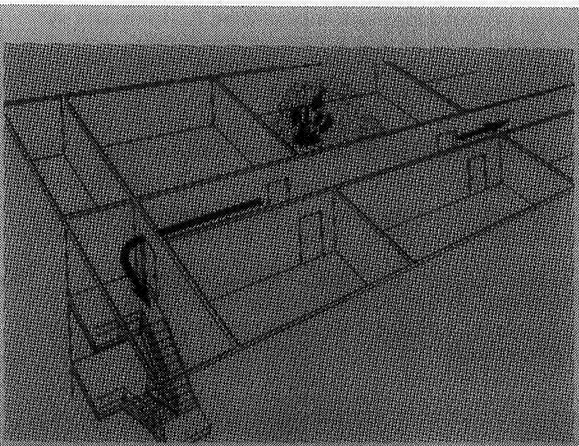
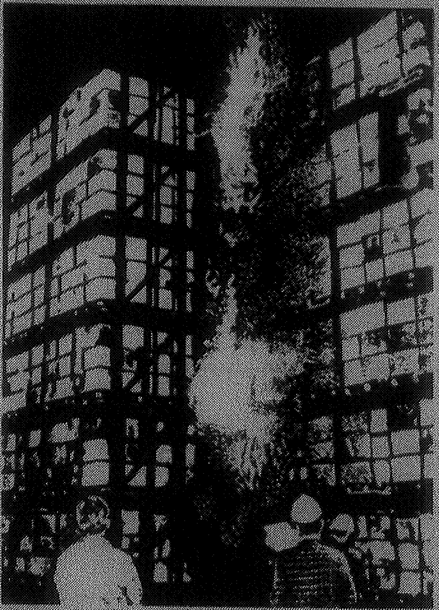
NUMBER 22 DECEMBER 1979

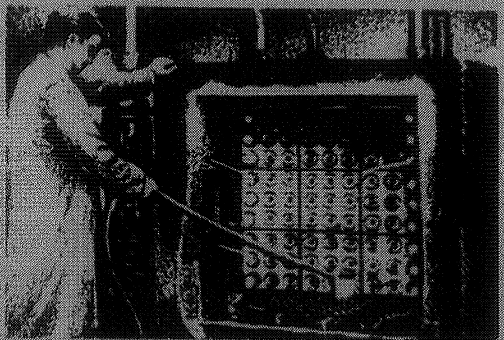
FPA FIRE PREVENTION Science and Technology



The computer simulation of smoke movement during building fires



The burning of solid materials



Towards a rational approach to fire safety

Flame retardent furane resins

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Science and Technology

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This paper gives a brief description of the new computer package developed by the Oscar Faber Partnership for predicting the movement of smoke during a building fire. Four levels of complexity in the simulation are possible and the results of these different types of analysis for a multi-storey building are described.

Reproduction simulée des mouvements de fumée lors de l'incendie d'un bâtiment.

Cet article décrit brièvement un système de reproduction par ordinateur des mouvements de fumée lors de l'incendie d'un bâtiment, mis au point par l'Oscar Faber Partnership. Ce système permet quatre degrés progressifs de complexité dans cette reproduction et notre article donne les résultats de ces différentes analyses pour un bâtiment à plusieurs étages.

Die Computer-Simulation der Rauchbewegung bei Bränden in Gebäuden

In diesem Artikel wird das von der Fa. Oscar Faber entwickelte Computer-Paket für die Voraussage der Rauchbewegung in einem Brand in einem Gebäude beschrieben. Vier Komplexstufen sind bei der Simulierung möglich, und die Ergebnisse dieser verschiedenen Analysestufen an einem mehrstöckigen Gebäude werden beschrieben.

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The burning of solid materials 9

The author investigates the burning of solid materials and emphasises the complex nature of the process. Complexities are due to such factors as type of ignition, thickness and nature of combustible material and its position in relation to ignition sources and ventilation openings.

La combustion des matières solides

L'auteur étudie la combustion des matières solides et souligne la nature complexe de ce phénomène. Les complications résultent de facteurs divers dont le mode de mise à feu, l'épaisseur et la nature de la matière combustible, ainsi que sa situation par rapport à la source du feu et aux ouvertures d'aération.

Die Verbrennung von Feststoffen

Der Verfasser untersucht die Verbrennung von Feststoffen und betont die komplexe Art des Verfahrens. Schwierigkeiten ergeben sich aus solchen Faktoren wie der Art Entzündung, Dicke und Art des entzündlichen Materials und seiner Lage in bezug auf die Entzündungsquelle und die Entlüftungsöffnung.

Towards a rational approach to fire safety 16

A methodology is suggested which regards fire safety as an aspect of a larger system. The occurrence of fire is viewed as a system failure.

Comment aborder rationnellement la prévention des incendies

L'auteur suggère une méthodologie dans le cadre de laquelle les mesures de prévention de l'incendie s'intègrent dans un système de plus grande envergure. L'éclatement d'un incendie témoigne alors de l'échec du système.

Auf dem Wege zu einem rationellen Vorgehen bei der Feuersicherheit

Es wird eine Methodologie vorgeschlagen, die den Feuerschutz als Aspekt eines größeren Systems betrachtet. Das Entstehen eines Feuers wird als Systemstörung gesehen.

Flame retardant furane resins 21

Furfuryl alcohol resins are being considered for use in fire retardant ducting. This paper reports on the results of laboratory tests on laminates for flame spread and smoke generation, and compares the performance of furane resin laminate with test requirements for ducting.

Résines furaniques ignifuges

On considére actuellement la possibilité d'utiliser les résines à base d'alcools furfuroliques à l'ignifugeage des conduits et canalisations. Cet article contient les résultats d'essais de laboratoire portant sur les caractéristiques de propagation de la flamme et de production de fumée de divers stratifiés et une comparaison du comportement des stratifiés de résine furanique avec celui exigé des matières utilisées à la fabrication des conduits.

Feuerhemmende Furanharze

Furfuryl-Alkoholharze werden für die Verwendung in feuerhemmenden Kanälen in Betracht gezogen. In diesem Artikel wird über die Ergebnisse von Laborprüfungen an Laminaten in bezug auf Flammenausbreitung und Raucherzeugung berichtet, und Vergleiche zwischen dem Verhalten von Furanharzlaminaten und den Prüfungserfordernissen für Kanäle werden angestellt.

The computer simulation of smoke movement during building fires

S. J. Irving, BSc Eng, Oscar Faber & Partners

An understanding of the spread of smoke during the course of a building fire is an important element in the design of the fire safety system. Smoke and heat are transported through the building by the air flows that exist due to stack and wind effects, and any mechanical ventilation supply. The recently developed computer programme simulates these air flows, and the changes that occur as the fire develops. The programme accommodates four levels of complexity in the model, which allows the user to balance the accuracy of the simulation and the computing time.
This paper briefly describes the model and presents the results for a fire in a test building, for the four levels of analysis.

The computer model

The spread of smoke through a building is caused by air movements driven by pressure differences between individual rooms and the external environment. The magnitude of the air flow is a function of the pressure difference between rooms and the resistance of the path (or paths) connecting them. Thus the smoke movement problem can be represented by a network, where the nodes represent rooms and the interconnecting branches represent the flow paths, eg ventilation ducts and cracks around windows and under doors. The spread of smoke and heat through the network can then be calculated by application of the laws of continuity, mass conservation, and energy conservation. The computer simulation has three distinct phases:

- definition of the flow network
- calculation of the steady state flow balance in the network
- calculation of the smoke and heat movement as the fire develops

Definition of flow network

The test building under consideration (Figure 1) is basically that described by Tamura[1]; there is a flow path between each room and the external environment, each room and the central shaft, and each room and the room immediately above and below. The resistance of each path is based on measurements of typical buildings as described by Tamura[1,2]. Based on this building description, the flow network shown in Figure 2 can be set up. The external environment is represented by two nodes, 1 and 43, representing the windward and leeward sides of the building. The network is described simply by specifying all the branches in terms of the two nodes to which they are connected. The programme uses this information to set up arrays which fully define the network and allow the immediate identification of the several nodes to which any one node is connected, and the properties of the connecting branches. This approach allows simple data input, and easily enables branches to be added, or removed. The resistance of each flow branch is defined using a data stream concept, thus avoiding

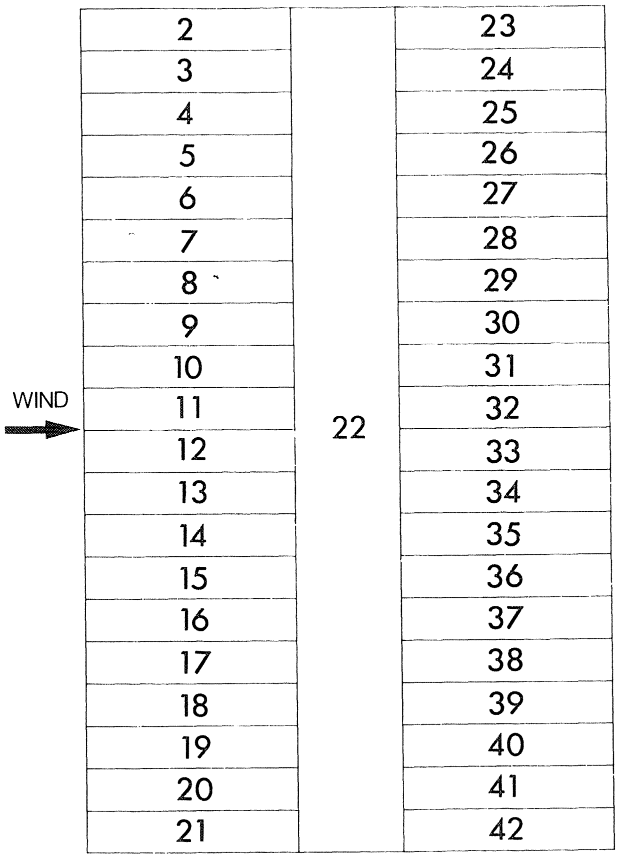

Fig. 1. Schematic diagram of building.

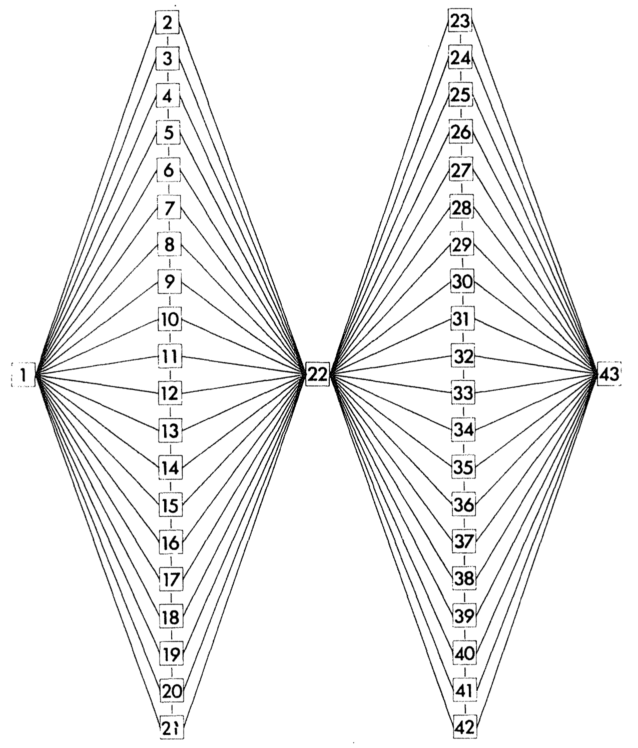

Fig. 2. Network description of air flow paths.

the need to duplicate data if the characteristics of several branches are identical.

Steady state flow balance

The steady state flows are set up by three separate mechanisms. Firstly, there is the stack effect caused by different air temperatures, and hence densities, between the inside and the outside of the building, resulting in different pressure gradients on the two sides of the external wall. In cold weather, this pressure difference across any opening causes air to enter the lower floors of the building and leave through the upper floors. Wind effect is the other environmental parameter which affects the air flow through the building. The pressure rise due to wind action on the external face of a building is given by:

$$p_W = C_p \tfrac{1}{2} \rho v^2 \qquad (1)$$

Where Cp is the wind pressure coefficient
  ρ is the air density
  V is the wind velocity at a given elevation

The wind velocity increases with height due to the boundary layer effect of the surrounding terrain (from open countryside to city centres) as described by Davenport[3]. The third mechanism for driving air through the building is any mechanical ventilation supply or extract, which can represent an important element in the factors controlling smoke movement through a building. The simulation of mechanical ventilation systems is particularly useful for testing pressurization as a means of protecting escape routes from smoke contamination.

Having identified the mechanisms causing pressure differences through the network, the steady state pressures and flows can be calculated. This is done by applying the law of continuity at each node in the network, ie for the i th node.

$$\Sigma\, g_{ij} = 0 \qquad (2)$$

where g is the mass flow in the branch connecting node i to node j. Each mass flow term is a function of the pressures in nodes i and j and the characteristics of the connecting branch. These characteristics can be of two forms

$$\text{(i)}\quad g = k\,(\rho \Delta p)^n \qquad (3)$$

where k and n are flow coefficients. The coefficient n can vary from 0.5 to 1.0 depending on the type of duct or crack.

$$\text{(ii)}\quad g = (a + b\Delta p + c\Delta p^2) \qquad (4)$$

where a, b, and c are coefficients defining a quadratic through the fan flow/pressure characteristic. Because of the non-linearity of these expressions, and the fact that typical building networks will have a large number of nodes, matrix methods for solving the flow balance are both cumbersome and expensive on computer core requirements. Consequently the network is balanced using a Newton Raphson iterative technique which progressively adjusts the node pressures until the total flow into each node is less than a specified tolerance.

