years ago the administration of the United States of America was convinced that a greatly increased effort was needed to reduce the number of fire fatalities, which in proportion to population was much higher than in other developed countries: The reaction to disasters has also been signficant. As Professor Rasbash has pointed out, in the United Kingdom (UK) we have, on average, one major disaster a year. Following each disaster some rules are made or amended. It is interesting to note that the Cullen Report on the Piper Alpha disaster has resulted in the use of Quantified Risk assessment (QRA) for off-shore platforms.[1] Following the Kings Cross fire, London Underground Ltd (LUL) quickly introduced new fire safety rules for underground train services. It was soon found necessary to commission QRA, in order to make the best use of the finite safety resources available to LUL, which were needed not only for fire safety but also for other types of hazard.[2] Efforts to measure costs and benefits of legislation are to be applauded and the rule makers should consider whether they have enough guidance from the researchers on how to carry out this type of assessment, and whether the fire statistics are giving the information needed. In the end, of course, a political judgement must be made on whether particular legislation should be introduced, but we would hope that it is always informed political judgement.

The Insurance Companies also wish to limit the overall damage year by year to the buildings they insure, so that they can cover the losses and make a profit. Since the companies are in competition, there is a limit to the premiums they can charge and to be successful they must also employ QRA. In the United Kingdom, the Loss Prevention Council publishes codes which are rather like national regulations in being very broad brush but easy for checking purposes. It is then up to the customer to negotiate terms with the insurance company, but not necessarily in an informed way.

A considerable amount of judgement is necessary for the determination of premiums when new types of process or new enterprises are to be insured, since there are no directly relevant statistics available. This is where science and measurement can assist judgement, so that a tentative risk assessment can be made.

RESEARCHERS

The use of scientific research and measurement is essential to the development of engineering relationships for design. The results of research and analysis must, of course, be published, so that they are first open to peer review. The publication should demonstrate that any developments in theory or new correlations take into account previous work in the field and the limits of application of any engineering relationships need to be established. The researcher is by nature a person who wishes to understand how a fire might behave, or what its effects might be in a particular set of circumstances. Often, the scenario adopted for research may be unrealistic, because it is necessary to isolate certain effects which are the subject of the study. Nevertheless, measuring effects and understanding and predicting what might happen are important driving forces for the researcher. The talents possessed by the researcher are not necessarily those needed for practical design, as discussed below. Indeed the solution of design problems is not very interesting to the researcher. Where judgement is concerned, it seems to me that the significant contribution of the researcher is in the identification of problems likely to arise in the future and the establishment of research programmes which anticipate them.

DESIGNERS AND PRACTITIONERS

What separates the designers and practitioners from the researchers is that they are not primarily trying to predict what might happen in their particular building or project. They are trying to establish what measures to introduce into that project in order to provide a satisfactory performance in fire. This task is tackled somewhat differently in fire engineering, compared with other branches of engineering.

Consider, for example, structural design: The engineer will design the structure for normal temperature conditions and loads and also for accidental loads. For example, the structure should be strong enough to withstand a wind force expected to occur, on average, once in (say) 50 years. However, for structural fire protection the design is not for the ‘50-year fire’, but is prescribed as a certain level of fire resistance. It may well be, of course, that for the specific project the required fire resistance of, say, 1 h will just be enough to withstand the 50-year fire, but that is not explicitly assessed. In fact, fire protected structures

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complying with regulations survive virtually all fires at the moment, which suggests that a rather larger return period than 50 years is used.

If we consider active firefighting by the Brigades, then the resources available are those considered sufficient to give a satisfactory performance. They are intended to give a performance which reduces losses to an acceptable level; they are not tailored to cope with every fire which might be predicted. The Brigades share the same problem as the fire engineer: the performance expected is not stated in such a way that the Brigades can demonstrate that they are doing the job efficiently. At the moment, when Brigades believe that their resources, technical and human, are not sufficient they rightly ask for extra measures such as compartmentation, smoke ventilation, automatic detection, automatic extinction. The Fire Brigades do not have an esimate of a critical fire size, that is, the maximum size of fire which they are able to control without such measures to help them. If the cost of these measures were to be included in the costs of the Fire Brigade it might encourage a more explicit cost benefit analysis of active firefighting. At the moment, the owner pays for the extra resources willy-nilly.

ENGINEERING APPROACH

The importance of an engineering approach to design is firstly an acceptance of the possibility of failure, i.e. for practical purposes the ‘worst-case scenario’ is not used. It might be thought that this approach can induce complacency about the current level of losses. However, it can also encourage efficient use of resources to reduce losses. Secondly, the engineering approach is important because it permits measured variations. For example, if sprinklers are installed, the fifty-year fire will be less severe and the fire resistance of the structure can be reduced. Other protective systems can also reduce the possibility of a large fire. The important objection to this statistical approach is that the data for fires are historical and less useful for prediction than data collected for weather. That is why judgement must also be exercised, but it is much better judgement if it is informed. If the required performance is based on a quantified engineering approach then it becomes easier to design the new measures needed when there are changes in use or changes in fire hazards.

The immediate benefit for the fire safety consultant of the engineering approach is that it gives scope for better building design and more efficient use of resources. The consultant is interested in the design of a specific building, unlike the rule-maker or the researcher, and needs the required performance defined in a way which permits flexibility and trade-off. Trade-off does not necessarily save money but it gives more choice and hence can improve design. The building or project will be provided for a specific use or uses and the fire safety measures, though necessary, must not frustrate the uses. People also want to be comfortable, to enjoy their surroundings, and they do not want to spend more money than necessary on fire safety when it could be used for more desirable purposes.

The client for the development will have limited resources available and must make decisions about how much is to be invested in the building now and what expenditure must be left for the future. It might be decided to give a building minimum fire protection measures, necessary for life safety only, and take the risk of large direct or indirect property losses in the future. The fire engineering consultant is able to advise the client on the likelihood of a fire reaching a certain size, and the beneficial effects of the various measures available to reduce the probability of large fires happening. Most of the measures designed to reduce fire losses were developed by the insurance companies; they are able to give the client more information about all the benefits to be derived by installing fire safety measures—such as saving property, avoiding interruption to business, saving jobs—in addition to quoting savings (if any) in premiums. However, in the end the commercial decisions must be made by the client, but they can be better informed decisions.

SIMPLE RULES

The development of simple rules for design is an important subject which needs input from the designer. In most circumstances the designer will not want to do detailed calculations, because they will not be justified by the assumptions made. Often it is not necessary to be precise, because a simple, though conservative, solution may be acceptable. For example, once the decision is made to use a concrete structure, the provision of 90-min fire resistance is not likely to be a burden, even if calculations could show that only 60 min is necessary. Or, in the design of a smoke control system, the use of Computational Fluid Dynamics (CFD) is not usually justifiable because a simple design which can extract a significant amount of smoke is all that is needed. However, there are circumstances where CFD can contribute to smoke control design and should be used; even so, the results of the analysis are likely to be used as an aid to judgement, not as an absolute solution.

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It is true to say that most design engineers are unhappy with complicated *solutions*: 'If it is that complicated, it can't be right' is the usual reaction. However, that does not mean that they are asking for simple rules. The simplification, if any, should be made by the design engineer, using judgement.

PRODUCTS

Product manufacturers are major contributors to fire safety. The demands of designers stimulate the development of new and improved products. Clearly defined performance requirements also stimulate manufacture; in general, when a need is identified the product will be developed. The formation of trade associations in the fire protection industry gives a general raising of standards, with better quality control and better specifications. The range of automatic sprinklers, automatic detectors, smoke control systems, passive protection materials and components available to the designer is much wider and will grow with the single market.

The very considerable technical skills within the industry, which have already resulted in many improvements in reliability, can more properly be recognized in a safety framework which is explicitly based on risk.

CONCLUDING REMARKS

Considerable basic knowledge exists in the field of fire engineering which is not yet being fully exploited for design. Those who seriously attempt to apply the knowledge are eventually driven to the conclusion that a risk-based fire safety system is the proper structure for design; many of them are also convinced that it is possible to make a start right now. Indeed, it is already being done in some areas.

A task which is at least as difficult as the technical one of establishing such a system for fire safety is that of persuading people to accept the different approach. Many of the arguments against are familiar ones and will not be pursued here. However, there are three aspects, at least, which should be taken seriously.

- Firstly, change may be for the worse. It is difficult for all of us to learn to do things in new ways, to understand how information can be used differently, and it is very worrying to anyone working in the safety field to have the present system changed, with the possibility of lowering standards, not raising them.

- Secondly, it is wrong to accept failures. Most people acknowledge that it is probably not possible, and certainly not practical, to achieve absolute safety, but they worry that if we do not aim for that we will slacken our efforts.
- Thirdly, it is misleading to rely on calculations. There is a worry that calculation and theory can be misused by ill-educated or unscrupulous designers to produce un-safe solutions.

In achieving a successful and well accepted design approach it is suggested that the following minimum conditions must be satisfied:

- the underlying assumptions must be scientifically correct;
- empirical data and guesses based on judgement must be openly acknowledged;
- if measurements are available they must be taken into account;
- several years of working with the system on the design of practical projects must ensue before firm guidelines are issued.

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PAPER 21

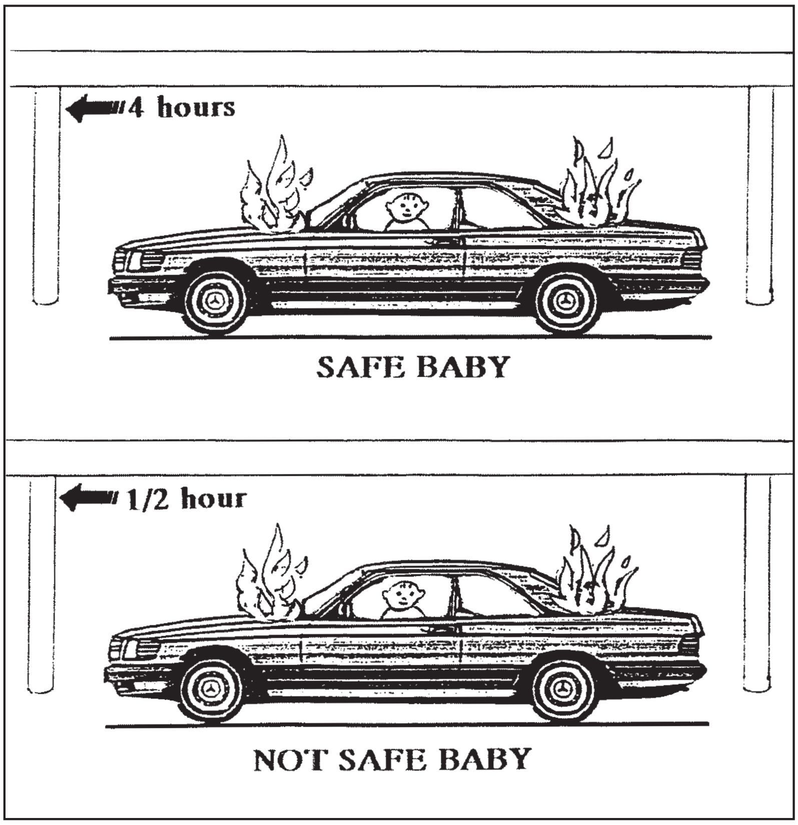
Magic numbers and golden rules

Margaret Law and Paula Beever, Arup Fire, Ove Arup and Partners, 13 Fitzroy Street, London, W1T 4BQ, UK, Proceedings of Fourth International Symposium on Fire Safety Science, Ottawa, Canada, 13 - 17 June 1994, pp78-84, 1994. International Association For Fire Safety Science (IAFSS), UK

This paper was presented to an audience that was predominantly made up of researchers, who generally feel that they ought to be interested in the work of practitioners, but in reality are not.

Paula Beever, then leader of Arup Fire, and I decided to try to catch their attention by jointly presenting the paper in the form of a dialogue. We also, by means of pictures, illustrated some of the foolish rules that exist in most countries. The audience was nervous and edgy to begin with, wondering where we were going, until a picture was shown that we referred to as the 'Baby in the Buick'. The penny dropped, there was a great howl of laughter, and we had them hooked.

'Baby in the Buick', reproduced from the original conference slides. Drawn by Margaret Law.



Magic Numbers and Golden Rules

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ABSTRACT

The application of fire safety research using engineering methods is frustrated by conventional attitudes. The desire of researchers to always achieve a greater level of understanding means that they cannot recognise that satisfactory engineering solutions may be achieved with partial information. The desire of regulators to have simple rules and tests for administrative convenience contrasts with the need of designers to have maximum flexibility in order to arrive at optimum solutions. The magic numbers embodied in regulations are accepted without question whilst any engineering solution is subject to a disproportionately high standard of proof. To move forward, rules need to have an engineering basis and to be goal related: the purpose of the rules needs to be understood by both researchers and regulators.

INTRODUCTION

The value of this scientific conference is that it provides not only a forum for the exchange of information but also an opportunity for the exchange of ideas. Indeed we understand that several new lines of research were conceived directly as a result of discussions at earlier IAFSS conferences. We, as practitioners, would also like to exchange ideas with scientists, and it is the purpose of this paper to stimulate similar discussions.

During the closing sessions of most fire research conferences there is a plea for more contributions from the practitioners - the consultants and the fire service - and there is normally a murmur of agreement to this from the audience. At the next conference, therefore, a token consultant and a token fire officer will each present a paper. From long experience as token consultants we know that any such paper will attract virtually no comment or there will be a trivial question which shows that the concepts have been misunderstood or ignored. It can be argued, of course, that the papers were badly written, but it is our view that many researchers are not interested in applications, that is how designers and firemen solve practical problems, or they are interested in only a very narrow field of fire engineering.

Not all researchers need to be interested in applications, but we believe that for many of us it would be beneficial if we could have a better understanding of each other's work. Therefore in this paper we are going to share some of our ideas and experiences and at times we will aim to be provocative.

SIMPLE SOLUTIONS NOT SIMPLE RULES

In general, the results of fire research will be applied in one or more of the following ways: product development; tests for products; regulations and design codes. Manufacturers can sell only those products which pass the tests and follow the rules. Unfortunately, the existing tests and regulations can prevent the application of good research because they are presented in a very simple way: Class 1, 2 or 3 for a material, or 45m escape distance, for example. This approach is perceived by the regulators to have two major benefits: firstly that it makes it easy for them to check that projects comply with the rules and secondly that engineers and architects only want to have simple rules. Both these assumptions are wrong.

When there are simple and arbitrary rules there are always more arguments and disputes than when an engineering approach is adopted, because the underlying technical assumptions are forgotten or not understood. When researchers reduce their results to a few 'golden' rules, they misunderstand the engineering design process. Engineers and architects do not set out to make life easy for themselves: they do not in fact seek simple rules. The designer aims for simplicity, reliability, quality and fitness for purpose in the end product be it a hotel or an offshore oil platform. The contribution of fire safety design to this process is no different from any other kind of design. A project must proceed subject to all kinds of constraints of which fire safety is one, but financial, traditional and political considerations may be just as influential. Good design will seek to harmonise conflicts and optimise outcomes, and this can better be achieved if designers are given the opportunity to make fullest use of the tools and data available.

Of course, there will always be a place for prescriptive standards: there should be a straightforward route for straightforward design. But let us not pretend that if these standards are applied they will always, in some magic way, give the best solution. As soon as they frustrate design we should be able to re-establish the rationale behind the rules and thereby develop new approaches.

REGULATORS AND THE BABY-IN-THE-BUICK EFFECT

There has been a considerable improvement in recent years in the response of many regulatory authorities to fire safety proposals based on engineering analysis rather than on regulatory compliance. Indeed, in some industries such as oil and chemicals, such approaches are rapidly becoming the norm. However, there is still an almost universal failure on the part of the authorities to grasp the significance of what is being presented to them.

A common misconception is that the role of the fire safety engineer is to predict in detail what will happen in the event of a fire. This is not the case. The fire safety engineer must produce a design which achieves adequate safety levels. In demonstrating this, the engineer may make use of some predictive techniques. But, perhaps surprisingly, these do not need to be precise or comprehensive in every instance. A small departure from a coded requirement does not place upon the engineer the task of carrying out a full fire safety analysis. We find that the regulators behave as though it does.

One reason for this is that regulatory authorities are comfortable with their magic numbers. If the distance to a door is no more than 45m, the building is safe. They need to think no further. But what if the distance happens to be 50m? Clearly a moderate improvement in some other fire safety feature of the building should quite easily compensate for the additional time required for people to travel the extra few metres. However, under such circumstances the fire safety engineer is frequently required to provide design fire specifications, smoke filling calculations, evacuation analysis and so forth even though a building designed to the magic numbers could not bear such rigorous analysis. The regulating authority may further assume the right to choose the fire scenario which is the basis for the design, regardless of how unlikely this might be. There can be endless "what if" questions and the fire safety issues can entirely dominate in what becomes an unbounded problem.

A simple, if absurd, example is as follows:

The standard fire resistance test gives a reasonable representation of the heat transfer inside a compartment containing a post-flashover fully developed fire, and we know that after flashover people inside the compartment will not survive. When it was demonstrated in a particular instance that the fire loading in car parks was low and that it was unlikely that fire in one car would spread to another, regulators opposed any reduction in fire resistance on the grounds that "people leave their babies in the car while they go shopping." Quite apart from the fact that there was no evidence that people left their babies in this way, the argument was obviously absurd. Nevertheless, the regulators considered that, in some magic way, the existing rules would protect the baby.

Current moves towards risk analysis in fire safety engineering may ultimately relieve us of this kind of arbitrary approach. In the meantime we are left to struggle in a system which tends to be strongly biassed against rational analysis.

The fact that total predictive capability is not needed by the fire safety engineer means that good use can be made of raw or incomplete research data. Information gathered for one purpose can be used for another. What is vital is that the information should be gathered in a scientific manner, published openly, and subject to peer review.

RESEARCH, INVESTIGATION AND THE RATCHET EFFECT

It might appear that the regulators are largely to blame for the failure to propagate the results of good research, but the researchers themselves are often at fault to a degree. Research is conducted in an environment where identifying the questions and posing solutions is conducted in a necessarily constrained manner. The emphasis is on obtaining an understanding, ideally with predictive capability, in a particular field by successively refining the questions which can be resolved. The researcher is therefore more acutely focused on what is not known than of the value of the knowledge which has been accumulated. A quite healthy but rather obstructive scepticism therefore may overlie the researcher's attitude to the use of the results in practice.

As a result, the transfer of technology from the researcher to the real world is subject to a bias in the form of a ratchet mechanism. Because fire research is almost entirely bound up with safety issues, and there is very little conducted on a purely fundamental level, there is an inherent prejudice in favour of releasing and applying results at the earliest stage if lives can thereby be saved. Thus if a researcher identifies a powerful toxin which could be given off by burning a particular material, this research is likely to be taken up rapidly and applied at an early stage in regulations. This may be contrasted with research carried out which shows that the current approaches to fire safety may be over restrictive. There is likely to be a very sluggish and more cautious take up of such research, with considerably more effort being made to verify any conclusions before the regulators feel they can take advantage of any benefits. An example of this would be in the field of sprinklers and fire. The evidence is considerable from a number of sources to suggest that sprinklered buildings are extremely safe from fire. It has even been suggested that a well designed sprinkler system with a very high level of reliability could be defensibly installed as the only fire safety measure in a building. This type of radical approach would clearly take a long time to be accepted, but even at present, the relaxations in fire safety measures for sprinklered buildings rarely reflect the high degree of enhanced safety. In some countries no relaxation of traditional fire safety measures is permitted at all.

The other ratchet which serves to increase fire safety provisions rather than otherwise is the rare but significant occurrence of major fires. Public attention is attracted quite rightly to any kind of tragedy which causes multiple deaths. Public tolerance of such incidents is low even where on a statistical basis the risk to any individual of becoming involved in such an event may be extremely small. As a result, major fires are the subject of intensive investigation and analysis.

The outcome of such studies is generally to identify the major contributory factors which led to the incident becoming as serious as it did. The investigation is likely to be conducted on several levels concerned with details of the initiation of and communication about the event, the behaviour of survivors, victims and firefighters, and theoretical and possibly experimental studies of fire and smoke behaviour. The results of all of these studies are likely to emerge as a set of recommendations for improvements in an attempt to ensure that such an incident could not be repeated. The problem is that the results are unlikely to be formulated as a series of alternatives, the implementation of any one of which would have avoided the tragedy, but rather as a set of measures which must be adopted as a whole. This approach, whilst very well intentioned, leads to new sets of golden rules because of a failure of rational analysis.

RESEARCH AND TECHNOLOGY TRANSFER: FORM FOLLOWS FUNCTION

In our view, the simple and complete description of "fire protection engineering" is that it is the application of science and engineering principles to protect man and his environment from destructive fire[1]. The very least we expect from researchers and practitioners is that they are scientific. This may sound obvious, but in practice we use various paradigms, that is we assume patterns of behaviour for the purpose of planning experiments and analysing the results, and also for engineering design. Such paradigms are extremely useful but need to be replaced or reviewed in the long term if they are not to get in the way of scientific analysis. One example is the use of visibility to define tenable smoke conditions, when it is actually narcotic substances and heat which kills people, not loss of visibility. Another is the use in design of the t-equivalent formula for a compartment fire, when the correct procedure is to estimate the temperature and duration of the fire directly.

The transfer of research and technology to practical guidance for engineers usually requires a great deal of effort in order to avoid misinterpretation and misapplication. It has at least three stages: selection and/or production of research results; analysis of these results and their relevance to the subject under consideration; preparation of a design manual. All these stages need to be published so that as circumstances and knowledge change, the guidance can be reviewed. Some examples of this approach are: the guidance on roof-venting of single storey factories, prepared by researchers, financed by a manufacturer of roof vents;[2][3] guidance on the fire safety of exposed exterior structural steel, prepared by consultants, financed by the steel industry;[4][5] guidance on the location of television towers in relation to buildings and prevention of spread of fire from floor to floor of a building via the window openings, prepared by a researcher, financed by Government[6]. None of these documents give golden rules such as "vents should be 5% of the floor area" or "bare steel should be 1.5m distant from the windows". They give practical engineering relationships.

Another valuable method of transferring research is in the form of codes of good practice. In our experience the fire engineering codes of practice suffer because the statements of what they are intended to achieve are either imprecise or missing altogether. There is merit in examining how codes of practice are prepared in other engineering disciplines.

As part of the removal of barriers to trade within Europe, structural Eurocodes have been prepared. These have had to be written very formally. For example: the principle has to be stated before a rule can be given; no commentary is allowed (although an explanatory note may be permitted); nothing is to be included which is already in another code. This formality forces the code authors to state in a consistent way what it is they are trying to achieve: a very difficult task. If they do the job properly, it is in principle possible for an engineer to read the set of principles and rules and design accordingly. In practice application manuals are being prepared. No doubt these manuals will have their quota of magic numbers and golden rules, but at least the underlying assumptions will be those in the formal code. In our view it would be a good discipline for our fire code writers to write a formal code. What we are saying is that form follows function: you decide what it is you want to do before you decide what tools you are going to use.

CONCLUDING REMARKS

From a global point of view, the prescriptive approach may produce the desired results: the total losses by fire, year on year, are kept below a certain level. Yet it is obvious that, even if all projects comply with the codes, they are not all equally safe. A change to engineering-based rules will give more uniform results but there will still be significant variations between projects. For any specific project, the fire engineer will have to use judgement in addition to rules, as would any other engineer, to satisfy the search for adequate safety. The judgement will take into account the other aspects of engineering design and the way the project will be operated, so that fire considerations can be set in context.

Information and data about fire behaviour will assist judgement. For this reason it is important that research information is not processed and subjected to the researcher's bias before it is published for the designer's use.

Secondly, we want the researchers to be viewing each problem as if it were fresh. Practitioners and regulators may feel comfortable with the old rules but researchers should not.

Thirdly, when researchers are asked to devise a test or formulate a rule they should first establish, in concert with the regulators, what it is they are trying to achieve. This should then be written down as a basis for what follows. When it is difficult to do this it would be better to delay the test or rule, since once it is published it is very difficult to get rid of it.

Lastly, we appeal for a rational approach to the regulation of fire safety design, which is goal related rather than disaster driven, which encourages flexibility and imagination, and which uncovers opportunities which can be fed back into research programmes.

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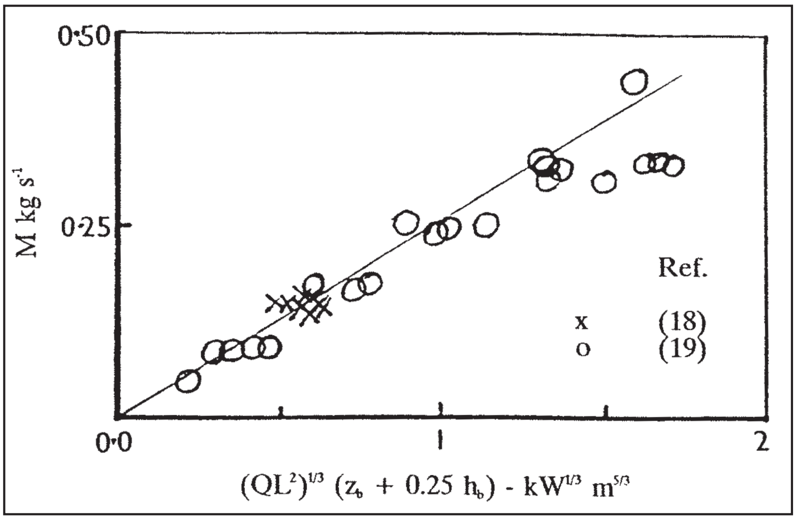
PAPER 22

Using science and hunting facts

Margaret Law, MBE, Ove Arup and Partners, London, England, Arthur B Guise Lecture, SFPE Seminar May 1994. Society of Fire Protection Engineers (SFPE), UK

Figure showing the relationship between mass flow of smoke above a balcony and the heat content of the plume, width of compartment opening and height above the virtual origin of the line plume.



This is the lecture given on the occasion of being awarded the Arthur B Guise Medal by the Society of Fire Protection Engineers in 1994. The choice of subject was up to me, and because science is the foundation of engineering it seemed appropriate to say something about it in relation to fire engineering. There also has to be empiricism, so the collection of data and measurements is very important.

USING SCIENCE AND HUNTING FACTS

By Margaret Law, MBE

Ove Arup and Partners, London, England

Introduction

Good engineering design is based on the application of science and engineering principles, measurements where available, and judgement. This paper gives illustrations of the application of science and research data to the solution of some practical problems.

Fire spread by radiation

After the Second World War, nations were concerned about the possibility of a nuclear war and one of the significant effects was known to be the spread of fire by thermal radiation from the fireball of an atomic bomb. In order to predict the likely radius of fire spread, experiments were therefore conducted to assess the intensity of thermal radiation which would cause pilot or spontaneous ignition of wood within a given exposure time.

Using conventional heat conduction equations(1), the surface temperature θ_F of a thermally thick specimen of wood exposed to an intensity of radiation I for a time t is given by

$$\frac{It}{\rho c(kt)^{1/2}\theta_F} = \frac{\beta}{1 - \exp\beta^2 erfc\beta} \qquad (1)$$

where $\beta = Ht/\rho c(kt)^{1/2}$, ρ, c and k are respectively density, specific heat and thermal diffusivity of the wood, H is the Newtonian cooling coefficient corresponding to θ_F, and erfc β is (1-erfβ). Fig. 1 shows the experimental data for spontaneous ignition of seven species of wood, with t being ignition time(2). The line is given by equation (1) with $\theta_F = 525$ K. For pilot ignition, equation (1) correlated the data with $\theta_F = 360$ K. Thus, an engineering relationship was derived which avoided consideration of the complex chemical and physical processes which actually lead to ignition. No doubt this information was incorporated into civil defence manuals but it was also available for general use and was soon applied to a building regulation problem - external fire spread between buildings. It had already been suggested that safe separation could be defined geometrically, by assuming a radiating intensity for a building fire and a maximum acceptable received intensity on the exposed building(3). The regulators expressed little enthusiasm for this type of approach until architects started to design external facades with very large glazed areas or with curtain walling of negligible fire resistance. Asked for help, we defined the acceptable intensity as 12.5 kW m^{-2} (0.3 cal cm^{-2} s^{-1}), which would produce a θ_F of not more than 360 K in steady state conditions i.e. there would be no pilot ignition. We treated the unprotected areas of the facade of the burning building as black body radiators but needed to define the fire temperatures. We had some limited experimental information about compartment fires, in particular the effect of ventilation and fire load on temperature, from which it was concluded that an intensity of radiation of 167 kW m^{-2} (4 cal cm^{-2} s^{-1}) would be representative of most building fires, with 84 kW m^{-2} (2 cal cm^{-2} s^{-1}) for compartments with low fire loads(4). These values resulted in required view factors of 0.075 and 0.0375 respectively. This approach, modified by the lawyers, was incorporated in the Building Regulations and represented the first introduction of an engineering solution in the fire part of the regulations.

