Smoke Control and Ventilation in Special Structures

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ABSTRACT

This paper is concerned with the need for adequate smoke control methods in special structures such as large space buildings, basements, shopping complexes, atria, factories, and warehouses for the protection of life and property and to reduce fire damage.

The paper deals with the physics of smoke and highlights the speed at which smoke will flow through a building, cutting off escape routes and increasing temperature with related dangers.

The background and history together with the current research in this specialized subject are covered, indicating the proven overall benefits in reducing fire losses.

Design methods and sample calculations are given for establishing smoke flow rates and possible smoke flow patterns in multistoried complexes and atrium designs. The paper covers a number of misconceptions in these areas.

Smoke ventilation may be interconnected with the use of the air-conditioning system, whilst operation and interaction with other fire suppression systems must be considered. Other smoke control measures such as pressurization are briefly covered.

Finally, the choice of equipment to effect smoke removal must be suitable and must operate under fire conditions. Unsuitable equipment may act in reverse to that intended.

This paper is generally based on U.K. research and requirements and brings together salient concepts and design ideas for the general awareness of the features and benefits of adequate smoke extract measures.

BACKGROUND

Fire and smoke in buildings are major hazards to life and property. Prevention and control systems must be as basic a concern to the engineer as systems installed to protect against other hazards such as building collapse and explosion.

Since 1965, some fires in large structures have created life threatening hazards, although only a small amount of material burned. The primary hazard is the development of heavy toxic smoke and gases. According to a study by the National Fire Protection Association (NFPA) on large loss-of-life fires, in practically all instances, the loss of life resulted from inhalation of heated, toxic, or oxygen deficient products of combustion (NFPA 1976).

For many structures, the time required for rapid total building evacuation can be too long. A large number of the occupants may be physically unable to evacuate the top areas of some high buildings. Recently, increased quantities of highly hazardous materials have been used in building construction as well as in furniture and decorations. These materials, in combination with new construction technology and office planning such as sealed windows, large central air-conditioning systems, and large open work areas, may create serious hazards to life in tall or large buildings or in buildings where occupants are restrained or confined.

LIFE SAFETY

The life safety of building occupants requires moving people out of the building or, if this is not possible, moving them to safe areas of refuge while the fire fighters extinguish the blaze. Because of the human factors involved, the fire safety engineer and fire fighter should have the answers to the following questions ahead of time. Are the occupants capable of helping themselves? Are they asleep? Are they physically restrained and not capable of movement? Can they be subjected to disciplinary control? Will they panic? Are they familiar with the building? Have they had training for evacuation?

Smoke is not only an irritant but also reduces visibility, causing disorientation. The toxicity of gases is another crucial danger with carbon monoxide, a product of incomplete combustion, as the chief danger. Before people can be safely moved, the fire and smoke must be detected, an alarm sounded, and the fire department notified. Time and speed of communication are critical factors. Upon arrival, the fire fighter has the staggering responsibility of evacuating people, getting rid of smoke, extinguishing the fire, saving the building and its contents, and in the process, preserving his own life.

PHYSICS OF SMOKE AND FIRE MOVEMENT IN SPECIAL STRUCTURES

What is Fire?

Fire may be defined as an uncontrolled combustion developing in space and time that produces heat with, generally, flames and smoke.

For a fire to start and continue, it requires heat, fuel, and oxygen. Combustible solids or liquids produce volatiles when they are heated and as they mix with air, they visibly flame adjacent to the parent material.

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The flames and hot gases rise as a plume that draws in surrounding air; it is this process that feeds the flame. At their tips, the amount of air entrained is many times that of the volatiles produced by the burning fuel. In effect, a fire acts as a pump drawing in the surrounding air, heating it, reducing its oxygen content, and contaminating it with combustion products.

The most hazardous toxic gas, because of its abundance, is carbon monoxide, which is produced by almost anything that burns. The smoke particles so reduce visibility for escape, that on average the contaminated air would need to be further diluted with one hundred to one thousand times its volume of air to see a distance of 8 m, which is regarded as the necessary minimum for safe evacuation. As the concentration of toxic combustion products increases, the chance of escape is reduced still more by disorientation, unconsciousness, and eventually death.

If the oxygen content of the air entrained by the flames becomes depleted, the first effect is to lengthen the flames and reduce the burning rate while the production of smoke and toxic gases increases. Flammable products of incomplete combustion also increase. If the oxygen content is reduced by about one-third, most flaming combustion ceases, although smoldering can continue.

How Does Fire Behave?

Predictably badly unless it is controlled.

The fire spreads by heating adjacent materials until they too emit flammable volatiles. At first, flaming will spread only to those materials that are licked by the flames or are close to them, but as the fire grows, the radiant heat produced increases and materials at greater distances from the fire are affected. When the fire has grown to the extent that flames reach the ceiling, any further increase results in flames mushrooming horizontally. These increase rapidly in length as the fire grows, igniting tops of goods in their path and radiating heat downwards so promoting further fire spread.

A slow burning oxygen starved fire in a small room can be contained by closed doors much longer than a fast burning one with adequate ventilation and the fire may extinguish itself due to the lack of oxygen. It is therefore best to close doors and windows in unoccupied rooms to reduce the risks. If a door should be opened to the oxygen starved fire, a dangerous situation may rapidly develop.

Large Undivided Volume Buildings

Fires in large compartments are quite different. Clearly capable of growing much larger than in a domestic room, the compartment would be full of hot smoky gases long before being starved of oxygen and would be difficult to enter even with breathing apparatus.