Smoke and heat movement as the fire develops

Having set up the steady state flows, it is possible to start a fire in a specified room, or rooms. The characteristics of the fire are defined by a prescribed temperature-time curve and a varying pollutant production rate. The movement of smoke and heat from the fire rooms to other spaces is assumed to take place entirely as a result of the air movement. Heat conduction through the building fabric is assumed to be negligible during the critical stages of the fire development. The spread of smoke and heat is determined by performing mass and energy balances for each node in the network. The conservation of mass gives

$$\Sigma\,(g_{ij} C_{ij}) + m_i = M_i \frac{dC_i}{dt} \qquad (5)$$

where
  g_{ij} is the mass flow rate in the branch joining nodes i and j
  C_{ij} is the concentration of smoke in that flow
      C_j for flows entering node i
      C_i for flows leaving node i
  m_i is the rate of smoke production in the room
  M_i is the mass of air in room i

The conservation of energy gives

$$\Sigma\,(g_{ij}\; S\; T_{ij}) + q_i = S \frac{d}{dt}(M_i T_i) \qquad (6)$$

where S is the specific heat
  T_{ij} is the absolute temperature of the flow in the branch joining nodes i and j
      T_j for flows entering node i
      T_i for flows leaving node i
  q_i is the heat generated within the room

Analysis of this smoke movement

The four levels of complexity in the analysis relate to the formulation of the mass flow rates from room to room.

The simplest form of the analysis is to assume that the flows through the building remain as they were at the beginning of the simulation. This form of analysis may be used to predict smoke movements in the case of a fully developed fire, if conditions can be regarded as steady. However, as a fire develops and temperatures rise, the stack effects will be modified; additionally the thermal expansion of the hot gases will change and perhaps even reverse some of the flows through the building. It is these effects that are simulated by the more complex levels of analysis.

The second level is to subdivide the course of the fire into a series of pseudo-steady states. After each time step, a new temperature distribution through the building is obtained by application of the energy balance, equation (6). A new flow balance can then be determined by using the new room temperatures to recalculate the room air densities, and then to update the stack effects. This approach assumes that the room static pressures remain constant. This assumption is clearly an approximation, and so the third level of the analysis does a full pressure/flow rebalance at every time step, using the iterative procedure described earlier.

The fourth level of the analysis is to carry out a full dynamic simulation, where the thermal expansion of the gas is accounted for, in addition to the effects of stack, wind and mechanical ventilation. This can be achieved by the simultaneous solution of the governing differential equations but this involves a very considerable computing effort. The approach adopted in the Oscar Faber Programme is to use an approximation which simulates the thermal expansion effect, without increasing the computing effort much above that for the variable stack effect analysis described previously. Again, the course of the fire is subdivided into a series of pseudo-steady states with, after each time step, the application of the energy balance to give a new temperature for each room. The increasing room temperature will cause the gases to expand and raise the room pressure. Consideration of the gas laws indicates that an increase in temperature has the same effect on the pressure as a proportionate increase in room air mass. The effect of the temperature rise in the room can be simulated by an additional 'pseudo mass flow' into the room, which is independent of the pressures in the room concerned and in the connected compartments. When the flows are rebalanced, the additional flow is included in the calculation, giving an out of balance to the real flows and a simulation of the expansion effect.

The application of these four methods to a twenty storey test building will now be described.

Smoke movement during the test building fire

For the test building considered (Figs 1 and 2), a fire was started on the leeward side of the third floor (Room 39). The characteristics of the fire were a constant smoke production rate and a room mean temperature-time history rising from the building interior temperature of 24 °C to 300 °C in the space of 18.0 minutes. (These particular characteristics are somewhat arbitrary and can be easily changed in the input data specification). The external environmental conditions were a temperature of 0 °C and a wind speed of 6.7 m/s at the reference height of 10.0 metres above ground level. Wind pressure coefficients of 0.8 and −0.6 were assumed for the windward and leeward sides of the building.

Levels of analysis

The first stage of the fire analysis is common to all the simulation methods, and involves the setting up of the steady infiltration into the building. This is done in a separate programme and the steady state pressures and flows are stored in a binary file for access by the smoke movement programme. Initial distribution of flows through the building is shown in Figure 3. The effect of the wind in biasing the stack effects can be clearly seen in that flow enters the building over the full height on the windward side and over the lower third on the leeward side. It is the way in which these building flows are considered during the course of the fire which differentiates between the various levels of analysis.

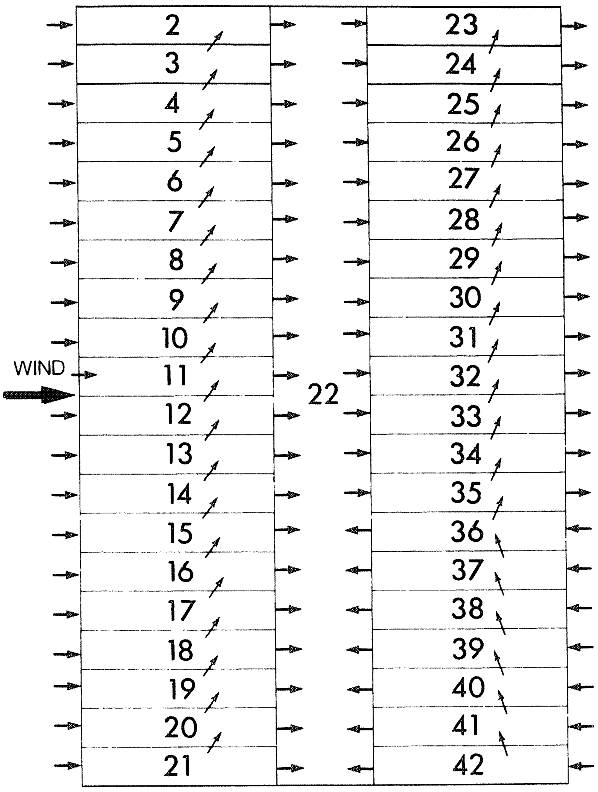

Fig. 3. Steady state pattern of air movement.

The steady state

The first form of the analysis, the steady state method, assumes that these initial flows remain constant during the course of the fire. Figure 4 shows the conditions in the fire room for this type of analysis. (Many of the graphs in this paper are drawn using plotting programmes which are a part of the smoke movement package). The simulation has predicted that smoke has penetrated to rooms 38 and 37 above the fire room by transport through floor-ceiling cracks. Smoke has also entered rooms 25-35 via the central shaft. The limitations of the steady state method can be seen from Figure 4, where the fire room temperature changes significantly during the course of the fire.

Constant pressure-variable stack

The changes in the flow pattern caused by the changes in room air temperatures and densities can be simulated by the other levels of analysis. The importance of these changes can be seen from Figure 5 which shows the flow pattern at the end of simulation for the second type of analysis (constant pressure-variable stack). In this case the increasing stack effect has overcome the wind effects over the top seven floors on the windward side, and also shifted the neutral plane on the leeward wall up by two floors. This means that the top seven floors on the windward side of the building are now predicted to have some smoke contamination; additionally, the

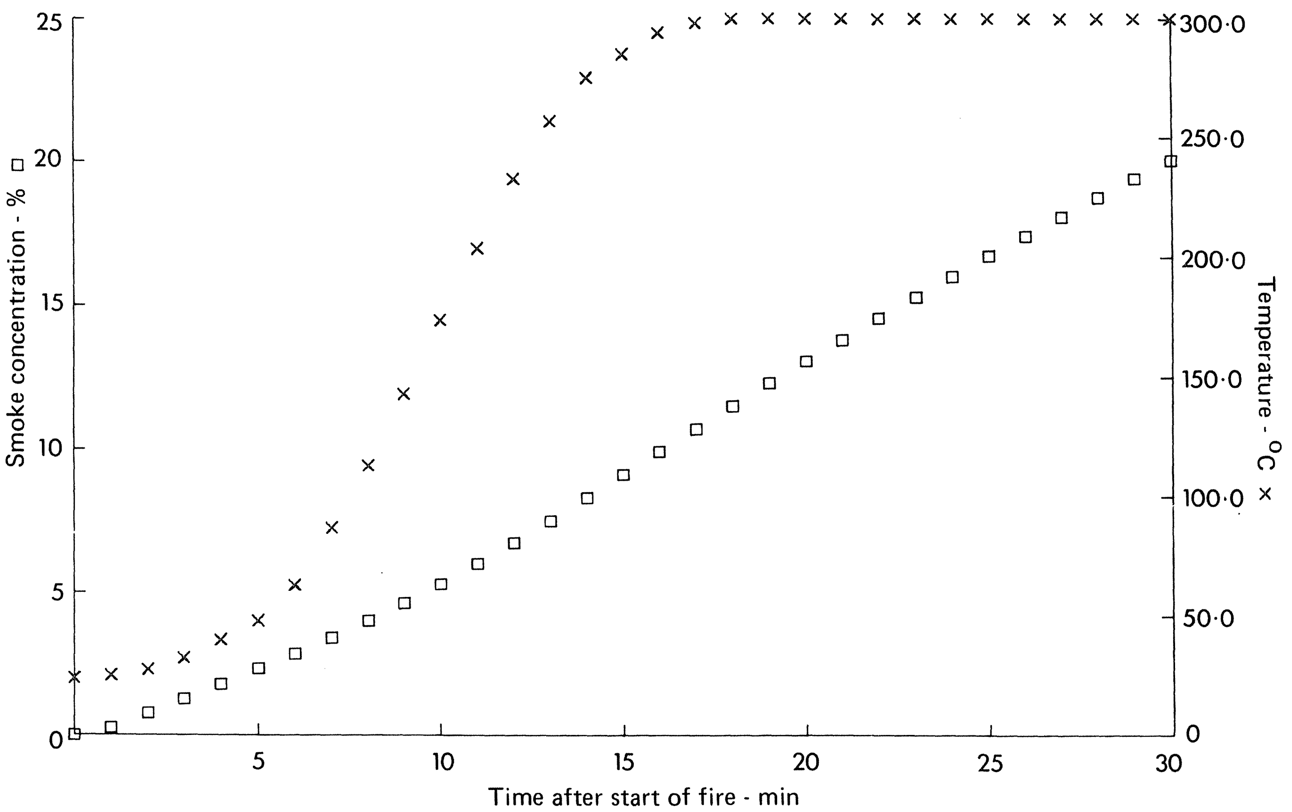

Fig. 4. Conditions in the fire room.

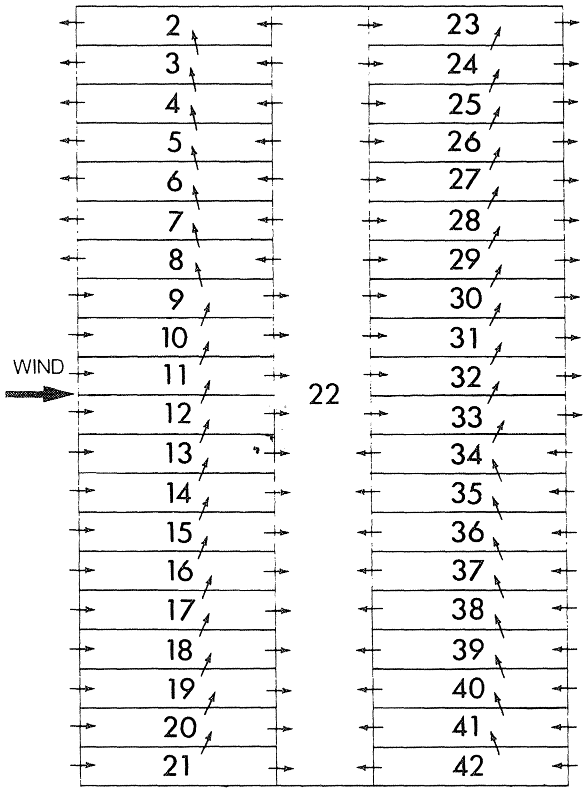

Fig. 5. Pattern of air movement after 30 mins of fire.

increased stack effects have increased the flow through the ceiling-floor cracks above the fire room by a factor of about three. This leads to a much greater smoke contamination of the rooms immediately above the fire. The effect of the smoke movement on the building as a whole can be seen from Figure 6 which plots the smoke concentration-time history for those rooms having a concentration above 1200 ppm (equivalent to a visibility range of about 10 metres).

Variable pressure-variable stack

The constant pressure-variable stack type of analysis, although a closer approximation to reality, is still an approximation since it is evident that as the stack effects change, then the static pressures will also change. By holding the static pressures constant, the stack effects are over estimated, and so the third level of simulation recalculates the static pressures at every time step by the use of the iterative procedure described previously.

Full dynamic situation

The importance of the thermal expansion is not readily apparent from a consideration of the flow patterns at the end of the simulation, since they are virtually identical to those at the end of the variable pressure-variable stack type analysis as the system approaches a new steady state. However, the important difference is seen in the form of the flow transients as the fire develops (Figure 7). This figure is a plot of the flow through the floor-ceiling cracks from the fire room 39 to the room above, 38. It can be seen that as the fire room temperature rises rapidly, the effect of the thermal expansion causes the hot gases to be expelled from the fire room at a much faster rate than that due to the increased stack effects alone. Additionally the expansion effect also overcomes the local stack action, and forces smoke downwards into the room below, 40, a situation which none of the other analyses had predicted. The importance of these expansion flows in terms of fire safety analysis can be seen from Figure 8 where the smoke build up in the central shaft is shown for the variable pressure-variable stack and the full dynamic analyses. The shaft is the main escape

Table 1
Room smoke concentrations (ppm) 20 minutes after the start of the fire

Room number	Steady state	Constant pressure variable stack	Variable pressure variable stack	Dynamic analysis
2	0	608	199	469
3	0	562	112	342
4	0	501	<100	197
5	0	433	0	<100
6	0	352	0	0
7	0	251	0	0
8	0	117	0	0
22	6919	7473	7141	7098
23	548	919	685	1103
24	546	890	658	1055
25	536	853	630	1007
26	519	811	599	958
27	497	762	567	909
28	472	708	533	857
29	444	648	496	803
30	412	579	456	743
31	378	499	411	677
32	339	400	360	602
33	293	258	298	513
34	237	<100	214	394
35	160	<100	<100	160
36	<100	<100	<100	<100
37	<100	107	<100	245
38	2818	6330	5794	7291
39	130660	121247	124084	107936
40	0	0	0	3297
Computer Time Units	1.0	1.2	5.4	15.4

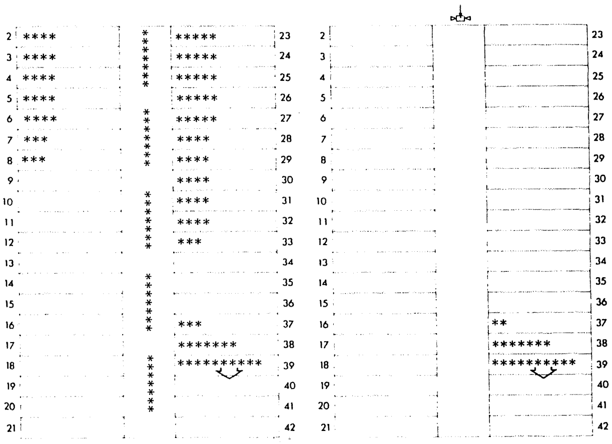
(i) No shaft pressurization (ii) With shaft pressurization

Fig. 9. Effect of shaft pressurisation on smoke spread—conditions 30 mins after start of fire.

building is the pressurization of the central shaft by means of a fan. This approach has been examined for the test building and the results are shown in Figure 9. The figure shows the smoke spread through the building after 30 minutes of fire for the original building and for the case with shaft pressurization. Each additional star in a room represents an increasing smoke concentration on a logarithmic scale. It can be seen that the pressurization has kept the central shaft completely smoke free, and the only rooms to have been contaminated with smoke are the fire room, and those immediately above. The smoke has entered these rooms via the floor-ceiling cracks, and this smoke movement could only be prevented by better stopping around service ducts and pipes between rooms.