Heat conduction in structural elements

From extensive programmes of fire resistance testing, it became clear that failure of an element could generally be defined in terms of temperature: on the unexposed surface of a separating element or at a critical location in a loadbearing element. It therefore seemed that expensive tests could be avoided by doing heat conduction calculations. Unfortunately, analytical solutions were not available for transient heat flow through assemblies of materials. Accordingly an analogue computer was built, exploiting the analogy between flow of heat and electrical charge(5). A resistance/capacity mesh represented the element, a voltage imposed on the "heated" face followed the standard temperature-time curve, and a specially modified resistor represented cooling to the ambient air. The computer was used to derive a series of scaling laws for fire resistance tests; it was so successful that the analogue quickly became obsolete(6). The practical application was that we could take the result of a standard fire resistance test and estimate the effect of varying the thickness of insulating material or the bulkhead thickness or the size of the steel section on the fire resistance of the element. A nomogram(7) and a more comprehensive account(8) were published. These methods have been adopted by the European Convention for Constructional Steelwork(9) and will continue within the context of Eurocodes.

While the standard furnace test is important, because it forms the basis of fire grading in buildings and regulations, designers would prefer to deal directly with building fires. Following numerous experiments with fully developed compartment fires in model and large scale rooms, it is possible to estimate an average compartment temperature θ_f (K), and a rate of burning R (kg/s) at full development, as illustrated in Figs. 2 and 3 for ventilation controlled fires(10). A (m^2) and h (m) are respectively the area and height of the ventilation opening, A_t (m^2) is the internal surface area (walls, floor, ceiling), D is the depth of the room behind the opening and W the room width. A reasonable estimate of the heating effect on the structure is obtained by assuming a step function temperature θ_f lasting a time τ = L/R(s) where L is total fire load (kg)(11).

Such information means little to regulators, and accordingly I attempted to relate the times of exposure t_e (min) in the standard test which would give the same steel temperatures as in the compartment fires, both for a protected steel column and for reinforced concrete.

The following equation was obtained empirically, as illustrated in fig. 4(12),

$$t_e = k \frac{L}{[A(A_t - A)]^{1/2}} \tag{2}$$

With t_e in min, k is approximately unity. The fact that the formula contains A not A $h^{1/2}$ worries people. However, in the model-scale-experiments, which were 0.5, 1.0 and 1.5m high, k did not vary with h (which in these experiments was also the compartment height)(13). In my view, equation (2) is interesting from a global point of view but for design, the temperature and duration of the fire should be estimated directly. Some recent experiments in much larger compartments may give us better estimates of θ_f and R; I await the publication of the results with interest. In practice, values of θ_f and R have been used to estimate the heating of structures in some unusual building types and have been incorporated in a design method described below, for external fire exposure.

Flames and smoke plumes

The use of weathering steel for the external structure of a building was hampered by the regulatory requirement for high fire resistance and hence the use of fire cladding. One way to avoid this was to use hollow sections cooled by water-filling, as designed by Seigel for the U.S. Steel Building in Pittsburgh. Another method was to place steel elements where the fire exposure was less severe than a compartment fire and the effects of cooling to the ambient air could be exploited. Ove Arup and Partners were commissioned to produce a design guide. We used correlations mentioned earlier to determine fire temperature and hence radiation from the room openings to the external elements. We used the comprehensive work of Yokoi(14), Seigel(15), Thomas and Law(16) to describe the flame trajectory and temperature. From theory and experimental data we obtained the flame height z (m) above the top of the opening as follows:

$$z + h = 12.8\,(R/w)^{2/3} \tag{3}$$

where w (m) is the opening width. The estimation of R, as described above, was therefore important. An engineering design manual was produced which described both radiative and convective heat transfer to external elements. It was based on theory and measurements(17). This method was adopted in American building codes, accepted in the U.K., and is incorporated in the Eurocodes.

In addition to flames, the flow of smoke plumes from doorways and other openings into corridors, shopping malls and atriums has received much attention because of the threat to life when smoke delays escape and overcomes people by noxious fumes.

When I was asked to design a smoke control system for a covered shopping mall with non-sprinklered shops, the accepted design guide was for sprinklered shops and assumed a fire size of 5 MW. Rather than extrapolating from this guide to a fire size of 10 MW, I thought I should go back to the original theory, specifically for flow round the edge of a balcony. I then by-passed the theory and examined the original experimental data. I found they easily fitted a line plume type equation, with an effective origin a little way below the balcony(18). Some recent experimental data have extended the range(19) and confirmed the earlier approach, as illustrated in Fig. 5. M (kg/s) is mass flow at a height z_b (m) above the balcony which is at a height h_b (m) above the base of the opening of the fire room. L (m) is the separation of channelling screens. In idle moments I also looked at data for horizontal mass flow M_o (kg/s) out of the upper portion of an opening of a fire room and found, for a fire size of Q (kW) the following:

$$M_o = k\,(Qw^2)^{1/3}\,h \tag{4}$$

The value of k varied between 0.041 and 0.092(20). For a given fire room the value of k varied significantly with the location of the source, being larger for a central position, and to a much lesser extent with the source geometry. At the moment I am still thinking how this information can be turned to account. From a dimensionless plot of a range of data my suggested correlation for design purposes is a value of 0.078 for k, with a convective heat flow of 2Q/3.

Concluding remarks

The examples given here show how engineering relationships have been developed using classic physical equations for heat transfer and a large amount of empiricism. This does not absolve the designer from having an awareness of the real processes of combustion, detection, extinction, reaction to fire and many other aspects of fire protection engineering. It is part of the engineer's responsibility to use these relationships as an aid to judgement, not a substitute.

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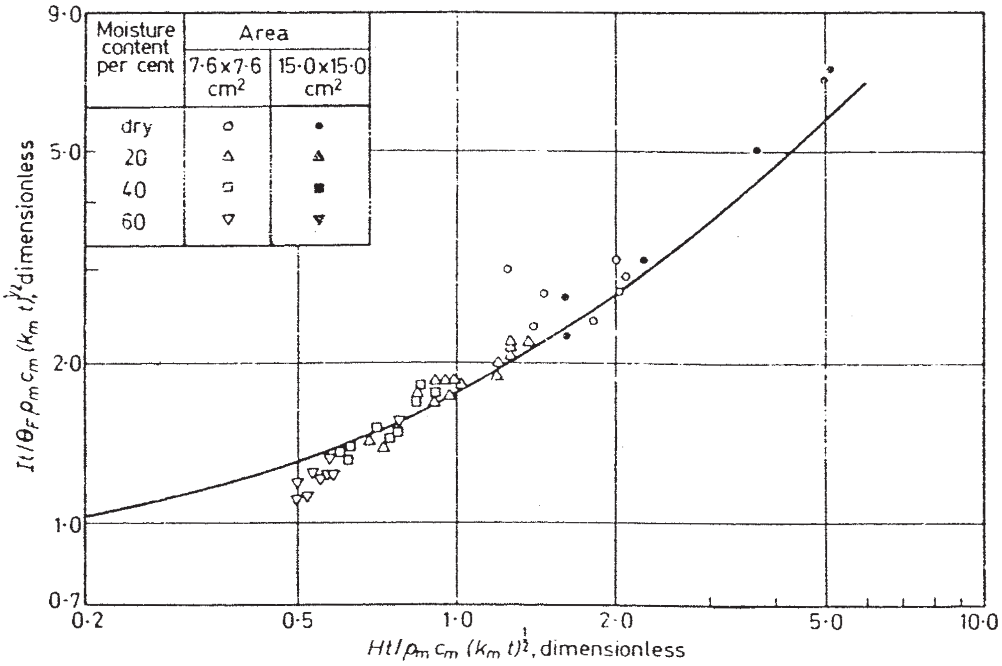

Fig. 1 Spontaneous ignition of seven species of wood by radiation

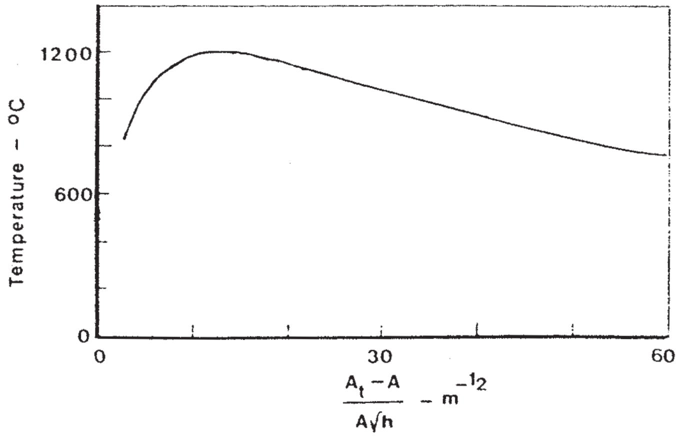

Fig. 2 Fully developed compartment fires - temperature

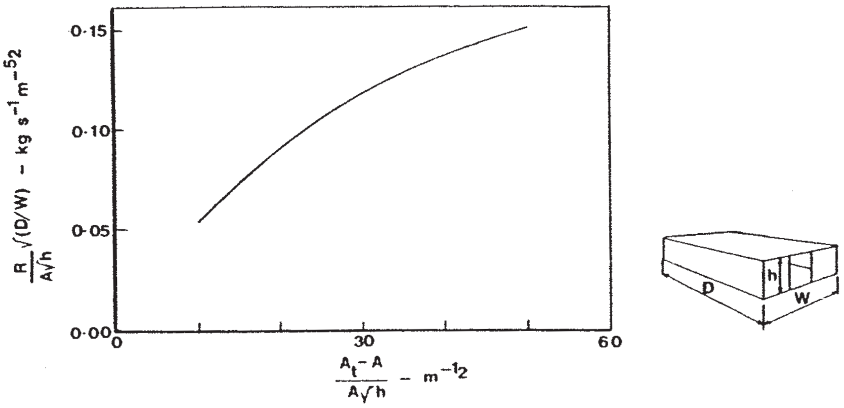

Fig. 3 Fully developed compartment fires - rate of burning

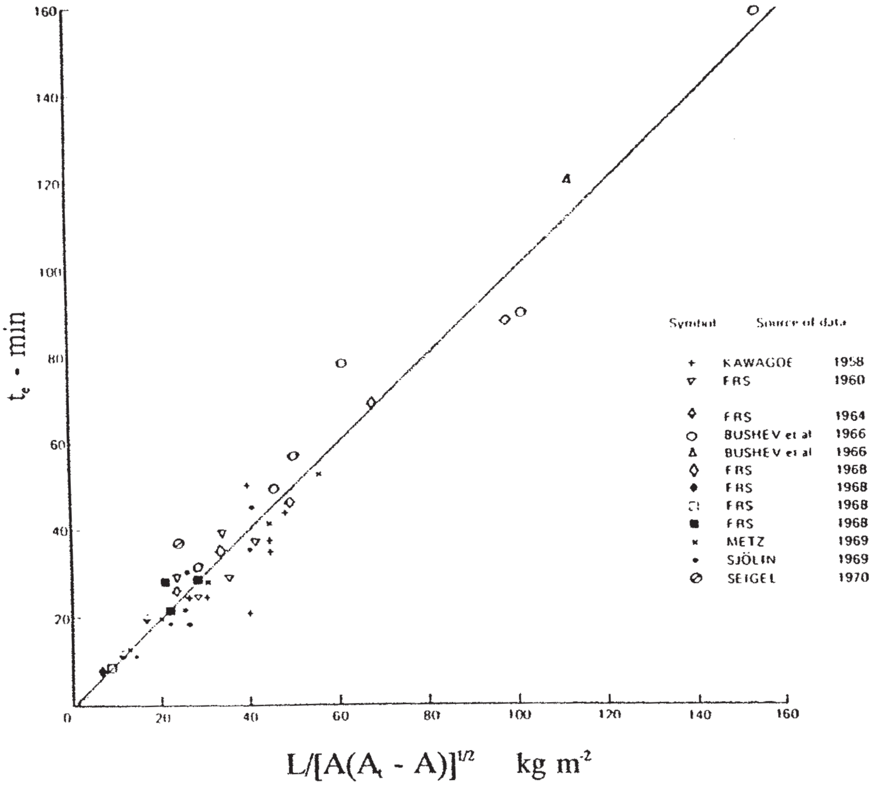

Fig. 4 Fully developed compartment fires - effective fire resistance

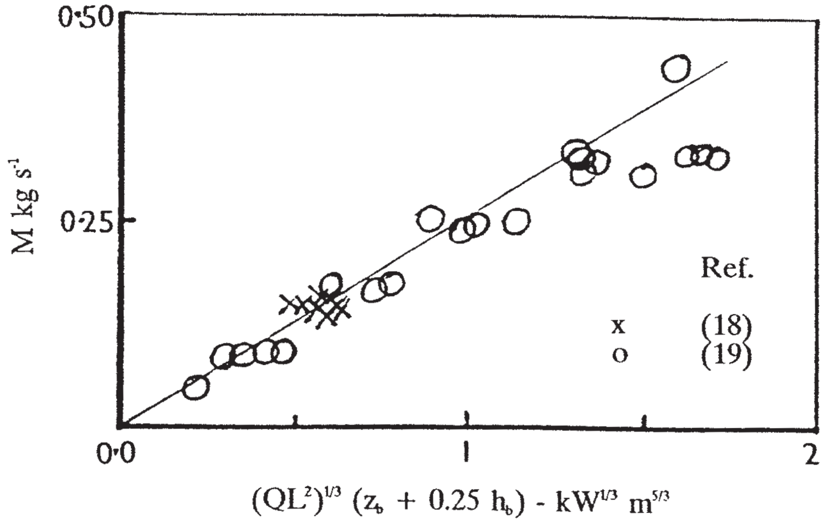

Fig. 5 Mass flow of smoke above balcony

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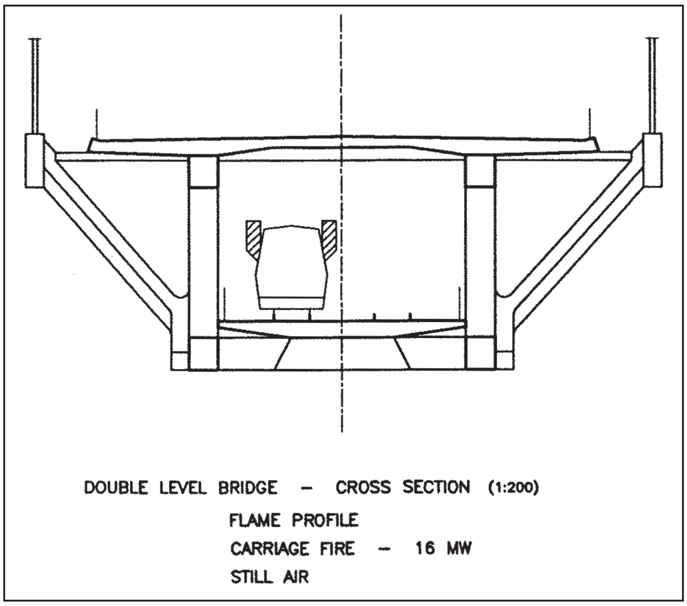
PAPER 23

Structural fire design of the Øresund tunnel

Chris Barber, Andrew Gardiner and Margaret Law, Arup Fire, Ove Arup and Partners, 13 Fitzroy Street, London, W1T 4BQ, UK, Proceedings of the International Conference on Fires in Tunnels, Boras, Sweden October 10-11 1994. SP Report 1994:54. SP Swedish National Testing and Research Institute, Boras, Sweden.

Arup Fire had been asked to specify the ‘fire loads’ for the various parts of the Øresund link between Denmark and Sweden, by which was meant the fire exposures to be used as the basis of design for fire resistance. The paper served a dual purpose, as a direct contribution to the Conference and as a record of the various design aspects and assumptions used.

Figure showing one of the many flame profiles used to describe potential fire impact on the Øresund Bridge. The eventual cable stay structure is shown in the plate.



STRUCTURAL FIRE DESIGN OF THE ØRESUND TUNNEL

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ABSTRACT

The assessment of the fire test exposure for the tunnel structure of the Øresund Link is described. Fire models are given for road vehicles, passenger rail carriages, road and rail petrol tankers and LPG tankers. Design fire exposures are proposed and related to the standard hydrocarbon test and the RSW hydrocarbon test.

KEYWORDS: Fire resistance; Road tunnel; Rail tunnel; Vehicle fire; Train fire, Petroleum pool fire, LPG jet fire; Hydrocarbon fire resistance test; RSW fire test.

1 Introduction

At the time of our initial involvement with the Øresund Link, considerable progress had already been made in drafting the Project Technical Design Bases (TDB) and the Project Application Documents (PAD). In addition, Risk and Hazard Assessment Reports for the Link and reviews of General Safety matters had been prepared. Our main contribution to this project has been to propose or confirm the Fire Actions to be adopted for structural fire design of the Link. In addition we have reviewed and commented on other aspects of fire safety contained in the TDB and PAD. In this paper we describe the work relating to the structure of the two tunnels, road and rail, which form one portion of the Link [1].

2 General approach

The first task was to model fire behaviour for the various hazard scenarios identified in the Risk and Hazard Assessments. For parts of this we were able to draw on previous work which we carried out for British Rail, in relation to subsurface stations, and Thai Railways in relation to the Bangkok elevated road and train project. The second task was to put these fire models into suitable code form for the structural engineers who would be using the Application Documents. For this purpose we relied on existing tests, wherever that was feasible. Although the structural Eurocodes deal mainly with design for the standard fire resistance test [2], the Eurocode for Fire Actions [3] recognises the use of other tests and also of so-called parametric fire exposures, where gas temperatures used for calculating the net heat flux are determined on the basis of physical parameters.

3 Fire resistance tests

Existing fire resistance tests heat an element of structure in a furnace which is controlled to give a prescribed temperature-time exposure at the surface of the test element. The standard fire resistance test is considered to be representative of fires involving mainly cellulosic type fire loads, such as found in dwellings, offices and shops. The hydrocarbon test [4] is considered to be representative of fires involving mainly plastics and liquid fuels, such as found in parts of industry and on oil platforms. The RSW test [5], developed in the Netherlands, is considered to represent the very severe conditions of the UK fire in the Summit rail tunnel, 1984 [6] and is specifically designed to test special linings for concrete structures. The RSW test is expected to provide a more severe attack than the other tests, on the integrity, adhesion and thermal performance of insulating materials applied to the structural elements.

Once the critical fire models had been established by our study, it was clear that it was not necessary to devise a new test for structural fire design of the Tunnels. This is to be expected, since furnace tests do represent fires within enclosures. However, for the Bridge portion of the Link, which is not dealt with in this paper, it was necessary to use a parametric fire exposure, to represent heat transfer in the open air.

4 Fire scenarios

The following fire scenarios were identified for study:

Road tunnel fires:
- Car
- Freight truck/bus
- Petrol tanker with leak - pool fire
- LPG tanker with leak - jet fire
- Multiple vehicle incident

Rail tunnel fires:
- Passenger carriage (post-flashover)
- Freight wagon
- Petrol tanker with leak - pool fire
- LPG tanker with leak - jet fire
- Locomotive fire
- Multiple wagon incident

The main parameters to be derived were (as relevant):
- Heat output
- Fire duration
- Flame height and deflection (under ceiling)

5 Roadway fire models

The principal source for roadway fire models is the Permanent International Association of Road Congresses (PIARC) [7] which adopted work by Heselden [8]. The fire sizes proposed relate to public fire safety in tunnels and the effectiveness of ventilation in assisting people to escape. As people will escape (if they are able) during the early stages of a fire, it is possible that the proposed heat outputs do not reach the worst values which could be generated when the fire has developed further. Accordingly we have reviewed the PIARC proposals.

5.1 Car fires

PIARC: up to 5 MW per car.

The heat output from motorcars has been measured many times, in order to confirm that well ventilated car parks can be constructed in steel without structural fire protection. The most recent publication [9] gives a range of peak heat outputs from single burning cars, all less than 2MW. For design purposes, 2.5MW would be conservative for a one-car fire.

Proposed car fire model: 2.5MW for 30 minutes, which is half the PIARC value.

5.2 Freight or bus fires

PIARC: up to 20MW per freight vehicle, bus or coach.

For freight, a load of solid polystyrene or polypropylene has been assumed. This can be compared with the fire in the Moorfleet Tunnel, Hamburg.

We assume the following properties:

	Polypropylene	Polystyrene	Ref.
ΔH_c - MJ/kg	39	27	[10]
m'' - kg/m^{2}s	0.018	0.034	[11]
ρ - kg/m^3	905	1050	[11]
We obtain:			
q - MW	12	16	
V - mm/min	1.2	1.9	

ΔH_c is chemical heat of combustion, m'' is burning rate per unit area, ρ is density, q is heat output for a lorry area of 2.5m x 7m, and V is the fuel surface regression rate. A conservative estimate is that the convective output is 2q/3, i.e. 10MW. The burning time could be very long, but it can be assumed that firefighting will end the fire before all the fuel is consumed.

A bus or coach with upholstered seats, curtains, baggage etc. can be assumed to have a similar heat output to a passenger carriage, as described in 5.1 below, of about 16MW, with a convective output of about 11MW for about 30 minutes.

Proposed freight/bus model: 15MW for 120 minutes, which is 25% less than PIARC.

5.3 Petroleum tanker with leak

PIARC: up to 100MW (assumes 50m^2 pool area of burning petrol).

Heat output depends on the pool area. Pool area depends on the entry flow of leaking fuel, and the location and capacity of any drains. The leakage flow depends on the diameter of the hole and the pressure head.

The main flow from a leakage rate is estimated by

$$m = C_o A \rho \sqrt{2gh} \tag{1}$$

where m = mass flow (kg/s)
C_o = 0.6 (-)
A = area of hole (m^2)
ρ = density of fuel = 740 (kg/m^3)
h = head = 2.0 (m)
g = 9.81 (m/s^2)

The pool area is given by

$$m = m'' A_f + m_d \tag{2}$$

where m'' = 0.055 (kg/m^{2}s)
A_f = pool area (m^2)
m_d = mass flow through the drain (kg/s)

The heat output is given by

$$q = m'' A_f \Delta H_c \quad \text{(MW)} \tag{3}$$

where ΔH_c = 43.7 (MJ/kg)

5.3.1 Leakage rate

The risk analysis considers the possibility of fuel leakage from ruptures of 15, 35, and 50mm equivalent diameter. These represent the potential failure of small diameter fuel lines or a deformation of a delivery hose flange. They do not represent the complete rupture of a delivery hose which would give a hole diameter of 100mm. For the holes considered values of m are 0.5, 2.7 and 5.6 Kg/s respectively.

5.3.2 Drainage rates

The road tunnel has cross-fall of 2% with some longitudinal fall to road gulleys at 22m centres. The drainage capacity of these gulleys, for water, is 4m^3/min. This is about ten times greater than the volume flow for the petrol leakage rate considered above.

The final fire size will depend critically on the position of the leakage point relative to a drainage gulley. This will define the extent to which a pool of fuel may spread over the road surface before unburnt fuel may enter the drainage system. The eventual fire size is proportional to the fire area as illustrated in Figure 1.

The significant benefit of even a limited amount of drainage is illustrated in Table 1 for the three leakage holes considered, using equations (1), (2) and (3).

Table 1

Effect of leakage diameter and drainage rate on fire size

Diameter (mm)	m (kg/s)	q (MW)			
		$m_d = 0$	1	2	5 (kg/s)
15	0.5	22	-	-	-
35	2.7	120	76	33	-
50	5.6	245	201	158	27

However, it would be possible in an accident for an obstruction to cause fuel to spread along the tunnel and to reach its steady state size before reaching a drainage point, as illustrated in Figure 2.

5.3.3 Ventilation

We considered whether ventilation could restrict the rate of burning and hence the fire size. The road tunnel, open at each end, is 9.7m wide and 5.5m high. Unfortunately most information for ventilation controlled fires is for roughly cubical enclosures, not tunnels.

From Bullen and Thomas [12] the following burning rate is given for polyethylene fires in a compartment where ventilation controls:

$$R = 0.03\,A\,H^{1/2} \quad \text{(kg/s)} \tag{4}$$

where A = area of ventilation opening (m^2)
H = height of ventilation opening (m)

This was based on data from fires in a relatively shallow compartment, depth equal to height.

Applying Bernouilli, the mass flow of air into the compartment is given by [13]

$$M_a = 0.5\,A\,H^{1/2} \quad \text{(kg/s)} \tag{5}$$

Assuming 14.6 kg of air to burn 1 kg petrol

$$R = 0.034\ A\ H^{1/2} \quad (\text{kg/s}) \tag{6}$$

which is similar to equation (4).

If turbulent entrainment into the flames is the mechanism for air inflow then the constant in Equation (5) would be less, approximately 0.2. However, we know so little about the effect of compartment shape for these fires that it would be prudent to take the higher value. Bullen and Thomas show that fuel evaporation rate in an enclosure is much higher than in the open and efficient combustion would be expected. Assuming 100% combustion efficiency, again to be prudent, and a value for ΔH_c of 43.7 (MJ/kg) for petrol gives

$$q = 1.3\ A\ H^{1/2} \quad (\text{MW}) \tag{7}$$

For the road tunnel

$$q = 1.3 \times 2 \times 9.7 \times 5.5 \times 5.5^{1/2} = 330 \quad (\text{MW}) \tag{8}$$

There is no evidence, from this admittedly very approximate assessment, that the size of the pool fires considered would be limited by ventilation.

5.3.4 Design fire size

After discussion with the Project Team it was considered that for design purposes the 35mm leak would be assumed. To be conservative, the benefit of drainage was discounted and no allowance was made for the reduction in head, and hence in leakage rate, with time. It was considered reasonable to allow for firefighting activity. Noting a discharge time for a full 23 tonne road tanker of about 140 minutes, a fire duration of 100 minutes was assumed, with firefighting.

Proposed petrol tanker model: 120 MW for 100 minutes, which is 20% greater than PIARC.

5.4 LPG tanker with leak

PIARC: presumed same as petrol tanker.

In the case of hazardous goods being transported under pressure, in particular LPG, it is possible to have a jet flame projecting some way from the point of rupture.

Again, the risk assessment reports refer to potential ruptures of 15, 35 and 50mm equivalent diameter. These are the same equivalent failures as may occur for a petrol tanker.

For a jet release downwards, with liquid propane release, the mass flow is given, assuming tank vapour pressure is constant at approximately 8 atmospheres by:

$$m = C_o A \rho u \qquad (9)$$

where

$$u^2/2 = gh + \Delta P/\rho \qquad (10)$$

m = mass flow (kg/s)
C_o = 0.6 (-)
A = area of hole (m^2)
ρ = density of liquid = 580 (kg/m^3)
g = 9.81 (m/s^2)
h = 2.0 (m)
ΔP = pressure difference ≃ 700×10^3 (kN/m^2)

For the three holes considered, the mass flows are 3, 17 and 34 kg/s respectively. For a 23 tonne fuel load the fire durations would be relatively small, of order half an hour.

For a gas only release, i.e. a jet release upwards during vapourisation, the duration would be much greater.

The vaporised LPG was modelled as a propane release with a constant 8 bar pressure in the tank. This is conservative because the pressure will decrease as LPG is released. Above 3 bar pressure the pressure relief valve would operate and release more LPG.