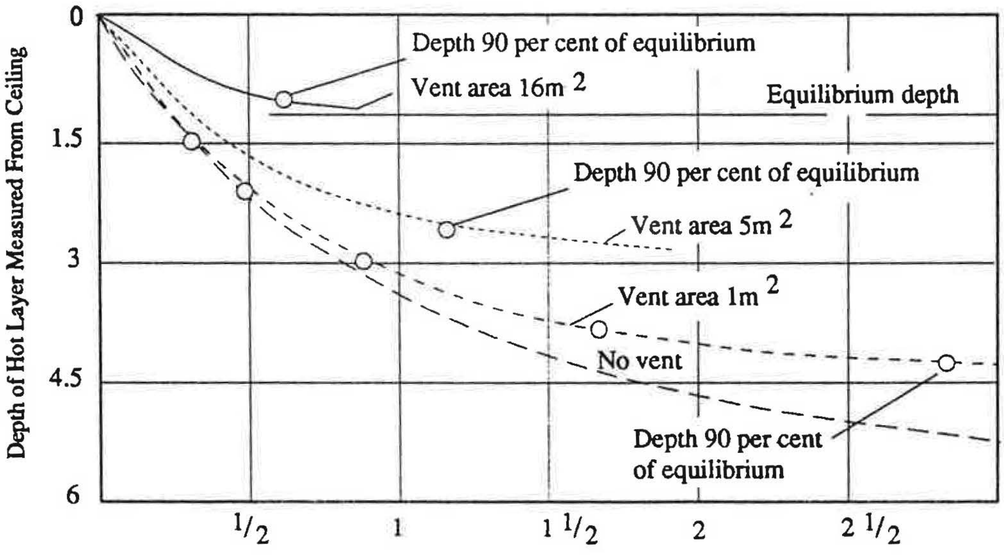
A 5 MW fire covering an area of 10 m^2 in an unventilated 1,000 m^2 building, 7 m high would take over 20 min to reduce the oxygen content to the point where flames die down.

Hot smoke would initially spread as a layer beneath the ceiling reaching walls in about 10 s. The smoke layer would then deepen and at the end of 1 min would have reached a depth of about 2.5 m. Thus far, it would not be a hindrance and might not even be perceived as a threat to the occupants since they would be in a 4.5-m deep layer of clear air flowing slowly towards the fire.

After 2 min, the layer would more than half fill the building and at 3 min would be down to head height. Before then, smoke would have mixed into the air flowing back to the fire enveloping anyone still there. From that point, escape is increasingly difficult.

Figure 1 indicates the speed at which smoke logging will occur in a simple single-story space. It follows therefore, that unless the building is very large, even a 3 m by 3 m fire could fill it with smoke before the arrival of the fire brigade in the absence of adequate smoke ventilation.

Even if venting occurs by accidental roof collapse, smoke clearance is a much longer process than smoke buildup. If this occurs after partial oxygen starvation, the



(Extract from U.K. FRS Technical Paper No. 10—Model Test Simulation, 1964)

Figure 1 *Speed at which smoke logging occurs in simple single-story spaces* flammable products of incomplete combustion can explode due to the inrush of air and the sudden increase in the intensity of the fire.

Basement Areas

In a similar way to a single-story structure, smoke from a fire in a basement will rapidly rise from the source and spread out beneath the ceiling to form a smoke reservoir. Because basement ceiling heights are likely to be low, the smoke will quickly build down to occupancy height. Unlike most other aboveground structures, the means of escape from a basement is usually upwards, which means people passing into stairwells or ramps up through the smoke reservoir.

Likewise, the task of the fire fighter is considerably more difficult for the basement since entry of men and fire-fighting equipment must be taken down through smoke levels. Temperature of gases, even in sprinklered buildings, will be higher in such a situation. The speed of smoke logging a basement without ventilation is indicated in Figure 2A.

Figure 2B shows that with adequate ventilation and sprinklers operating together on a thermal device, the situation changes and the level of visibility can be maintained for a longer period, at a higher level.

Warehouses and Factories

Smoke logging in taller buildings can be rapid as in buildings with less height where there is a growing fire situation. Figure 2C indicates the depth of the smoke layer in a simple warehouse and shows the increase in the area of clear visibility when ventilation takes place on the release of a thermal link-operated hatch. The graph also gives an indication of the likely operation point of the first sprinkler, only when smoke is almost to floor level.