The value of the computer package

The computer package described in this paper is a useful tool in the design of the fire safety system of compartmentalized buildings. The package can be used to calculate the flows through a building caused by the action of wind, stack and mechanical ventilation. These flow rates vary as the fire develops, and these varying flows can be used to calculate the spread of smoke and heat from room to room. In the past, the thermal expansion of the hot gases has usually been ignored. The present model approximates this effect and it is clear that it can exert a very significant influence on the rate and the extent of the smoke spread.

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The burning of solid materials

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The burning of solid materials in fires is complex. The complexities spring from the many variations in the nature of solid materials, the size and shape of each solid object and the position of each object relative to others and to sources of heat. In any assessment of fire hazard, possible sources of ignition and the ensuing burning or flame spread must be considered in the context of these variations.

Ignition

Several different types of ignition of solid materials have been recognized:

Spontaneous ignition with external heating refers to the appearance of a flame in the volatile material evolved from the solid material when exposed to an external heating source.

Pilot ignition refers to spontaneous ignition with external heating but with the additional aid of an external ignition source in the volatile stream formed when the material is heated.
In both of these cases, the flame may appear only momentarily at the surface and this is called transient ignition. Sustained or permanent ignition is said to occur when the flame is maintained at the surface and the material continues to burn in the absence of additional heat.

Spontaneous ignition by self heating occurs when generation of heat within the material by exothermic chemical reactions raises the temperature of the material until it bursts into flames.
A further type of ignition is also discussed in the literature; *glowing ignition* occurs if the surface glows without the presence of a flame.

Ignition tests

The ease with which a material ignites may be assessed by either of two properties, for example:

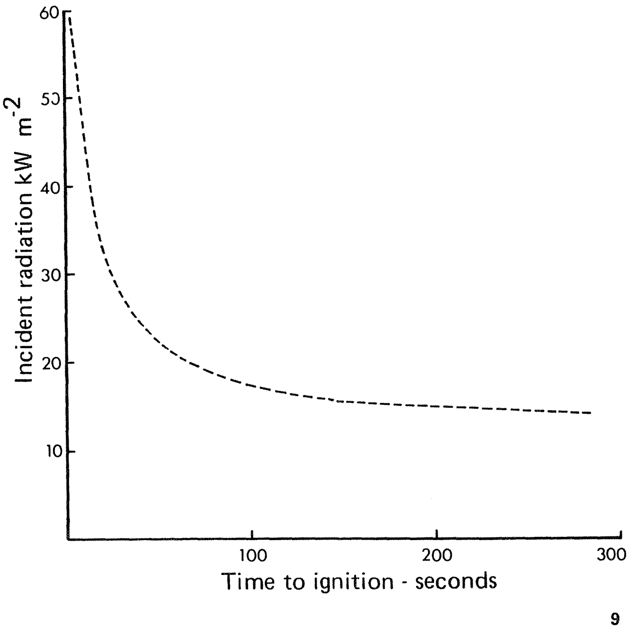
- the minimum quantity of radiant energy falling upon the material which causes ignition.
- the time taken for the material to ignite when subjected to radiation above the minimum level.

Several heating sources have been used in ignition tests. In the radiant panel tests, a gas-air mixture is forced through a porous ceramic plate and burned on the surface. The sample is placed opposite the panel and is kept far enough away that it is not in contact with the hot combustion gases. Heat transfer to the sample is therefore by radiation from the panel, with no convective heating. Radiant panels are usually limited to fairly low rates of emission (80 kW m $^{-2}$) by the relatively low temperature of the panel (approximately 1100 K). Carbon arcs have been used to obtain irradiation levels of up to 400 kW m $^{-2}$ in which case the effective black body temperature of the carbon arc was about 5500 K. Smaller but still relatively high irradiation has been achieved with tungsten filament lamps (2800 K), graphite resistance furnaces (2000 K) and solar furnaces.

Data on ignition

The incident radiation is the primary independent parameter in most studies and the time to ignition is almost invariably measured. Other parameters measured or calculated in ignition tests include the surface temperature and the temperature distribution within the specimen, the rate of weight loss of the sample, absorption of radiant energy by the sample, size of sample, moisture content and convection effects.
The rate of rise of the temperature of the surface and the time (t) to ignition depends on the amount of energy supplied to the surface. Fig. 1 shows the

Fig 1. Effect of incident radiation on ignition times



ignition times for pilot ignition of wood plotted in terms of the amount of radiant energy incident on the sample. If the amount of radiation is less than a minimum value the surface temperature does not increase to the ignition temperature however long the sample is exposed to the radiation. This minimum value is determined from experiments at several levels of incident radiation (Q). A plot of Qt^{-1} or $Qt^{-\frac{1}{2}}$ and extrapolation to zero gives the minimum or critical level of radiation. This value is always lower than the minimum amount of radiation required in practice because prolonged exposure to radiation changes the nature of the fuel itself and the volatile matter produced also changes. Table 1 is a list of critical radiation levels for a number of materials.

Table 1 Critical radiation levels[1]

	Critical radiation kW m^{-2}	
	Pilot	**Spontaneous**
Wood	14.65	29.31
Wood, painted	16.75	23.03 to 50.24
Hardboard	10.46	—
Textiles	—	35.59
Hemp, jute and flax	—	41.87
Cork	3.35	23.03

In many cases, 12.6 kW m^{-2} is chosen as a safe level in studies made to predict safe distances from burning buildings[1].

Several methods have been used to estimate the surface temperature at ignition—placing thermocouples in contact with the surface of the sample[2], extrapolation of the interior temperatures measured at the time of ignition to the surface[3], the use of radiation detectors at the sample position[4] and calculation[5]. The critical surface temperature is called the ignition temperature of the material although it is not a fundamental property of the material.

Simms and Law[5] estimated pilot ignition temperatures for wood to be about 350°C and spontaneous ignition temperatures about 525°C and Bamford predicted the minimum rate of weight loss at ignition to be about 2.5×10^{-4} g cm^{-2} s^{-1} for wood.

The effects of varying spectral absorptivities and transmissivities of cellulosic materials have been examined[2] primarily because the spectral distribution of energy is different for different radiation sources. Of course, once the surface layers have carbonised, the materials become nearly opaque to thermal radiation. Simms[6] has given a number of empirical factors to apply to various materials to correct for absorptivity effects.

Walker *et al.*[7] showed the significance of these effects in tests on the ignition of cotton fabric. They showed that ignition of white cotton fabric occurred in less than one-third the time if radiation from a flame instead of from a tungsten lamp (2500 K) was used. The differences in ignition times were caused by the high absorptivities of the cotton fabric at wavelengths characteristic of emission from the flame and low absorptivities at wavelengths at which the emission from the tungsten lamp was strongest. When absorbed irradiances were set equal, ignition times were found to be the same.

The area of samples used in ignition tests is significant in some cases. Alvares *et al.*[8], after discussion of the effects of free convection on ignition of cellulose by thermal radiation, concluded that the height of a vertical sample was important if the irradiation was less than about 15 kW m^{-2}.

Interpretation of ignition data

Although ignition can easily be recognised in a test or in practice by the appearance of a flame, this is not an observation which can be conveniently applied to the analysis of fire. Other indirect criteria of ignition are used including the following.

Ignition is said to occur when

- the surface temperature reaches a critical value[9]
- the mean temperature reaches a critical value[6]
- there is a critical rate of evolution of the volatiles[10]
- a thermal feed back criteria for the sustained spontaneous ignition of thin materials is satisfied[11]
- surface decomposition reactions become self sustaining[12].

The first criterion is most often used and times to ignition have been predicted for spontaneous[3] and pilot[15] ignition based on the heating of inert samples by uniform and constant[13, 14] radiation.

Oxygen index test

A different kind of test, based on burning in a selected atmosphere, provides a numerical index of the ease of burning of materials. The oxygen index is the lowest concentration of oxygen in a mixture of oxygen and nitrogen which will support sustained combustion. A specimen of the material, which is usually in the form of a thin sheet, is held centrally in a glass chimney. The mixture of oxygen and nitrogen is fed to the base of the chimney and the material ignited to burn in a candle-like manner. The test was originally developed to test polymers but many other materials have now been assessed in this way. Isaacs[16] has presented data on a large range of materials and Table 2 is a selection from these.

Table 2 Oxygen index of various materials[16]

Material	Approximate values of oxygen index
Rigid plastics	
Perspex	17
Polystyrene	18
Nylon 6-6 (dry)	24
PVC, various	30, 40, 45
Polytetrafluoroethylene, Teflon	95
Foam plastics	
Polyurethane	17
Natural rubber foam	17
PVC foam	22
Fabrics	
Cotton	19
Rayon	19
Wool	24
Flame-treated cotton	27
Rubber	
Neoprene	26
Wood and paper	
Filter paper	18
Birch	21
Oak	23

An alternative method of conducting this test is to use mixtures at different temperatures and thus estimate the temperature at which burning would be sustained in a mixture containing 21 per cent by volume of oxygen. Figure 2 is an example of data obtained in such a test.

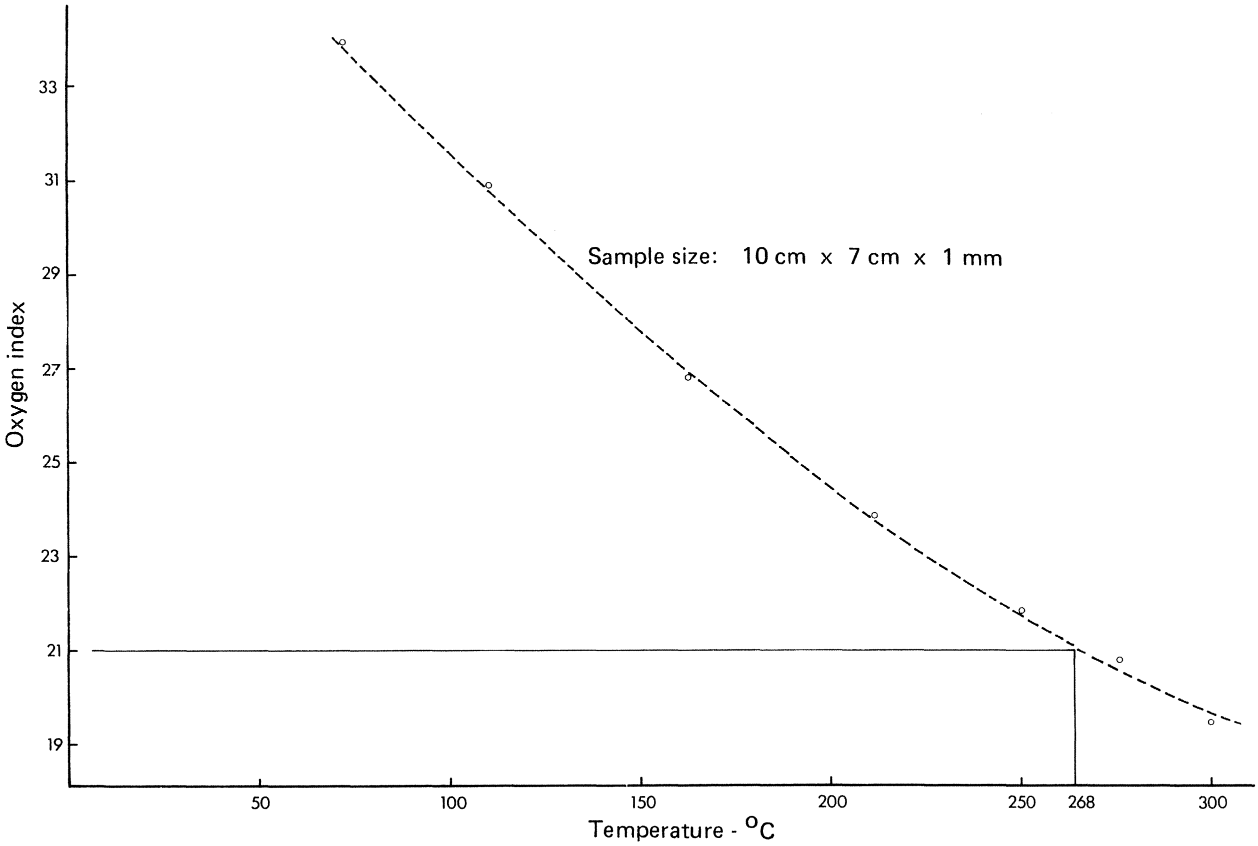


Fig 2. Temperature index of a glass-reinforced polyester (containing flame retardants)

Fire spread

The rate of fire spread in a number of situations is compared with the flame speed in laminar premixed flames in Table 3 (Thomas[17]).