For a compressible fluid being released into air the following equation was developed from the work equation:

$$\left(\frac{G}{A}\right)^2 \mathrm{Ln}\left(\frac{P_1}{P_2}\right) = \frac{P_1^2 - P_2^2}{2P_1 \nu_1} \qquad (11)$$

where G = mass flowrate of compressible fluid (kg/s)
A = area of hole (m^2)
P_1 = initial pressure of compressible fluid (Pa)
P_2 = final pressure of compressible fluid (Pa)
υ_1 = specific volume of compressible fluid at pressure, P_1 (m^3/kg)

The initial pressure of the compressible fluid (propane) is 8 bar (800 x 10^3 Pa) and the final pressure is atmospheric (100 x 10^3 Pa). The specific volume of propane at 800 x 10^3 Pa can be shown to be 0.067 m^3/kg. Substituting into (11) gives a mass flowrate of propane per unit area of orifice (G/A) as:

$$(G/A) = 1681\ kg/m^2 s$$

The hole sizes of 15, 35 and 50mm equivalent diameter were used to determine the propane release rate.

For the holes considered, the mass flows would be 0.3, 1.6 and 3.3 kg/s giving fire sizes of 14, 74 and 150 MW and maximum fire size duration of 1300, 240 and 120 minutes respectively without firefighting. The fire sizes are of the same order as those derived for petrol spillage; however, the jet is likely to be much more destructive, because it is localised. Structural fire protection materials may be unable to withstand jet impingement; therefore it is possible that there would be local overheating. However, if the structure is designed to survive a local failure, such a jet fire could be accepted, provided there is material protection for the rest of the structure which satisfies the furnace test. Firefighting would be expected to cool and limit the fire effects. This is discussed further in section 6.

5.5 Multiple vehicle incident

Multi-vehicle fires have not been considered on the basis that the petroleum based fires are the most critical. Subject to final risk analysis checking, it seems unlikely that more than one tanker will be involved in such an incident. Because of different rates of burning and the generally much smaller fire loads of other vehicles, the peak heat output of such a fire will not increase dramatically. There may be some increase of theoretical fire duration, but again this is not likely to be significant due to firefighting activity.

5.6 Summary of road tunnel fire

Table 2

Design fires for single vehicles on roadway

Scenario	**Size (MW)**	**Duration (minutes)**	**Paragraph**
Car	2.5	30	4.1
Freight/bus	15	120	4.2
Petrol tanker	120	100	4.3
LPG tanker	up to 150	60	4.4

6 Railway fire models

6.1 Passenger carriage

A fire in a passenger carriage is very similar to a fire in a furnished room. The incidence of flashover, which is a sudden transition to a state of total surface involvement in the fire of the combustible materials within the room, is an important event. Before flashover people have a chance to escape from the carriage, after flashover they do not. After flashover, the heat output from the fire rapidly increases, windows break and most of the heat emerges into the rail tunnel. Escaping passengers in the tunnel are exposed to heat and toxic gases and there will be heat exposure of the tunnel structure. For the purposes of this paper, the relevant part of the scenario is the post flashover, fully developed fire. In a passenger carriage, flashover will occur when the heat output is of order 1MW.

It is reasonable to assume that, with the large window areas found in carriages, there will be ample ventilation for the contents to burn freely. The resultant heat output can be estimated from the type and disposition of the materials or from rate of heat release measurements or from a combination of these. Significant heat exposure, is expected to last about 30 minutes, after flashover. Available information, based on calculation and testing, is summarised in Table 3.

Table 3

Estimated maximum heat output from post-flashover fires
in various passenger carriages

Rail System	**Carriage**	**Peak Heat Output - MW**
British Rail	415[1]	16
British Rail	Sprinter[2]	7
Thai Railways	Sleeper[3]	16.3
Thai Railways	Wooden Seating[4]	14.0

[1] An older type passenger carriage with upholstered seating and combustible linings.
[2] A modern carriage with fire retardant upholstered seating.
[3] An open sleeping car with all bedding and vanity curtains arranged in the night-time positions. (See Figure 3 for fire development).
[4] An old passenger carriage with solid wooden seating and wall linings.

The British Rail fire sizes have been both calculated and confirmed by test. Detailed reports are confidential [14].

The Thai Railways figures have been calculated and reported for another project [15]. The curves in Figure 3 have been derived from various data, most obtained from the SFPE Handbook.

It is understood that figures of the order of 15MW have been measured in tests associated with the EUREKA project in Norway.

Figure 4 shows a flame trajectory from a carriage fire, calculated using a fire engineering design manual [16].

For design purposes, a fire of 16MW heat output, lasting 30 minutes, is considered conservative for one passenger carriage on fire.

6.2 Freight wagon

A freight wagon would have a larger burning surface area than a freight vehicle. By comparison with the calculation in 4.2 we would expect a higher heat output, say up to 30 MW with the duration again depending on firefighting activities.

6.3 Petroleum tanker with leak

The heat output considerations are the same as for roadway fires, described in 4.3 but it is considered more likely that there will be a 50mm diameter leakage hole. With the conservative assumptions of no drainage and constant head, the heat output for design is 245MW and for a 64 tonne fuel load the duration could be 190 minutes without firefighting. Assuming firefighting is available, the design fire proposed is 245MW for 100 minutes. This fire size is more than double PIARC.

6.4 LPG tanker with leak

The jet fire sizes for 15, 35 and 50mm leak have already been assessed in 4.4, for a road tanker. The rail tanker, since it carries more fuel, could have a greater fire duration. Additionally, in the rail tunnel, the jet flame could impinge on an adjacent wagon and cause fairly rapid increases in pressure such that the valves will blow within some 10-20 minutes. Whilst the overall fuel inventory would lack oxygen to burn freely, the ensuing tank rupture and possible BLEVEs would cause a very severe long duration fire. There appears to be a significant risk that firefighters would be endangered by the speed of escalation of a serious event. In view of the significant life risk of such a fire, it may be necessary to limit the carriage of LPG in the rail tunnel to a single tanker. Firefighting would be more difficult in the rail tunnel.

6.5 Locomotive fires

The limited, anecdotal, evidence of the size of locomotive fires indicates that they fall well within the range of freight and pool fires considered above.

British Rail have advised 30 MW as an indicative fire size for diesel locomotives, based on a fuel leakage.

We have no information on fire sizes associated with large electric locomotives, which often have on-board automatic fire suppression. For older type multiple units, electric motor fires of the order of 6.8 MW have been calculated for Hong Kong's MTR system.

6.6 Multiple wagon fires

As discussed in 6.4, a jet fire from an LPG tanker can impinge on an adjacent tanker and give a serious event. Otherwise it is considered unlikely that more than one wagon or carriage will be burning at any one time, particularly taking into account firefighting activities.

The analysis given in 5.3.3 suggests that ventilation could control fires in the rail tunnel, which measures 6.5m wide and 6.5m high, to a heat output given by

$$q = 1.3 \times 2 \times 6.5^{2} \times 6.5^{1/2} = 280 \quad (\mathrm{MW}) \qquad (12)$$

Very roughly, we would expect a limit on fire size of about 300MW.

6.7 Summary of rail tunnel fires

Table 4

Design fires for single vehicles on rail

Scenario	**Size (MW)**	**Duration (mins.)**	**Paragraph**
Passenger carriage	16	30	5.1
Freight	30	120	5.2
Petrol tanker	245	100	5.3
LPG tanker	up to 150	120	5.4

7 Fire exposure of structure

7.1 Petrol tanker

For assessing fire resistance, we postulate that a significant area of an element of structure is exposed on one or more faces to heat transfer from the fire. For both road and rail tunnels the most severe scenario for fire resistance design is the petrol tanker fire.

The design fires assume no drainage and the pool areas, given by equation (2), are shown in Table 5. There will be significant extension of flames beyond the pool area, under the tunnel ceilings, and an assessment of this flame extension is also given in Table 5. This assessment was made as follows:

Thomas and Karlsson [17] derive the following expression for flame radius under a ceiling for a fire source in the corner of an enclosure:

$$\frac{L_r}{H*} = 6.39\sqrt{Q*}\left[\frac{250}{\Delta T}\right]^{3/4} - 0.60 \qquad (13)$$

where L_r = flame radius (m)
H^* = $H + 3D$ (m)
H = ceiling height (m)
D = fire diameter (m)
Q^* = $\dfrac{Q}{\rho_o C_p T_o (H^*)^2 (gH^*)^{1/2}}$ -
Q = heat output (kW)
ρ_o = density of ambient air ≃ 1.2 (kg/m^3)
C_p = specific heat of air ≃ 1 (kJ/kgK)
T_o = absolute temperature of ambient air ≃ 310 (K)
ΔT = time-averaged temperature rise at edge of flame (K)

A value of 180 for ΔT gives good agreement with experimental data for $L_r/H < 1.2$. The experimental facility, being small, could not give reliable data for larger L_r. For our purposes we think it reasonable to use the equation for greater L_r/H.

Figure 5 illustrates the corner fire and we can consider it to be one quadrant of a free standing fire. For a free standing fire, of heat output Q and diameter D also illustrated in Figure 5, equation (10) becomes, substituting Q/4 and $\Delta T = 180$:

$$\frac{L_r}{H*} = 4.1\sqrt{Q*} - 0.60 \qquad (14)$$

where H^* = $H + 1.5\,D$ (m)
D = diameter of free standing fire (m)
Q = heat output of free standing fire (kW)

L_r has been calculated as 11m for the road tunnel fire and 14m for the rail tunnel fire, assuming they are free standing. The geometry of the tunnels means that the flames will be channelled. The flame length would be approximately flame area divided by tunnel width as shown in Table 5. As a check we can use the following equation [18], setting ΔT to 180 at the flame edge:

$$\Delta T/\Delta T_{imp} = 0.29\,(H/l_b)^{1/3}\exp[-\,0.20\,(Y/H)\,(l_b/H)^{1/3}] \qquad (15)$$

where ΔT = gas temperature rise at ceiling level (K)
ΔT_{imp} = ΔT directly over the fire (K)
l_b = half channel width (m)
Y = distance along channel from plume impingement (m)

Assuming ΔT_{imp} = 1200, the flame areas are about 400m² for both locations, which suggests the values in Table 5 are not unreasonable.

Table 5

Pool areas and flame areas for petrol tanker fires in tunnels

Location	**Size MW**	**Pool area m²**	**Flame area m²**	**Flame length m**
Road	120	50	380	40
Rail	245	100	620	100

We conclude that in the road tunnel, some 40m length of flame exposure is expected and that for the narrower rail tunnel the length would be about 100m. This ignores any beneficial effect of drainage.

7.2 LPG jet fires

The LPG jet fire for both road and rail has been taken as the 50mm equivalent diameter hole for leakage. Based on the statistical evidence in the QRA reports this size was used here to describe the worst case release. A one hour fire duration may be taken as limiting where the Fire Brigade can successfully approach the fire. This is more likely for the road tanker event.

Flame temperatures on average are approximately 1100°C and relatively instantaneous. Flame lengths are approximately 20m with impingement area of under 1m².

There is a concern that for a jet fire in the rail tunnel directed upwards, then the spread of flame and consequent engulfing of adjacent tankers will cause a very rapid escalation of an LPG train fire. This will be an explosive event with a very short duration. It will occur approximately 10-15 minutes after the initiating event.

Even though risk assessment reports have considered that such events should not be accounted for in design, the timescale and severity of event suggest that limitations on the running of LPG through the tunnels should be considered.

We conclude that with a single jet fire it would be possible to confirm that localised over heating or destruction would not lead to structural failure. The structural fire protection provided for petrol fires will give protection for more general heating if another type of vehicle becomes involved during the single jet fire.

8 Fire resistance testing

It is normal to express the fire resistance of a structure in terms of a standard temperature-time curve which relates to a standardised test method. Fire protection materials, including concrete, which perform satisfactorily in fires involving normal building contents, may lose their insulating properties and crack or spall when exposed to petroleum or jet fires, because of the rapid attainment of very high surface temperatures. Where petroleum based fires are most critical, a hydrocarbon based test curve should be used. The standard hydrocarbon curve, which can last for up to 4 hours is shown in Figure 6.

There are two conditions to be considered, dependent on whether the fire is fuel-bed or ventilation controlled. Based on the fire scenarios considered and the ventilation calculations given in 4.3.3 and 5.6 all fires are fuel-bed controlled. However, in the rail tunnel, the difference is small (245MW compared to 300MW) and if any fire escalates it will tend to be ventilation controlled.

The RSW test is considered appropriate for hydrocarbon ventilation controlled fires. It is a specific test for linings rather than for structure and it uses high temperatures but for a duration of 2 hours only. See Figure 6.

8.1 Comparison of hydrocarbon test exposures

The Project Technical Design Basis gives performance criteria for road-tunnel fire insulating material (section 5.4.2 of the TDB). The RSW hydrocarbon test curve specified, rises to a temperature of 1350°C and lasts 2 hours. The performance criteria are given in terms of temperatures within the protected concrete structure at the end of the test. These are:

380°C at the concrete/insulation interface
250°C at the reinforcement.

The alternative standard hydrocarbon test curve given in Eurocode 1 (ENV curve) rises to a lower temperature of 1100°C but can last up to 4 hours. Typical criteria for failure are 550°C for high yield reinforcement and 400°C for prestressing tendons [19].

It is felt that because there are long duration pool fire scenarios that can occur in the road tunnel the following question should be asked:

> "For an insulation system achieving the acceptance criteria for reinforcement and concrete surface temperatures under the RSW curve exposure, what would the corresponding temperatures be for exposure to the ENV test curve of 4 hours duration?"

The comparison was calculated using a one-dimensional thermal conduction model. Under the RSW curve fire exposure the target surface temperature of 380°C was reached at 2 hours at an equivalent concrete depth of 83mm. This means that the insulation material must have the thermal performance of 83mm of concrete in order to pass this criterion.

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After 4 hours exposure to the ENV curve the temperature at the same depth is 500°C.

Similarly the target reinforcement temperature of 250°C was reached at a depth of 105mm with the RSW curve exposure. After 4 hours with the ENV curve exposure, a temperature of 390°C is reached at the same depth.

In comparing the two test results, one concludes that:

(i) For reinforcement temperatures, meeting the stated criterion implies that the reinforcement and prestressing strands will maintain more than 50% of their ambient strength after 4 hours exposure to an ENV hydrocarbon fire test. This is a normally acceptable serviceability condition.

(ii) Concrete/insulation interface temperatures are higher in the 4 hour ENV test than in the RSW test. This may adversely affect the adhesion of the insulation in a prolonged fire but this seems unlikely.

(iii) The two temperature criteria taken together effectively require the reinforcement cover to be at least 22mm for normal weight concrete.

(iv) The maximum surface temperature of the insulation will be higher in the RSW test, which therefore gives a higher standard for material stability than the ENV test.

The conclusion is that the method of specification of the RSW curve in the TDB will deal with very high temperatures in shorter duration fires but at the same time should maintain serviceability for longer duration, slightly cooler fires and is acceptable accordingly.

8.2 Recommended test exposures

The rail tunnel, which may have fires approaching ventilation control or may contain fires of long duration should be able to survive the 2 hour RSW test and also the 4 hour standard hydrocarbon fire test. Protective materials which satisfy the performance criteria for the RSW test will also give adequate protection for the longer test.

Despite the possibility of jet fires, the maximum temperatures will be lower in the road tunnel due to the smaller fires and better relative ventilation. A specification of 2 hours fire resistance as measured in the standard hydrocarbon test would be adequate.

Proposal. Rail tunnel: Concrete structure to be protected to satisfy the temperature criteria of the 2 hour RSW test.

Road tunnel: Concrete structure to be protected to satisfy the fire resistance criteria when exposed to 2 hours of the standard hydrocarbon test.

9 Concluding remarks

For structural fire design of the Øresund road and rail tunnels the critical fire exposures are the petroleum pool fires. The other, smaller, fire models were developed by us principally in relation to passenger safety. We have included them in this paper 'for the record' and for general interest. Our brief was to propose or confirm test exposures for structural fire design. The degree of precision and depth of analysis we used was sufficient only to achieve this broad aim. However, where possible, we have used more than one calculation method to check that our proposals were adequate. In other words we adopted a standard engineering approach.

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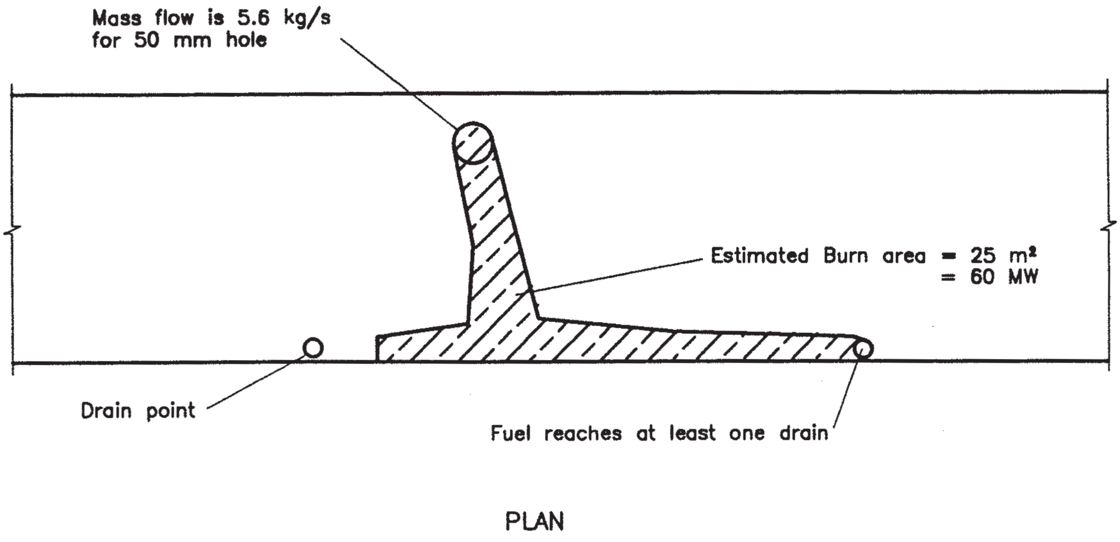


Figure 1 Typical Burn Area for 50 mm Fuel Release in Road Tunnel

MLFIG1

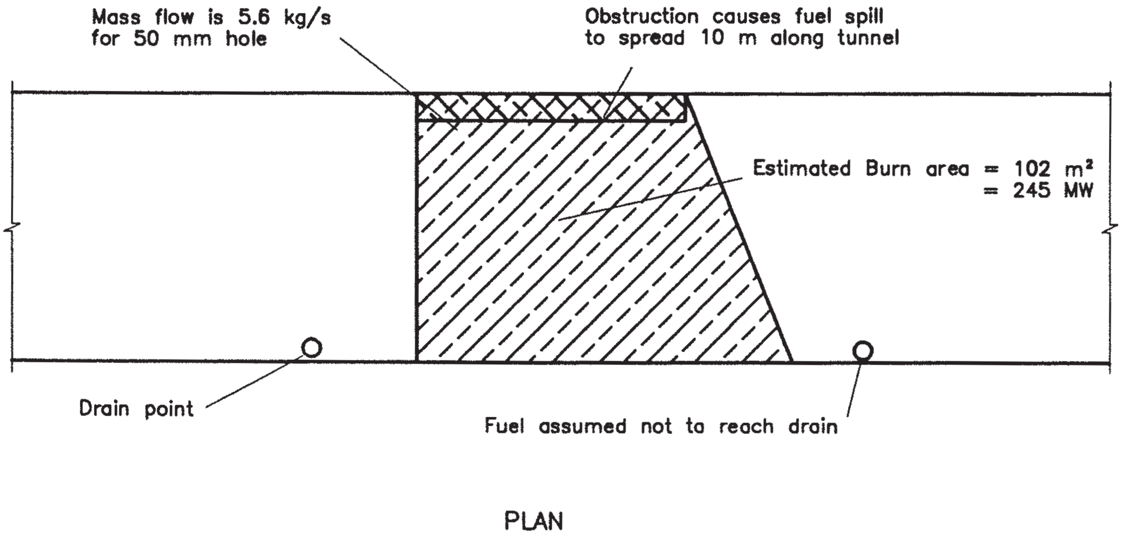
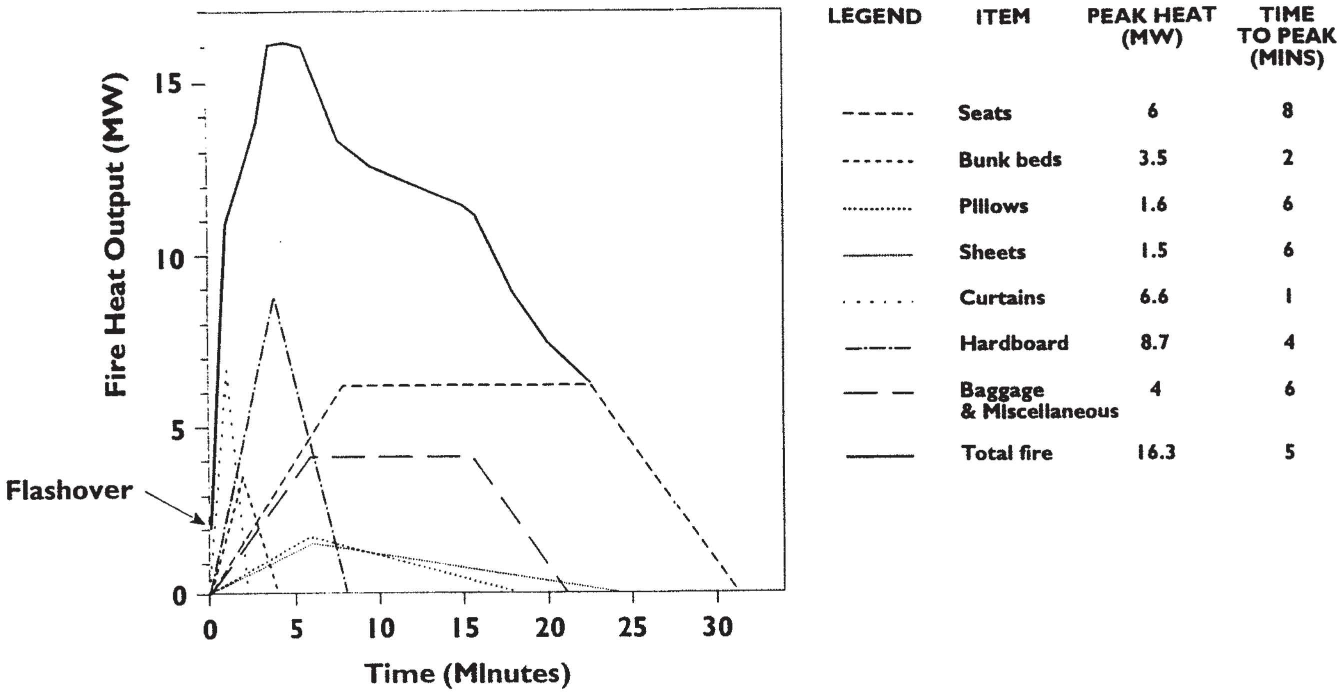


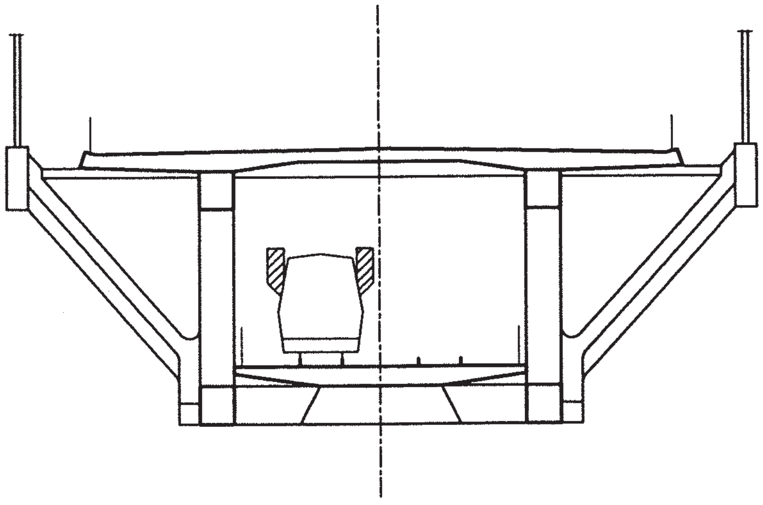
Figure 2 Maximum Burn Area for 50 mm Fuel Release in Road Tunnel

MLFIG2



LEGEND	ITEM	PEAK HEAT (MW)	TIME TO PEAK (MINS)
- - - - -	Seats	6	8
- - - - - -	Bunk beds	3.5	2
··········	Pillows	1.6	6
———	Sheets	1.5	6
· · · · · ·	Curtains	6.6	1
—·—·—	Hardboard	8.7	4
— —	Baggage & Miscellaneous	4	6
———	Total fire	16.3	5

FIGURE 3 THAI RAILWAYS SLEEPING CAR



DOUBLE LEVEL BRIDGE – CROSS SECTION (1:200)