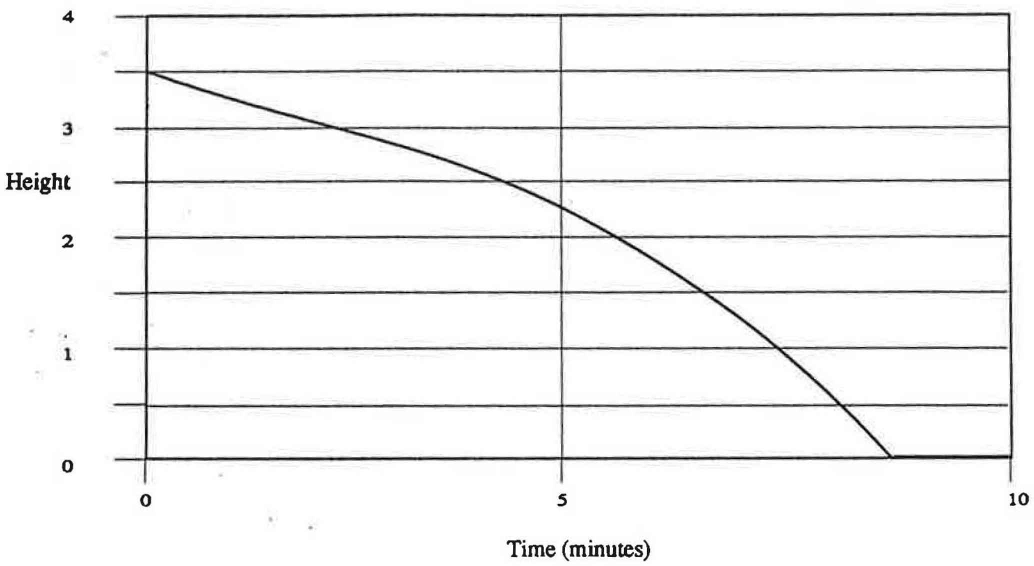


Figure 2A *Speed of smoke logging in basement*

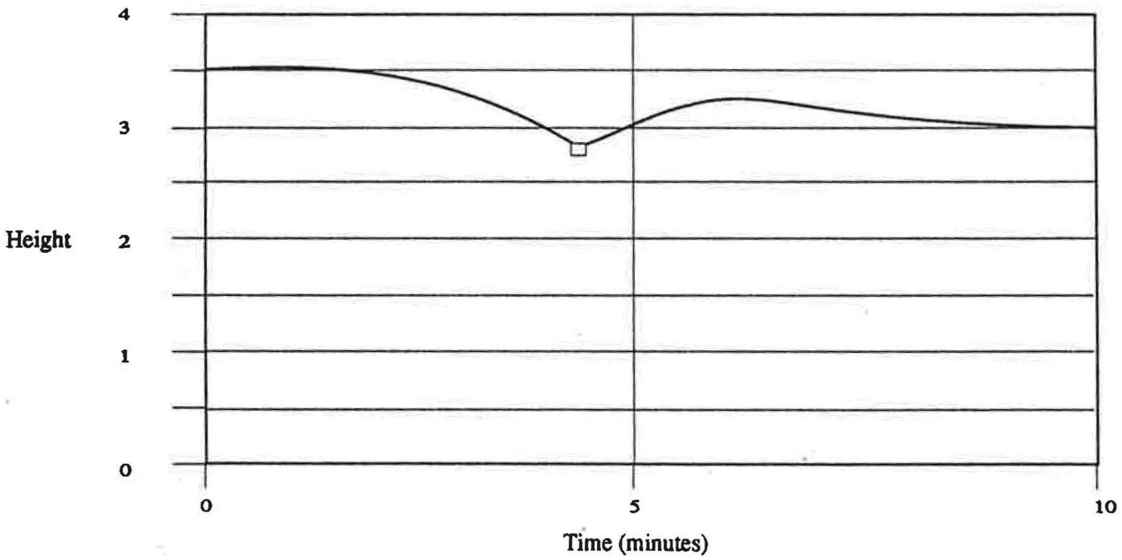


Figure 2B *Speed of smoke logging in basement*

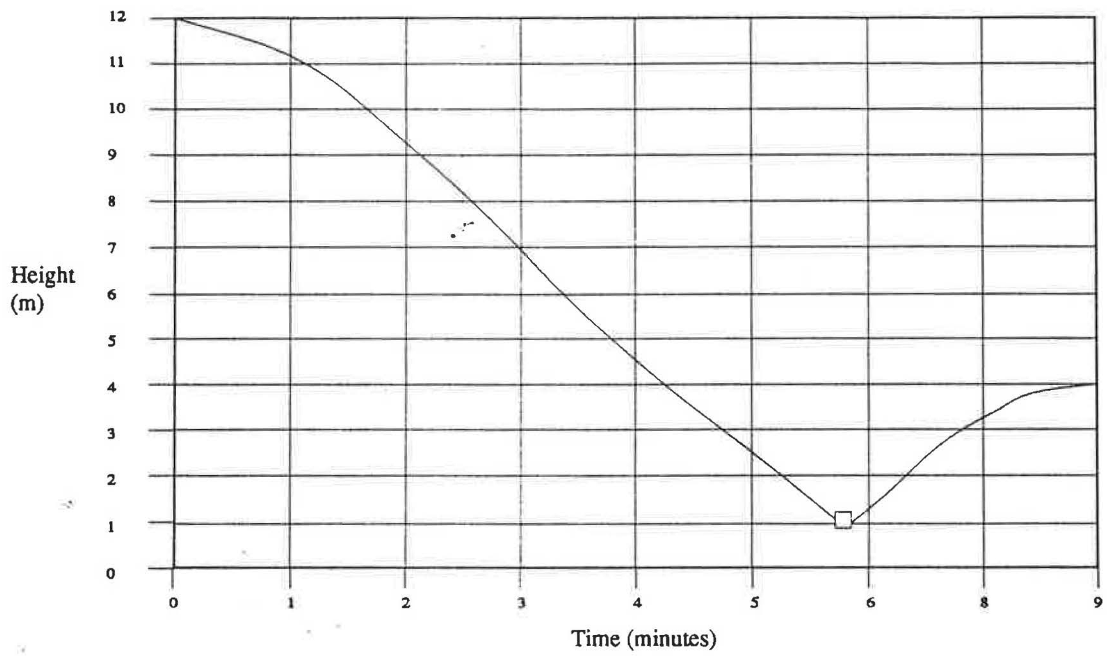


Figure 2C *Smoke flow graph—warehouse building*

Shopping Centers and Open Multilevel Areas

Initially, smoke flow in a retail shop will behave much like that in a single-story building; however as hot gases from the shop flow first into the common mall and then under balconies to higher levels, the volume and mass flow considerably increase as mixing of air takes place. The danger now is that escape routes on upper levels will be quickly affected and escape times considerably extended. This is a particular problem in buildings open for public use where occupants may not be totally familiar with their surroundings. In these cases, people will attempt to exit by the way they know and that will usually be the way they came in. This will cause congestion and possible panic.