Table 3 Spread of fire or flame[17]

	Rate of spread of fire or flame $m\ h^{-1}$
Charring of wood	0.02
Smouldering of dust layers (still air and against air flow)	0.04 to 0.15
Cribs of wood in still air	0.3 to 5
Card, 10 g m^{-2}, horizontal	15
Urban fire, still air	60
Gorse and heather, winds $< 4m\ s^{-1}$	20 to 60
Card, cotton, upwards	100 to 800
Urban fire, wooden houses, wind $20m\ s^{-1}$	1000
Forest crown fires	1000 to 10 000
Laminar premixed flames	4000 to 100 000

Many solid components of differing size and composition are involved in a fire but testing of a particular material often involves flame spread over a single component. Although tests on single components will presumably lead to greater understanding of the more complex behaviour in a fire, such behaviour cannot be completely predicted from these tests alone and many workers have investigated the burning of structures.

Thickness of materials

Thin materials burn faster than thick materials and this is reflected by their ease of ignition when heated by an external source. (Thin material is less likely to be ignited by heat generation within the material because of cooling from the surface). Thick materials may very well be ignited but are less likely to continue burning when the igniting source is withdrawn. The cold interior of the material absorbs too much of the heat generated by combustion for combustion to continue.

Papers and fabrics burn with a rate of spread V which is inversely proportional to the thickness of the material:

$$tV = C_1 \qquad (1)$$

where t is the thickness, and C_1 is a constant[17, 18]. Since fire spread can be considered as a series of successive ignitions, thin materials burn faster than thick ones because thin materials are raised to their ignition temperature more quickly. From a different point of view, a relationship of the kind shown in eq. 1 demonstrates that heating is by a source external to the fuel. Such a source may be the flame itself.

Parker[19] and de Ris[20] have produced expressions of the same kind for the velocity of flame spread over thin fuels although their explanations of the mechanism of preheating are slightly different. The velocity V is given by de Ris as

$$V = \frac{\sqrt{2}\,k\,(T_f - T_v)}{\rho\,\lambda z\,(T_v - T_o)} \qquad (2)$$

where k is the thermal conductivity, ρ the density, λ the specific heat, z the thickness of the fuel and T_f, T_v and T_o are flame, vaporisation and original temperatures respectively.

Complementary to his expression for flame spread over thin fuels, de Ris[20] has also produced an equation for the velocity of flame spread over thick fuels on the basis of the preheating of fuel ahead of the advancing flame.

Porous fuels

A different relationship from eq. 1 holds for porous fuels like beds of litter or pine needles on the forest floor:

$$\rho V = \text{constant} \qquad (3)$$

where ρ is the density of the fuel.

This result is a consequence of heating of the unburnt fuel ahead of the advancing flame through the bed itself by the burning embers (Fang[21], Sandhu[22] and Thomas and Simms[23]).

Sticks and cribs

The duration t of burning of a stick of wood has been shown to be given by

$$t \propto d^n \qquad (4)$$

where d is the thickness and n is approximately 1.5. Eq. 4 can be derived by considering the heating of an inert material to a particular temperature at the surface when subjected to external heating as long as cooling from the surface is taken into account[13].

Of course, if a stick is of sufficiently large diameter it will not continue to burn alone once a completely external source of heat is removed. Other sticks or material burning in the vicinity may provide the necessary heat, a process which is the basis of the successful burning of large lumps of fuel on a grate.

In practice, a fire consuming solid materials involves flame spread over a number of components arranged in some particular fashion or structure. The simple laboratory studies of this kind of fire have involved stacks or cribs of a single material. Even with this simple situation, the progress of combustion is not well understood although various models have been proposed and a number of correlations produced[24, 25, 26, 27].

It appears necessary to distinguish between cribs of high and low voidages and Smith and Thomas[27] have correlated a great deal of data by

$$R \propto (hA_vA_s)^{\frac{1}{2}} \qquad (5)$$

where R is the burning rate (mass/time), h is the height of the crib, A_s the surface area of the fuel and A_v the total cross sectional area of the vertical shafts. The burning rate is determined from the characteristic weight loss/time curve for the burning of a crib (Fig. 3). Most of the weight loss takes place at a constant rate which is the value used in the analysis of the burning of cribs.

Fires in enclosures

The way in which a fire starts and continues to burn can be illustrated by examining the variation of the temperature of the material in the vicinity of the source of the fire (Fig. 4). Ignition occurs at A after which the temperature remains relatively low. At B, the material in the vicinity of the source rises sharply and combustible materials (fuel) begin to burn actively. The relatively quick ignition of more fuel in this way is called 'flashover'. The temperature continues to rise until heat losses equal the heat produced by combustion. After this (C), the temperature falls because the amount of fuel burning decreases—the fire decays.

In a real fire, the temperature in a room or building changes with position as well as time. The use of a single temperature implies the use of an average. A fire is obviously very complex but it is possible to make some prediction of the changes in temperature with time when a fire occurs on the basis of a few assumptions. These assumptions are:

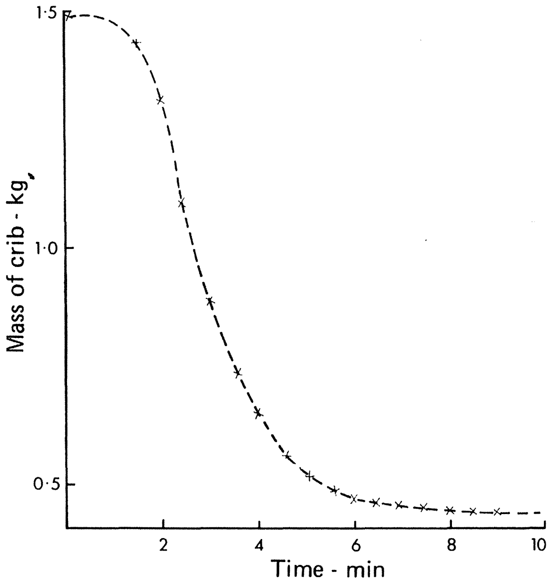


Fig 3. Mass of burning crib (wood)

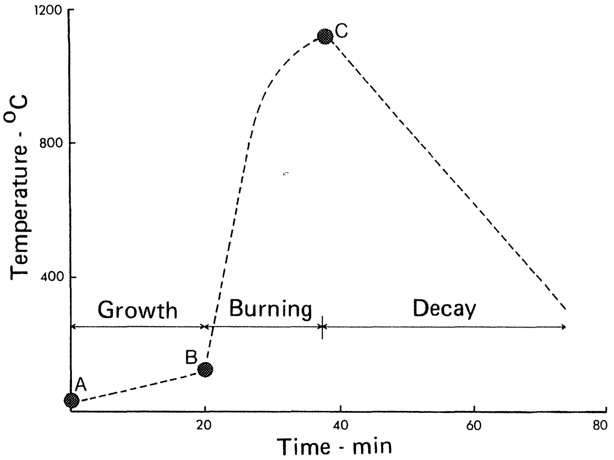


Fig 4. Temperature course of fire

- the temperature in the room is uniform
- the rate of burning is controlled either by the rate at which air reaches the burning material (through the windows) or by the surface area of the fuel.

Growth of a fire

Although the temperatures during the growth period are low, the duration of this period is very important because the development of the fire can most easily be prevented during this stage. In practical terms, people can also escape from a fire during this time.

The duration of the growth period depends on:

- the presence of large areas of easily combustible fuel such as some walls and ceilings
- quantity, size and spacing of fuel
- size and position of ignition sources
- size and position of openings in the room
- direction and velocity of wind.

Burning and decay

For burning to continue in the room, the products of combustion must continue to pass out of the room and air for combustion to pass into the room. For the case of a single opening such as a window the flow of gases through the opening is as shown in Fig. 5. The hot products of combustion flow out of the room through the upper part of the opening and cold air is drawn in through the lower part. In some cases, the rate of combustion of the fuel in the room is determined by the amount of air supplied which, in turn, depends on the size of the opening (of height H and area A). If the opening is sufficiently large and plenty of air is available the rate of burning is then determined by the surface area of the fuel.

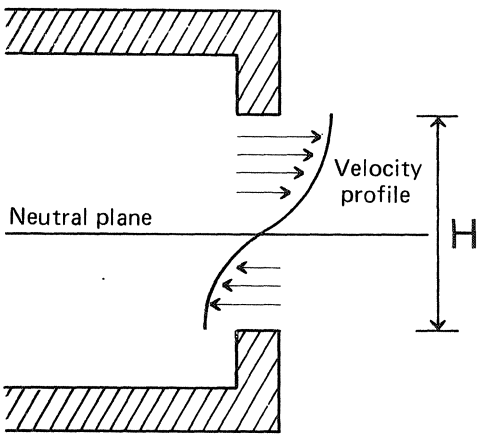


Fig 5. Flow of air and combustion products through a window opening

Control of the rate of burning of fuel in a room by ventilation or the surface area of the fuel depends on the ratio $AH^{\frac{1}{2}} S^{-1}$ where S is the surface area of fuel. According to data on fires, fuel loads of 40-100 kg m^{-1} are mainly ventilation controlled.

Lie[1] has shown that, if burning is controlled by ventilation, the burning rate of the fuel is proportional to the dimensions of the opening.

$$M = C_2 AH^{\frac{1}{2}}$$

where C_2 is a constant. (6)

$AH^{\frac{1}{2}}$ is referred to as the ventilation factor. Experiments have shown C_2 to lie between 5 and 6 and a value of 5.5 is often used.

A heat balance on the room can produce values of the fire temperature as a function of time—the temperature course. Although the temperature course of a fire depends on many factors, it is possible to describe it in terms of two parameters based on the ventilation, the wall area and the quantity of combustible material in the room:

(1) an opening or temperature factor
$F = AH^{\frac{1}{2}}/A_w$ m$^{\frac{1}{2}}$

(2) theoretical fire duration $t = W.A_f/5.5\ AH^{\frac{1}{2}}$ min

where A_w is the area of the walls, A_f the area of the floor and W is the fire load density, that is, the amount of wood per unit floor area that produces, on combustion, a quantity of heat equivalent to that by combustion of the fuel in the room.

The two factors may be interpreted in the following way:

(1) $AH^{\frac{1}{2}}$ is proportional to the burning rate or rate of heat production. F is therefore proportional to the rate of heat production per unit area of the walls.

(2) Similarly $5.5\ AH^{\frac{1}{2}}$ is the burning rate as given by eq. 6 and WA_f is the amount of fuel to be burned.

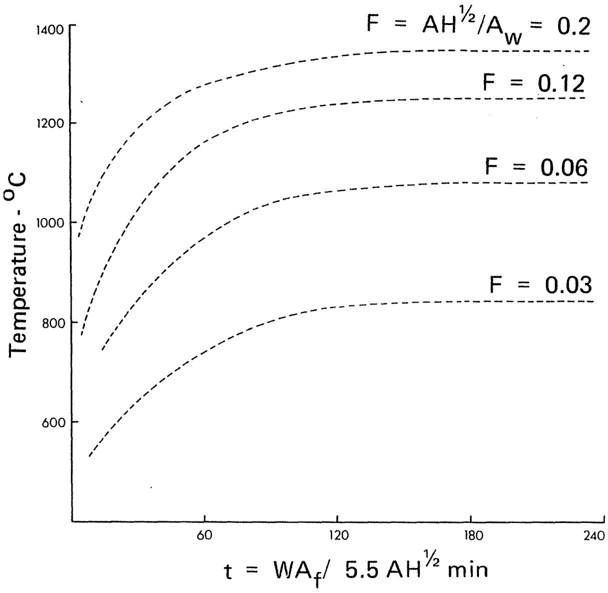


Fig 6. Temperature of ventilation-controlled fires

The ratio of these gives the duration of burning. In practice, of course, the burning rate is not constant but plots of weight loss of fuel against time have shown the burning rate to be approximately constant for about 80 per cent of the burning expressed in terms of the amount to be burned.

The prediction of temperatures during a fire may be made by calculating F ($AH^{\frac{1}{2}}/A_w$) and t ($WA_f/5.5\ AH^{\frac{1}{2}}$). The value of F is used to select the appropriate temperature/time curve from those given in Fig. 6 (after Lie[1]). From time t, the fire decays and the temperature falls. There does not appear to be a satisfactory way of determining the temperatures of a fire during the decay period and, consequently, some empirical values are accepted. For a fire with a burning period of less than one hour the temperature is assumed to fall 10°C min^{-1}; with a period of greater than one hour the rate is taken to be 7 °C min^{-1}.

Lie[1] has given the following example for a room:

Window area and height: $A = 1.67$ m^2; $H = 1.8$ m

Total area of bounding surface and area of floor:
$A_T = 48$ m^2; $A_F = 9$ m^2

Fire load: $W = 100$ kg m^{-2}

$F = 0.047$ m$^{\frac{1}{2}}$ and $t = 1.22$ h

The temperature course of the fire for $F = 0.047$ m$^{\frac{1}{2}}$ is obtained from Fig. 6 up to a time of 1.22 h. After this time, the temperature is assumed to fall at a rate of 7 °C min^{-1}.

Combustion of dusts

When a solid combustible material is in the form of a powder or dust in air, it ignites readily and combustion is rapid; the presence of a flammable gas is unnecessary. The most favourable situation for rapid burning is when particles are dispersed in air so that the air has easy access to each particle but combustion can still take place when the dust lies in a layer, although less rapidly. Also, subsequent dispersion of the dust will lead to more rapid combustion.

Although rates of combustion in a dust layer are less rapid, the temperature at which ignition occurs in a layer is lower than that of the dispersed dust (Table 5). In both cases, the ignition temperature is determined by the balance between heat generated

Table 4 Types of explosion

Type of explosion	Flame speed	Speed of compression or shock waves from flame	Pressure	Pressure rise
	m s^{-1}	m s^{-1}	kN m^{-2}	MN m^{-2}s^{-1}
Deflagration	1 to 10	330	1000	100
Detonation	330	330	3000	—

by reaction at a particular temperature and heat losses at that temperature. When the rate of heat generated exceeds that which can be lost, the temperature rises rapidly and ignition occurs. The heat losses from particles in a dust layer are lower than those from particles dispersed in a gas and, consequently, the temperature at which the rapid rise takes place is lower.