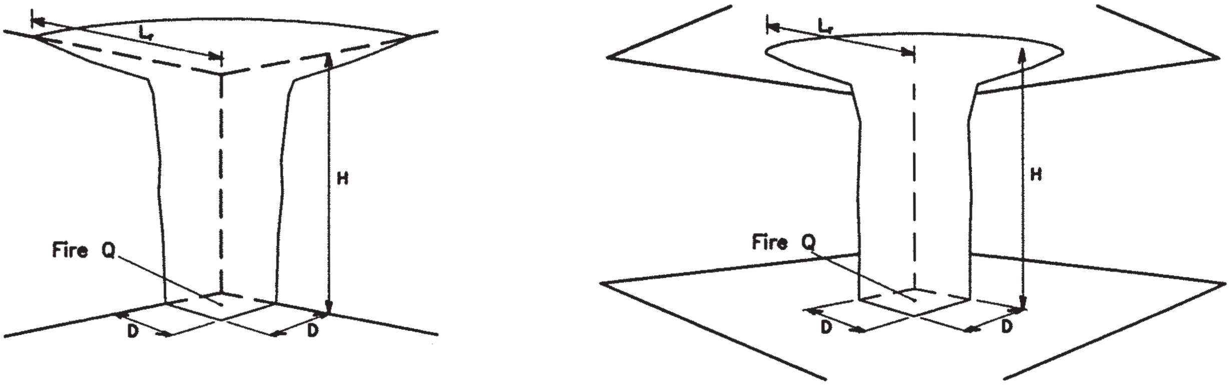
FLAME PROFILE

CARRIAGE FIRE – 16 MW

STILL AIR

Figure 4 Carriage Fire Flame Profile

MLF104



Corner Fire

Freestanding Fire

Figure 5 Flame radius under ceiling

MLFIG5

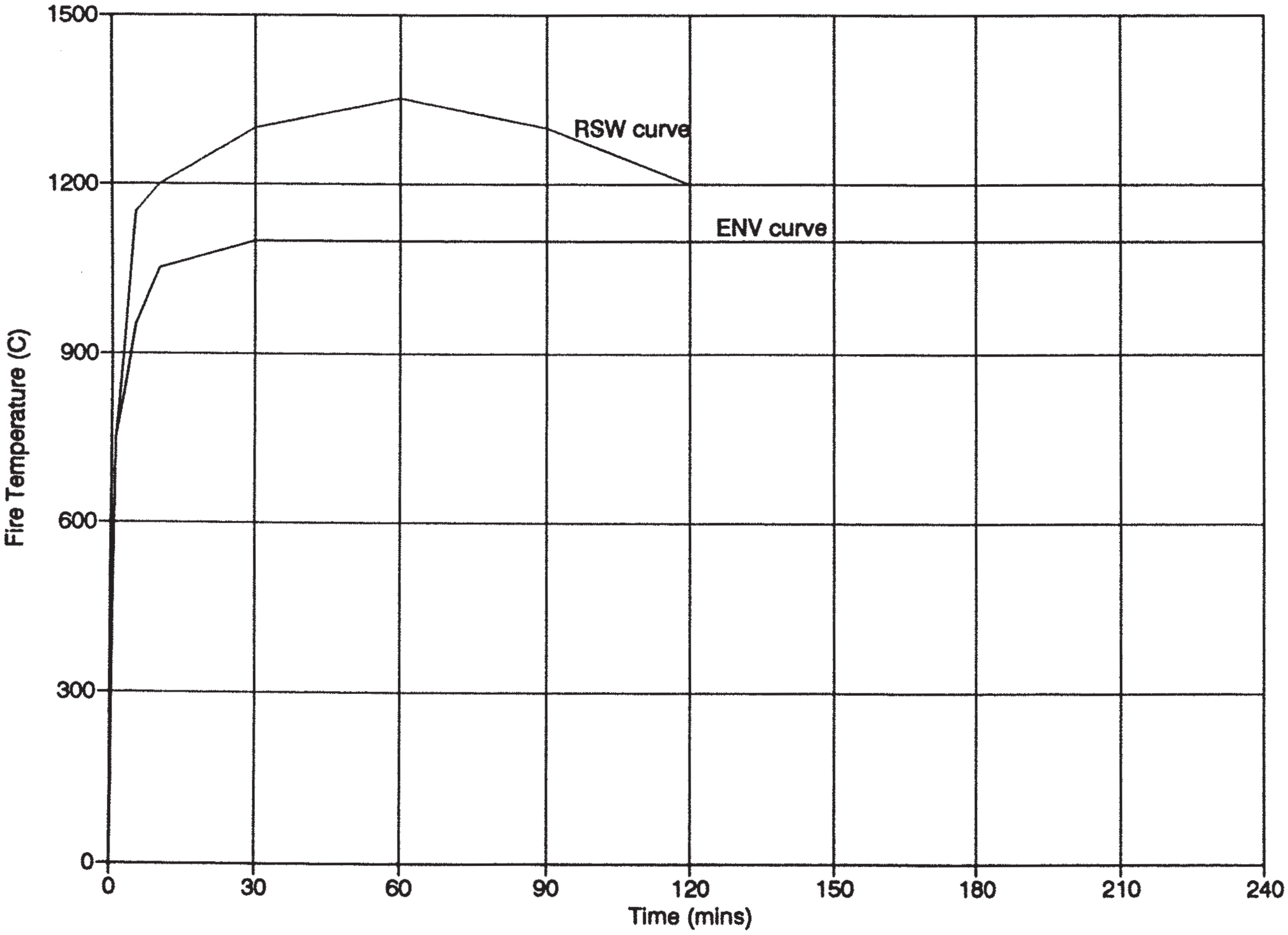


Figure 6 Hydrocarbon test curves

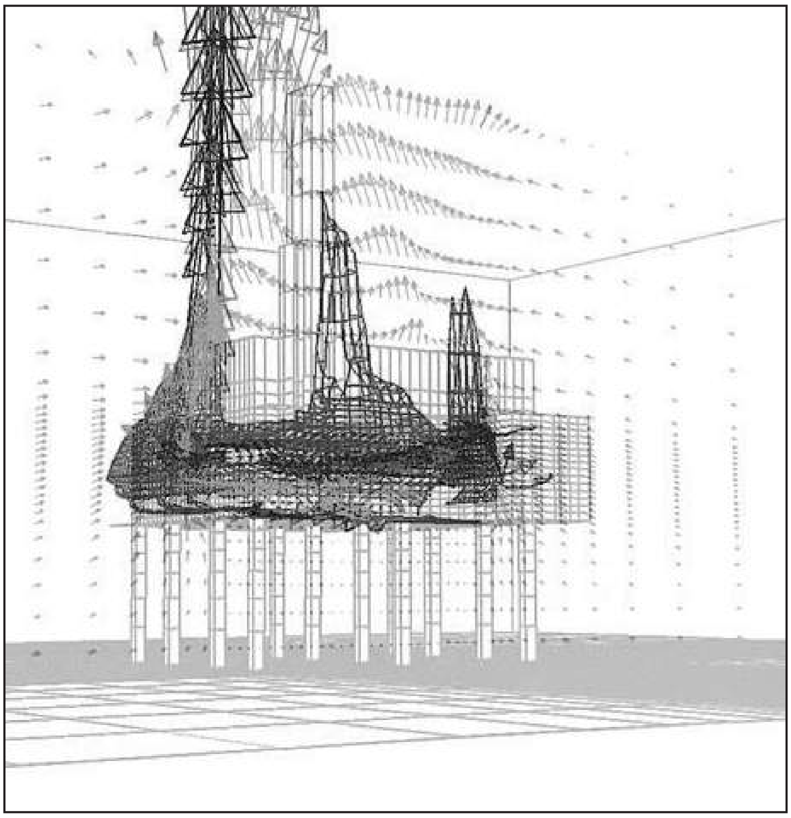
PAPER 24

Design models for smoke control and evacuation

Margaret Law MBE, Consultant to Arup Fire, Seminar Fire Safety Management in the Process Industry, 21 March 1995, AEA Conference Centre, Warrington. Institution of Fire Engineers (IFE), Leicester, UK

It seemed that engineers in the process industry might not realise that there were various fire engineering relationships used in the design of non-industrial buildings that could be adapted for use in industry. This paper gives a broad summary of the information available.

Computer graphic of a computational fluids dynamic model used on BP Forties Charlie, an offshore oil platform. Many of the relationships given in this paper can be used on both offshore and onshore structures.



DESIGN MODELS FOR SMOKE CONTROL AND EVACUATION

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INTRODUCTION

Design models are used to assess whether the safety measures provided are likely to give a reasonable standard of protection. While intended to be representative, the models do not usually predict exactly what might happen in practice. In engineering design, factors can be introduced to take account of uncertainties in models, as they are for input data such as material properties or numbers of people assumed to be at risk. The models described here are thus an aid to judgement and are not predictions or rules which arbitrarily pass or fail a design.

THE EFFECTS OF FIRE AND SMOKE ON PEOPLE

People may be temporarily or permanently injured or even killed by heat and toxic products from a fire. The severity of the effects on human beings is very dependent on the exposure time. Escape route design therefore aims to give people easy access to a protected zone or a place of safety. It is generally recognised that loss of visibility caused by smoke obscuration and eye irritation can delay escape to the extent that people may be overtaken by the injurious products.

Heat injury may arise by direct skin contact with hot smoke and flames, including inhalation of hot gases. Even without contact, injury can be caused by heat radiation on exposed skin. Injury by toxic products, of which carbon monoxide is commonly predominant, can lead to loss of judgement, disorientation, unconsciousness and death, according to the concentration and duration of exposure. Even relatively cool, low toxicity smoke can cause significant loss of visibility.

CRITICAL CONDITIONS FOR AVOIDING DEATH OR INJURY

For design, it is desirable to codify the limits of acceptability of various fire effects. Some suggested values for toxicity are given in Table 1, which is intended to help the designer to estimate whether there is likely to be a toxic threat to the occupants. More detailed studies would be necessary for post-flashover and poorly ventilated fires but, in relation to escape of occupants, it is the pre-flashover, well ventilated fire which is likely to be relevant.

TABLE 1

Design values of critical conditions for toxicity

Chemical products	5 minutes		30 minutes	
ppm	incapacity	death	incapacity	death
Carbon monoxide	6000	12000	1000	2500
Hydrogen cyanide	150	250	90	170
Hydrogen chloride	500	16000	200	<12%
Smoke organic irritants*	1.2	7	1.2	1.2

*Effects expressed in terms of smoke extinction coefficient.

Some suggested values of critical temperatures are given in Table 2.

TABLE 2
Design values of critical temperature for different exposure conditions

Type of exposure	Effect	Temperature
Radiation	Severe skin pain	185^{o}C black body
Conduction	Skin burns 1 sec hot metal	60^{o}C
Convection:		
30 minutes	Hyperthermia	100^{o}C
< 5 minutes	Skin/lungs burns, hot gases	120^{o}C
< 1 minute	Skin/lungs burns, hot gases	190^{o}C

Although loss of visibility is not directly life-threatening, it may determine whether a person is able to escape from a fire. Tests have established that most people turn back if they reach smoke which reduces the visibility below 8m. It can be assumed that fire fighters wearing breathing apparatus will feel their way through thick smoke, unless the temperature exceeds the values given in Table 2.

ALERTING PEOPLE TO DANGER

People may be alerted by direct observation or other ways:

* hearing an alarm bell or siren
* hearing from another occupant or fire fighter
* hearing broadcast instructions - automatic or live
* seeing broadcast instructions - automatic or live

After being alerted, various actions may be taken:

- investigation
- immediate start of evacuation procedure
- delayed start of evacuation until convinced of danger

The evacuation procedure may begin with:

- collecting belongings
- looking for friends/relatives
- carrying out emergency procedures for plant/equipment

Numerous studies of the behaviour of people when they are alerted have given indications of the time which may elapse before they decide to make their way towards an exit. For design purposes the many reasons for delay need to be categorised, and a suggested approach, giving a so-called pre-movement time or interval, is illustrated in Table 3. This approach takes into account the type of occupant: including degree of mobility and familiarity with surroundings, and the type of alarm: whether a simple bell, an announcement of fire or announced instructions for further action.

TABLE 3

Examples of design values for pre-movement interval

Occupancy	Pre-movement interval - s		
	Alarm bell	PA	Directive PA
Hospital	480	300	180
Place of Assembly	300	180	120
Office	240	180	160

NB This table is based on work by J Sime, given in the draft British Standard Code of Practice for the application of fire safety engineering principles to fire safety in buildings (8 June 1994)

Clearly, in an industrial enterprise, training the staff in procedures to protect themselves, the plant and any visitors gives beneficial control of pre-movement activities.

MODELLING FIRE GROWTH IN AN ENCLOSURE

Models have been developed for smoke movement from fires in enclosures so that the need to protect the occupants can be assessed. If the fire flashes over in the enclosure - a condition described as sudden transition to a state of total surface involvement in a fire of combustible materials in the enclosure - then the oxygen content is very much reduced, the carbon monoxide content is very much increased, and any people remaining inside will not survive. Therefore, the early, pre-flashover stages of the fire are most relevant to safety of people within the room where the fire starts. Both pre-flashover and post-flashover fires are relevant to safety beyond the room if heat and smoke are released through openings or ducts into other parts of the building. Flashover is expected to occur when the layer of hot gases which accumulates at ceiling level above a fire reaches a temperature of about 600°C. This condition is not attained until there are sustained flames at ceiling level, spreading horizontally from the area of impingement.

For smoke control design, the following aspects of the fire source are of interest:

* rate of mass loss
* nature of the burning material(s)
* geometry of the source

The rate of generation of heat and, to a significant extent, of smoke particles and toxic products, is determined by the mass loss rate. Estimates of the yield of fire products per unit mass burnt are illustrated in Table 4 for flaming combustion. In vitiated combustion, the yields for toxic and smoke products are much higher. In Table 4 , H_C is the heat generated per unit mass burnt and ε is the mass of smoke particles per unit mass burnt.

TABLE 4

Fire products with flaming combustion

Material	H_C MJ/kg	Y_{CO} kg/kg	Y_{HCN}, Y_{HCl} kg/kg	ε kg/kg
Timber	13.0	0.020	0	<0.01-0.025
Polyvinyl chloride	5.7	0.063	0.25-0.5*	0.12-0.17
Polyurethane flexible	19.0	0.042	0.001	<0.01-0.11
Polyurethane rigid	17.9	0.180	0.011	0.09-0.11
Polystyrene	27.0	0.060	0	0.15-0.17
Polypropylene	38.6	0.050	0	0.016-0.10

*HCN yield depending upon formulation plasticised-rigid.

The hot plume above the fire increases in volume as it rises due to entrainment of the ambient air. The expansion and buoyancy of this heated and contaminated air - usually referred to as smoke - causes it to spread within and beyond the fire enclosure. For this reason, a design fire for smoke control design may simply be characterised by its heat output. Indeed, the nature and concentration of the smoke and toxic products any be of secondary importance if the smoke control design aims to keep the smoke layer above head height.

The rates of heat output of growing fires in commonly found furnishings and other commodities have been studied for many years, since these are particularly relevant to the operation of automatic detectors and following detection, to the safety of people and goods. These fires have been classified for design purposes and a frequently used approach is the so-called tee-squared fire:

$$Q = 1000(t/t_g)^2 \qquad (1)$$

where Q = rate of heat release (kW)
t = time after effective ignition (s)
t_g = characteristic time to attain 1000kW (s)

Suggested fire classes and the corresponding values of t_g are given in Table 5.

TABLE 5
Classification of growing fires

Class	**t_g (s)**
Slow	600
Medium	300
Fast	150
Ultra-fast	75

Illustrations of different class fires are given in Table 6.

The mass rate of air entrainment into the fire plume varies not only with the heat output but also with the geometry and location of the source. These matters are dealt with in the next section. However, an important measure to limit fire size and hence, the generation of heat and smoke, should first be considered.

TABLE 6

Maximum rates of heat release and class of fire

Localised fire	Class	Max RHR (kW)
Waste paper basket	slow	18
TV set	medium	290
Latex foam pillow	medium	117
Christmas tree	ultra-fast	650
Wardrobe 3.2mm plywood*	ultra-fast	6400
Wardrobe 12.7mm plywood*	ultra-fast	3100

* with clothes

If the fire is controlled by an automatic sprinkler system, it is usually assumed that the rate of heat release ceases growing once the first sprinkler has operated. A typical fire size at operation would be of the order of 1MW but is variable. For example, because of a time lag in heating the sprinkler head to its operating temperature, the fire size at operation is greater for fast growing fires than for slow ones. It also varies with the height and radial distance of the sprinkler from the fire and the type of head. These effects can be calculated, a well known program being DETACT. Before operation, people would be expected to have moved away from the vicinity of a 1-2 MW fire, because of the heat, and thus they would be beyond the area of sprinkler operation. Most sprinkler heads operate at temperatures below 100^{o}C and therefore it may be assumed for design that flashover will not occur in a sprinklered enclosure, since cooling by the spray will maintain the smoke at a low temperature.

MODELLING SMOKE MOVEMENT

Inside an enclosure, the fire plume is usually treated as axi-symmetric, originating on the floor away from the walls. Occasionally a line source may be appropriate. If smoke spills from an opening in the enclosure, the entrainment in the vertical portion of the spill plume may be treated as if from a line source when near the opening and as an axi-symmetric plume when far from the opening. In calculations, the mass flow of combusted fuel is usually neglected, because it is small compared with the mass flow of air entrained into the plume. The following paragraphs give estimates of entrainment for different types of plume.

Axi-symmetric plume

(a) Pool fires

The height of the luminous zone above the fire may be taken as

$$z_l = 0.27Q_c^{2/5} - 1.02D \qquad (2)$$

where z_l = height of luminous zone(m)
Q_c = convective heat release rate = 0.7Q(kW)
D = pool diameter(m)

The mass flow of air entrained into the plume above the luminous zone may be estimated from

$$M = 0.071Q_c^{1/3}(z - z_o)^{5/3} \qquad (3)$$

where $z > z_l$
M = mass flow of entrained air(kgs^{-1})
and z_o is height of virtual source(m) given by

$$z_o = 0.096Q_c^{2/5} - 1.02D \qquad (4)$$

(b) Solid fuel fires

The height of the luminous zone above the base of the fire may be taken as

$$z_l = 0.020Q_c^{2/5} \qquad (5)$$

where $Q_c^{2/5} > 14.0$

Q_c = convective heat release rate (kW) $\hat{=}$ Q/1.5

and D = diameter or side dimension of source(m)

or

$$z_l = 0.035Q_c^{2/3}/(D + 0.074Q_c^{2/5})^{2/3} \qquad (6)$$

where $Q_c^{2/5} < 14.0D$

The mass flow of air entrained into the plume above this zone may be estimated from

$$M = 0.071Q_c^{1/3}z^{5/3} \qquad (7)$$

where $z > z_l$

These equations may be used for square and circular sources or rectangular sources where the longer side is up to three times the shorter, and D is calculated as the diameter of a circle of equal area.

An alternative equation used for square or circular sources is

$$M = 0.188Pz^{3/2} \qquad (8)$$

where P = perimeter of source(m)

$z_l < z < 2.5P$

$200 < Q_c/A_s < 750$

and A_s = plan area of source(m^2)

Line source

For a line source, where D_s, the longer side, exceeds three times the shorter side, the height of the luminous zone may be estimated from

$$z_l = 0.035Q_c^{2/3}/(D_s + 0.074Q_c^{2/5})^{2/3} \qquad (9)$$

The mass flow above the luminous zone may be estimated from

$$M = 0.21Q_c^{1/3}D_s^{2/3}z \qquad (9)$$

where $z_l < z < 5D_s$

or

$$M = 0.071Q_c^{1/3}z^{5/3} \qquad (10)$$

where $z > 5D_s$

Spill plume from an opening

Entrainment in the vertical plume above the opening may be estimated from

$$M = 0.23Q_c^{1/3}w^{2/3}(z + h) \qquad (11)$$

where w = width of opening(m)

h = height of opening(m)

z = height of plume above top of opening(m)

When there is a balcony above the opening, entrainment above the balcony may be estimated from

$$M = 0.36Q_c^{1/3}L^{2/3}(z_b + 0.25h_b) \qquad (12)$$

where $L = L_c$ with channelling screens

$L = (w + b)$ without channelling screens

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L_c = separation of channelling screens(m)
b = horizontal projection of balcony(m)
z_b = height of plume above balcony(m)
h_b = height of balcony above base of opening(m)

Smoke flow under the ceiling of a corridor

The velocity of a flowing layer beneath a ceiling may be estimated from

$$u = 0.7(gQ_cT/\rho_o c_p T_o W_c)^{1/3} \qquad (13)$$

where u = velocity(m s^{-1})
g = acceleration due to gravity = 9.81(m s^{-2})
T = absolute smoke temperature(K)
ρ_o = density of ambient air $\hat{=}$ 1.2(kg m^{-3})
c_p = specific heat of air $\hat{=}$ 1(kJ kg^{-1} K^{-1})
T_o = absolute ambient air temperature $\hat{=}$ 290(K)
W_c = width of corridor or channel(m)

Assuming conservation of heat, the depth of the layer is given by

$$D_l = [MT/\{38W_c(T - T_o)^{1/2}\}]^{2/3} \qquad (14)$$

where D_l = depth of layer(m)
M = mass flow entering layer(m)

Smoke accumulation in an enclosure

A simple zone model postulates that smoke rises to form a smoke layer of uniform depth and temperature, with a substantially smoke-free layer below it. A smoke control system is frequently designed to maintain a minimum height of the clear zone for a specified time. This height may be related to keeping people's heads out of smoke or to avoiding spillage to an adjacent space. When there is a large smoke reservoir, the smoke zone may only reach the critical level after escape is complete. If not, smoke ventilation can maintain the smoke zone at an acceptable height. See Figure 1.

The elapsed time at which the base of the smoke zone is at a height z above the fire is obtained by solving the differential equation

$$\rho_o A_F \frac{dz}{dt} + M + \frac{Q_c}{T_o c_p} = 0 \qquad (15)$$

where A_F = plan area of smoke zone(m^2)

Although Q_c usually varies with time, a satisfactory solution can be obtained by using an average value of Q_c over the time period concerned in equation (15). When smoke extract is needed, the mass flow into the smoke layer at the critical height can be evaluated at the time of interest and then smoke ventilation of equal capacity provided.

Flashover

The above relationships are not suitable when flames are touching the ceiling and flashover is a possibility. To check on whether flashover is to be expected, the minimum heat output to cause flashover can be estimated from

$$Q_{FO} = 500(Ah^{1/2} \alpha_k A_t)^{1/2} \qquad (16)$$

where Q_{FO} = Q_c at flashover(kW)
A = area of ventilation opening(m^2)
h = height of ventilation opening(m)
α_k = effective heat transfer coefficient($kW\ m^{-2}\ K^{-1}$)
A_t = internal area of walls, floor, ceiling(m^2)

Suggested values of α_k are given in Table 8.

TABLE 8
Values of effective heat transfer coefficient

Enclosing material	α_k (kW m^{-2} K^{-1})
Concrete	55×10^{-3}
Brick	36×10^{-3}
Plaster	21×10^{-3}
Plasterboard	13×10^{-3}

MODELLING EVACUATION

It is often said that people do not behave like ball bearings and that escape models of this type are therefore misleading. However, such models used judiciously can indicate whether an escape route is likely to be adequate for a group of escaping people, even though an individual's behaviour may not be predicted. Both conventional codes and flow calculations based more explicitly on measurements of moving people will be discussed here.

Conventional codes

Conventional codes place a limit on the travel distance from any point within an enclosure to an exit. The exit must lead to a protected zone - corridor, staircase or compartment, or the open air unaffected by fire. The codes assume that each 1m of exit width will accept 200 people (behaving like ball bearings) in 2.5 minutes. Except for small rooms, the codes assume that people may not be able to use one exit, because it could be blocked by the fire. Tables 9 and 10 illustrate some conventional guidance.

TABLE 9
Examples of limits on travel distance(m) to the nearest exit

Use of enclosure		Choice of direction	
		Yes	No
Office		45	18
Shop*		45	18
Industrial:	normal risk	45	25
	high risk	25	12
Plant room:	within room	35	9
	to exit (if beyond room)	45	18

*The exit may lead to a smoke-controlled mall.

TABLE 10
Examples of limits on the number of people allocated to an exit

Exit width m	Maximum number of people
0.8	50
0.9	110
1.1	220
over 1.1	200 x width*

* Larger numbers per metre may be allocated for sports stadia and for exits from smoke-controlled shopping malls.

For Table 9 there are no explicit assumptions about fire growth or 'pre-movement intervals'. No distinction is made between enclosures with sprinkler systems, or smoke control systems, and those without. It can readily be observed in practice that the design aspect of conventional codes which limits the speed of departure from a theatre, for example, or a football stadium, is the width of the exits rather than the distance travelled to reach them. Table 3 illustrates the importance of the pre-movement interval ie the delay before people start to move towards an exit, and if this information is combined with smoke and evacuation models there is an opportunity to assess the relative importance of travel distances and exit widths for specific projects.

In escape design, it is generally assumed that the routes of travel themselves, being suitable for normal use, will serve for emergencies. For example, there will be no unsuspected steps on an otherwise level route, no significant changes in the going and rising of stairs and no steep ramps.

Travel speeds for design

Measurements of the speed of travel of people in both crowded and spacious conditions have been codified as follows:

The travel speed for able-bodied adults on level or ramped areas with plenty of space may be taken as 1.2 m s^{-1}; in busy spaces it will be lower, about 1.0 m s^{-1}. For design, the following may be used:

$$S_t = 1.4(1 - 0.266D_{pop}) \qquad (17)$$

where S_t = travel speed(m s^{-1})
D_{pop} = population density on floor or treads(persons m^{-2})
and $0.54 < D_{pop} < 3.8$

On stairs, travel speed along the line of treads may be estimated from:

$$S_t = k(1 - 0.266D_{pop}) \qquad (18)$$

where values of k may be obtained from Table 11.

TABLE 11

Travel speed on stairs

Riser m	Tread m	Constant k	Max S_t* m s^{-1}	Max S_t x D_{pop}* persons s^{-1} m^{-1}
0.20	0.25	1.0	0.85	0.95
0.18	0.25	1.10	0.95	1.00
0.17	0.30	1.15	1.00	1.10
0.17	0.33	1.25	1.05	1.15

*Value not to be exceeded

The calculated total rate of flow of evacuating persons past a point in a route is given by :

$$F_c = S_t \times D_{pop} \times W_e \qquad (19)$$

where F_c = calculated flow(persons s^{-1})
W_e = effective width of route(m)

These equations may be used where S_t x D_{pop} does not exceed the values given in Table 11 for stairs, or 1.3 elsewhere.

Effective width

It has been observed that people moving along a corridor or stairway stay clear of the walls, handrails and other obstacles. The width of the 'boundary layer', for each wall or obstacle, is subtracted from the actual clear width of the route to give the effective width, W_e. Some values of effective boundary width are given in Table 12.

TABLE 12
Boundary layer widths

Escape route element	Boundary layer m
Stairways, wall or side of tread	0.15
Railings, handrails*	0.09
Theatre seats, stadium benches	0.00
Corridor, ramp walls	0.20
Obstacles	0.10
Wide concourse, passageways	0.46
Door, archways	0.15

*For handrail, use only if it projects more than 0.06m from a wall.

Estimating visibility

In practice,smoke control aims to keep people's heads clear of smoke so that they can survive and find their way. However, it is sometimes useful to estimate the visibility, particularly during the early stages of a fire in a large space.

Visibility may be defined as the furthest distance at which an object can be perceived. For the same density of smoke, the ease of perception will depend on how the object is lit. Assuming 'normal' lighting, visibility through smoke may be estimated from:

$$S = 3/K \qquad (20)$$

where S = visibility(m)
K = extinction coefficient(m^{-1})

A light emitting object, such as an illuminated sign, is more visible and:

$$S = 8/K \qquad (21)$$

For flaming combustion of wood or plastics:

$$K = 7.6 \times 10^{-3} \times m_S \qquad (22)$$

where m_S= mass concentration of smoke aerosol($kg\ m^{-3}$)

Table 4 gives values of the yield of smoke product per kg of combusted fuel. The fuel mass combusted can be estimated directly or from:

$$\int_0^t R\,dt = \int_0^t (Q/10^3 H_C)\,dt \qquad (23)$$

where R = rate of burning of fuel($kg\ s^{-1}$)
and H_C is given in Table 4

The average value of m_S is obtained by dividing the smoke yield mass by the smoke volume. For design, the minimum value of visibility is usually taken as 10m.

CONCLUDING REMARKS

It is a common experience that when one starts to make a more 'realistic' design assessment one proves that everything is dangerous. This is to be expected when a large number of conservative assumptions are made in a deterministic procedure, thereby postulating an extremely unlikely event. It is therefore wise to compare the results of the calculations with what would be required by the conventional codes and judge accordingly. Probably, the most immediate application of these models is the assessment of the effects of alternative strategies in order to judge which combination of measures will give the best result for the resources available. The other valuable contribution is the assessment of the effects of new hazards which may necessitate a departure from the conventional code requirements.

SOURCES OF INFORMATION

This paper refers to only a small proportion of the information available. The following publications are particularly useful for those seeking data and relationships.

The SFPE Handbook of Fire Protection Engineering. Society of Fire Protection Engineers/National Fire Protection Association, Quincy, MA. September 1988.

D Drysdale. *An introduction to fire dynamics*. John Wiley and Sons, 1985.

Guide for Smoke Management Systems in Malls, Atria and Large Areas. NFPA 92B, 1991 Edition. National Fire Protection Association, Quincy, MA.

Smoke control in atria - Engineering relationships for smoke control in large spaces. Technical Memoranda 16. Chartered Institution of Building Services Engineers. (Ready for publication 1995.)

Guide to Fire Engineering. CIBSE. (In preparation.)

Useful background information is given in:

Approved Document B Fire Safety. The Building Regulations 1991, London, HMSO, 1992.

BS 5588 series, British Standards Institution, London.