Atria

Atria are not new—the Romans were building them over 2,000 years ago. These days, what can loosely be called an atrium attracts people because it is a more comfortable, safe place where they can work, shop, or live in a controlled environment.

Modern atria usually present a low risk. However, high potential hazard and a common factor of fires in this type of building increases the difficulty of controlling fires at lower levels, thereby affecting lives on upper levels. In this case, technology has lagged behind the designers who have built large atria without understanding the principles of smoke extraction. This paper explains some basic principles.

The graphs shown in Figures 2A, 2B, and 2C are a result of computer simulation based on early work by the U.K. Fire Research Station on model tests, which have since been verified in full-scale tests. The graph is based on a growing fire.

Benefits

There are a number of methods of controlling the movement of smoke in buildings, and several different reasons for wanting to do so.

Primarily, smoke control is designed to protect means of escape and to ensure safety of life for the building's users. This is achieved by restricting the spread of smoke by adequate ventilation to increase visibility, remove toxic gases, and reduce temperature. This gains time for all. It is also achieved by the more familiar means of keeping escape routes clear by means of fire doors, barriers, ventilated lobbies, and by pressurization of stairwells. It should nevertheless be realized by all, that other motives are possible and indeed vital in reducing loss.

A heat and smoke control system can also be designed as a direct aid to fire fighting. This is especially true of smoke venting systems in warehouses and factories having few people usually present but having valuable contents. The aim is to restrict the lateral spread of fire, allowing it to be seen from a distance and fought more easily, more safely, and (perhaps most important) more quickly. The increased visibility not only allows more time for fire fighters to enter, but conversely more time for occupants to escape.

A system can be designed to help directly protect the building's structural integrity by releasing heat from inside the building. Experience has shown that fires have been kept smaller by the process of releasing heat, but it must be recognized that sprinklers are particularly effective in this role, since the airflow necessary for ventilation allows the fire to continue to burn unless checked by the fire brigade. However, a smoke control system that is primarily designed to assist the fire brigade will obviously serve to protect the building indirectly by making the area tenable.

Smoke ventilation also assists indirectly in the reduction of fire loss by reducing water damage. By allowing fire fighters improved visibility and the opportunity to see the fire, the correct application of water can be achieved whilst the restriction of the spread of heat at high level limits the operation of sprinklers to an area over the fire where they can be of best effect.

Additionally, the early release of partially burnt gases which will accumulate at high level restricts the effects of explosions and flashover commonly associated with late venting, either by roof collapse or manual venting after the fire is well established.

Smoke and heat ventilation systems can therefore be designed for both the protection of life and property in special structures, particularly large areas with large individual spaces such as factories, warehouses, shopping complexes, sports halls, basement areas, and atria.

History, Research, and Development

Smoke ventilation is not a new concept. Historically, the need for venting was forced on the public and safety authorities by theater fires.

1881	Vienna Ring	No venting	449 died
1887	Exeter Theater Royal	No venting	186 died
1903	Chicago Iroquois	Vent installed but not operating	566 died
1911	Edinburgh Palace	Vented over stage	None died in the audience

In the Iroquois Theater fire, people sitting in the gallery were stifled before they left their seats, while in Edinburgh, with a fierce fire on stage, they had time to play the National Anthem before the audience left.

Apart from numerous tests over the last 30 years at the U.K. Fire Research Station on models of single-story factories, shopping malls, and warehouses, there have been many full-scale fire tests, starting at Uxbridge in 1957, Portsmouth in 1966, Lyon in 1984, to Ghent in 1989. Almost weekly, the Belgian Fire Insurers (ANPI) demonstrate the effect of venting a building at Louvain Le Neuve, where observers regularly express astonishment at the speed of smoke logging in an unvented building, while the use of vents keeps the smoke to a distinct layer just below the roof.

British Ropes (1962 and 1972) and the Rootes Group (1959 and 1960) both had two fires in similar buildings, one unvented and the other vented. In both cases, the vented fires limited damage and made fire fighting straightforward.

Much experience is gained by examining the effects of smoke exhaust in real live fires. One specialist company has over 70 case histories documented where venting has cleared the air, reduced damage, and eased fire fighting.

The prevention of flash fires by venting is rather difficult to demonstrate, but often enough, the absence of venting has been the cause of disaster. In 1957, an exploding gas cylinder at Jaguar Cars U.K. finally opened the roof, but until then any approach to the fire had been impossible. The same situation arose at Linde AG Wiesbaden where control only became possible after the concrete roof of the enormous refrigerator store collapsed. The roof over the largest cotton warehouse in Europe at the Port of Le Havre