A dust explosion is the combustion of a cloud of dust which results in a rapid increase in pressure or volume. The increase in pressure and/or volume arises principally from the heat developed and the volume of gases generated by combustion. Flame speeds are high in explosions and, consequently, rates of heating often greatly exceed rates of cooling causing pressure and expansion effects already referred to. Typically, the flame speed is in the range 1 to 10 m s^{-1} although shockwaves travel ahead of the flame through the unburnt dust cloud at a velocity of about 300 m s^{-1}. In this case, the shockwave provides an early indication of the explosion.

These flame speeds are much less than the velocity of sound in the gaseous products of combustion and the explosion is called a deflagration. Theoretically, it is possible for the flame speed to reach the velocity of sound and accompany the shockwave (about 300 m s^{-1}) but it is believed that detonations cannot develop from the initial deflagrations which occur in industrial plant. Consequently it is usual to design for the possibility of a deflagration, which is an easier proposition as the data in Table 4 show.

A cloud of dust can, of course, be burned in a controlled way as in a pulverised fuel furnace. In this case, however, the supply of fuel and oxidant is controlled and combustion takes place in equipment designed for it.

Explosibility of dusts

Explosibility is the term used to describe the ability of a dust to cause an explosion. A flame can only propagate through a dust cloud if the concentration of the dust lies between the lower and upper explosibility limits. These limits depend on the composition of the dust, particle size, moisture content and the type of ignition source used. In addition, the result from a particular test depends greatly on how well the powder has been dispersed. The lower limit can be determined reliably, but, because of the difficulties of dispersion (small pockets of low concentration can occur), the upper limit is not easy to measure. In any case, there is less interest in concentrations at the upper limit as far as safety is concerned because it is not practicable to maintain an atmosphere with considerable quantities of dust dispersed in it.

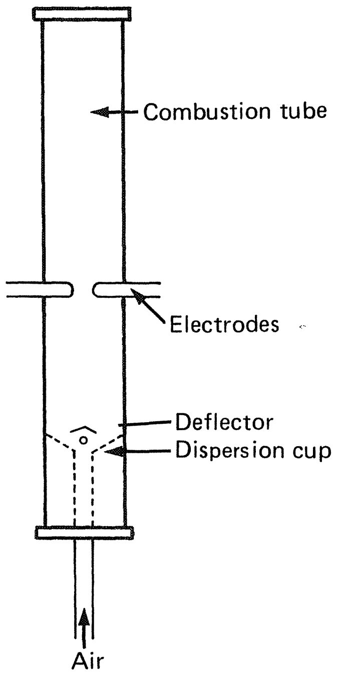


Fig 7. Explosibility test - vertical

Measurement of dust explosibility

The simplest test is one in which a dust/air mixture is observed for ignition and flame propagation in a glass

Table 5 Explosion characteristics of some dusts

	Minimum ignition temperature °C		Minimum explosion concentration	Minimum ignition energy	Maximum explosion pressure	Maximum rate of pressure
	cloud	layer	g l^{-1}	mJ	kN m^{-2}	kN m^{-2}s^{-1}
Flake aluminium	610	320	0.045	10	876	137900
Caprolactum	430	—	0.07	60	669	11720
Activated carbon	660	270	0.1	—	634	11720
Coal (37% VM)	610	170	0.055	60	621	15860
Cocoa	500	200	0.065	120	476	8270
Coffee	360	270	0.085	160	262	1030
Lycopodium	480	310	0.025	40	517	21370
Wheat flour	380	360	0.050	50	752	25510

or perspex tube. A number of versions of this kind of apparatus exist[28] but all are based on the dispersion of the dust by a quantity of air in the presence of a source of ignition. A standard procedure involves the dispersion of the sample of powder from the type of cup shown in Fig. 7 by air from a reservoir of 460 cm^3 capacity and at a pressure of 280 kN m^{-2}. Ignition is obtained from a pair of electrodes or an ignition coil.

In this way, dusts are deemed to be explosible (group (a)) or non-explosible (group (b)). The latter are considered not to be capable of producing an explosion but still may be a fire risk. A classified list of industrial dusts is available from HMSO[29].

An explosible dust can be further tested in order to determine the extent of the explosion hazard and the following attributes of the dust/air mixtures have been measured for a large number of dusts.

- Minimum ignition temperature.
- Minimum oxygen concentration at which ignition occurs.
- Minimum dust concentration for ignition.
- Minimum ignition energy.
- Maximum explosion pressure and rate of pressure rise.

Palmer[28] has listed these characteristics for many dusts; Table 5 is a small selection from the list.

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Towards a rational approach to fire safety

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In order to understand fully the nature of fire safety, which ranges from social values to engineering hardware, it is necessary to attempt to consider it as a part of a 'dynamic whole'. Fire may be regarded as a failure of a system. A methodology which may be of help in attempting to approach fire safety from this point of view is suggested.

Fire safety is often considered in a fragmentary way. That is to say, the elements which combine to produce fire and possible loss of life or injury are often effectively regarded as independent of each other. Such a disjointed approach must inevitably lead to a superficial appreciation of the problems. In order to gain a deep and comprehensive understanding of the nature of the risk in a particular situation, it is necessary to attempt to consider all aspects of the problem in a coherent way. As a part of this an elucidation of the factors involved and the relationship between them is vital. The fire safety in a given situation results from the interaction of a number of 'parts'. That is, fire safety is a characteristic of an entire system and in order to understand fire safety it is necessary to understand the system.

Systemic approach

The word 'system' has been used in many different ways; in this paper the broad definition is adopted that a system is any entity, conceptual or physical, which consists of inter-dependent 'parts'. There is discussion as to just what a 'part' is[1], but such considerations will not be pursued further here and it will be assumed that a 'part' may be fairly easily understood. A closed system is such that no interaction takes place with elements outside the system. Ultimately there is only one closed system —the Universe. Smaller systems will be open to a greater or lesser extent.

A system may be considered as failed if there are aspects of the system which are regarded as undesirable by one or more people involved. Whether or not something represents a 'failure' depends upon one's point of view and position within the entire system. With this in mind it is possible to think of fire as a failure of a system.

In order to gain a full understanding of the fire situation it is necessary to consider the systems involved and to look beyond the immediate horizon. There is a need for a 'systemic approach' to the fire problem and a systemic approach is not the same as a systematic approach. The word 'systematic' may be thought of as implying 'methodical' or 'tidy', but 'systemic' implies something else. To employ a systemic approach is to appreciate the 'dynamic wholeness' in a situation; to see pattern and interrelationship within a complex whole.

A mode of thinking may be systematic and yet not be systemic. The significance of the concept of the 'whole' has been graphically and simply illustrated by McPherson[2]. He takes the example of a swarm of gnats as a 'whole' and points to 'the fact that each and every gnat turns back towards the centre of the swarm whenever it finds itself at the edge, which is a behavioural property that cannot be understood by only counting the gnats and tracking their motions'. The realization that it is necessary to look upon things as a dynamic whole is not new; it goes back to at least 500 BC, when Heraclitus put forward his idea that everything is in a state of perpetual change. The 'essence of Being is becoming' and all is part of the 'Universal flux':

> *'One cannot step into the same river twice,*
> *nor touch substance twice in the same state . . .*
> *Into the same rivers we step and we do not step'.*

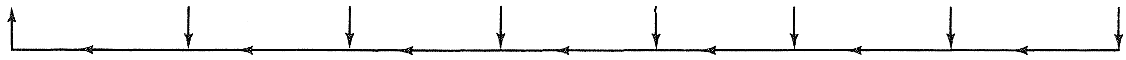
It is interesting that Heraclitus regarded all bodies as transformations of just one element—fire. If anything, it is more important to have this active, all embracing view of things today that it was 2500 years ago. A problem needs to be seen in its context and not in isolation.

Methodology

In order to carry out a 'systemic study' it is necessary to have an idea of the objectives of the study and an appropriate methodology. Which methodology is suitable depends upon the study objectives and the nature of the systems involved. It is useful to consider systems as either 'hard' or 'soft'[3]. A 'hard' system is one in which the parts and relationships are well defined and quantified, such as an engineering system. A 'soft' system is one in which not all the parts and relationships are easily defined and quantified. All systems in which human beings play a large part are essentially 'soft'. Also, it may not be possible to give exact expression to the objectives of a study of a soft system, at least at the beginning.

A possible appropriate methodology for fire safety might be:

1	2	3	4	5	6	7	8
Formulation of 'the problem'. Description of the problem. Parts involved and relationships between the parts. Systems involved. 'Objectives' of the study.	Development of models with respect to the systems involved. 'Objectives' associated with the systems. Structures; processes; flows; constraints; forces. Models may be verbal; mathematical; physical. Broad qualitative models and quantitative (eg fault tree) models may be employed.	Examination of specific past failure situations. Each failure should itself be examined from a systemic point of view. 'Near miss' situations. Statistics and other information.	Select areas for further research or investigation.	Consideration of 'the problem' in the light of the earlier stages of the study. Generation of ideas on how to tackle the 'problem'.	Evaluation of possible courses of action and consequences.	Carrying out action.	Appraisal. Assess the position and keep cycling round; things are never 'closed'.



Although this methodology is written as a series of steps it should not be regarded as a 'sausage machine' which, when completed, produces a 'correct answer'. The need will probably arise to return to earlier steps and cycle round. It will almost certainly be necessary to return to the stage 'Formulation of the problem' more than once. The methodology should be regarded as dynamic and not static. The 'problem' may become very complex and there cannot be a single simple 'solution'.

However, the methodology does provide a guiding structure. Within the structure techniques may be used which may be 'sausage machines' to a greater or lesser degree. A technique has limited aims and does not in itself constitute a systemic approach.

Some comments on the stages are in order:

1 Formulation of 'the problem'

Why is the study being carried out? What has prompted it? What are the initial objectives of the study? In the case of hospitals the 'problem' might be rather tentatively stated as 'How to increase fire safety in hospitals'. However, the exact statement of the 'problem' might alter as the study progressed. For example, it might improve fire safety to reduce the number of electrical appliances in a hospital, but then the absence of a particular electrical instrument might have a very damaging effect with respect to some other aspect of the system. There will be conflicting objectives.

Considering the hospital fire safety problem further, some of the relevant systems might be:

- Patients.
- Nursing and medical staff.
- General public.
- National Health Service.
- Department of Health and Social Security.
- Home Office.
- 'Design system' for construction of hospitals.
- 'Fire safety design system' for construction of hospitals.
- Hospital 'fire safety system'. (After construction).
- Fire brigade.
- Ambulance service.
- Local authority.
- Fire research system.
- Technical systems.
- Systems directly associated with the chemistry and physics of fire processes.
- Manufacturers of fire safety and other equipment used in hospitals.
- British Government.
- British socio-economic system.
- International socio-economic system.

Most of these systems will overlap. The order given above is not meant to imply any kind of 'order of importance'; it is simply a list of some of the systems which might be pertinent to a study. Other systems may also be relevant.

2 Development of models with respect to the systems involved

A model is a representation of some aspect of reality. There are many different types of model, ranging from broad verbal statements to deterministic mathematical models. One may also consider physical models. In addition to models which are intended to represent a situation in a 'direct' manner, there are 'simulation' models which are a way of viewing something by a conscious analogy. Mathematical probabilistic models of this type might use, for example, the Monte Carlo technique. An example of a physical simulation model would be the representation of the flow of a river and its tributaries by flow of electrical current through wires.

Most of the systems encountered have 'objectives' associated with them. That is, there may be aims and expectations which people have with respect to a system. A person or a group of people may want one or more things from a system. However, the objectives of a person or group may conflict. Also, that which a person or group wants from a system may conflict with that which another person or group wants from the system. For example, the objectives of a manufacturer of motor cars will be different from the objectives of a buyer of a motor car. In general, for any complex system involving human beings, there will almost certainly be conflicts of objectives. It is desirable to minimize these conflicts. Clarification and understanding of objectives and how they arise is necessary.

The structures, processes and forces existing within systems and crossing system boundaries need to be investigated. Flows of information and materials both within systems and between systems need to be understood. There may also be constraints for a given system, for example, the amount of money received by a local authority from government may be fixed.

The models should help us to understand better the relationship within the system as a whole.

However, a word of warning is necessary regarding the use of models. All models have limitations and it is vital to be aware of what those limitations are. The assumptions, both explicit and implicit, in each model must be clearly realized. It is as important to know what a model cannot say as to know what it can say. This is true for both quantitative and qualitative models. In particular, for quantitative models, it is important not to attach an unjustified significance to numbers which result. At an obvious level there are uncertainties which will be associated with models. For numerically quantitative models these may be expressed as, for example, 'errors' or 'confidence limits'. Numerical results should be seen in their context. According to the mathematician Gauss a lack of appreciation of the value of mathematics is 'nowhere revealed so clearly as by meaningless precision in numerical studies'.

Another issue raised in the application of specific methods is that models, and techniques in general, may on occasion be applied to situations for which they are not appropriate. It has been said that this is the most common form of mis-use[3].

In addition to these 'overt' points there may also be misconstruction at a deeper level. A simplistic approach can sometimes lead one to effectively ascribe to models powers which they do not possess; one might almost call this a fetishism which is sometimes associated with models. For example, if one wishes to compare risk situations then a relevant quantity to take into account would be the probability of fatality associated with each risk. It would, however, be foolish to pretend that a comparison of the probabilities of fatality represents a comparison of the risk situations. Such over-simplicity is sometimes an implied assumption if not an explicit one. There are many different dimensions involved in each risk and not all of these dimensions may be quantifiable. A comparison of the risk associated with cardio-vascular disease and that associated with road accidents is not straight forward. Looking at the probabilities of fatality is to consider only one aspect of these risk situations.

Having sounded these cautionary notes it must be said that the appropriate use of models may be a great aid to our comprehension of the whole. Further, one particular technique can be mentioned which might be used within the guiding methodology. Both deterministic and probabilistic models may be of use and one probabilistic technique is fault-tree analysis (see page 19). This is a method for logically combining events which may contribute to a final 'most undesired event'.

