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FIRE AND SMOKE MODELS—THEIR USE IN THE DESIGN OF SOME LARGE BUILDINGS

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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:

$$Q = at^2 \qquad (1)$$

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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:

$$Q = Q_o \exp b\,(t - t_o) \tag{2}$$

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):

$$A(T) = A\,(0) \exp \theta T \tag{3}$$

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

$$R = k\,Ah^{1/2} \tag{4}$$

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):

$$Q_{fo} = k_1\,(h_k\,A_t\,Ah^{1/2})^{1/2} \tag{5}$$

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:

$$M = k_2\,Q^{1/3}\,y^{5/3} \tag{6}$$

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

$$T_A - T_o = k_3\,Q^{2/3} / y^{5/3} \tag{7}$$

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:

$$T_p - T_o = Q / MC_p \tag{8}$$

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):

$$\frac{z}{D} = k_4\,(Q^2 / D^5)^{1/3} \tag{9}$$

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):

$$\frac{z}{D} = -1.02 + k_5\,(Q^2 / D^5)^{1/5} \tag{10}$$

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):

$$M = k_6\,P\,y^{3/2} \tag{11}$$

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

$$M = k_7 (QL^2)^{1/3} y \tag{12}$$

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

$$T_a - T_o = (k_8/z)(QT/w)^{2/3} \tag{13}$$

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:

$$M = k_9 (Qw^2)^{1/3} h \tag{14}$$

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:

$$M = k_{10} (Qw^2)^{1/3} y \tag{15}$$

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):

$$M = k_{11} (QL^2)^{1/3} (y - 0.85H) \tag{16}$$

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:

$$M = k_{12} [Q (L + 0.22y)^2]^{2/3} (y - 0.5H) \tag{17}$$

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:

$$Q_p = k_{13} Q \tag{18}$$

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

$$z + h = k_{14} (R/w)^{2/3} \tag{19}$$

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:

$$\frac{-dy}{dt} = [(M/d_o) + (Q/d_o \cdot T_o)]/S \tag{20}$$

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/ft²·s·°F (13 kW/m²·°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

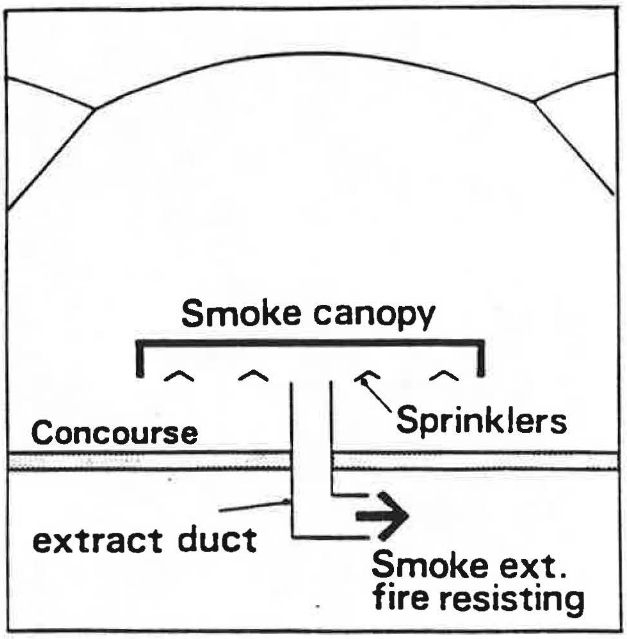

Figure 2 Stansted Airport passenger terminal

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

$$Q = 598 \exp [0.173 (T - T_o)] \quad \text{Btu/s}$$

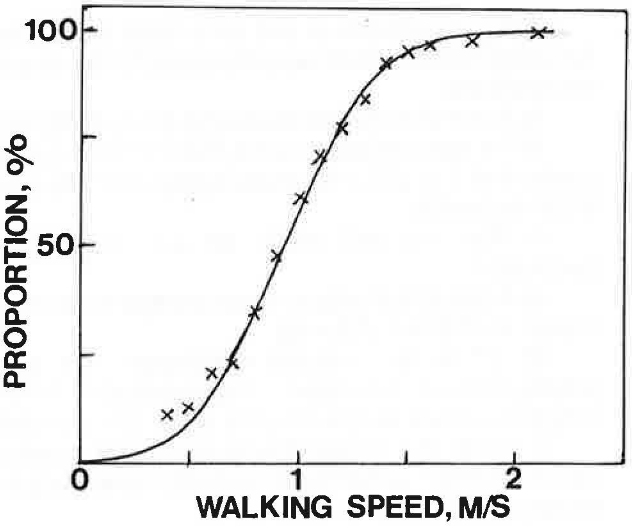

Figure 3 *Distribution of walking speeds in a reclaim area*

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 ft^2 (9 m^2) 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 ft^2. 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.