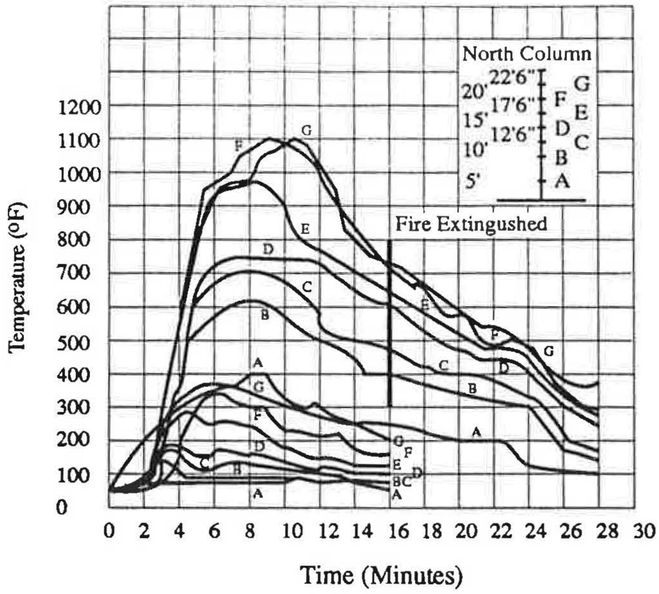


Figure 3 *Effectiveness of venting in reducing temperatures*

also had to collapse and vent hot gases in 1983, after an explosion, before fire spread could be checked.

Various tests have demonstrated how effective venting is in the reduction of temperatures. At Portsmouth, in a building with a mean height of 6 m, the temperature reached 590°C in 8 min, but rose to only 200°C when the building was vented. At breathing level the temperatures were 180°C and 35°C, respectively, allowing the area to be tenable (Figure 3).

In the same building with all openings closed to provide a sealed structure, the burning design fire could only reduce the oxygen content to 18%, a point well above the level where flaming combustion would cease.

One question that often concerns a number of people, is that ventilation will encourage the fire and increase the rate of burning.

The rate at which fire burns depends on the type and distribution of the fuel as well as the supply of oxygen. In a large space building, there is always enough oxygen to keep a fire going irrespective of venting.

The fire draws its air by natural convection whilst vents, usually at high level in the roof, merely drain off the heat and smoke rises to the roof space. The density of smoke is also less for a fire deprived of fresh air. Over a period of time, the burning rate of a vented and unvented fire is similar.

World research has produced the works that can be taken as the basis for current design (see References).

LARGE UNDIVIDED VOLUME BUILDINGS

System Designs and Fire Regimes

These include most industrial premises, many warehouses, underground structures, shopping complexes, atria, and other more specialized types of buildings.

Basic Principles. For the above large volume areas (in practice more than 1000 m^2 undivided), the same basic approach should be followed for the design of a smoke control system for protecting those escape routes running through and open to the large undivided volume. The intention is to keep the smoke in the upper reaches of

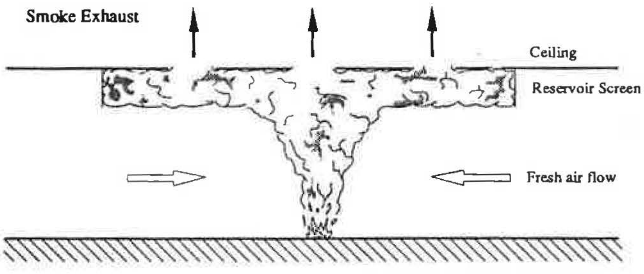


Figure 4 *Principle of system needed to contain smoke in welldefined layer*

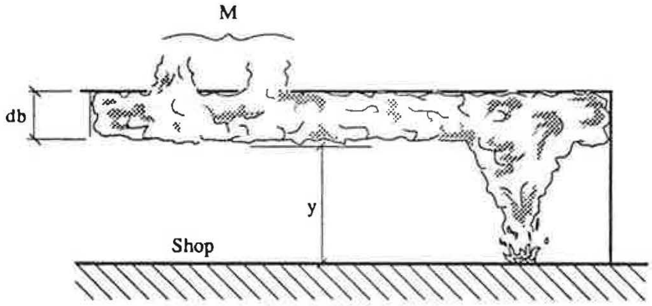


Figure 5 *Hot smoky gases entering (and being removed from) ceiling layer*

the building, leaving clean air near the floor to allow people to move freely. This stratification or layering of the smoke is made possible by the buoyancy of the hot smoky gases produced by the fire and it follows that to be most successful, the high level layer must remain warm.

This type of smoke control system is usually called smoke ventilation or smoke spill (Figure 4) where air mixes into the hot fire gases as they rise; these mixed gases form a layer beneath the ceiling, which is contained within a smoke reservoir. The boundaries of this reservoir can be screens, walls, or other features. Smoky gases are removed from the reservoir at least as rapidly as they enter from below, either mechanically (using fans) or naturally (using buoyancy of the gases to drive them through openings in the roof). Sufficient air must enter the building below the smoke layer to replace the extracted gases or the system will not work. These principles apply to all types of building in this class.

Basic Design Procedure

The design of an adequate smoke venting system depends on a large number of factors such as:

- Building dimensions and structure
- Contents and layout
- Special hazards
- Fire/smoke detector system
- Building occupancy
- Escape routes
- Call out time of fire brigade
- Sprinklers
- Likely fire development size
- Adjacent structures

Detailed guidance on the design of smoke ventilation systems can be found in FRS Technical Papers No. 7 (1963) and 10 (1964) and Hinkley (1986) for industrial premises, Morgan for shopping complexes, and FRS/Colt (1984 and 1987) for atria designs. However, most systems can be approached using a standard design sequence shown in Table 1, but because of variable parameters concepts of each building, each requirement has to be assessed separately.

For the single-story warehouse, workshop, or factory where protection of life and property is concerned, the detailed calculations from various nomograms in Fire Research Technical Paper No. 10 (1964) and shown in Figures 5, 6A, and 6B, allow the area of ventilation to be calculated once parameters such as building height, smoke depth, and anticipated fire size are established. Case histories of subsequent fires in buildings with such designs incorporated show that the theory calculations stand up in practice.