3 Examination of specific past failure situations

Studies of past fires are obviously of crucial importance. Each past fire should itself be considered from an overall systemic point of view. 'Near miss' situations should be studied i.e. situations which very nearly could have produced a failure but in fact did not. 'Failure' might be taken to mean, for example, 'injury or death due to fire'.

Information, both statistical and non-statistical, should be considered. In the case of hospitals, information afforded by hospital staff could prove to be very useful.

4 Select areas for further research or investigation

Both experimental and/or non-experimental work might be pursued. For example, it might be decided that it would be useful to carry out some specific tests. Different kinds of survey could be considered. In the hospital case it might be decided to ask staff to answer survey questions.

5 Consideration of 'the problem' in the light of the earlier stages. Generation of ideas on how to tackle 'the problem'

Radical changes in the systems may be necessary. Given the understanding of the situation reached so far, what possible changes seem suitable as a means of eliminating or minimising the 'problem'? Alternative ideas may be tentatively suggested.

6 Evaluation of possible courses of action and consequences

Each of the alternatives to emerge in the previous stage should be considered in detail. An attempt must be made to elucidate the full implications of each alternative.

7 Carrying out action

8 Appraisal

Whatever actions are carried out the study is never 'finished'. It will always be necessary to re-think old ideas.

Before leaving this discussion of the stages of the methodology it is important to make the general point that the investigators themselves are also part of the system under study and this must be realized[4].

Finally it might be suitable to make a specific point. One of the questions that has been raised in the past is: 'What about the potential accident you haven't thought about?'. Hopefully an appropriate use of a

Fault-tree analysis

Fault-tree analysis is just one technique which may be used within a guiding methodology. It is included here because it is a method which may be unfamiliar to many outside the field of 'engineering systems'. Also it serves as an example of a general class of techniques which may possibly be of help within fire safety considerations. It is not meant to imply that this type of model is necessarily 'better' than other techniques which may also be employed within a guiding structure. As stressed in the main article all techniques should be used with caution and circumspection.

Fault-tree analysis is a way of logically combining factors that may contribute to produce a 'most undesired event'. It may be represented by a diagram resembling a tree with the 'most undesired event' at the top and 'sub-events' forming the branches. Information may be thought of as passing from the branches to the final top event. The events are connected via 'logic nodes' and these may be taken to correspond to AND gates and OR gates. For the OR gate the output event exists if one or more of the inputs exist. For the AND gate the output event exists if, and only if, all the inputs exist. (It should be pointed out that an 'event' may be a condition such as, for example, whether or not a particular material is flammable.)

Trees constructed along these lines have been used in the nuclear and chemical industries. In the nuclear power case, for example, the protection system for a reactor has been examined from this point of view. The sub-events in a tree like that used in the nuclear power case are events such as a wiring fault or the failure of a power supply. Frequency values or probabilities may be associated with these events. For example a sub-event may be taken into account in the form of the probability of occurrence each month. Figure 1 shows a small segment of a fault tree for the automatic protection system of a nuclear power station. If the pressure within the core becomes dangerously high then one or more sensors should detect this and transmit signals through the elements of the protection system to cause the control rods to drop. The reactor should then go into a 'safe state'. The 'most undesired event' which could exist in this context is that the control rods would not drop when they should do, which is represented on the tree as 'no trip'.

It might be fruitful to attempt to apply such a technique in the case of fire. However, when one tries to do this it is found that a number of difficulties arise. A crucial difference between a fire development situation and a system similar to a power station protection system is that of time involvement. Unlike the nuclear case the elements that combine in the fire situation depend upon time in a very complex way and so cannot be concatenated in a simple manner. The modelling is a great deal more complicated because of this. Also there are a very large number of factors to be considered in the fire situation covering the fields of material properties, geometry and people's behaviour. It will also be necessary to understand the physiological effects of the products of fire if we are to relate it to injury and fatality. The fundamental knowledge in these fields may well be inadequate.

Before fault-trees can be applied in other than a very primitive manner a general theoretical framework needs to be developed. However it might still be useful at this stage to ask what might result from an examination of a particular fire from the point of view of fault-tree analysis. With this in mind a study of the fire which occurred in Coldharbour Hospital in July 1972 was carried out by the author and has been presented[5].

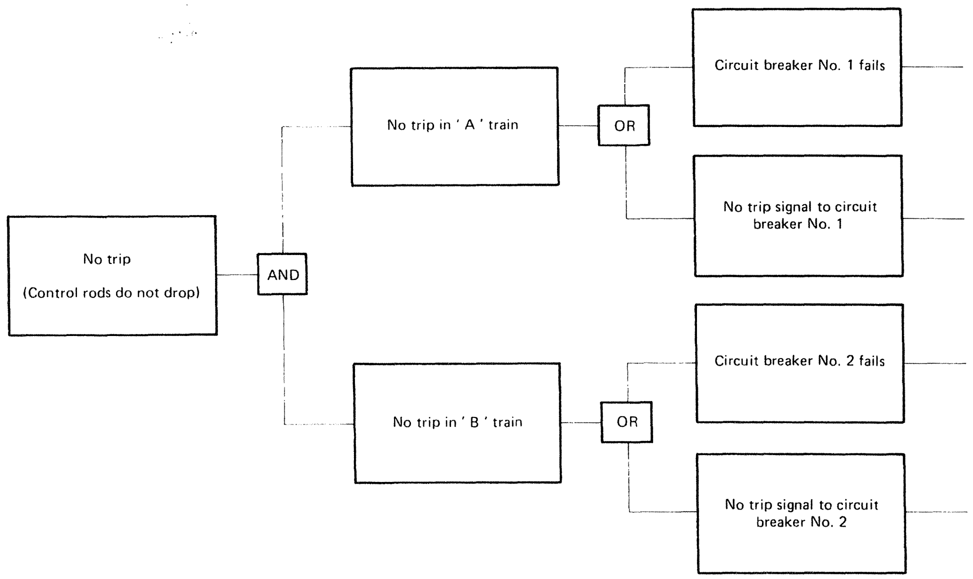


Fig 1. A small segment of a fault tree for the protection system of a nuclear power station

methodology such as that outlined above would help to overcome the problem raised by this question.

Conclusion

Fire safety needs to be examined from a systemic point of view and not in a disjointed or narrow fashion. Fire is a product of a system and it is necessary to understand the 'dynamic wholeness' of things in order to fully understand the failure.

To carry out a study from a systemic point of view it is necessary to have a guiding structure (or methodology) which is dynamic and not static. Within a methodology specific techniques may be employed which have specific tasks.

A possible outline for such a methodology has been suggested and it is hoped that such a framework would help in the task of exploring as many aspects of the problem as possible.

Essentially, the central theme of this paper has been the need to consider things in their entirety. Concern about fire safety has been the 'starting point' for consideration. However, as has been mentioned, in any complex situation involving human beings there will be conflicting objectives and in any action taken it is necessary to be fully aware of this. We need to try to minimise the conflicts and contradictions within the system as a whole.

In a sense the 'problem of fire safety' is rather analogous to the process of representing a mathematical function by expanding it in a 'complete set of functions'. Different 'complete sets' may be used to represent the function but when the expansions are each carried to infinity they ideally give the same thing. Different complete sets may be regarded as different 'starting points'. Fire safety has been the 'starting point' in this paper but if we view things as a whole then in principle all aspects of a system should enter into consideration no matter what is the starting point.

Actions should be a product of a consideration of the whole in the widest sense and fire safety is just one of those aspects.

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Acknowledgements

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Flame retardant furane resins

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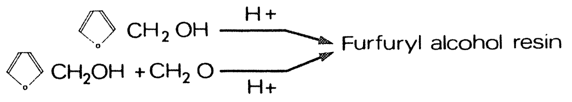
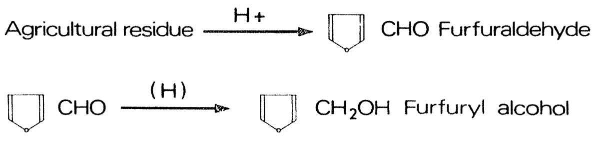
The flame retardant properties of furfuryl alcohol resins are shown in the following summary of tests on laminated glass manufactured with furane resins. BS 476 tests[1] for ignitability, fire propagation, surface spread of flame and fire resistance gave good results, though these figures do not necessarily predict the fire characteristics of these laminates under actual large-scale fire conditions. Further investigations with the 'Room Corner' test showed that furane resins can reduce flame spread and smoke generation rates to satisfy the stringent NFPA test requirements for ducting[2].

Furfuryl alcohol resins are prepared by homopolymerization of furfuryl alcohol or copolymerization of furfuryl alcohol with formaldehyde, according to the following equations:



The basic raw materials for furfuryl alcohol resins are agricultural residues such as oat hulls, corn cobs and sugarcane bagasse. Digestion with strong acid converts pentosans in the residues to furfuraldehyde. Hydrogenation converts furfuraldehyde to furfuryl alcohol.



Furfuryl alcohol resins, as produced above, are too viscous to use and are relatively unreactive. Monomeric furfuryl alcohol or furfuraldehyde are effective reactive diluents. The amount of diluent added depends on the viscosity requirements of the final application. Ambient temperature cures are achieved by addition of strong mineral acids or aromatic sulphonic acids. Latent elevated temperature cures result when organic acid anhydrides of BF3 complexes are used.

Furfuryl alcohol resins are inherently flame retardant. The pseudoaromatic heterocyclic ring carbonizes when exposed to fire and/or elevated temperatures to form a tenacious char. When forced to burn by application of an external fire source, very little smoke is evolved.

Flame retardant GRP laminates

Furfuryl alcohol resins would appear to be likely candidates for fabrication of flame retardant ducting because of their proven corrosion resistance. Commercially available furane systems have been applied in this way for some years now in the UK. The need for combined corrosion and fire properties is found typically in the pharmaceutical, atomic energy, speciality chemical and semi-conductor industries.

American requirements

In the USA, NFPA Code 91[2] controls material selection for these ducting applications. As specified by this Code, selected materials must have flame spread (FS) ratings of <25 and smoke ratings of <50 when tested in a full-scale (7.62 m) 25 ft. ASTM E-84 Tunnel (American Society for Testing and Materials). Table 1 shows the results of these tests on selected resins:

Table 1
E-84 Tunnel Data

Resin	*FR Additive*	*Flame Spread*	*Smoke Rating*
Furane	None	70	120
Polyester[3]	None	~300	~1200
Polyester[4]	Halogen/Sb_2O_3	15	412

The lowest values, obtained with the non-flame retarded furfuryl alcohol resin, obviously do not meet NFPA Code 91 requirements and work was accordingly initiated about 3 years ago to evaluate commercially available flame retardant additives as a means of reducing furane flame spread and smoke values to <25 and <50 respectively. This early work demonstrated that the requirements of NFPA

Code 91 could be met using 15 *ph* (parts per hundred of resin) of TRIS [tris (2,3-dibromopropyl) phosphate] if the laminates were given an extensive post-cure through eight or more hours at 135 °C:

Resin	*FR Additive*	*Flame Spread*	*Smoke Rating*
Furane	TRIS	23	30

QUACORR 1500 FR was accordingly formulated on the basis of these data and a paper describing the properties of this resin was presented at the February 1977 Society of Plastics Industry Meeting in Washington DC.

British tests

In the UK, laminates fabricated using this resin system were subjected to the BS 476 Fire tests on building materials and structures. Tests at Parts 5, 6 and 7 were run, and the results are as follows:

Part 5. Ignitability test for materials: Not easily ignitable
Part 6. Fire propagation test for materials:
$i_1 = 2.46$ $I = 8.19$
Part 7. Surface spread of flame test for materials: Class One.

Following the good Part 6 result, a 1.83 m×0.61 m diameter section of ducting was subjected to the preliminary Part 8 test for structural integrity retention of ducting at temperatures up to 850 °C.

The test section successfully retained its structural integrity for the thirty minute period required.

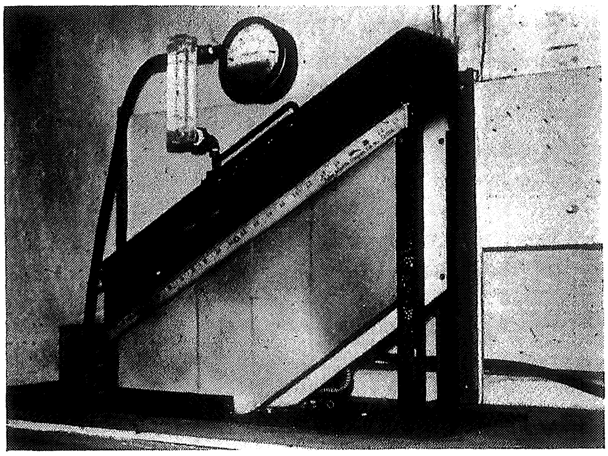
Alternative additives to TRIS

[tris (2, 3-dibromopropyl) phosphate]

Early in 1977, for environmental reasons, a programme was initiated by Quaker Oats in the USA to find a replacement for TRIS. Because of the cost of running full scale E-84 tests, a Monsanto Two-Foot (0.61 m) Tunnel and a National Bureau of Standards Smoke Chamber were selected as small scale laboratory procedures for screening flame retardant additives. The laboratory test equipment is shown opposite.

More than fifty flame retardant additives have been evaluated to date with these procedures. Laminates 3 mm thick were layed-up with 3 plies of PPG-ABM 450 gm^{-2} glass mat, a widely available type of glass fibre, so as to contain about 70 per cent resin and 30 per cent glass.

After an overnight ambient cure, the laminates were post-cured four hours at 82 °C. Some of the representative compounds tested and the test results obtained are given in Tables 2, 3 and 4.



Laboratory equipment for small-scale flame retardance tests (a) Monsanto Two-foot tunnel.