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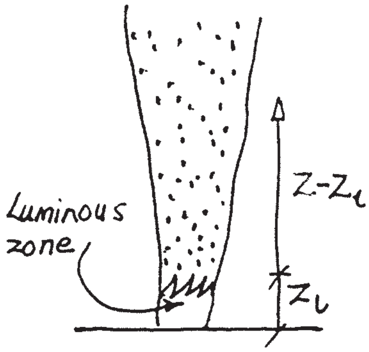


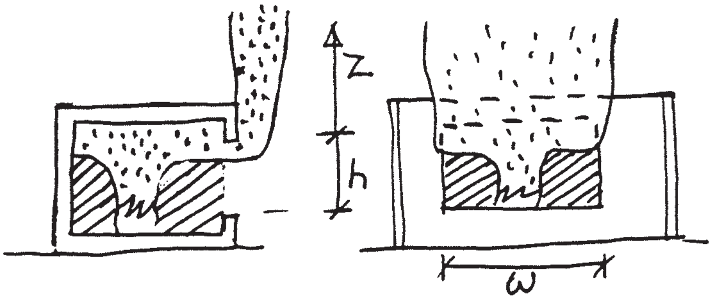
A Plume above a fire on the floor away from the walls of the room

B Vertical plume from the opening of a fire room

C Vertical plume from the opening of a fire room, after flowing round a balcony

D Smoke filling a fire room with a low level leak

B



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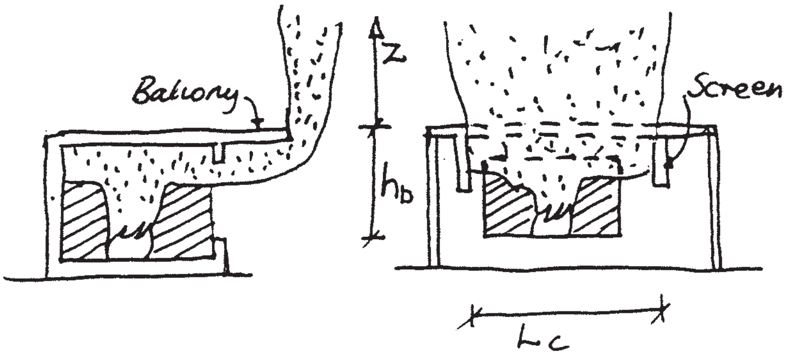

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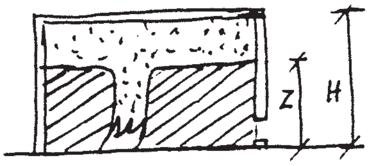

PAPER 25

The origins of the 5MW design fire

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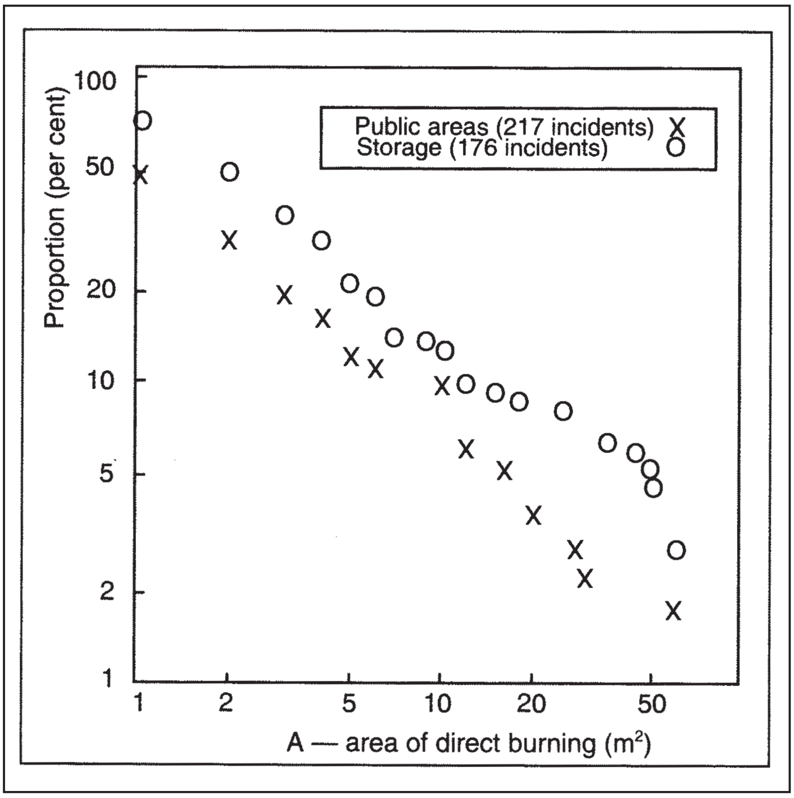
Figure showing the statistical data for the proportion of fires exceeding a given area of direct burning in retail premises.



The 5MW fire was proposed by the BRE as a design fire for the purpose of defining the size of a vent or the extract rate of a fan in the smoke control system of a covered shopping centre. People did not know why this value was adopted. I found nine different explanations stemming from the BRE alone. It spread into American codes. American fire safety engineers were using it without understanding its justification. This paper sets down the results of my own investigations and includes statistical data. It also comments on the design approach.

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The Origins of the 5MW DESIGN FIRE

BY MARGARET LAW, MBE, ARUP FIRE

In the design of smoke extract in sprinklered shopping centres it is normally assumed that the fire measures 3m × 3m on plan and has a heat output of 5MW(1). This has been questioned by those who point out that such a fire would set off many more sprinklers than the presumed four. On the other hand, it is claimed that this design fire is supported by statistical data(2). Some people have adopted this design fire in another context without understanding its justification(3). There have been various explanations and a selection is given in the Appendix. Accordingly, the origins of the 5MW fire have been investigated and will be described here, together with subsequent information.

THE KEY publication is considered to be one by Peter Hinkley, published in 1975(4). He describes an experiment in a fire compartment representing a shop, giving on to a corridor representing a covered pedestrian mall. A rack was loaded with combustible material to simulate a rack in a 'do-it-yourself shop'. Two minutes after the fire was ignited it was large enough to operate sprinklers and smoke was pouring out of the open front of the shop. The operation of the sprinklers halted the rapid spread of fire although it continued to produce large volumes of smoke. Later on in the paper it is stated "The size of fire most generally assumed is one covering a floor area of 3m × 3m; this is considered to be reasonable if the fire is being controlled by sprinklers. In order to make some estimates of the temperature of the gases which have to be exhausted it is necessary also to make some assumption about the heat output of the fire. Experiments with the fire described in the 'do-it-yourself shop have shown that when sprinklers were operating its peak burning rate was about ½MW/m^2 so that a heat output of 5MW will be assumed for the purposes of this paper."

This establishes the most likely source of the 5MW, 3m × 3m, design fire. The experimental data will now be reviewed.

EXPERIMENTS WITH SPRINKLERED FIRES

Hinkley gives three references to experiments with sprinklered fires. One is 'Smoke production of sprinklered fires (low water pressure)'(5) which will be discussed here. Another is 'Smoke production of sprinklered fires (high water pressure)' which was in preparation and never published. There is also 'Experiments with a glazed shop front'(6) which is not directly relevant to our topic but will be referred to briefly.

The experimental shop measured 3.8m wide by 7.7m deep × 2.85m high. The front opening was 3m wide and 1.6m high (from floor level to the base of a fascia board). The 'mall' was 6m wide × 17m long × 3.1m high, open at the far end(7).

Two upright spray sprinklers, rated at 79°C , were installed in the fire compartment, one near the front and one near the rear (over the fire), at a separation of 3.8m and a height of 2.45m above the floor. Each sprinkler was capable of discharging 1.23l/s at a water pressure of 124kN/m^2. Compared with current practice, we estimate that the time of operation of the sprinklers could be slightly delayed because the heads were 400mm below the ceiling, rather than flush, and water application could be reduced because the area of operation was 14m^2 rather than the maximum of 12m^2 for Ordinary Hazard (OH) systems. The water pressure though low, could represent the 'worst case'. In general we think the sprinkler protection was not unreasonable, though tending to give a conservative result because in practice there would have been adjacent lines of sprinklers.

Four tests were carried out with a rack 'loaded with miscellaneous cellulosic combustibles and foamed plastics to represent a display in a typical do-it-yourself home handyman's shop'. Two shelves were used and the total weight of combustible material was about

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100kg, most of which was contributed by wooden slats and plywood. Hinkley states that the rack measured 1.2m × 2.4m in plan × 1.8m high. It was considered that as a result of malpractice in a shop the top of a rack might be ‘filled in’ so that an overhead sprinkler would be markedly less effective than normally expected. Accordingly, a canopy was installed over the rack in three of the tests, so that the sprinklers were prevented from effectively tackling the fire.

The heat output of each fire was estimated by comparing the temperature and depth of the smoke layer in the mall with values obtained for non-sprinklered fires of known heat output.

Table 1 shows some data and estimates.

The peak smoke temperature and heat output of the non-sprinklered fire were not sustained because they were generated by the burning of thin fuels and plastics which quickly burnt out, leaving the fire maintained by thicker wood fuel elements.

The test fires described in (6), with different fuel arrangement, were on the same rack but heat output was not estimated. The sprinklered fires, with or without canopy, started to decline at four minutes though one without a canopy did increase somewhat at seven minutes.

The only other work we are aware of which has studied sprinklered shop fires, also in racks, was designed to assess the potential benefit of sprinklers on smoke conditions in the room of fire origin and did not address the question of the 5MW fire(8).

Table 1
Tests with fires in a rack

Test number	110	115	117	116
Sprinklers	No	Yes	Yes	Yes
Canopy	Yes	Yes	Yes	No
Peak heat output (MW)	3.2	0.8	0.8	0.3
Sprinkler operation time (min)*	–	1.4	2.0	2.0
Peak output time (min)	3½	3	3	4
Control/extinction time (min)	–	12	10	5

*Over fire

Table 2
Horizontal fire-damaged area in retail premises 1978

Area m^2	Number of incidents Public areas	Non-Public areas	Total
0 or minimal	27	28	55
1-10	25	41	66
11-50	–	8	8
51-100	–	–	–
over 100	–	1	1
		Total	130

Table 3
Number of sprinkler heads opening in shop fires

Number of heads	Number of incidents Retail 1978	Complexes 1976-78	Total
0	66	71	137
1-2	50	45	95
3-5	6	4	10
>5	1	–	1
NS*	7	3	10
		Total	253

Discussion

If we assume the fire area to be the same as the rack area, 3m^2, then the unsprinklered fire gives a peak output of about 1MW/m^2, the sprinklered shielded one about 0.3MW/m^2 and the sprinklered unshield one about 0.1MW/m^2. So why does Hinkley suggest 5MW and a 3m × 3m sprinklered fire? In fact, two further tests were carried out to assess the sprinkler spray cooling effect on the gases. A tray of kerosene was placed under a cooled canopy, which prevented water reaching the fire. One test was with the sprinklers and one without and the sprinklers reduced the sensible heat of the gases in the mall by about a half. So it is likely that Hinkley applied the ‘half’ rule to the 1MW/m^2 peak output.

The ‘worst’ location for a fire source i.e. for delayed response, is to be as far away as possible from the sprinkler axis. This would be at the centre of a 3m × 3m grid, if that is assumed to represent a typical spacing of heads, although maximum possible spacing would be 3.6m × 3.0m. We could then expect four heads to operate, which would control most fires. We take 3m × 3m = 9, say 10m^2, resulting in 5MW when the half rule is applied.

We can conclude that the 5MW, 3m × 3m, sprinklered design fire presupposes a fuel load which can give a sustained heat output of 1MW/m^2 and a fire which is shielded in some way over a 3m × 3m area so that it is not affected by the sprinklers. The sprinklers are assumed to stop fire spread beyond the 3m × 3m fire area and to remove half the heat by cooling the gases. A recognition that the 5MW fire would actuate more sprinklers, giving more cooling, is not explicit.

STATISTICAL DATA

Statistics for fire damaged area in sprinklered retail premises have been analysed by Morgan & Chandler(2). Data are shown in table 2.

It will be noted that this is a small sample and it was considered that a zero probability that the fire in a public area would exceed 10m^2 was not credible. Accordingly an ‘informed guess’ was made that less than 4 per cent in practice would exceed 10m^2 in public areas.

A record of fire-damaged area does not tell us what amount of heat was evolved. For this, the number of sprinkler heads opening is more informative (see table 3).

Morgan & Chandler do not separate these data into public and non-public areas, but they do include some for complexes, which they conclude are representative of shops and vice versa. Only one incident opened more than five heads but this is too small a sample for general conclusions.

It was noted by Morgan & Chandler that in sprinklered premises, public areas showed a much better record (in relation to fire-damaged area) than non-public areas and that the

Fractile	Public Areas		Storage	
%	A	N	A	N
20	3	2	6	3
10	7	3	12	4
5	16	4	50	4

Table 4 Values of Area of direct burning (A-m^2) and Number of Heads (N) for different fractiles

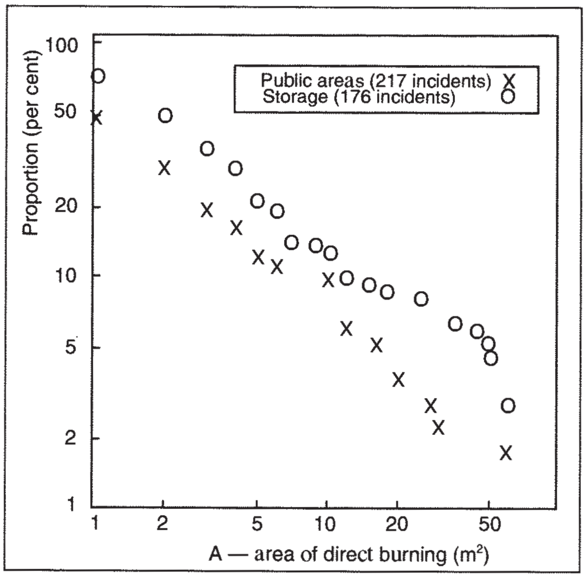

Figure 1: Proportion of sample with A or more area of direct burning. (1984-87).

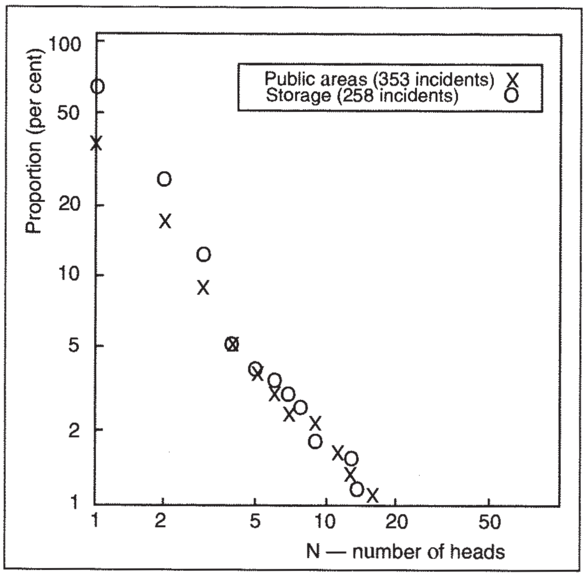

Figure 2. Proportion of sample with N or more heads operating. (1981-87).

difference was 'almost certainly due to the potential fuels in public areas being spread-out rather than stacked, thus giving sprinklered sprays better access to the seat of any fire'.

We are not aware of further analyses of this type. However, we have obtained some data from the Home Office for sprinklered retail premises. Figure 1 shows the distribution of 'Area of direct burning' for the public areas (Code F) and storage (Code G) in 1984-87. Figure 2 shows the distribution of number of heads operating in public areas and storage in 1981-87. (The area records were not available for 1981-83). Figure 1 shows the well-known cluster effect round the value 10m^2; interpolating between adjacent values gives a value of 7 per cent for the proportion of incidents of 10m^2 or more. Figure 2 shows a 5 per cent proportion of incidents with four or more sprinklers operating. Table 4 shows fractiles for the two effects.

Table 4 illustrates that the area of direct burning at these fractiles is roughly twice as big in storage as in the public areas. Moreover, one more head is likely to be activated in storage; this is in agreement with Morgan & Chandler's observations. However, even at the 5 per cent fractile, only four heads operate. Accordingly, it appears that less than 5 per cent of the sample could have given a 5MW fire before sprinkler operation. Less than 2 per cent of the sample opened more than ten heads.

COMMENTS

More than twenty years ago, the Fire Research Station identified a major hazard when covered shopping malls were introduced; it then went on to show how ventilation would alleviate smoke conditions in the malls. Their experiments showed that very thick smoke could be produced and without ventilation would quickly fill a mall such as their experimental one, which was representative of a number of real malls at that time. The standard of management of covered shopping developments is believed to have been in general lower then than it is now. It is unlikely that an old-style shop such as Gamages, which was visited by the Fire Research Station(9), would be representative of a shop in a modern centre today. When we consider the information available at the time we have no quarrel with the design fire suggested by the Fire Research Station. It was based on measurements and it was duly conservative. However, it is probable that even then few people knew what it was based on.

We have two general comments. One is that when drafting a design method, it is preferable to base it on the best representative information available at the time and then use 'factors of safety' to allow for uncertainties.; If worst-case assumptions are introduced in the early stages it is very difficult to know just what the final result means. With the engineering approach of explicit assumptions and factors for uncertainty, it is possible to make adjustments, up or down in the light of changed circumstances or data. This is the approach favoured for structural design. The other comment is that designers should not adopt a design fire intended for another purpose, just because it is in a published document. If they do not know what it represents, they should make a fresh assessment.

With respect to covered shopping centres, we would comment as follows: If one were to carry out a more representative calculation of a sprinklered fire and then multiply the required extract capacity by a factor, say 1.5 or 2, to allow for uncertainties, then the resultant extract rate might well be similar to what one would calculate for the 3m × 3m, 5MW design fire. Why, then, bother to change it? One, because fears of there actually being a 5MW plume in the mall menacing the shoppers would be allayed. Two, because worries about small variations in features such as screen depth and reservoir size could be kept in proportion. Three, where other fire safety measures, such as automatic detection and voice alarm, management, escape routes, are provided to a high standard, the level of protection afforded by the smoke management system can be put in perspective. In this way, the fire safety engineer can follow the advice in Approved Document B and look at the fire safety design as a whole.

CONCLUSIONS

The 5MW, 3m × 3m, sprinklered design fire presupposes a fuel load which can give a sustained heat output of 1MW/m^2 and a fire which is shielded in some way over a 3m × 3m area so that it is not affected by the sprinklers. The sprinklers are assumed to stop fire spread beyond the 3m × 3m area and to remove half the heat from the hot gases by cooling. There is no recognition that more sprinklers might be actuated and give more cooling.

Statistical data indicate that such a fire is likely to occur in less than 5 per cent of fires in sprinklered shops, even in storage areas where stacked goods are more common than in the public areas. Where sprinklers operate, it is unlikely that the heat output would be sustained at 5MW. Accordingly, consideration should be given to adopting a more representative design fire for sprinklered shopping centres, including spray cooling of smoke, with explicit factors to allow for uncertainties in such matters as entrainment models, stock layout, fire growth models, performance of fans and vents. Any smoke control design needs to be viewed in context with other safety measures in the project.

MARGARET LAW

The Origins of the 5MW DESIGN FIRE

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APPENDIX

QUOTATIONS RELATING TO THE 5MW 10m² FIRE

1979. It is essential to specify a maximum fire size to be able to design a smoke control system, and this sprinkler-controlled fire is taken as the largest the system should have to control. This output would be given by a fire of base dimension 3m square, burning at a rate of 0.5MW per square metre of base area. This latter value, in turn, is the average of values obtained in experimental sprinklered fires at FRS.
H. P. Morgan, Smoke control methods in enclosed shopping complexes of one or more storeys: a design summary. BRE Report, 1979.

1981. These measures are calculated on the basis of a design fire (the 'largest likely') of 3m × 3m in size when sprinklers are present. This figure was originally based on a largely subjective survey of the contents and fire risks of existing stores. Subsequently, a different approach, using the statistics of the number of sprinklers opening in Ordinary Hazard 3 category buildings, suggested that more than eighteen heads opened in about 6 per cent of fires. Extrapolation from other work completed this picture by showing that a 3m × 3m fire of about 5MW output would open eighteen sprinklers when the ceiling height is 5m. This 3m × 3m, 5MW fire has been used in most recent smoke control designs.
H. P. Morgan and S. E. Chandler. Fire sizes and sprinkler effectiveness in shopping complexes and retail premises. Fire Surveyor, 1981, 10 (5) 23-28.

1982. For shopping malls, FRS has used the UK Fire Statistics computerised data-base to deduce a 'largest likely' fire for retail premises. This fire is of 5 megawatt heat output and is 3m × 3m in size, when sprinklers are present, and is used as the basis for calculation when designing smoke control systems in malls. There has been a tendency to use the 5 megawatt design fire for smoke control in all types of building. This is potentially misleading, since it strictly applies only for fires in sprinklered retail premises.
BRE Digest No. 260. Smoke control in buildings: design principles. 1982.

1985. A useful rule-of-thumb estimate is to assume half a megawatt (i.e. 500kW) heat per square metre of fire. This is comfortably larger than nearly all solid-fuel fires found in practice.
H. P. Morgan. A simplified approach to smoke-ventilation calculations. BRE information Paper IP 19/85, 1985. N.B. The above advice appears to be for non-sprinklered fires.

1988. Analysis of reported areas of fires in sprinklered shops in the UK showed that fires exceeding 10m² in area had a relative frequency of less than 4 per cent. This area is generally accepted for design purposes within sprinklered shopping complexes in the UK. From experimental evidence the corresponding design heat output is 5MW.
P. L. Hinkley. Smoke and heat venting. Chapter 2-3 of SFPE Handbook of Fire Protection Engineering, NFPA Quincy Mass 1988.

1988. An analysis of fires in retail premises had earlier been carried out by Morgan & Chandler. This work suggests that fewer than 4 per cent of fires in sprinklered retail premises exceed the design fire size of 9m². Fires in unsprinklered retail premises were also studied to establish the effectiveness of sprinklers. Their data for both sprinklered and unsprinklered fires in public areas is expressed graphically in figure 1.
J. P. Gardner. Unsprinklered shopping centres. Design fire sizes for smoke ventilation. Fire Surveyor, December 1988 41-49. N.B. The curve for sprinklered fires shown in the Figure 1 mentioned above is a guess, not a line through data.

1990. Note that even here, the statistical evidence is not strong (see for example Morgan & Chandler) for shopping malls. Further research is currently in hand to improve this statistical basis. It follows from the foregoing that there is a strongly subjective element in assessing what fire size is acceptably infrequent for safety design purposes. A 12m perimeter (3m × 3m) 5MW sprinkler controlled fire has become the accepted basis in the UK for a smoke ventilation system in a sprinklered shopping centre.
H. P. Morgan and J. P. Gardner. Design principles for smoke ventilation in enclosing shopping centres. BRE Report, 1990.

1990. An analysis of fires in public areas of retail premises has suggested that fewer than 4 per cent fires exceed the design fire area. (Note that the 'sprinklered' curve in figure 23 is drawn to conform to Morgan & Chandler's interpretation of the statistical data and to have approximately the same form as the 'unsprinklered' curves it can be seen that the latter is more reliable).
H. P. Morgan and J. P. Gardner. Ibid.

1994. In the present work the following, in terms of fire area and convective heat flux, are used to illustrate the calculation procedures adopted:
(a) Retail (sprinklered shops) 10m², 12m perimeter;
(b) Offices (sprinklered) 16m², 14m perimeter.
...It should be noted that the design fire size for (a) was originally chosen by the Home Office and Scottish Home and Health Department...
G. O. Hansell and H. P. Morgan. Design approaches for smoke control in atrium buildings. BRE Report, 1994. N.B. Heat output is given for sprinklered office (1MW), but not for retail.

ABOUT THE AUTHOR

After many years at the Fire Research Station, Margaret Law joined the Ove Arup Partnership in 1974 to act as an adviser on fire engineering for projects being designed within the firm and on other projects in appropriate circumstances. She was concerned with all aspects of fire safety, particularly in those buildings for which the standard rules and requirements of regulations are not directly applicable. She retired at the end of 1990 and is now a consultant to the Partnership.

She has a BSc degree, is a Fellow of the Institution of Fire Engineers, a Fellow of the Society of Fire Protection Engineers (USA) and a Member of the Institute of Fire Safety. She is a director of the SFPE and a council member of the IFS.

She was appointed a MBE in 1993, for services to fire safety.

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PAPER 26 The New Code of Practice (Part 1) - The philosophy and understanding

Margaret Law MBE, Consultant, Arup Fire, Partnership in Fire Safety Engineering Design of Buildings, Seminar at AEA Technology, Warrington, UK, 4 and 5 May 1995. Institution of Fire Engineers (IFE)

The ‘New Code of Practice’ was the draft British Standard that, with amendments, was published as DD240: Fire safety engineering in buildings. I was one of the consultants engaged by the lead consultant, Warrington Fire Research, to assist in the preparation of the draft. On being asked to make an Introduction to the Seminar under the above title, it seemed useful to address head on the reservations and concerns of those not familiar with the fire safety engineering approach. The concerns expressed most often were about ‘cutting things to the bone’ and the acceptance of risk, which meant the rejection of the ‘worst case scenario’.

Plates showing the Royal Exchange Theatre, Manchester and the Eden Project, Cornwall. Both projects engineered fire safety from first principles, using evacuation and smoke movement models.

THE NEW CODE OF PRACTICE (PART 1) -
The philosophy and understanding

Margaret Law MBE
Consultant, Arup fire

INTRODUCTION

Being uneasy about the use of the word philosophy in relation to fire safety engineering, I turned to the OXFORD DICTIONARY of Current English (1984) to find the following definition:

Philosophy ***n.*** use of reason and argument in search for truth and knowledge of reality especially of the nature of things, and of the principles governing existence, perception, human behaviour, and the material universe; particular system or set of beliefs reached by this; system of conduct in life.

I would suggest that although engineering design uses reason and argument it is not primarily a search for truth and knowledge of reality. It can be described as the application of science and engineering principles to achieve a satisfactory performance in reality. What is satisfactory is a matter for judgement so that, logically, there is nothing absolute in an engineering code. It follows that the code we are discussing today is designed to help designers, their clients and the approving authorities to reach a judgement about the adequacy of the measures proposed to protect people and property from the effects of destructive fire. It is possible to use this code simply as a check list, to make sure that significant issues are not overlooked. However, it is more important than that, because it shows how to adopt a quantified approach to the assessment of the relative benefits of different measures, in order to arrive at the optimum solution. It permits an assessment of different options so that the client can decide about resources and it helps the designer to decide what needs to be done and how to present the results of the analysis. It may well produce solutions which are very similar to the guidance in Approved Document B but that is not a problem. The code is not inventing new standards of fire safety. It is encouraging new ways of tackling the problems and identifying the solutions so that the information we have can be more fully exploited to achieve the desired end result: better design.

BETTER DESIGN

This brings us to an important aspect of the code. Its prime aim is not to save money, although it is of course always important to avoid waste. It is primarily designed to concentrate the mind on the objectives; this then leads on to an identification of the criteria for success and to a consideration of the various ways in which the objectives can be met. Some solutions will fit the building use better than others; if they do, they may well be favoured by the designer and the client even if they are more expensive. Whether money is saved or not, good design will favour fire safety and it uses the resources available to better effect.

CUTTING THINGS TO THE BONE

There is a fear that engineering calculations can be so precise that a small change in circumstances can lead to a serious reduction in the standard of fire safety. The code tackles this in two ways: first, it recommends that there should be sensitivity tests, to check the robustness of the solutions, and secondly, it recommends factors to allow for uncertainties in such matters as the input data, the engineering relationships and the reliability of the equipment. We can add to this the possibility that what is installed in practice may well exceed the specification. For example, the designed smoke extract may be $28.1m^3/s$ but if the available fans are rated at $20m^3/s$ then two will be installed, giving over design. It is these practical considerations which tend to make the engineer relaxed about whether the design value calculated is more precisely 28.3 instead of 28.1, say. However, the engineer may fail to realise that such a 'discrepancy' could well alarm the checking authority.

CHANGE OF USE

Many people are worried about changes in use which may make the installed protection facilities less effective, because they were designed for different purposes. This is really a variant of *Cutting things to the bone.* The code encourages the provision of a robust design, with redundancies which can accommodate minor changes. As mentioned above, sensitivity tests are also recommended. In addition, the code recommends the provision of a fire safety manual which documents the reasons for the facilities provided. The significance of major changes can thereby be assessed and appropriate adjustments undertaken. This appears to be an improvement on the prescriptive code approach, which of course, is faced with the same problem.

CALCULATIONS AND REAL LIFE

Once an attempt is made to carry out calculations - the speed of flow of people through an exit, for example - the result is likely to be challenged, on the basis that fires and people behave unpredictably. A simple, and perhaps sufficient, reply is that the aim is not prediction but an estimation of the adequacy of the proposed facilities, if people want to use them. Notwithstanding this, it does seem right to identify any particular kinds of behaviour which might need special consideration. For example, I have recently been told of an incident in a shop where two old people sat down in an escape stairway through tiredness, thereby blocking the way of all those behind them. If this is considered to be an important aspect to take into account in design, then one solution would be to widen the stairway, another would be to train the staff to take control and guide the slow people along. The important point is that in the engineering approach, real problems can be addressed, while they would possibly be ignored when the prescriptive code approach is applied. In general, engineering methods have to pass a higher standard of proof than a prescriptive code, some would say unreasonably so.