TABLE 1
Basic Design Procedure—Smoke Ventilation

1. Decide on the maximum size of fire to be considered.
2. Decide the height of the smoke layer's base.
3. Calculate the amount of air mixing into the rising gases before they enter the ceiling layer (this equals the required extraction).
4. Check that the smoke reservoir is of adequate depth and area.
5. Ensure that the vents (or extraction openings) are of the correct size and distribution.
6. Check other factors (*e.g.*, sprinkler cooling).
7. If any discrepancies, redesign and go back to 1.

Fire Research Technical Paper No. 7 (1963) provides a formula for more specific calculation of the mass flow of hot gases from a fire under given conditions. This calculation is reconfirmed in the most up-to-date investigation (Hinkley 1986).

$$MF = 0.2PY\ 3/2 = kg/s \qquad (1)$$

where:

MF = mass flow in the plume entering the smoke layer, kg/s
P = perimeter of fire, m
Y = height from base of fire to smoke layer, m

It can be seen from Equation (1) that the mass flow of gases to be exhausted considerably increases as the height of the clear layer increases. This is because of the entrainment of cooler air as the gases rise.

It can also be seen that the mass flow of gases to be exhausted has little relationship with the building volume. Hence the previous design methods, based on air changes per hour, would not be suitable for effective smoke control.

Heat Output and Gas Temperature

If the heat output from the fire can be assessed, then the temperature of the gas layer can be established. The greater the mass flow, the lower the smoke/gas temperature but the more exhaust ventilation is required.

$$\Delta t = Q/MF \qquad (2)$$

where:

Q = heat flux of fire, kW
Δt = temperature rise, °C
MF = mass flow of gases, kg/s

The exhaust volume (m^3/s), if a powered fan system is to be used, can then be calculated from the above information.

$$V(m^3/s) = MF/1.2 \times Tc/To \qquad (3)$$

where:

Tc = exhaust absolute temperature
To = ambient absolute temperature

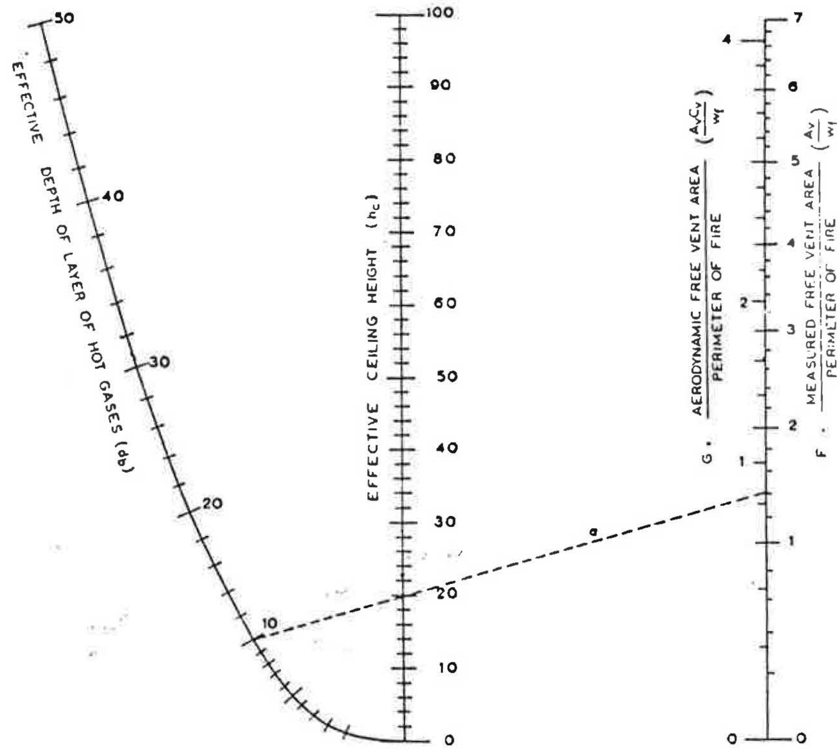


Figure 6A Nomogram indicating venting of large but not fully developed fire

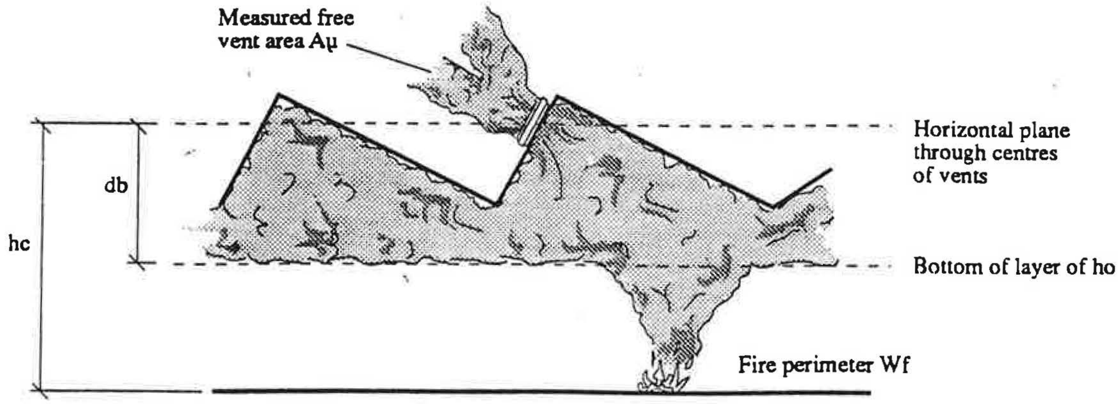


Figure 6B Notation used in nomogram of large but not fully developed fire

TABLE 2
Mass Flow, Temperature, and Volume Rate of Extraction of Gases from 5 MW Fire (Ignoring Cooling)

Mass Flow Rate (Mass Rate of Extraction), kg/s	Temperature of Gases Above Ambient, °C	Volume Rate of Extraction (at Maximum Temperature), m^3/s
9	556	21.5
12	417	24
15	333	26
18	278	29
24	208	34
30	167	39
36	139	43
50	100	55
65	77	67
80	63	79
95	53	91.5
110	45	103.5
130	38	120
150	33	136

As an example, Table 2 indicates the values of mass flow/gas temperature/volume rate of extraction, volume flow rate, and temperature of gases from a 5 MW fire (ignoring cooling).