(b) National Bureau of Standards smoke chamber

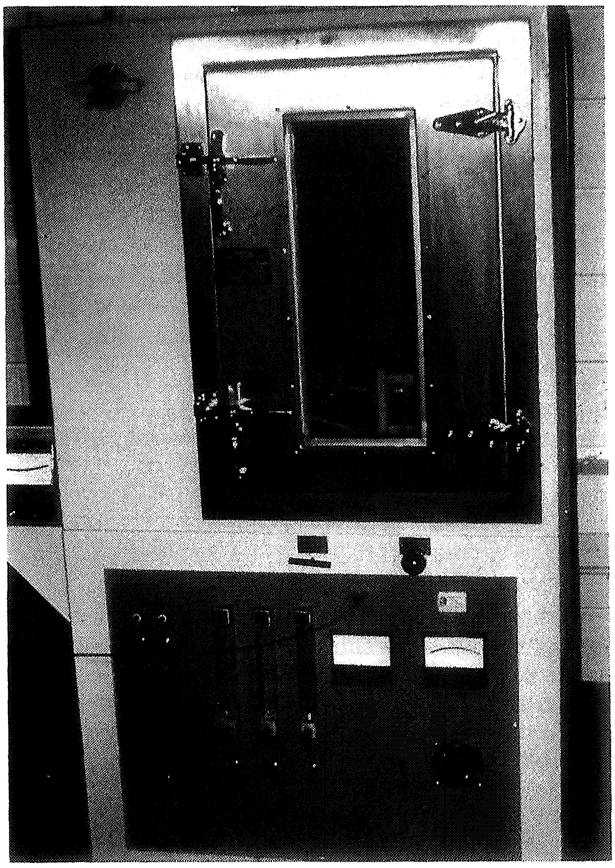


Table 2
Halogenated aliphatic compounds
Monsanto two-foot tunnel/NBS chamber data

Compound	Percent Cl	Percent Br	Additive phr	Flame spread in Burn	Smoke density Max.
Hexabromobutene-2	—	89	11.6	11.8	24
2,3-Dibromopropanol	—	73	15	12.0	22
Brominated Alcohol	—	74	15	13.2	17
2,3 Dibromo-2-butene-1,4-diol	—	65	15.9	13.5	71
Brominated Alkyl Ester	—	50	20.6	13.8	37
Br_4-Vinylcyclohexane	—	74	13.9	15.0	—
Typical Brominated Aliphatic Compound	—	47	21.9	15.3	—
Br_4Cl-Cyclohexene	—	—	13.2	15.7	—
Brominated Aliphatic Glycol	—	50	15	18.4	—
Br_2-Neopentyl Glycol	—	61	16.9	19.0	—
Chlorinated Paraffin	68	—	15	20.9	63
Control (No FR Additive)	—	—	—	18.2	62

Table 3
Halogenated aromatic compounds
Monsanto tunnel/NBS chamber data

Compound	Percent Cl	Percent Br	Additive phr	Flame spread in Burn	Smoke density Max.
Br_8-Diphenyl Ether	—	80	12.9	16.0	—
Br_4-Phthalic Anhydride	—	69	15	16.8	87
2,3-Dibromopropyl Ether of Tribromophenol	—	75	13.7	17.0	—
Br_5-Diphenyl Ether	—	71	10	17.3	174
Decabromodiphenyl Ether	—	83	12.4	17.7	62
Br_5-Ethylbenzene	—	80	12.9	19.5	—
Control (No FR Additive)	—	—	—	18.2	62

Table 4
Phosphorous containing compounds
Monsanto tunnel/NBS chamber data

Compounds	Percent Cl	Percent Br	Percent P	Additive phr	Flame spread in Burn	Smoke density Max.
Tris (2,3-dibromopropyl) Phosphate	—	69	4.4	15	11.5	24
Ammonium Polyphosphate	—	—	32	5	12.7	66
Haloalkyl Phosphate	?	38	?	15	13.5	59
Haloalkylaromatic Phosphate	?	?	?	15	17.4	175
Aromatic Phosphate	—	—	?	15	17.4	185
Organic Phosphate	—	—	21.5	15	20.5	230
Triaryl Phosphate	—	—	?	15	21.3	263
Dimethylmethyl Phosphonate	—	—	25	15	21.4	126
Tricresyl Phosphate	—	—	8.4	15	22.5	321
Diamylamyl Phosphonate	—	—	10.6	10	23.0	—
Control (No FR Additive)	—	—	—	—	18.2	62

Based on these small scale test results, highly brominated aliphatic compounds appear to be the most effective additives. (Table 2). Halogenated aromatic compounds (Table 3), as well as most phosporous compounds (Table 4), show little improvement compared to the non-flame retarded furfuryl alcohol resin control—in fact, many of the compounds appear to increase rather than control flame spread and/or smoke density (Ds).

Of the compounds tested, Hexabromobutene-2 (HBB-2) and 2, 3-dibromopropanol (DBP) appeared to give the best results. They were therefore selected for scale-up to the 25 foot (7.62 m) ASTM E-84 Tunnel. Data for samples prepared with different levels of additives and given different cure schedules are given in Table 5. Panels containing TRIS were prepared and included in these tests as controls.

As can be seen from the data in Table 5, HBB-2 appears to be comparable to TRIS in that the laminates required a cure through eight hours at 135 °C to achieve a smoke generation in the E-84 Tunnel of 50 or less. Surprisingly, the 2, 3-dibromopropanol (DBP) gave smoke generation values of less than 50 with cure temperatures as low as four hours at 65 °C. In addition to the lower smoke results, DBP is a liquid which readily dissolves in the resin as compared to HBB-2, which must be dispersed as an insoluble powder.

Although DBP would not be expected to react with the furfuryl alcohol resin during cure, this additive does not appear to plasticize the resin, nor does it appear to be fugitive based on initial physical test data as well as after immersion in a series of ASTM media for six months at 65 °C, as illustrated by the data in Tables 6 and 7.

There has been a great deal of concern in recent years as to the reliability of small scale tests in pre-

Table 5
E-84 tunnel test data

Additive	phr	Cure conditions	Flame spread	Smoke	Fuel contribution
None	—	1 Hour at 93 °C	70	120	0
Tris(2,3-dibromopropyl)Phosphate	15	4 Hours at 82 °C	25	76	0
		8 Hours at 135 °C	23	30	0
Hexabromobutene-2	11.6	4 Hours at 82 °C	25	65	0
		8 Hours at 135 °C	23	50	0
Dibromopropanol	15	35 Days at Ambient	23	83	0
	15	4 Hours at 65 °C	18	30	0
	15	4 Hours at 82 °C	18	46	0
	15	6 Hours at 93 °C	25	38	0
	15	8 Hours at 135 °C	25	49	0
	20	4 Hours at 82 °C	23	59	0
	10	6 Hours at 93 °C	25	62	0
	7	4 Hours at 82 °C	20	70	0
	5	4 Hours at 82 °C	36	70	0

dicting performance in large scale fires. This study was accordingly expanded to include testing in a 2.44 m×3.66 m enclosed room using a 13.61 kg woodcrib (see diagram).

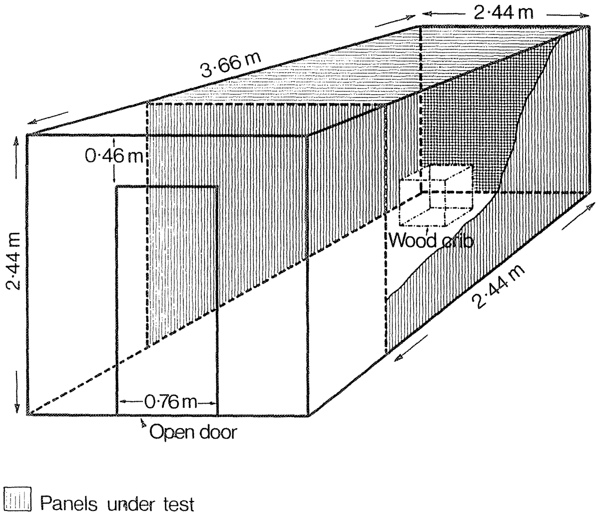
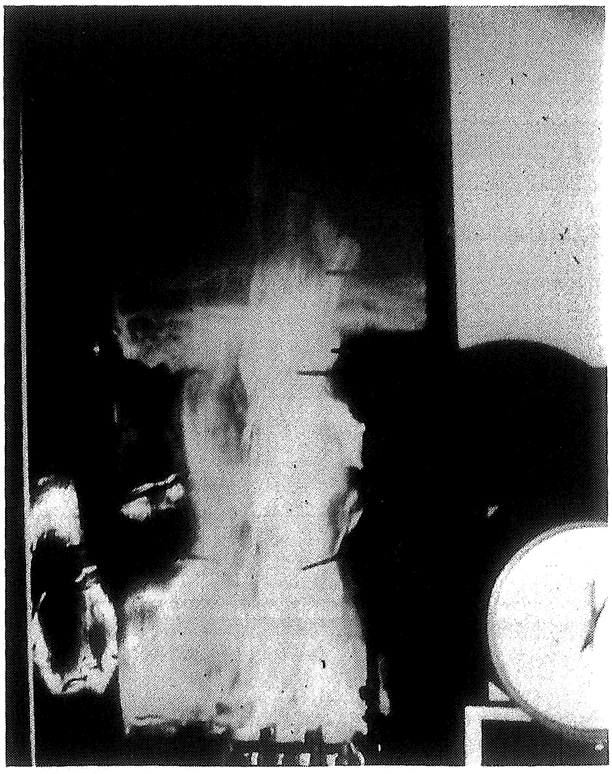


Table 6 Physical strength data Effect of added fire retardants			
Additive concentration	Tensile strength (psi)	Flexural strength (psi)	Flexural modulus
None	11300	18400	696000
15 phr TRIS	10400	19900	760000
15 phr HBB	—	17900	865000
15 phr DBP	12900	18300	765000

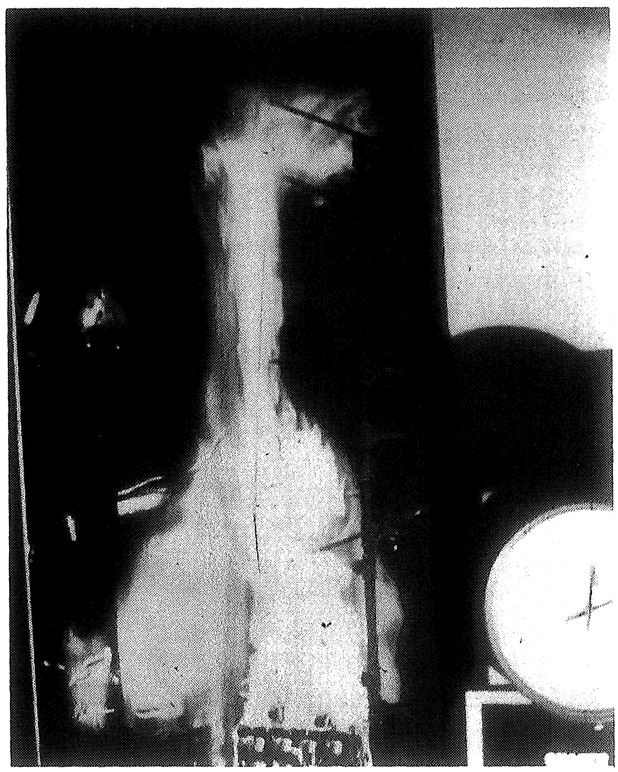
Table 7
Corrosion resistance data
Immersion for six months at 65 °C

Media	Barcol Hardness	% Flexural Property Retention Strength	Modulus
25% H_2SO_4	50	76.8	54.4
15% HCl	49	90.2	75.4
5% HNO_3	42	90.7	87.2
25% Acetic Acid	42	75.8	61.8
15% H_3PO_4	44	72.7	68.0
5% NaOH	45	67.0	58.0
10% Na_2CO_3	45	72.7	64.0
Sat. NaCl	45	86.8	76.9
5% Alk. SO_4	44	94.1	90.6
Deionised Water	44	73.0	64.0
Ethyl Acetate	31	97.1	67.1
Heptane	62	121.0	136.0
Methyl Ethyl Ketone	37	100.0	76.0
Monochloro-benzene	54	108.0	98.0
Perchloroethylene	60	126.0	122.0
Toluene	59	113.0	96.0

The 'Room Corner' test is an excellent and financially viable method of testing the performance of materials when continuously exposed to a flame source. It also creates conditions for 'flashover' which, in the minds of many researchers these days, is the most important factor in a fire. Under the continuing fire condition, vaporized materials trapped at ceiling level by the door transom can ignite. A small fire can, under these conditions, become a raging inferno in a very short time, and we were concerned to measure whether we would obtain this effect with furane materials.