WORST CASE SCENARIO

Calculations are very often based on a fire scenario, and for the purposes of proof the *worst case* is often assumed. The problem is that in most projects the assumption of a series of very unlikely events results in an excessively conservative solution. One has to consider the likelihood of a given event, or combination of events, in order to arrive at a reasonable and adequate solution. Thus we become interested in probabilities. Suppose we wish to prevent fire spread from one part of a building to another. The prescriptive code specifies a wall of a certain fire resistance. However, if the fire door in that wall is open, a developed fire is likely to spread. The prescriptive code determines that the door is shut, but the worst case scenario assumes that the door is open. The probabilistic approach assesses the probability that the door will be open and the probability that the fire will spread through that open door. If the probability of undesirable consequences is too high, it can be reduced by, for example, fitting an automatic door closer. The door closer itself has a certain probability of failure so that it may or may not be sufficient. If not, automatic sprinklers, which reduce the probability of a large fire, may offer better protection. On the other hand, the automatic detection and alarm system may alert the fire brigade so effectively that no extra measures are needed, even allowing for the possibility of failure of the automatic system and delayed arrival of fire fighters.

The probabilistic approach is usually a combination of deterministic calculations and assigned probabilities. The deterministic calculation is carried out to determine the result of a given scenario. The probability of that scenario and its consequences can then be estimated. The code recognises both types of approach - deterministic and probabilistic.

TRADE OFF

The term *trade off* is often used with the implication that the designer is *getting away with something.* In a way that is correct. The chief reason that trade off is attractive is that it gives more flexibility in design. If, for example, sprinklers permit a reduction in the standard of structural fire protection, then the designer has a wider choice of protective materials which may include those which suit other (non-fire) purposes as well as being aesthetically desirable and yes, we hope, cheaper. A smoke extract system may give scope for longer travel distances to an exit. In general, the benefits of trade off are easier to quantify in a probabilistic approach.

GOOD MANAGEMENT

When we were drafting the code, we all agreed that good management can give safer buildings because of good housekeeping, regular maintenance and regular staff training. The problem is how to recognise these benefits and hence encourage the development of good management. It does seem that it can be taken into account more easily in a probabilistic approach.

PROPERTY PROTECTION

Although protection of people is the most important objective, this code can also be used to assess what property protection is needed. However, this is a fire engineering code, not an investment code, which means that it can quantify what damage a fire can do and what benefits the various safety measures can confer in reducing the damage. The financial decisions must be made elsewhere. For example, is it worth while installing firefighting equipment in a food store if a small whiff of smoke means that the contents are rendered worthless? Would money be better spent on fire prevention, or compartmentation to reduce the likely loss? Would it be better not to spend any extra money if the owner is prepared to accept the risk? The code can give an estimate of how likely it is that there will be a fire, so that the owner can make an informed decision.

For insurance purposes, the code can be used to quantify the effects of new building designs and new types of risk. Comparative, if not absolute, assessments can be made and sensitivity tests carried out.

DATA AND FORMULAE

Details of the Subsystems will be given by the speakers following this presentation. The flow charts define the structure of the Subsystems and are not susceptible to change. We had some discussion about whether a simple description of the Subsystems was sufficient for the code. On balance it was thought that it would be helpful to include some data and equations to illustrate how the systems could be used. However, these data and equations are not rules and others may be better or more relevant. Indeed, any method and data which can be authenticated may be adopted. This approach follows the precedent set by Building Regulations and is designed to complement them. As specified in the code, the appropriate information will be identified in the qualitative design review, which takes place before any entry is made into the Subsystems.

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CONCLUDING REMARKS

It is always difficult to grasp a new code until it has been used on an actual project or projects. It is probable that this code is not going to be applied to many buildings at first, and not used very often to appraise whole buildings. To begin with, I foresee selected Subsystems being used to build up cases for trade off. Then, as we become more used to handling the concepts, we will be able to take a global look at fire safety in this country and feed the new ideas back into the Approved Document. I also foresee that the code will stimulate a demand for different fire tests, for more research and for better provision and analysis of statistical data. It will encourage the development and manufacture of improved protection systems with explicit records of quality control for the products and their installation and maintenance. I hope that by the end of this Seminar you will agree that using this code can give better safety standards than we have at the moment and that we can afford to adopt it.

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PAPER 27

Measurements of balcony smoke flow

Margaret Law, Arup Fire, Ove Arup and Partners, 13 Fitzroy Street, London, W1T 4BQ, UK, Fire Safety Journal, 24 (1995), pp 189-195. Elsevier Science, UK

Reprinted from Fire Safety Journal, Vol.24 No.2, Measurement of Balcony Smoke Flow, pp 189-195, Copyright 1995, with permission from Elsevier.

The BRE published in 1993 the results of experiments in a model atrium with smoke flow above a balcony. Accordingly, I revisited the work given in Paper No. 14. The line plume approach was confirmed and extended and this work was incorporated in the design method published by CIBSE.

Computer graphic of the proposed refurbishment of St Pancras Station, London. The scheme design used relationships contained in this paper as the basis for smoke movement analysis and is just one example of many projects where this technique has been applied.

Measurements of Balcony Smoke Flow

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(Received 23 January 1995; accepted 1 March 1995)

ABSTRACT

Recent measurements of smoke flow above a balcony are compared with an earlier correlation and an equation for mass flow is developed for design purposes. Comments on the location of the virtual source are invited.

NOTATION

b	horizontal projection of balcony (m)
h	height of opening (m)
h_{b}	height of balcony above base of opening (m)
L	separation of channelling screens (m)
L_{d}	$L + 0{\cdot}22(x_{\mathrm{v}} + 2\Delta)$
L_{e}	effective plume width, no screens (m)
M_{b}	mass flow under balcony (kg/s)
M_{v}	mass flow vented from atrium (kg/s)
M_{w}	mass flow from opening (kg/s)
Q	output of source (kW)
w	width of opening (m)
x_{v}	height of smoke layer base above balcony (m)
Δ	depth of virtual source below balcony (m)
$\bar{\theta}_{\mathrm{b}}$	average temperature rise of balcony layer (°C)
$\bar{\theta}_{\mathrm{w}}$	average temperature rise of opening layer (°C)

INTRODUCTION

Hansell *et al.* have recently published the results of some smoke flow experiments in a model atrium.[1] These extend the range of data obtained earlier by Morgan and Marshall[2,3] which were given alternative correlations by Law[4] and Thomas.[5] A simple analysis, extending and confirming these correlations, is given here. The results can have practical applications for design.

THE MODEL

The model atrium was just over 3·06 m high and about 3·3 m^2 on plan. Warm air, from electric heaters in a box, flowed into the atrium through a vertical opening at its base, 0·4 m high by 0·4 m wide. In most tests there was a balcony above the opening, 0·535 m above the atrium floor. The warm air was mechanically extracted from the top of the atrium and, by adding artificial smoke, it was possible to view the position of the base of the warm layer flowing under the balcony and the base of the warm layer accumulated below the atrium vent. There were three depths of balcony, 0·125, 0·25 and 0·50 m.

SMOKE FLOW BENEATH THE BALCONY

The average temperature of the layer emerging from the opening, $\bar{\theta}_w$, is plotted against Q, the output of the heater in kW, in Fig. 1, which shows

$$\bar{\theta}_w = 47Q^{2/3}. \qquad (1)$$

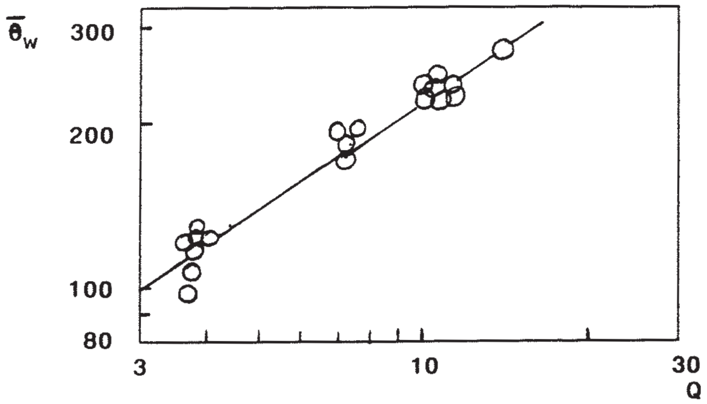

Fig. 1. Variation of average temperature of layer emerging from the opening with output of source.

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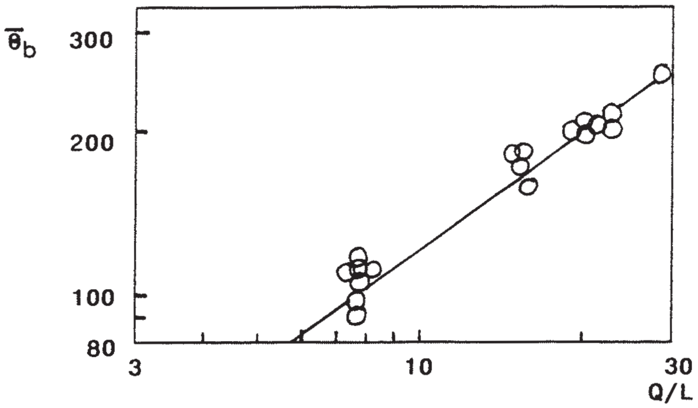

Fig. 2. Variation of average temperature of layer under the balcony with output of source and separation of channelling screens.

Equation (1) can be written as

$$\bar{\theta}_w = 26\,(Q/w)^{2/3} \tag{2}$$

where w = opening width = 0·4 m.

The average temperature of the layer under the balcony, $\bar{\theta}_b$, is plotted against Q/L in Fig. 2, where L (m) is the distance between screens placed under the balcony to channel the flow towards the atrium. Figure 2 shows

$$\bar{\theta}_b = 26(Q/L)^{2/3}. \tag{3}$$

Assuming conservation of heat, we obtain from eqns (2) and (3):

$$M_b = M_w \times (L/w)^{2/3} \tag{4}$$

where M_b = mass flow under the balcony (kg/s) and M_w = mass flow from the opening (kg/s).

The estimated convective flow from the opening was 0·74Q, giving:

$$M_w = 0{\cdot}028(Qw^2)^{1/3} \tag{5}$$

$$M_b = 0{\cdot}028(QL^2)^{1/3}. \tag{6}$$

Equation (5) may be written

$$M_w = 0{\cdot}072(Qw^2)^{1/3}h \tag{7}$$

where h = height of the opening = 0·4 m.

The value of 0·072 is within the range (0·041–0·092) found by Law[6] for various sets of experiments in small compartments. The variation is caused mainly by differences in compartment geometry and location of

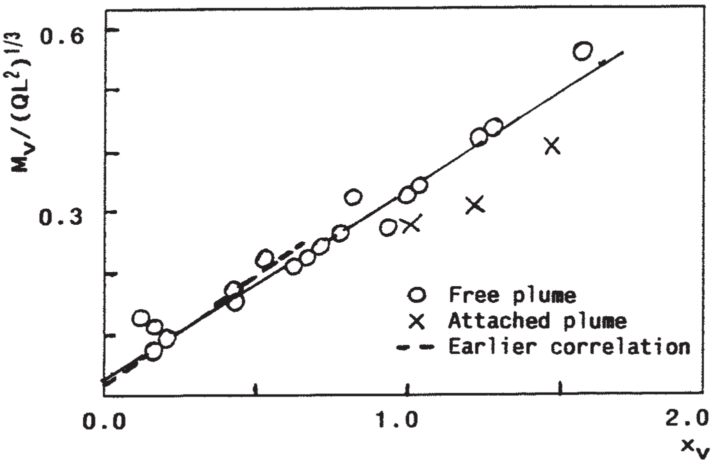

Fig. 3. Variation of clear height above balcony with mass flow from the top of the atrium.

the fire source within the fire compartment. These aspects are discussed more comprehensively by Thomas.[7]

SMOKE FLOW ABOVE THE BALCONY

With the 0·25 and 0·5 m deep balconies, there was a freestanding plume. With the shallow balcony, 0·125 m deep, the plume became attached to the wall above the balcony. Figure 3 shows the variation of $M_v/(QL^2)^{1/3}$ with x_v for the freestanding plumes, where M_v (kg/s) is the mass flow of warm air vented from the top of the atrium and x_v (m) is the height of the base of the warm layer above the balcony. (The balcony was 0·41 m above the base of the opening.) The regression line shown is

$$M_v = 0{\cdot}31(QL^2)^{1/3}(x_v + 0{\cdot}104). \qquad (8)$$

If we assume that M_v is equal to the mass flow into the base of the layer, then eqn (8) gives the mass flow for the vertical plume at height x_v.

Note that when x_v is zero, $M_v = 0{\cdot}032(QL^2)^{1/3}$ which is slightly larger than M_b, from eqn (6). Design guidance[8] suggests that the vertical flow at the balcony edge would range from 2·2 to 3·0 times the horizontal flow in these experiments (without downstand).

The earlier correlation given by Law[4] is shown as a dashed line in Fig. 3. The equation derived was

$$M_v = 0{\cdot}34(QL^2)^{1/3}(x_v + 0{\cdot}075). \tag{9}$$

This earlier correlation also gave no evidence of a significant increase in mass flow as the layer turned the corner.

The intercept 0·104 in eqn (8) is about $\frac{1}{4}$ of the height of the balcony above the base of the opening while the intercept 0·075 in eqn (9) is about $\frac{1}{5}$. Taken together, the data give:

$$M_v = 0{\cdot}31(QL^2)^{1/3}(x_v + 0{\cdot}102). \tag{10}$$

Three test runs with the 0·125 m balcony, where there was attachment of the plume to the wall before it reached the base of the layer, showed that the mass flow reduced by about 15%. The data are shown in Fig. 3.

Thomas[5] proposed the following formula for M_v which takes into account added entrainment at the ends of the plume:

$$M_v = 0{\cdot}21Q^{1/3}[L + 0{\cdot}22(x_v + 2\Delta)]^{2/3}(x_v + \Delta) \tag{11}$$

where Δ (m) is the depth of the virtual source below the balcony. He found inconsistencies in values of Δ obtained from different measurements. For these data, eqn (11) gives a good correlation with $\Delta = 0{\cdot}205$, a virtual source midway between the balcony and the base of the opening. Figure 4 illustrates the data where

$$L_d = L + 0{\cdot}22(x_v + 2\Delta) \tag{12}$$

$$2\Delta = 0{\cdot}41. \tag{13}$$

NO CHANNELLING SCREENS

In further experiments the channelling screens were removed and the balcony flow became diffuse and ill-defined. An effective balcony plume width, L_e, has been derived by comparing the values of x_v observed with and without the screens. These show that

$$L_e \cong w + b \tag{14}$$

where b = horizontal projection of the balcony (m).

Equation (14) also applies to the no-screen data discussed earlier.[4] Note that L_e does not describe the actual plume width under the balcony but it can be used to estimate smoke height above the balcony.

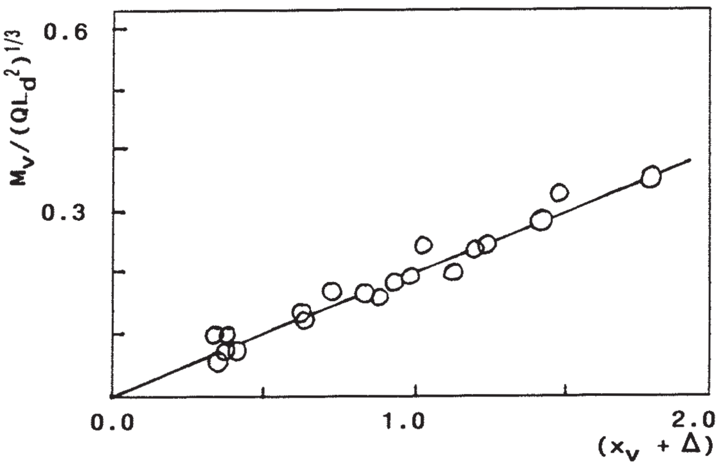

Fig. 4. Effect of end correction on correlation, with $\Delta = 0{\cdot}205$ m.

DISCUSSION

This simple analysis confirms that plume flow above a balcony can be estimated from simple, well-established relationships which are easy to use for design purposes. The location of the virtual source of the balcony plume is expected to be a function of the layer depth, temperature and perhaps the opening height. For practical purposes a value 0·25 times the balcony height above the base of the opening appears reasonable if eqn (10) is used:

$$M_v = 0{\cdot}31(QL^2)^{1/3}(x_v + h_b/4)$$

where h_b = height of balcony above base of opening (m).

The equation by Thomas with the end correction looks a promising improvement if the location of the virtual source can be identified and comments on this would be welcome. The simple rule which has been derived, for enhancing atrium extract when channelling screens are omitted, gives more freedom to designers.

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PAPER 28

A review of formulae for t-equivalent

Margaret Law, Arup Fire, Ove Arup and Partners, 13 Fitzroy Street, London, W1T 4BQ, UK, Proceedings of Fifth International Symposium on Fire Safety Science, 3-7 March 1997, Melbourne: Australia. International Association For Fire Safety Science (IAFSS), UK

Some compartment fire experiments in a deep, well-insulated enclosure 2.75m high were carried out in the BRE laboratory at Cardington. The primary purpose was to compare results with the t-equivalent equation for large compartment fires that was given in the Eurocode for Fire Actions. The results were interesting to me because of the work described in Paper No 6 and because of the alternative relationships that had been developed by other workers.

Plates reproduced from Paper 5 showing compartment fire experiments where fuel load density and ventilation area were both varied; experimental data that is still much in use today.

A Review of Formulae for T-Equivalent

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ABSTRACT

Formulae for t-equivalent, from Ingberg to Eurocode 1, are reviewed and compared with experimental data for compartment fires. Results for some deep compartment fires suggest that current heat balance models may need re-assessment. It is suggested that t-equivalent is not a useful parameter for design purposes.

KEYWORDS: t-equivalent, compartment fires, fire resistance.

NOTATION

A_F	Floor area	m^2
A_h	Area of horizontal opening	m^2
A_t	Surface area of internal enclosure	m^2
A_v	Area of vertical opening	m^2
b_v	$12.5 (1 + 10 \alpha_v - \alpha_v^2)$	-
C	thermal capacity of steel element	kJ/K
c	specific heat capacity	kJ/kgK
D	depth of compartment	m
H	compartment height	m
H_N	normalised heat load	$s^{1/2}K$
h	height of vertical opening	m
K	thermal conductivity	kW/m.K
k_f, k_b	factors to take into account insulation of compartment	-
L	fire load expressed in weight of wood	kg
L"	L/A_F	kg/m^2
R	thermal resistance of protective material	K/kW
t_{max}	time in compartment fire when steel element reaches maximum temperature	min
w_f	ventilation factor	$m^{-1/2}$
q_t	fire load expressed in calorific value divided by A_t	MJ/m^2
α_h	A_h/A_F	-
α_v	A_v/A_F	-
δ	the lesser of $0.41 (H^3/A_v\sqrt{h})^{1/2}$ or 1	-
θ_s	steel temperature	K
θ_f	fire temperature	K

INTRODUCTION

The term t-equivalent is usually taken to be the exposure time in the standard fire resistance test which gives the same heating effect on a structure as a given compartment fire. The compartment fire is characterised by such features as fire load, ventilation and compartment dimensions.

The first person to propose an engineering relationship was Ingberg [1] and the most recent development is given in the Eurocode for Actions [2].

DESCRIPTION OF FORMULAE

Ingberg started fires in rooms with office furniture and allowed all the fire load to burn out, with the ventilation adjusted to give the most severe result. He then compared the areas under the temperature-time curves with areas under the standard temperature-time curve above a threshold temperature. The following relationship was developed:

$$t_e = k_1 L'' \qquad (1)$$

where t_e is t-equivalent (min), L'' is fire load (wood) per unit floor area and $k_1 \approx$ unity when L'' is in units of kg m^{-2}. Ingberg's pioneering work has been used as the basis of most fire grading requirements worldwide.

Kawagoe and his colleagues in Japan [3] identified the importance of the ventilation parameter $A_t/A_v\sqrt{h}$ when performing a heat balance to determine temperature, where A_t is the area of the internal envelope (walls, floor, ceiling) , A_v is the area and h is the height of the ventilation opening (window or doorway). They also derived values of t-equivalent by comparing areas under their calculated temperature time curves (assuming a burn out) with area under the standard curve also above a threshold temperature. The values were proportional to L" and were weakly dependent on the ventilation parameter. The following relationship can be derived from their paper:

$$t_e = k_2 L''(A_t/A_v\sqrt{h})^{0.23} \qquad (2)$$

where k_2 is 1. 06 and $5 \le At/Av\sqrt{h} \le 30$ ($m^{-1/2}$).

Work in the UK [4] showed the significance of fire load per unit ventilation area, L/A_v, where L is the fire load in kg of wood. Law [5] then developed a t-equivalent from the results of a CIB experimental research programme of wood crib fires, allowed to burn out, in model compartments 0.5m, 1.0m and 1.5m high [6]. The maximum temperature which would be attained by a protected steel element was chosen for comparison with the heating effect of the standard fire. See Appendix for method. The values of t_e were found to be independent of scale and height of ventilation opening. The best correlation was obtained from the product of (L/A_v) and a term taking into account A_v and the solid surfaces to which heat is lost:

$$t_e = k_3 L'' A_F / [A_v(A_t - A_F - A_v)]^{1/2} \qquad (3)$$

where A_F is floor area of compartment (m^2). In this correlation, A_F was not included in the evaluation of solid surfaces because the floors were very well insulated. In all the experiments the openings were full compartment height. Law then analysed temperature-time curves for a number of burn-out fires in larger scale brick and concrete compartments (approximately 3m high) [7] and developed:

$$t_e = k_4 L'' A_F / [A_v(A_t - A_v)]^{1/2} \qquad (4)$$

where k_4 is 1.0. In this correlation, the floor areas were included in the evaluation of solid surfaces. These data also showed no significant effect of h on t_e.

Magnusson and Thelandersson [8] developed a method to calculate the temperature-time curve of a burn-out compartment fire, with input parameters of an 'opening factor' $A_v\sqrt{h}/A_t$ ($m^{1/2}$) and the fuel load per unit internal envelope area q_t (MJ/m^2). Assuming a calorific value of 18MJ/kg for wood:

$$q_t = 18L''A_F/A_t \tag{5}$$

For ease of comparison, a conversion from MJ to kg of wood will be used in this review. (The data were originally obtained from wood crib fires). The Magnusson and Thelandersson calculations were for a 'standard' brick or concrete compartment. For compartment boundaries with different thermal properties, the input parameters can be multiplied by a factor k_f which ranges from 0.5 (poorly insulated) to 3.0 (well insulated) with 'standard' compartments taking the value 1.0 [9]. Pettersson [10] then adopted the Law approach to t_e but instead of experimental curves, used the family of calculated temperature~time curves for standard compartments to derive:

$$t_e = 1.21\,L''A_F/(A_v\sqrt{h}A_t)^{1/2} \tag{6}$$

Equation (6) is similar to equation (4) but includes $\sqrt{h}$ because of the input parameters in the method for calculating temperature-time curves. Equation (6) can be modified to take into account the thermal properties of the compartment enclosure by applying the factor k_f to each input parameter. This yields:

$$t_e = 1.21\,k_f^{1/2}L''A_F/(A_v\sqrt{h}.A_t)^{1/2} \tag{7}$$

Harmathy and Mehaffey [11] developed a normalised heat load H_N ($s^{1/2}K$), for total heat penetrating the compartment boundaries, taking into account $A_v\sqrt{h}$ and the proportion of heat evolution in the compartment, δ. Their purpose was to characterise the potential for fire spread (failure of fire resistance). Based on the results of many experiments, and tests in the DBR/NRC floor test furnace, they give the following relationship for t_e and concrete elements:

$$t_e = 6.6 + 9.6 \ x \ 10^{-4}H_N + 7.8 \ x \ 10^{-9}H_N^2$$

$$for \quad 0 < H_N < 9 \ x \ 10^4 \tag{8}$$

$$\text{where} \quad H_N = 10^6(11.0\delta + 1.6)L''A_F/[A_t(K\rho c)^{1/2} + 1810(A_v\sqrt{h}.L''A_F)^{1/2}] \tag{9}$$

$$\delta = 0.41(H^3/A_v\sqrt{h})^{1/2} \ or \ 1, whichever\ is\ the\ less \tag{10}$$

and H is compartment height (m). $(K\ \rho\ c)^{1/2}$ is the thermal inertia of the compartment boundaries where K, ρ, and c are respectively thermal conductivity, density and specific heat. For concrete, the thermal inertia is 2190 ($Jm^{-2}s^{-1/2}K^{-1}$). Equation (8) is given approximately by:

$$t_e = 0.0016H_N$$

$$for \quad H_n \leq 9 \ x \ 10^4 \tag{11}$$

Eurocode 1 [2] for Actions gives the following:

$$t_e = k_b q_t(A_t/A_F)(6.0/H)^{0.3}[0.62 + 90(0.4 - \alpha_v)^4/(1 + b_v\alpha_h)]\mathrm{z} \tag{12}$$

where α_v is A_v/A_F, α_h is A_h/A_F, A_h is area of horizontal openings in the roof (m^2), b_v is 12.5 (1 + $10\alpha_v - \alpha_v^2$), k_b depends on the thermal properties of the enclosure and (6.0/H)[0.62 + 90 (0.4 - $\alpha_v)^4/(1 + b_v\alpha_h] > 0.5$, $b_v \geq 10.0$, $0.025 \leq \alpha_v \leq 0.25$. This equation is based on work by Schneider et al [12,13]. The element of structure chosen for comparison is a reinforced concrete slab. The calculations of fire behaviour, based on a heat balance, were made using the MRFC (Multi-Room-Fire-Code) computer program developed at the University of Kassel.

For $\alpha_h = 0$, i.e. no horizontal openings, and $k_b = 0.07$, equation (12) may be written:

$$t_e = 1.26 L'' w_f \tag{13}$$

where w_f is $(6.0/H)^{0.3}$ $[0.62 + 90\,(0.4 - A_v/A_F)^4]$.

For $A_F < 100$ m² the following is also given:

$$t_e = k_b q_t (A_v \sqrt{h}/A_t)^{-1/2} \tag{14}$$

where $0.02 \le A_v\sqrt{h}/A_t \le 0.20$. The value of k_b ranges from 0.04 to 0.07 and where no detailed assessment is made a value of 0.07 is recommended. Equation (14) is then virtually the same as the Pettersson equation (6).

EXPERIMENTAL DATA COMPARED WITH FORMULAE

Experimental

The various formulae will now be compared with experimental data from post flashover fires in "full-scale" compartments. Most of the test compartments have been the size of a small room - less than 30 m² in area and some 2.5 to 3m in height. They have had one or more vertical openings but no horizontal ones. The boundary enclosures have normally been brick and/or concrete, occasionally with an internal layer of insulating material. Accordingly these test rooms are described in this review as 'small standard compartments'. Some recent experiments have been carried out in a larger and deeper room, 128 m² in area, with a depth to width ratio of 4:1 and with very well insulated internal surfaces, with one small test room for comparison [14]. Accordingly these test rooms are referred to in this review as a 'deep insulated compartment' or 'small insulated compartment'. The main features of these test rooms are listed in Table 1.

TABLE 1. Main features of well insulated compartments and calculated t-equivalents

Test	H	D	A_F	A_v	h	L"	t_e
1	2.75	22.9	128	15.4	2.75	40	106
2				15.4	2.75	20	55
3				7.7	1.47	20	76
4				7.7	1.47	40	155
5				3.7	1.73	20	113
6				1.95	0.375	20	172
8*				14.4	2.68	20.6	62
9				14.5	2.75	20	61
7⁺	2.75	5.6	32	3.75	2.75	20	39

* Plasterboard lining added internally
⁺ A_v/A_F chosen to be the same as in Test 2

Not many of the experiments included sample test elements for direct comparison with the results of standard fire resistance tests. Accordingly the values of t_e for all the experiments have been derived from the temperature-time curves within the compartments using the procedure adopted by Law as described in the Appendix.