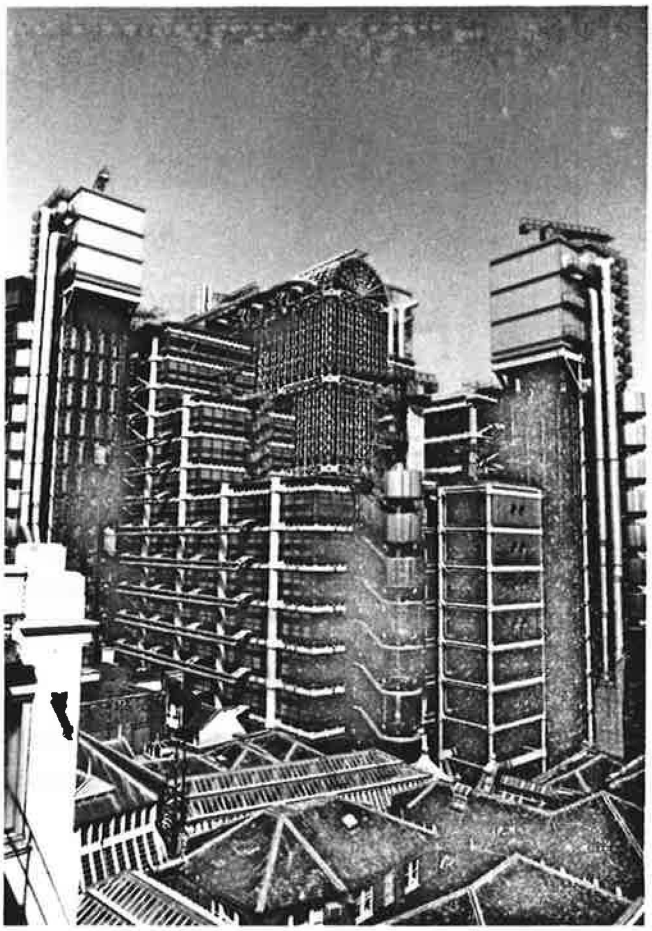

Figure 4 *Lloyd's building, London*

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.

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:

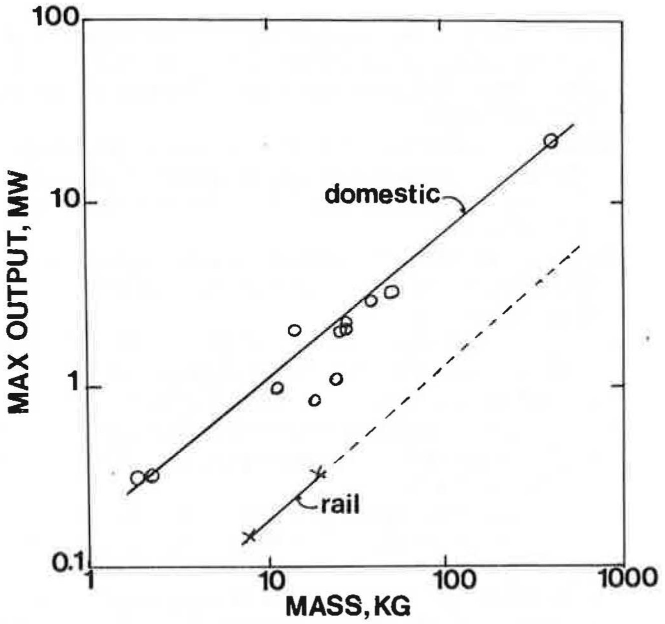

***Figure 5** Heat release rates from furnishings*

$$Q = 9.5 \exp[0.025t] \text{ for } t < 148$$
$$Q = 380 \exp[0.010(t - 148)] \text{ for } t < 349$$
$$Q = 2850 \exp[0.005(t - 349)] \text{ for } t > 349$$

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.

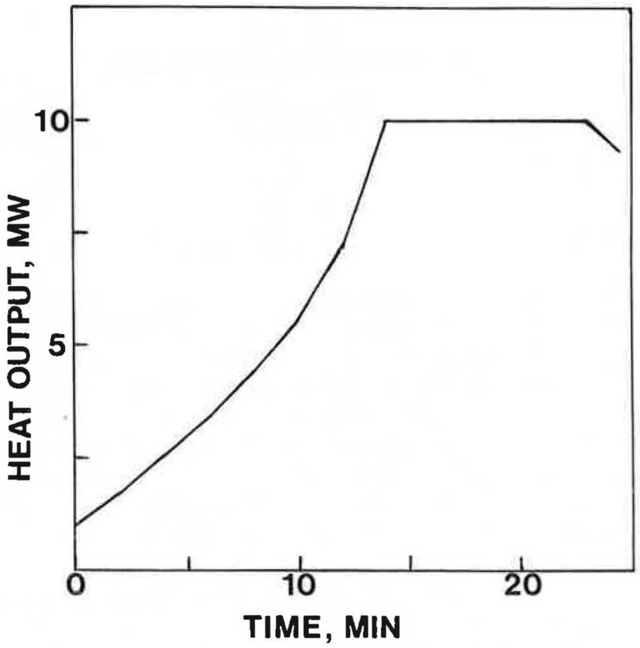

***Figure 6** Design fire for railway carriage*

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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