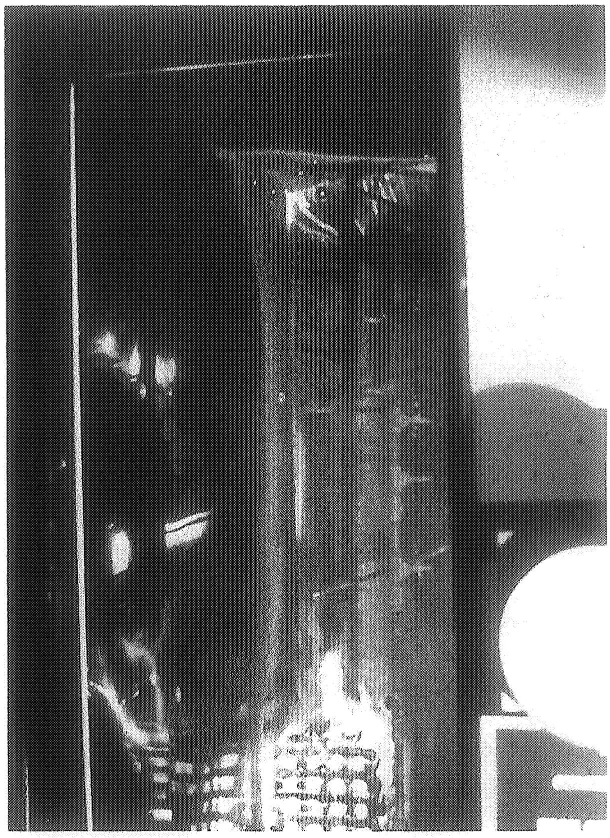
Room burning test with flame retardant furane panels
(a) 5 minutes after ignition



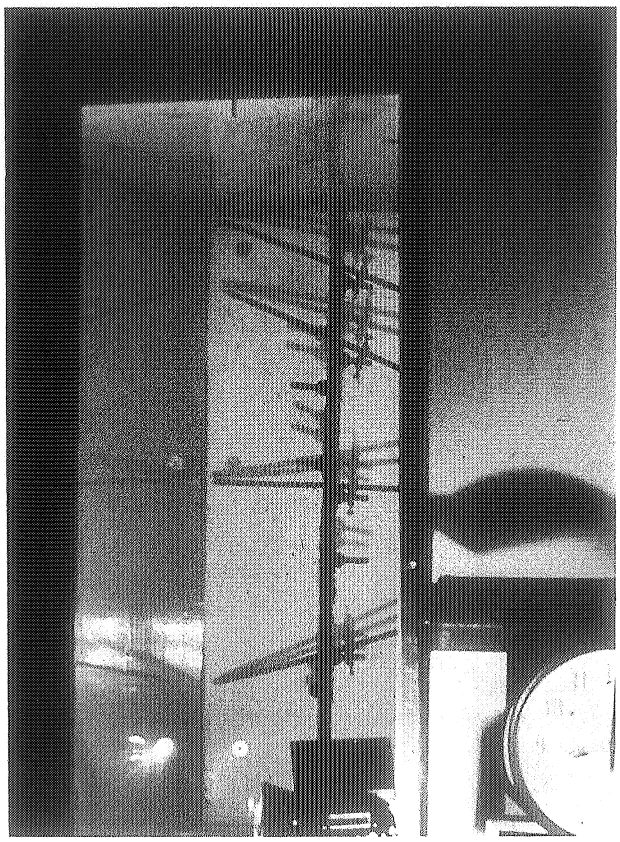
(b) 10 minutes after ignition

In the test, the crib is ignited and allowed to burn against the far corner of the room, the significant point being that the 13.61 kg crib will burn for about twenty minutes and the test panels, bolted to the walls and ceiling are continuously exposed to flame for this period.

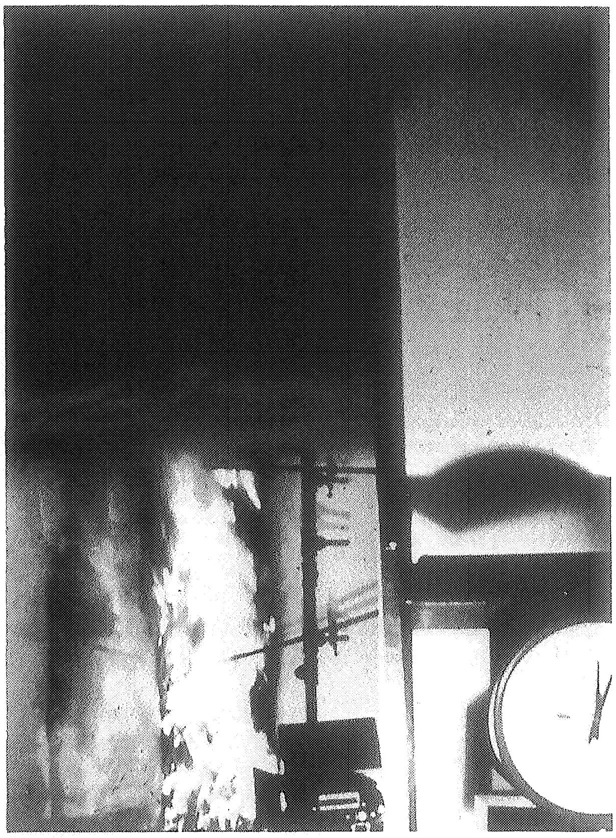
The dramatic flame retardance shown by FR furfuryl alcohol resin (E-84 values of FS <25 and smoke of <50), as compared to a halogenated polyester containing 5 per cent antimony oxide (FS and smoke levels reported to be 15 and 412, respectively) are shown in Plates 00 to 00. Although the FR



(c) 20 minutes after ignition



Room burning test with flame retardant halogenated polyester
(a) ignition



(b) 3 minutes after ignition

(c) 5 minutes after ignition

polyester was reported to have a lower flame spread than the FR furfuryl alcohol resin, as measured in the E-84 Tunnel, it is evident that significantly greater combustion of the FR polyester occurred, as evidenced by visual observation during the tests (Plates 00 to 00), by the higher temperatures observed at various points along the wall at the ceiling (figures 1, 2 and 3), by occurrence of 'flash-over' with the FR polyester but not with the FR furfuryl alcohol resin, as evidenced by visual observation and temperatures observed at the top of the doorway (Fig. 4), and by visual appearance of the panels when examined after extinguishment of the fires (Plates 11 and 12). The dramatic difference in smoke generation is shown by the photocell data in Fig. 5.

(d) Extent of damage

Room burning test: comparison of the performance of furane and polyester panelling in simulated fire conditions. Smoke values of 412 were recorded with FR polyester but < 50 with FR furane laminate

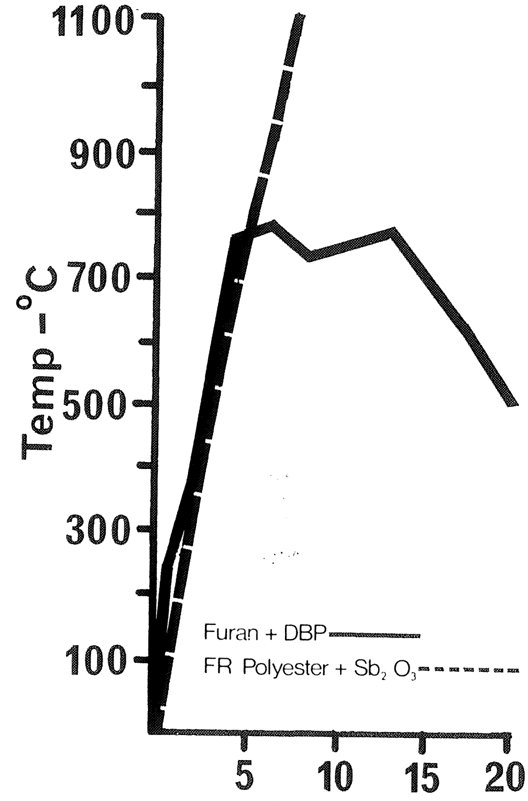


Fig. 1. Temperature in corner above crib at 2.13 m level.

Conclusions

Furfuryl alcohol resins are inherently flame retardant as evidenced by E-84 Tunnel results for a non-flame retarded laminate with FS of 70 and a smoke generation value of 120.

Further improvement of fire performances, as needed to pass US requirements for ducting and to give good results in BS 476 tests adapted to ducting, can be achieved by incorporation of suitable flame retardants.

The Monsanto Two-Foot (0.61 m) Tunnel and NBS Smoke Chamber appear to be effective small scale laboratory test procedures for predicting performance of furfuryl alcohol resin laminates in a large scale E-84 Tunnel Test.

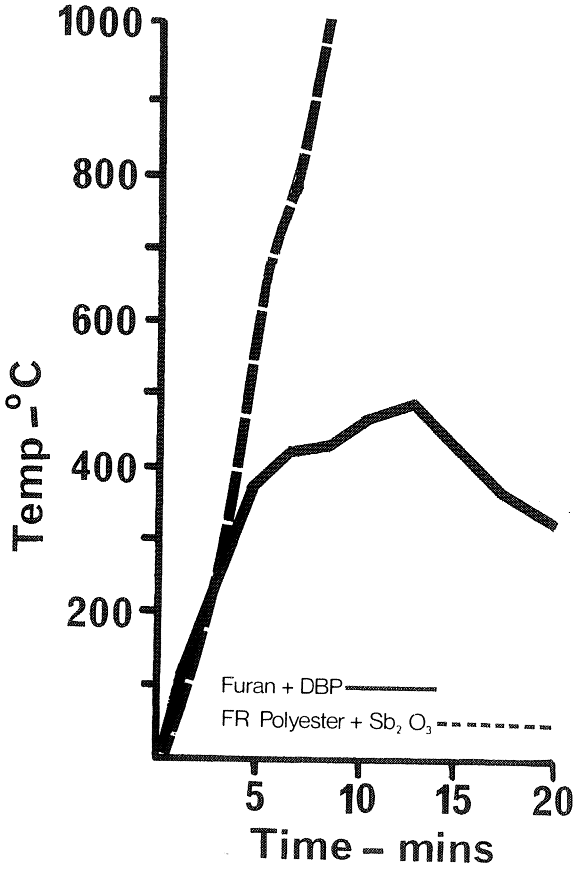


Fig. 2. Temperature along wall 1.22 m from corner at 1.52 m level.

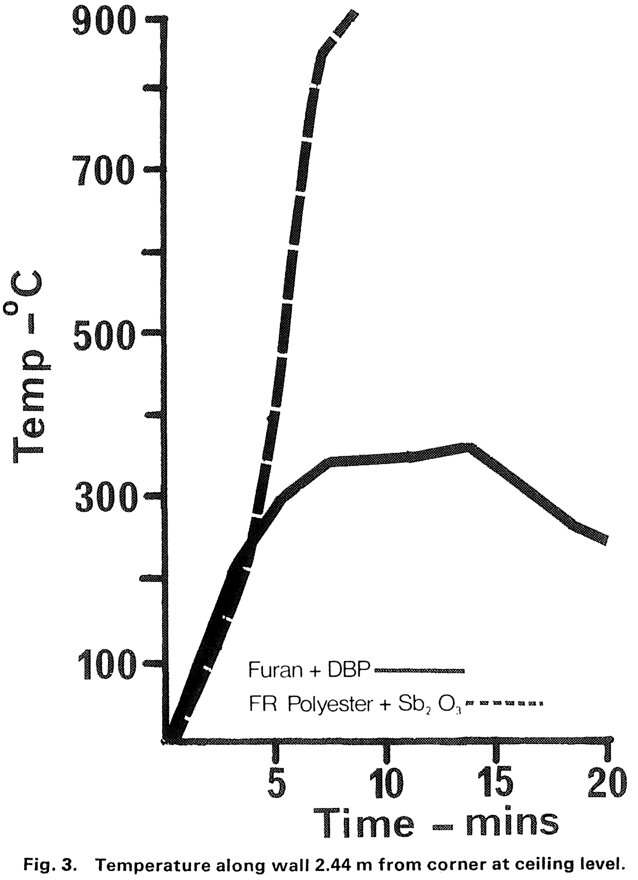


Fig. 3. Temperature along wall 2.44 m from corner at ceiling level.

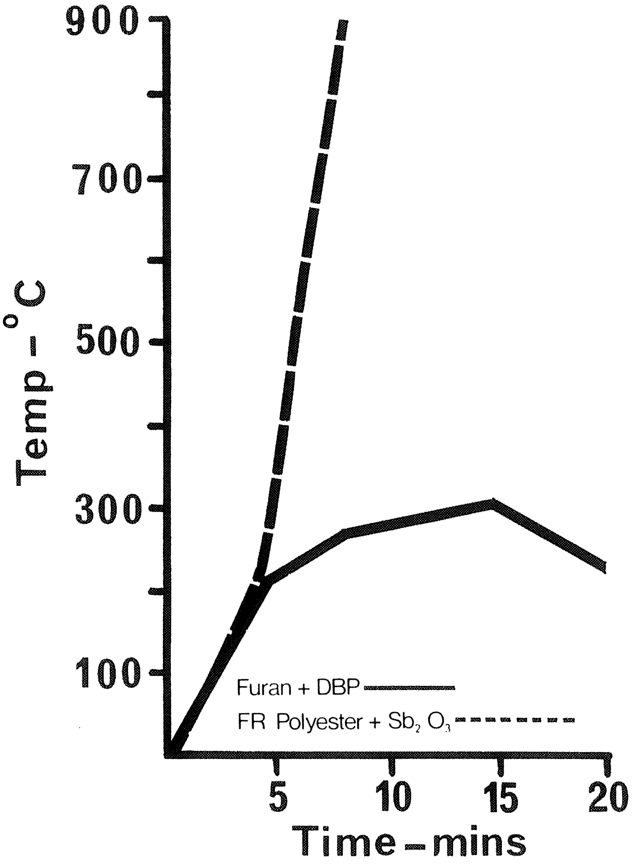


Fig. 4. Temperature at top of doorway opening.

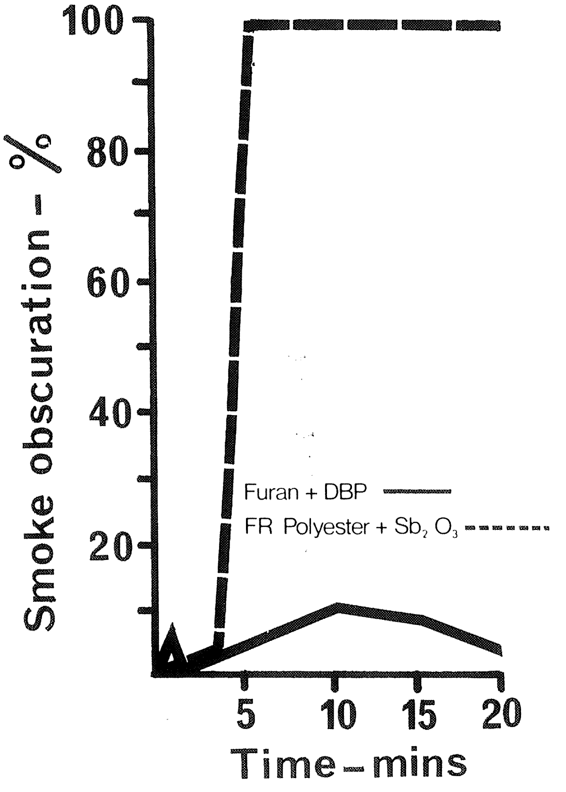


Fig. 5. Smoke development.

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