The calculation procedure assumes an efficient furnace, thereby avoiding test house bias, an aspect discussed later. The curves for the small compartments are usually assumed to be representative of a uniform temperature distribution but the assumption of uniformity is known to be more unrealistic for large compartments. This is demonstrated by the results of the deep compartment tests, where the fires burnt progressively from front to back after flashover, regardless of where the ignition source was located. Although the temperature-time curves given for three locations - near the open end (front) at the middle and towards the rear of the deep compartment (back) - were similar in any one test they were displaced in time. Thus, failure would occur first near the ventilation opening, and these are the values of t_e given in Table 1. However, as Table 2 shows, the values of t_e are not sensitive to the locations. The time to reach the maximum steel temperature at the back is about 15% greater than the time at the front.

TABLE 2. Calculated t-equivalent from temperature-time curves reported for the well insulated compartments

Test	t_e - min			t_{max}	Time lag (front to back)
	Front	Middle	Back	min	
1	106	116	109	110	20
2	55	63	61	65	10
3	76	83	78	100	10
4	155	158	151	170	20
5	113	116	104	140	25
6	172	190	194	400	50
8	62	70	61	110	15
9	61	75	70	65	15
7	39	-	-	35	-

Correlation of Data

Figure 1 shows t_e plotted against L". The Ingberg equation (1) is a reasonable average for the small compartment results but there is considerable scatter. The formula is not satisfactory for the deep compartment data.

Figure 2 illustrates that equation (2), derived from Kawagoe and Sekine, is very conservative for small compartments and does not remove much scatter. It is not satisfactory for the deep compartment.

Figure 3 illustrates that the Law equation (4) removes much of the scatter, but a higher value of the slope, 1.75, is needed to correlate the deep compartment results.

Figure 4 illustrates that the Pettersson equation (7) also removes much of the scatter. To correlate the deep compartment results, a curve appears more appropriate than a straight line. This curvature is caused by the incorporation of $\sqrt{h}$ in the formula, an aspect discussed later.

Figure 5 illustrates that the Harmathy and Mehaffey equation (11) gives a reasonable correlation for the small compartment results. As with the earlier formulae, the results for the deep compartment need a line of greater slope, of about 0.0049.

FIG 1: INGBERG CORRELATION

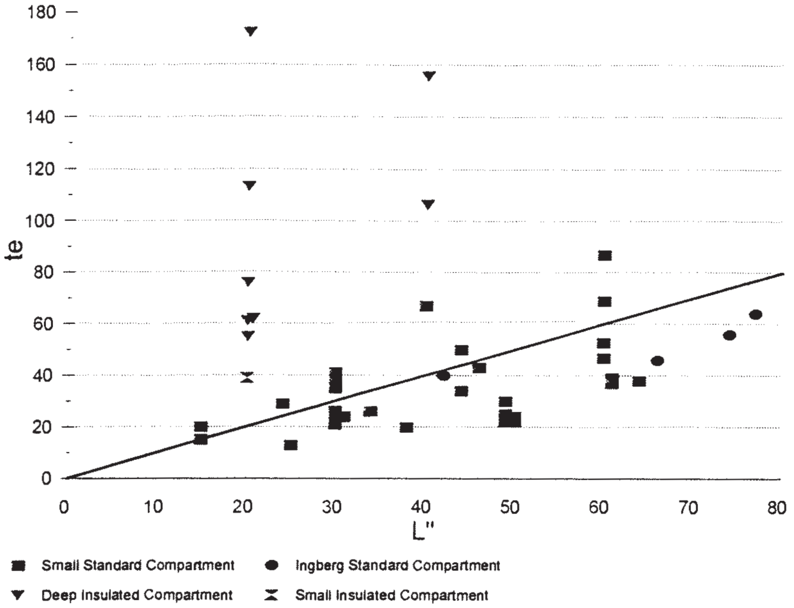

FIG 2: KAWAGOE & SEKINE CORRELATION

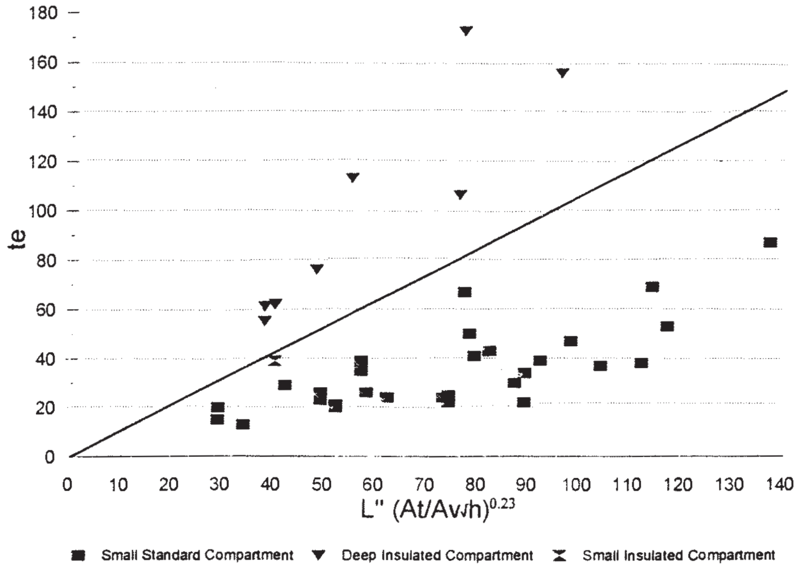

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FIG 3: LAW CORRELATION

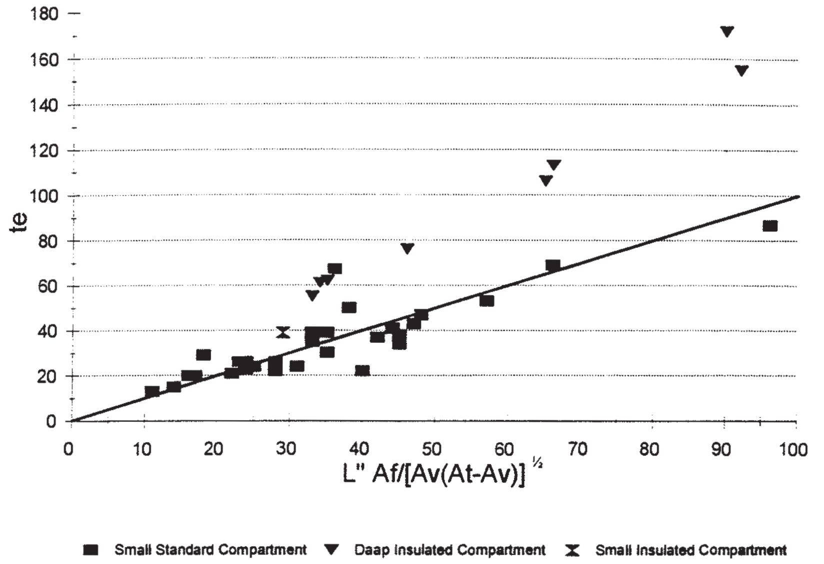

FIG 4: PETTERSSON CORRELATION

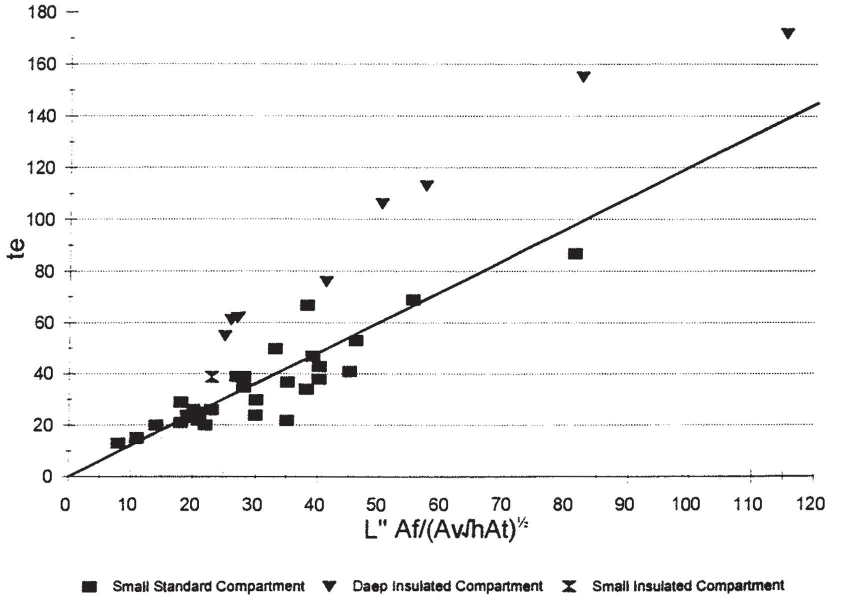

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FIG 5: HARMATHY & MEHAFFEY CORRELATION

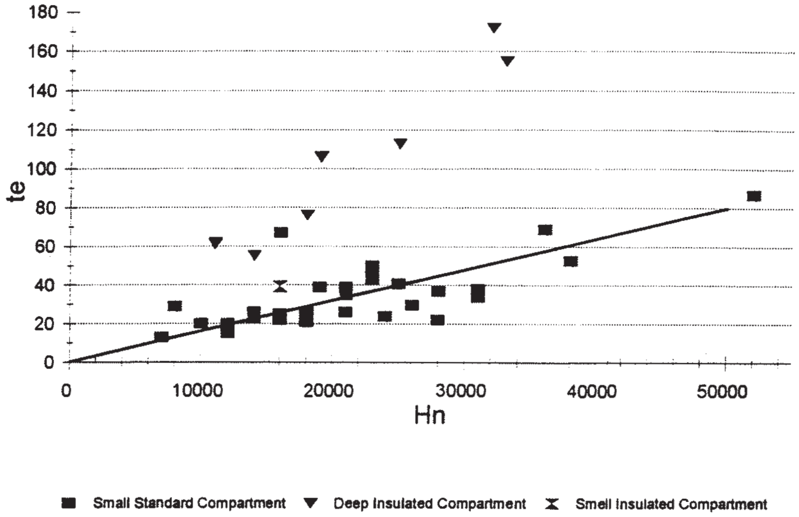

FIG 6: EUROCODE CORRELATION

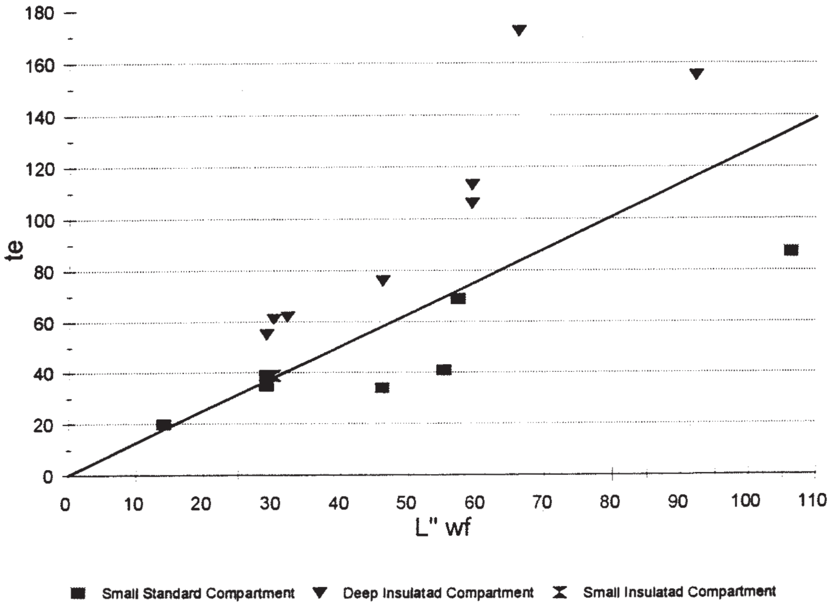

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Figure (6) illustrates that the Eurocode equation (13), for compartments without horizontal openings, does not give a satisfactory correlation of the results for either small or deep compartments. A straight line correlation does not appear very satisfactory for either set of data. It should be noted that results have not been plotted for those small compartments where A_v/A_F exceeds 0.25, because that is outside the limits of applicability of equation (13).

Of the six correlations described above, the more promising ones are Law, Pettersson and Harmathy and Mehaffey, the third giving an explicit recognition of $(K\rho c)^{1/2}$. However, it is necessary to examine further the deep compartment results.

DEEP WELL-INSULATED COMPARTMENT DATA

Effect of Variables

A regression analysis of the log values of t_e, L'', A_v and h (A_F, A_t and H being constant) shows that L'' and A_v are significant at better than the 0.1% level but h is not significant at the 20% level. The absence of significant h effect was noted by Law in the earlier analysis and appears to be confirmed here. The regressions obtained are:

$$t_e = 14.4\,(L'')^{0.93}/(A_v)^{0.52} \tag{15}$$

$$t_e/L'' = 11.7/(A_v)^{0.53} \tag{16}$$

The importance of L' and $\sqrt{A_v}$ are clearly established for these data, as they have been for the small compartments. As the relationships are empirical, there is no obvious theoretical explanation for the lack of h effect. A heat balance study may give an explanation.

Effects of Insulation

We note that if we adopt the value 3 for k_f (well insulated compartments), then in Equation (7) the slope for Pettersson would be 1.21 x $\sqrt{3}$ = 2.1 and the slope for Law would be $\sqrt{3}$ = 1.7. Such lines would be close to the deep compartment data. However, before leaping to the conclusion that the higher values of t_e for the deep compartment can be attributed to the greater insulation, we should note that the small well-insulated compartment result appears to belong to the small *standard* compartment family. This is consistent with earlier work. Thomas and Heselden found that the fire was not very sensitive to changes in the conductance of the wall (conductance = thermal conductivity/wall thickness). A change of 100% in conductance gave about 5% change in fire temperature and 17% in rate of burning [6]. Heselden [15] carried out a heat balance for a small compartment and found that a mineral wool lining resulted in only slightly higher temperatures than when the surfaces were vermiculite plaster and refractory concrete. He points out though, that the proportion of the heat transferred to the walls, ceiling and floor was not more than 30% of the heat released, even with the less well insulated compartment. Law's values of t_e for small compartments [7] included a few for well insulated walls which gave results not dissimilar from the standard walls. If the k_f = 3 value is applied to A_t in the Harmathy and Mehaffey formula, we get some, but not sufficient improvement in slope, which again suggests that insulation is not necessarily the important effect. Finally, we may note that in Test 8 a plasterboard lining was added to the walls and ceiling. Some plasterboard panels on the ceiling opened, exposing timber studding and thereby increasing the fire load (from 20 to 20.6kg/m²), but the wall panels remained intact for most of the test. This change in $(K\rho c)^{1/2}$, by a factor 10, made no significant difference to t_e, as can be seen by comparing the values for Tests 8 with those for Tests 2 and 9. However, the fire development was much slower in Test 8, an effect attributed by *Kirby et al* to the generation of copious amounts of water vapour. Accordingly the time taken to reach the critical temperature was about 45 minutes longer.

Effect of Location

The values of t_e calculated at the different locations, and shown in Table 2, indicate that the location has little effect on the value of t_e but affects the time at which the maximum steel temperature is attained.

Comparison with Furnace Test Data

Kirby et al reported values of t-equivalent using measured temperatures of protected steel elements in the well insulated compartments to compare with the results of standard fire tests. It would be expected that test furnaces tend to give larger values of t_e than an efficient furnace. Harmathy and Mehaffey estimated that the NRC/DBR furnace gave values nearly 10% greater. Table 3 shows the values derived from the test elements at the front of the well insulated compartments.

Table 3. Experimental values of t_e for protected elements at the front of the well insulated compartments. The calculated value of t_e from Table 1 also shown

Test	Thickness of Vicuclad (mm)			Calculated t_e
	20 Beam	30 Column	70 Column	
1	-	121	-	106
2	64	61	-	55
3	80	78	-	76
4	168	132	-	155
5	110	102	-	113
6	97	108	195	172
8	62	64	130	62
9	68	61	122	61
7	54,55	54,55	-	39

For most of the tests there is reasonable agreement between calculated and measured t_e. However, Tests 6, 8 and 9 show that the third sample element gives approximately double the value of t-equivalent derived from the other two. Kirby et al suggest that this might be attributed to the difference in maximum steel temperature, but it could not account for such a large discrepancy. Another possibility is an error in the standard test result used for comparison. A fourth sample element was installed for five of the tests, by another body collaborating in the experiments, but the results have not been published as yet (May 1996).

For Test 6 only there is a big difference between the calculated value of t_e and the results for the beam and the first column. The reason for this is not known. It is not expected that the calculated time would give larger values than the test elements. When the further data are published it may be possible to assess the reliability of the comparisons based on sample elements.

Discussion of the Deep Compartment Data

It appears that the depth of the compartment has an effect on t_e, over and above that which can be allowed for by the increases in insulation and in internal surface area A_t. Earlier work [6] has already shown that the ventilation controlled rate of burning is affected by the compartment depth to width ratio and some such effect on t_e appears to be important here.

THE FUTURE FOR T-EQUIVALENT

For the purposes of design, t-equivalent gives a general feel for the total heating effect of a fire but it does not differentiate between a short, hot fire and a longer, cooler fire with the same t_e. It is often important to know the temperature of the fire, in order to assess radiant heat transfer and the reaction of materials which are temperature sensitive. Fire engineers may wish to estimate the fire temperature and the fire duration separately. Such estimations will rely on performing a heat balance for the compartment. Earlier work has already demonstrated that the rate of burning can be affected by the depth of the compartment. The data yet to be published, by the collaborative body, for the deep compartment fires will assist a heat balance analysis.

CONCLUSIONS

None of the existing formulae give satisfactory correlations of t-equivalent for the experiments reported by Kirby et al for deep well-insulated compartments. The Eurocode formula is not satisfactory for small compartments either.The values of t_e for the deep compartments are strongly correlated with L'' and $A_v^{0.5}$ but h has no significant effect.The values of t_e for the deep compartments appear to be not sensitive to the insulation of the enclosure.There is an anomaly in the values of t_e derived from the sample elements and this should be explored further when all the test data are published.A heat balance should be carried out for the deep compartment fires when all the test data are published. Fire engineers may not find t-equivalent a useful parameter for design when it is important to assess fire temperature and fire duration. Such an assessment will need to take into account the heat balance yet to be performed for the deep compartment.

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APPENDIX

Calculation of t-equivalent from a temperature-time curve.

The maximum temperature obtained by a protected steel element in a compartment fire has been calculated using iterative procedures and the following equation:

$$\frac{d\theta_s}{dt} = \frac{\theta_f - \theta_s}{RC}$$

where θ_s is steel temperature, t is time, θ_f is fire temperature. R is the thermal resistance of the protective material, C is the thermal capacity of the steel, and the temperature of the heated surface of the protective material is assumed to be the same as the fire temperature. For a given fire temperature-time curve, a value of *RC* has been deduced which gives a maximum value of 550°C for θ_s. The time to attain 550°C with the standard temperature-time curve and this value of RC, gives the value of t-equivalent. The comparison is not sensitive to the value of maximumθ_s chosen for comparison, within the range 400-600°C. Some calculations of diffusion of heat through concrete have yielded similar values of t-equivalent [7].

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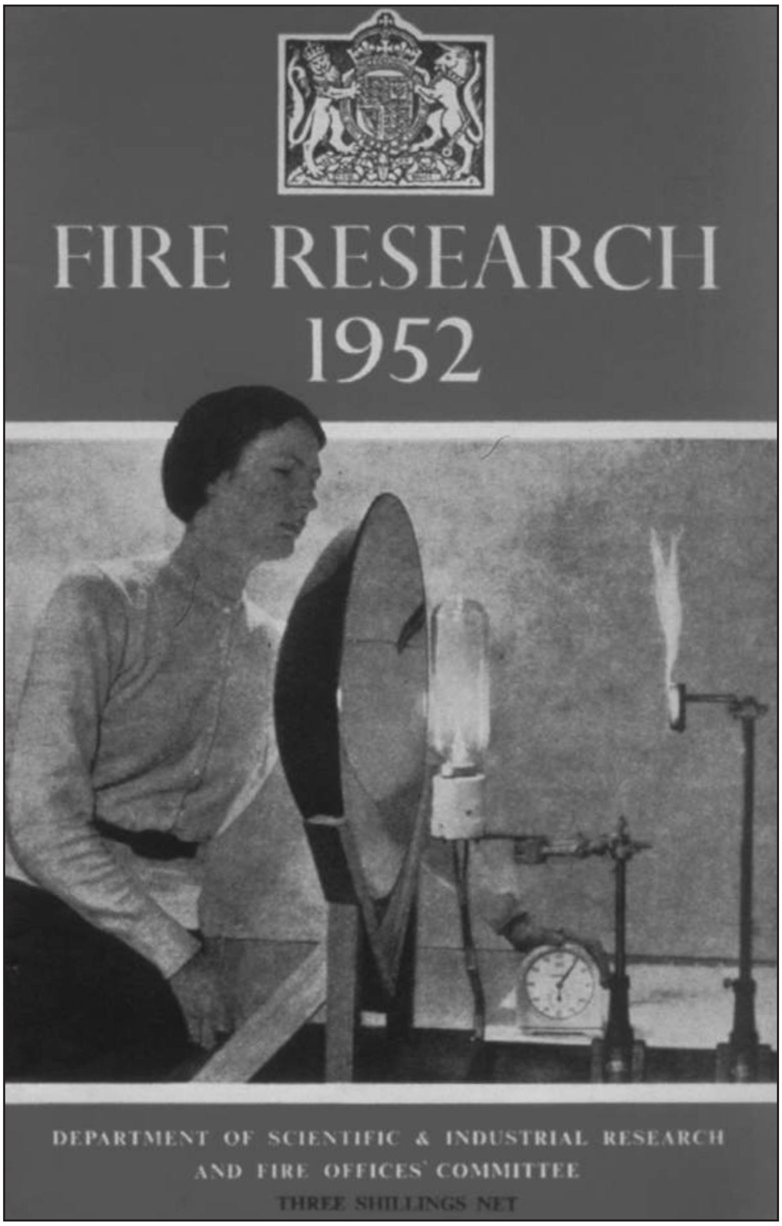
Developments in the discipline of fire safety engineering

Margaret Law MBE, Visiting Professor of Fire Safety Engineering, School of Computing & Mathematical Sciences, University of Greenwich, An inaugural lecture delivered at the University of Greenwich, 3 June 1997. University of Greenwich, London, UK

As I had been appointed Visiting Professor in the School of Computing and Mathematical Sciences, I chose to highlight in my inaugural lecture some fire engineering studies that relied on various computational methods in use before the modern computer was developed. The lecture also illustrates how fire engineering models have been applied in practice.

Plate showing the front cover of the Fire Research Station Annual Report featuring Margaret Law. This was her first year as a fire researcher and the picture shows Margaret carrying out experiments on the ignition of wood (Paper 4).


FIRE RESEARCH
1952

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AND FIRE OFFICES' COMMITTEE
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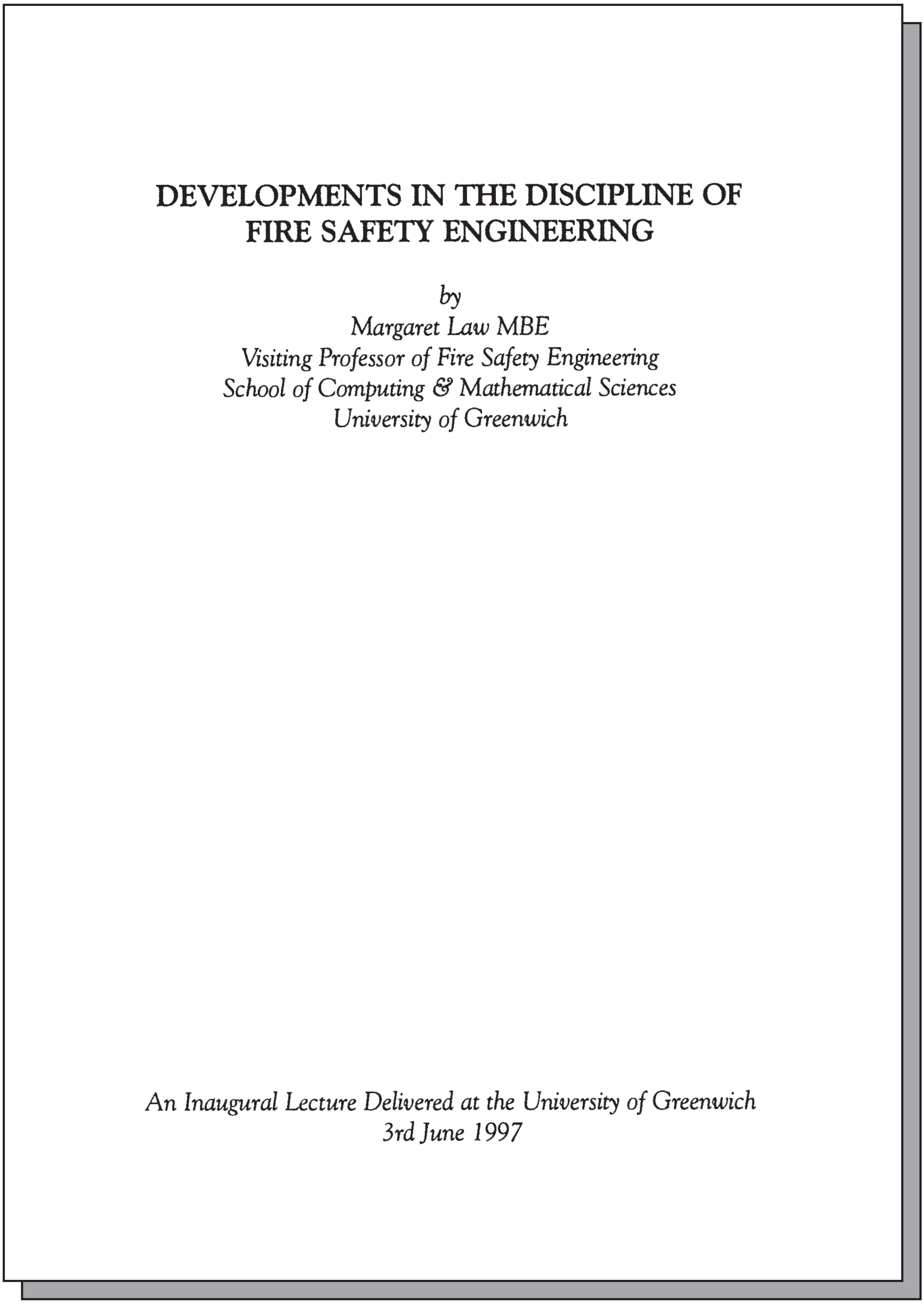

DEVELOPMENTS IN THE DISCIPLINE OF FIRE SAFETY ENGINEERING

by
Margaret Law MBE
Visiting Professor of Fire Safety Engineering
School of Computing & Mathematical Sciences
University of Greenwich

An Inaugural Lecture Delivered at the University of Greenwich
3rd June 1997

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Margaret Law MBE

Margaret Law was born in London and graduated in physics and mathematics from the University of London. She joined the Fire Research Station and worked there on a range of projects related to ignition, fire dynamics and structural behaviour. The application of research to solve practical problems was of particular interest to her and in 1974 she joined the Ove Arup Partnership to act as an adviser on fire engineering for projects being designed within the firm and on other projects in appropriate circumstances. She was concerned with all aspects of fire safety, particularly in those buildings for which the standard rules and requirements of regulations are not directly applicable. At the end of 1990 Margaret Law retired and is now a Consultant to the Partnership. The list of projects she has worked on includes: the Centre Pompidou, Paris; Lloyds, London; Stansted Airport Terminal, Essex; Kowloon Bay Depot, Hong Kong; Kansai Airport Terminal, Japan; The Ark, Hammersmith. She was a visiting researcher at the Science University of Tokyo in 1987. She remains actively involved in National and International Committees concerned with fire safety.

Since becoming a consultant, Margaret Law has received a number of national and international awards, and in 1993 was appointed MBE for her services to fire safety.