Natural Smoke Extract

For natural (gravity) systems of smoke release, the aerodynamic area of opening can be found either from using nomograms, Figure 6A, or, more accurately, by taking into consideration factors of temperature and inlet and extract air ratios using the following formula (FRS Technical Paper No. 7 1963):

$$A_v C_v = \frac{M}{P_o}\left[\frac{T_c^2 + (A_v C_v / A_i C_i)^2 T_o T_c}{2g\, d_b\, \theta_c\, T_o}\right]^{1/2} \qquad (4)$$

where:

$A_v C_v$ = aerodynamic free area of natural ventilation, m^2
A_v = measured throat area of ventilators for the reservoir being considered, m^2

Ai = total area of all inlets, m^2
Cv = coefficient of discharge (usually between 0.5 and 0.7)
Ci = entry coefficients for inlets (typically about 0.6)
M = mass flow rate of smoke to be extracted, kg/s
Po = ambient air density, kg/m^2
g = acceleration due to gravity, m/s
db = depth of smoke beneath ventilator, m
θc = temperature rise of smoke layer above ambient, °C
Tc = absolute temperature of smoke layer, K
To = absolute temperature of ambient air, K

The resulting area of the opening is then related to the design and efficiency of the vents to be used.

Design Fire

As a general rule, the larger the fire the greater the quantity of smoke and the larger the required capacity of the smoke ventilation extract. It is clearly impossible to design a system to cope with the largest possible fire, since there is no limit to the size of fire. In general, however, larger fires are rare and the design can be for a "largest likely" fire defined in some appropriate manner.

In single-story buildings, consideration would be given to the risk, building location, and call out time of the fire brigade, as well as to the existence of fire alarms and detectors. For example, a fire in a building fitted with smoke detectors is likely to be smaller in size by the time the fire brigade arrives than one without. Much can be gained from experience, case histories, and hard logic to determine the likely fire size when tackled.

Except in special cases, the smallest fire to be considered in relation to the use of Fire Technical Paper No. 10 (1964) would be 3 m by 3 m, whereas in a high risk area the fire size may be considered as 10 m by 10 m.

For shopping malls, the Fire Research Station has used the U.K. Fire Statistics computerized data base to deduce a "largest likely" fire for retail premises. This fire is of 5 MW output and is 3 m by 3 m in size when sprinklers are present and is used as the basis for calculation when designing smoke control systems in malls. There has been a recent tendency to use the 5 MW design fire for smoke control in all types of building. This is potentially misleading, since it strictly applies only for fires in sprinklered retail premises.

Height of Smoke Base

If the internal geometry of the building is known, it is simple to select the height above the highest occupied floor of the case of the buoyant smoke layer hugging the ceiling. This should be sufficiently high so that people can move freely beneath it without encountering smoke. Where the primary concern is the protection of easily damaged goods or other contents, the smoke base needs to be above these goods.

The base of a buoyant layer is never sharply defined, being "fuzzier" for cool smoke than for hot. This fuzziness must be allowed for in choosing the height of the smoke base and explains why a single-story mall can have a smoke base at least 2.5 m above the floor, while a two-story mall with a cooler buoyant layer should have at least 3 m above its upper floor.

The calculations shown in Equation (1) will generally hold good for fires in single-story structures, basements, and the larger space of a shopping complex or atrium, although smoke movement in these latter areas may change due to other factors.

Shopping Complexes

Where individual larger shop units extend over more than 1300 m^2, separate smoke spill systems should be considered and the mass flow calculation given in Figure 5 will apply. With a larger number of smaller shops, as in a complex, it would be impractical to individually vent each unit and hence it can be expected that exhaust from the common mall or central void would occur, provided the smoke depth at ceiling level is above the heads of those escaping.

Experiments have shown that smoke passing from a shop into a mall will approximately double in quantity before turbulence damps out sufficiently to prevent further entrainment of air. Hence, in such a situation as Figure 7, the mass of hot smoky gases that must be removed from the mall ceiling reservoir each second is double the value given by Equation (1) where Y is now the height from the floor to the base of the smoke layer in the mall area.

Multistory malls having several shopping levels with one or more voids and openings vertically connecting the different levels are far more difficult to successfully ventilate, since the hot smoky gases rising from the lower levels to a higher will mix with large quantities of air and can spread to balconies of the upper levels.

In such cases, the volume of entrained air can be reduced by the use of adequate screening, and one suggestion is shown in Figures 8A and 8B.