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DEVELOPMENTS IN THE DISCIPLINE OF FIRE SAFETY ENGINEERING

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INTRODUCTION

It is only in recent times that Fire Safety Engineering has been recognised as an academic discipline: indeed, it was as late as 1973 that David Rasbash joined Edinburgh University as the first Professor of Fire Engineering. In parallel, fire engineering consultancies also started to grow: these no longer confined themselves to such routine matters as specifying sprinkler system layout or deciding the location of fire doors as specified in an arbitrary code. The consultants recognised the need to apply science and engineering principles to the design of fire safety, particularly for projects which could not be realised if they had to comply strictly with existing rules and regulations. Fortunately, there was already a sound body of research which could be used as a basis not only for lecture courses but also for consultants' advice.

The insurance industry had for many years played a major part in research, the development of fire safety measures, testing of products and the collection of statistics. Support for fire research from public bodies became more significant after the Second World War, not least because co-operative research during wartime had demonstrated its value. Many countries established fire research laboratories at this time. This paper will describe some research projects carried out in the succeeding years, and give illustrations of how the results and engineering models have been used in fire safety design. It is this experience which can inform a new generation of general codes for fire safety, and which needs the support of those academic institutions which have recognised the importance of the discipline of fire safety engineering.

FIRE SPREAD

Throughout history urban fire spread has been a major problem, with property loss being in general more significant than life loss. We can recall the Great Fire of London in 1666, which alone caused more destruction than bombs in the same area during the whole of the Second World War (Milne, 1986). Of the many civilian problems which had to be tackled afrer that war, two relevant to fire research will be discussed here. One major concern was the threat of nuclear attack. The spread of building fires and the human injuries which had been caused by the thermal radiation from the fireballs of atomic bombs came as a surprise to some, though the effects might have been predicted. Consequently, much attention was paid to the intensity of heat radiation to be expected, according to the distance from the seat of the explosion, and the likely effects, in terms of ignition of buildings and injuries to skin. The second major concern was the need for new buildings, not only to replace those destroyed by bombs but also to compensate for the lack of building activity during the wartime years. New forms of construction were being developed and their performance in fire needed to be assessed.

Ignition by radiation

Research was directed at assessing the intensity of radiation which could cause ignition of buildings during the relatively short duration pulse of heat from an atomic explosion. Wood was selected as the most representative combustible material and families of curves for different species were obtained by experiment, showing how the intensity of radiation which caused ignition varied with exposure time. It was considered important to develop an engineering model for ignition, but because the chemical reactions leading to combustion are complex, it was decided to try a simple thermal model. The surface temperature of the heated face of each wood specimen at the moment of ignition was calculated using conventional heat conduction equations (Carslaw & Jaeger, 1959) and it was found that the temperature was independent of species and exposure time (Simms & Law, 1967). For spontaneous ignition this temperature was 530°C and for pilot ignition, where an adjacent small flame could act as a pilot light, it was 370°C. Thus an engineering model of ignition by radiation was derived which avoided consideration of the complex chemical and physical processes involved. No doubt this information was incorporated in civil defence manuals but it was also available for more general use. In particular, we can note that the intensity of radiation needed to cause ignition has to be above a certain value to take into account the significant cooling of the heated wood to the surrounding air when it approaches the ignition temperatures. Thus a threshold intensity of radiation can be defined by this model, below which ignition will not occur, however great the duration of heating. We will see later how this model has been used in practice.

Fire grading of buildings

The rules for the rebuilding of London which were drawn up after the Great Fire limited the use of combustible materials, specified the construction of walls and floors in terms of brick thickness, and limited the size of the building according to the width of the street. In the 19th century, the development of large industrial buildings and warehouses posed great problems for the fire fighters because the fires could become too large to be controlled by fire hoses. Therefore the maximum acceptable fire size had to be determined in order to limit the likely loss and the extent of spread. Rules for compartment size were drawn up, based on advice from the fire brigade and insurance bodies. This meant that large buildings had to be divided by fire barriers into so-called compartments. The limit on compartment volume of 250,000 ft^3 has survived to this day, expressed in the metric equivalent of 7000 m^3.

The type of construction deemed acceptable for compartmented buildings relied originally on *ad hoc* fire tests and practical experience, but in the 20th century a standard fire resistance test was developed in which a loaded element of construction, such as a column or floor, was placed in a furnace and heated in a standard way until it failed to support its load or failed as a fire barrier. The failure time defined its fire resistance. This test (BS 476: 1987) is still used worldwide today to grade elements of building construction, although it does not directly relate to building fires in practice. As far as traditional forms of construction were concerned, there was of course much wartime experience of the practical effects of fire because of the extensive bombing. It was following this experience that researchers in the UK developed a method whereby the temperatures reached in walls and columns during a real fire could be estimated from the colour changes in brickwork mortar and concrete. These changes were compared with the temperatures reached in a similar element when subjected to the standard test for various times. An equivalence was derived which related fire load density to hours in the standard test (Ministry of Works, 1946). Fire load density was the total heat content of the combustible materials divided by the floor area of the compartment. (More recently heat content has been replaced by the equivalent weight of wood.) At that time, it was already recognised that the severity of building fires depended not only on fire load density but also on ventilation and compartment size. Therefore research was initiated into the behaviour of so-called compartment fires.

Calculation of heat conduction in building elements

The examination of fire damaged buildings and the measurements made in fire-resistance tests indicated that structural failure could be related to the attainment of a certain temperature at a critical part of the building element (for example, at the steel reinforcing bars in reinforced concrete). This is because building materials undergo physical and mechanical changes when heated; in particular they lose strength when hot, the extent of loss depending on the temperature reached. It was considered, therefore, that calculation of heat conduction in the building elements when exposed to the standard fire could be an economical alternative to the furnace test procedure because it would indicate the time at which a “critical temperature” might be reached within the element. The difficulty was in performing the calculations — which were for transient heat flow and not steady state — with a variable rate of heating and an element which could be composed of two or more materials, each with their own thermal properties. An analogue computer was constructed to overcome this difficulty (Lawson & McGuire, 1953). It exploited the fact that the flow of charge through electrical resistance and electrical capacity is the same as the flow of heat through thermal resistance and thermal capacity, with voltage being analogous to temperature rise. A voltage which varied with time, in the same way that furnace temperature was varied in the test, was applied to a network representing the element of construction. The timescale was reduced — one hour being represented by 100 μs in the analogue — so that voltage measured at a selected point on the network was displayed as a trace on a cathode ray tube. Diffusion of heat through a layer of building material had to be represented by a mesh of finite elements because electrical resistors and condensers are supplied separately; the mesh of the network near the “heated face” was fine but could be more coarse at the cooler end. This technique is familiar nowadays to those solving similar problems using spreadsheets. The net result of this work was the development of a series of scaling relationships which could be used to generalise results obtained from standard fire resistance tests (McGuire *et al.* 1975).

Compartment fires

A compartment fire is one which produces significant heat transfer to the structure, significant radiation and convection through openings such as windows and doorways, and fatal heating and asphyxiation of any people within that compartment. These conditions are experienced after flashover, a condition when there is total surface involvement in a fire of combustible materials within a room or compartment. Fire resistance is relevant to post-flashover fires. Localised heating of structures can of course occur before flashover, but the standard fire resistance test is not really relevant to these heating conditions.

Flashover is not expected to occur before sustained flaming has reached ceiling level and flames start to spread horizontally. In the open, flames are generally between one and two fire diameters high, so that for a 3m high ceiling a fire would need to be about 1.5m across for

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flames to reach ceiling height. It follows that small fires in large spaces may not cause flashover.

Studies of post-flashover compartment fires, in small- and large-scale rooms, gave information about the temperature and duration of fire within the compartment, the radiation and flames emitted from the windows. The rate of fuel consumption and hence the rate of heat generation was measured and estimates were made for the distribution of this heat: to the surrounding structure, the outflowing flames and hot gases, to the exterior by radiation, and to the fuel bed itself. A heat balance approach can be applied to solve various practical problems.

PRACTICAL APPLICATIONS OF FIRE SPREAD RESEARCH

Exposure hazard

The possibility of fire spread by radiation from one building to the next has been referred to as the "exposure hazard" (Ministry of Works, 1946). This was controlled in the past by street width and by having external walls of fire resistant construction such as brick and stone with, in practice, only some 30% of the wall area being occupied by windows, although there was actually no legal limit on the proportion of glazing which could be installed. When new curtain walling systems were introduced after the Second World War, they had been rejected because they did not have the resistance required by the bye-laws. However, a curtain walling system which was 100% glass, i.e. with negligible fire resistance, did comply with the bye-laws because it could be called a window! This anomaly in the bye-laws needed to be removed. A method had already been suggested (Bevan & Webster, 1950) whereby a maximum acceptable rate of heating on an exposed building would be defined, the intensity of radiation emitted from the building on fire would be estimated, and the attenuation of radiation with the distance from the radiating building would be calculated in order to determine a 'safe' location for the exposed building.

The maximum acceptable intensity of radiation was obtained from the civil defence research on ignition of wood, the threshold value for pilot ignition being adopted, on the assumption that a spark or flying brand could be adjacent to the heated surface. The work on compartment fires showed how fire temperatures varied over the range 600 to 1200°C, and how the intensity of radiation emitted from the burning room varied with fire load and window area. The intensity of radiation reduces with distance from the facade according to an inverse square law, the shape of the radiating area, and the orientation of the receiving surface. The fractional reduction in intensity is the configuration factor, and equations are available for simply shaped radiators, such as rectangles, but computation for irregular shapes is complex. Therefore, an optical analogue computer was devised using the fact that light is transmitted in the same way as heat radiation (Lawson & Hird, 1953). A box was constructed with an illuminated screen at one end which could be viewed by a photo-cell. A scale model of a building facade was created in black card and used to mask the screen, so that only the windows and emerging flames were visible. The flame shapes were copied from a photograph of a burning building. The photo-cell was used to measure the light intensity when in contact with a window and when at the scaled distance of the exposed building. The fractional reduction in light intensity gave the configuration factor.

It was necessary to express this information in a way which could be used in The Building Regulations, which was a legal document. Two radiating intensities were identified, one for buildings with low fire loads and one for buildings with high fire loads. The necessary configuration factor, which controlled the distance between the buildings, could be modified not only by changing the window size but also by changing the compartment size, since this controlled the extent of the radiating area in the facade. The biggest legal problem was that control could only be exercised on the distance to the boundary of the site of the exposing building, and not to the facade of the exposed building. For this reason, if for no other, a simplified calculation of configuration factor was devised which did not rely on the optical analogue. This method of determining space between buildings to limit fire spread, using calculations of heat radiation from burning buildings, was probably the first example of applying physics to the building regulations for fire (Law, 1963).

Calculation of fire resistance

The prescriptions of building regulations and codes for structural fire protection are to this day expressed in terms of standard fire resistance, which is measured for single elements heated in a standard way. Each time a new protection material is developed, or traditional materials are used in a new way, a test or tests must be carried out. The scaling relationships, obtained using the analogue computer described earlier, have proved valuable in the analysis of the results of tests on structural steel elements (ECCS, 1985). In particular, the thermal properties of materials — conductivity and specific heat — which normally vary with temperature can be assigned average values which are adequate for engineering purposes. At the moment, these values are inferred from standard test results, rather than being measured directly, and they have not been presented in a form which can be readily used for non-standard heating conditions. Calculation rules are available, however, for standard fires only, in the Eurocodes. Mechanical properties of materials at high temperatures are also available in the Eurocodes.

Equivalent fire resistance — compartment fires

The comparison of heating effects of real fires and standard fires published by the Ministry of Works in 1946, gives a similar relationship to that derived earlier by Ingberg (1928), who measured temperature-time curves in experimental fires in rooms with office furniture. He related the areas under these curves to areas under the standard temperature-time curve. Both relationships are of the form

$$t_e = k_1 L^{//}$$

where t_e is equivalent time (min), $L^{//}$ is fire load (wood) per unit floor area and $k \simeq$ unity when $L^{//}$ is in units of kg m^{-2}. In Japan, (Kawagoe & Sekine, 1963/64) had studied the behaviour of compartment fires and had identified the importance of the ventilation parameter $A_t/A_v\sqrt{h}$ when performing a heat balance to determine compartment fire temperature, where A_t is the area of the internal envelope (walls, floor, ceiling), A_v is the area and h the height of the ventilation opening (window or doorway). They calculated temperature-time curves and, following Ingberg, equated areas to derive a relationship between t_e, $L^{//}$ and the ventilation parameter. Work in the UK (Fire Research 1965 (1966)) showed the significance of fire load per unit ventilation area, L/A_v, where L is the fire load in kg of wood. Law (1971, 1973) then developed a relationship based on the results of experimental fires in model- and large-scale rooms, with the equivalence based on heating effect (temperature rise) at critical locations in the element of structure. This related t_e, L^{77} and a parameter $A_F/(A_v\ (A_t-A_v))^{1/2}$ where A_F is floor area and (A_t-A_v) represents the area of internal surfaces through which heat is conducted (a term used in heat balance calculations). Pettersson (1973) then used the Law approach to equivalence, but based it on temperature-time curves calculated using a heat balance method developed by Magnusson and Thelandersson (1970). His relationship is similar to Law's. A review of these and later relationships is given by Law (1997).

There are circumstances where a fire engineer would prefer to estimate fire temperature directly rather than using equivalence to an arbitrary test. This is because the intensity of radiation from a fire is an important factor in fire spread and its value depends on temperature. In addition, a rapid increase in temperature and high absolute temperatures can affect structural elements more severely than the standard test, so much so that a supplementary hydrocarbon test has been devised which is considered to be more representative of fires in industries using solvents and in offshore oil platforms.

Calculating compartment fires — internal effects

The engineering models developed for estimating temperature variation with time assume that there is a uniform temperature within the compartment, although it is known that this is a large approximation. In particular, where there is restricted ventilation the fire will burn progressively back from the ventilated end (Thomas & Heselden, 1972; Kirby *et al.* 1994). However, this simple model can be adequate for many designs. Accordingly, families of temperature-time curves have been derived for different fire loads and ventilation factors, which may be used to calculate heat transfer to structural elements within a compartment. These curves are contained in a handbook relating to fire-exposed steel structures (Pettersson *et al.* 1976) and similar curves are given in the structural Eurocodes.

Calculating compartment fires — external effects

The calculation of the hazard to nearby buildings exposed to radiant heating has already been discussed. There are, however, other external hazards which have also been studied.

In Japan, a question was asked about the possibility of flames emerging from a burning building and putting an adjacent TV mast at risk. To answer this, a comprehensive study of flame projection was carried out by Yokoi (1960). He first derived correlations for temperature and velocity distribution in the plume of hot gases rising above alcohol fires burning in rectangular trays. By treating the upper half of a window as the rectangular heat source, he then derived similar correlations for the plumes rising from various size and shape windows in a model room containing alcohol fires. He obtained good agreement between the results of his model tests and experiments using wood fuel in large-scale experiments. He then produced a family of curves relating flame temperature, window shape, height above the window and rate of heat supply. In practical applications he calculated the rate of heat supply using the estimates of rate of burning obtained by research on compartment fires.

Thomas (1961) showed how Yokoi's curves could be brought together in a single correlation. Thomas and Law (1974) analysed the data of Yokoi and some other workers to give a correlation for the location of the flame tip. This work proved valuable in solving a design problem for the steel construction industry.

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Fire-exposed external structures

A weathering steel had been developed in the 1960s which, if left unpainted, would acquire a weathered external layer or skin giving protection from rust and corrosion to the steel beneath. Its use was attractive for bridges and other external structures since it did not need to be painted. However, when this steel formed the structure on the exterior of a building the benefits were not realised because the bye-laws and codes required all elements of building construction, whether inside or out, to have the same standard of fire resistance, which could only be achieved by clothing the steel with fire-cladding material. It was known that at certain locations outside the building the heating would not be so severe as inside, and that steel would not necessarily need to have fire cladding. A design method was commissioned jointly by the American Iron & Steel Institute and Constrado, for use by engineers. The resultant code (AISI 1977; Law & O'Brien, 1981) shows how to calculate the temperature and size of the projecting flames, the temperature inside the room or compartment, and the resultant heat transfer to the external steel elements. Provided the bare steel does not get too hot, structural failure can be avoided. The background analysis was by Law (1978) and the design method by Law and O'Brien (1981). The method is included in codes in the USA and in Eurocodes.

Offshore structures

Research from outside the field of fire engineering contributed to studies of the flame exposure of structures on offshore oil platforms: the flame envelopes were estimated using calculations by environmental physicists of the wind speed and direction to be expected in this environment. The calculations used computational fluid dynamics (CFD), a calculation technique which divides two- or three-dimensional space into finite elements or cells and which has also become widely applied in the study of pre-flashover fires in buildings.

SMOKE SPREAD

The term smoke is commonly used to describe the cloud of hot gases carrying the noxious and irritant substances and the smoke particles produced by combustion. The smoke mixes with the surrounding air and moves outward and upward through a building because heat causes expansion and buoyancy. If the smoke reduces visibility it can delay escaping people so that they may be overtaken by heat and toxic gases.

Fire fighters have always recognised the importance of releasing heat and smoke from a burning building so that they can enter to assist escape and to tackle the fire. Nowadays they can wear breathing apparatus, but this does not help them to see through the smoke or protect them from heat. Therefore, windows and doorways will be opened and pavement lights broken out. Fire fighters will also rely on compartmentation — 7000 m^3 limit on volume — to subdivide the building. These measures are not recognised as useful protection for other people already in the building and the traditional approach for them is to install smoke barriers — for example, smoke doors and fire doors — and to provide enough exits so that a person will be within a specified walking distance of a door which leads to a protected route.

The traditional measures, whether for fire fighters or other people, have been found difficult to implement in various modern buildings: factories whose subdivision is not practical, and

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developments such as covered shopping centres where the simple smoke door/limited travel distance approach is not feasible. Any alternative approaches need to be based on a better understanding of how smoke moves and accumulates. The initial studies were concerned with analysing the behaviour of fire and smoke plumes: not only those above the source itself but also those spilling out of openings such as doorways.

Studies of fire plumes

When a fluid is introduced into one of a different density, it flows upward if the surrounding fluid is more dense and downward if the surrounding fluid is less dense. Familiar examples are smoke rising above a bonfire out of doors and down draughts in a room from air cooled by window glass. Hot air is less dense than cold air.

When the plume of hot gases rises above a fire the ambient air is entrained into it, which increases the size of the plume, but also decreases the temperature and concentration of smoke particles and toxic gases. The smoke accumulates at ceiling level and begins to stack down. Most smoke control designs aim to prevent this accumulated layer becoming too deep, for example extending down to head level, for a specified period of time. Early plume studies were made by Yih (1952), Taylor *et al.* (1956), Yokoi (1960) and Lee and Emmons (1961); these gave information about the velocity and temperature along the axis and the amount of air entrained into the rising plume at different heights above the source. Because smoke and heat detectors are commonly placed at or near ceiling level, designers of detection systems have extended this work in order to quantify the temperature and velocity of hot gases flowing horizontally after impinging on the ceiling. These early studies include ones by Thomas (1955), Pickard *et al.* (1957) and Alpert (1972).

The spill plume above the opening of a room containing a fire has received less attention, although it is of practical importance, as we will see later. Experimental studies in a 1/10th scale model were initiated by Morgan and his colleagues (Morgan & Marshall, 1975). A correlation of various data obtained was suggested by Law (1986; 1995), adopting the Yokoi approach, and similarly by Thomas (1987).

Studies of the effects of smoke on people

Important studies of the effects of smoke on visibility and the influence of illumination were carried out in Japan by Jin (1970); the results supported and extended earlier work in the UK, for example by Rasbash (1951). The introduction of plastic materials into fittings and furnishings of buildings was viewed with concern because of the great amounts of smoke evolved. This was caused by the nature of the materials and rapid burning rates. Fire fighters have since become accustomed to wearing breathing apparatus in virtually all fire incidents where it is necessary to enter the building on fire. Many studies have been made of the toxicity of combustion products and the heat effects since both these aspects give rise to injury and death (Purser, 1995).

PRACTICAL APPLICATIONS OF SMOKE SPREAD RESEARCH

Ventilating industrial fires

The development of factories with large undivided spaces, in order to accommodate modern production methods, posed problems for access by fire fighters because relatively small fires could cause the space to be smoke-logged. Without fire fighting, hot gases could spread out under the roof spaces and possibly cause flashover. The solution would be to divide the roof into compartments or reservoirs by screens extending downward from the ceiling, each reservoir being equipped with an automatic ventilator. The area of the ventilator in the fire affected reservoir would be large enough to prevent spillage of smoke and heat to adjacent reservoirs for the envisaged size of fire. This would leave the lower levels of the factory free of smoke and accessible to fire fighters.

A theoretical and experimental study of roof venting, sponsored by a manufacturer of ventilation systems, was undertaken in order to quantify the flow of hot gases through the roof vents (Thomas *et al.* 1963). It took into account the research work carried out on plumes and went on to develop equations for flow of hot gases through vents for various configurations of roofs and screens. A design manual based on this work was also produced by Thomas and Hinkley (1964). The experimental study included a hydrodynamic analogue which exploited the similarity between plume flow of a liquid introduced into another of a higher density and the warm plume above a fire: a model of a factory was filled with a brine solution and the flow of hot gases from a fire on the floor was simulated by the flow of coloured water having a lower density.

Covered shopping centres

In the design of new towns, and developments in existing ones, it was common to find shopping centres with pedestrian access only. It was thought that areas free of traffic would be more enjoyable for shoppers. Unfortunately, by the 1960s, many of these had become miserable, windswept and rainswept areas with poor management and dwindling support by customers. The architectural solution was to roof over the malls, which had the dual benefit of shielding the customers from the weather and permitting more attractive finishes and open shop layouts. This approach, combined with good management, was largely successful in attracting custom.

These new types of shopping centre posed safety problems to the building authorities. What had been a succession of small buildings was transformed into one large one, thus breaking the compartmentation rules. There was a real worry about fire spread: for example, some of the early covered malls had very low roof slabs so that any flames emerging from a burning shop would be immediately deflected horizontally, instead of flowing upwards as formerly, and fire would rapidly spread to adjacent shops. The solution was to make each shop into a compartment, except for the front wall, and to install automatic sprinklers, which are designed to operate while the fire is still small and to control its growth until extinguished by the fire brigade. Sprinklers are more successful than compartmentation in reducing fire spread and fire losses.

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The other problem identified by the researchers was the potential smoke logging of the malls. People emerging from a shop would no longer be in the open air and would have to travel some distance along the mall to reach an exit. Meanwhile, smoke could be travelling under the ceiling faster than a man could walk. Various solutions were discussed: stop the smoke getting into the mall, either by using a shutter or by having within-shop smoke extract, or let the smoke into the mall and deal with it then. The third option was the one chosen, and the solution was similar to that used for industrial buildings: place screens at regular intervals beneath the mall roofs and install automatic ventilators in the reservoirs thus formed. This would localise the heat and smoke effects and leave the remaining parts of the malls relatively unaffected and available for escape. Experiments in a mock-up mall were carried out and guidelines established by Hinkley (1975). In design, it was possible to assume that the fire would be restricted in size by the sprinklers and the standard of extract determined accordingly. Later guidance, by Morgan (1979) incorporated his work on spill plumes, though subsequently reservations have been expressed (Hansell *et al.* 1993).

The atrium building

An atrium is used to introduce light and space into a deep building. It may also be used for ventilation, a function of the old style light wells. When the enclosure of the atrium is similar to an external enclosure it is not immediately obvious that the risk of fire spread upwards is made any worse, but a roof over the atrium will keep in smoke which, as it stacks down, may spread into the adjoining floors and threaten the people inside. Moreover, there may not be any enclosure between the building and the atrium and the old compartment rules will certainly be broken.

The solution which has been adopted to limit upward fire spread in tall atrium buildings is to have the floor slabs made to compartment standards up to the atrium edge and to install automatic sprinkler systems at each level. In low-rise atrium buildings where people can escape easily, it may not be essential to install these measures. However, the matter of smoke spread in the atrium needs to be addressed in relation to escape design, for high and low buildings, if smoke rises from a fire on an adjacent floor. Smoke extract from the atrium, or from the floor where the fire starts, can be provided if necessary using similar approaches to those developed for industrial buildings and shopping centres.

An early example of a modern atrium in London is the Lloyds building. The lower floors are completely open to the atrium, thus preserving the tradition that all trading takes place in one room. The upper floors, used as offices, have glazed enclosure. All floor areas, except the atrium base, are protected by sprinklers, and mechanical smoke extract is installed at rhe top of the atrium. During discussions with the design team, I noticed some diagrams showing patterns of air flow in the atrium. These had been prepared by our environmental physicists using, as I learnt later, computational fluid dynamics (CFD). They were exploring the possibility thar in winter there might be cold down draughts near the base of the atrium, caused by cold glass at high level. I asked immediately if they would do similar smoke movement calculations — after all it was the same physics — and this was the start of a fruitful collaboration.

In Lloyds, as in many atrium buildings, the base of the atrium is kept virtually free of fire load. This is because sprinklers placed at roof level would be too high up to be effective. Later, an alternative sprinkler system was developed by our fire group, in collaboration with a sprinkler manufacturer and a detector manufacturer, which permits free use of the atrium base (Peacock & Frost, 1991).

Airport terminals

Airport terminals are designed to move large numbers of people effectively through various procedures on their way to embark or afrer they have disembarked, and this seems to fire engineers to work in favour of efficient escape from fire. However, this efficiency is achieved by having uninterrupted spaces in the terminals and this can conflict with the compartmentation rules.

The terminal at Stansted, UK, has a single-storey public concourse with an undercroft containing baggage handling, service road and so on. The client wanted a flexible building, where it was easy to change layouts. Accordingly, for fire safety, we developed a cabin concept. We considered the circulation areas to be relatively free from sources of heat and smoke and thus reasonably safe, provided we could deal with potential fires in such areas as duty free shops and restaurants. It was not practical to compartmentalise them so an ‘open cabin’ was developed: a canopy would be placed over each shop or restaurant, to act as a smoke reservoir, with sprinklers and smoke extract installed inside to prevent smoke spillage into the concourse. Offices which did not need to be open to the public could be in ‘closed cabins’ designed to deal with heat and smoke without affecting the public. The design of smoke extract for the open cabins had already been established by the earlier work on shopping centres.

What presented more difficulty was the design of the escape routes. In our opinion, the best routes would lead directly to the open air at ground level through the glazed enclosure of the concourse. The routes preferred by the fire authority took people down to the service road because in this way travel distances to an exit did not exceed the 45m laid down in escape codes. However, in view of the height of the roof above the concourse (some 12m) we believed there was enough reservoir to hold smoke while people escaped at the concourse level. Our client was interested in further studies, and we first measured walking speeds of passengers in the most crowded conditions, identified as in the baggage reclaim area (Law, 1990). Our environmental colleague calculated smoke accumulation, assuming a growing fire and no smoke extract, and we were able to show that evacuation through the enclosure could still be completed well before smoke conditions became adverse (Waters, 1989). It was at this time, having noticed our computer graphics illustrating structures, that we asked for similar graphics to illustrate our smoke calculations. These explained the results more clearly than graphs and were novel in the fire engineering world at that time.

Later, in the fire safety design for the new airport terminal at Kansai, Japan, we introduced not only the cabin concept but also the island concept. The Japanese authorities were concerned that fires might start in a pile of luggage, for example, and spread to others by radiant heat transmission. The concept of islands of separated fuel load had earlier been identified by Marchant (1979). We were able to calculate the exposure hazard by estimating the size of the fire and showing that the intensity of radiation was too low to ignite adjacent islands (Beever, 1991). The ignition model of 30 years ago was still proving its worth.

CONCLUDING REMARKS

This brief review has dealt with only a small part of the research carried out. In part, it has selected projects which illustrate different methods of computation. Such tools may be used to study particular problems, for example the escape of passengers from an aircraft on fire (Galea, 1994). They can be used to answer ‘what if’ questions and to carry out sensitivity

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tests. They can also generate design guidelines based on an engineering model. The starting point, however, must be an engineering model which is scientifically consistent and with stated limits of application. Soundly based models, however simple, endure.

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