Alternatively, individual exhaust from each floor could be considered. Figures 9A and 9B illustrate in schematic form a mall, whose upper floor is penetrated by voids that will leave a considerable area for pedestrians. On the lower

$Ms = 0.2PYs^{3/2}$ $\quad$ $Mm = 0.4PYm^{3/2}$

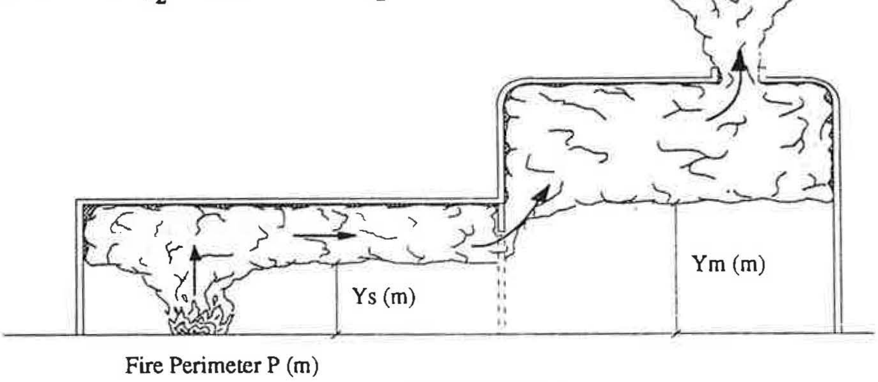


Figure 7 *Entrainment into plume*

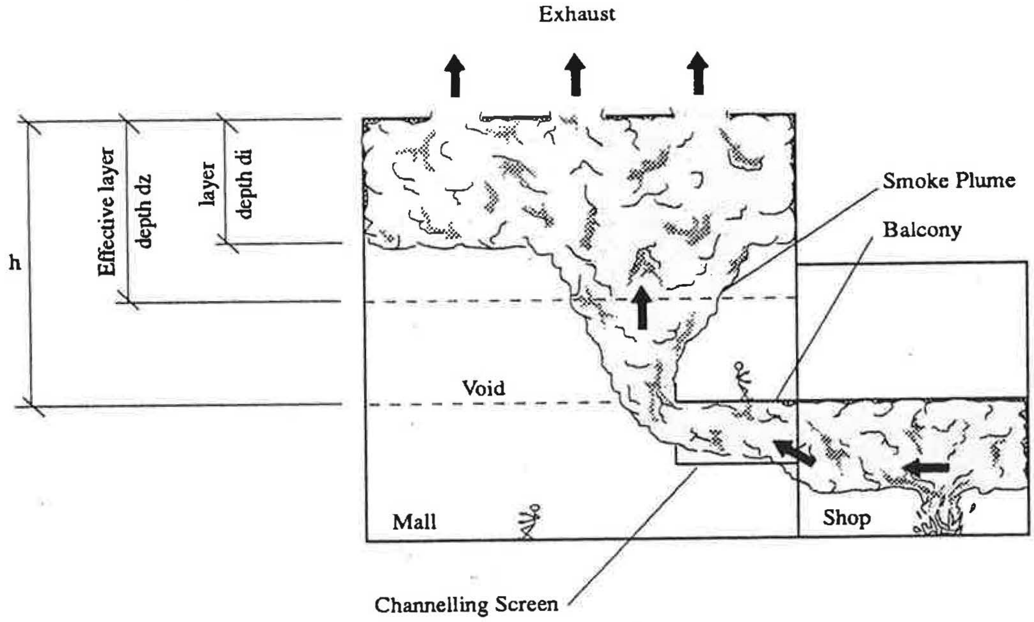


Figure 8A *Use of smoke channeling screens to produce compact rising plume—section*

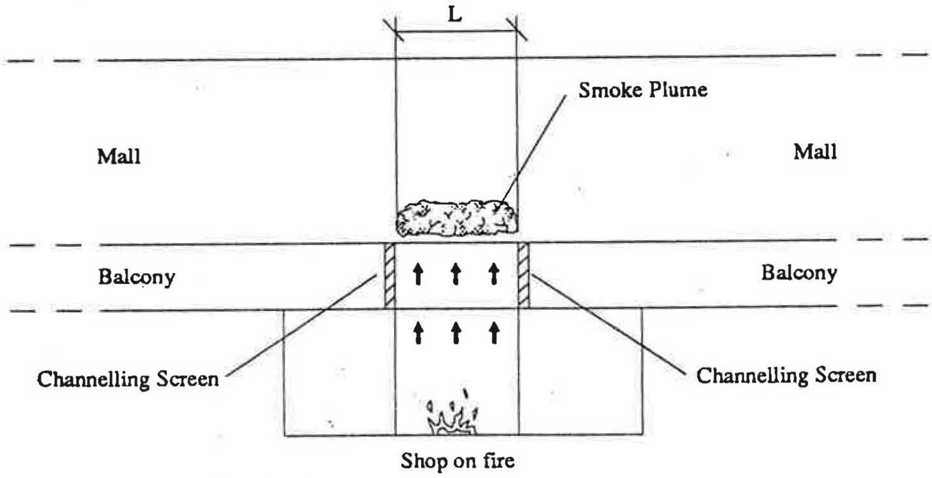


Figure 8B *Use of smoke channeling screens to produce compact rising plume—plan*

floor, there is a large area situated below the upper deck. If suitably screened, the area below can be turned into a ceiling reservoir similar to that of a single-story mall albeit of a more complicated geometry. This reservoir can then be provided with its own smoke extraction system. Other screens can be positioned across the mall to limit the size of the reservoir, as for a single-story mall.

Where smoke flows through the small void (Figures 10A and 10B), care must be taken if the upper levels are used as escape routes. The quantity of smoke entering the ceiling reservoir can be found by using graphs (such as Figure 8C) that relate the mass flow rate of gases to the height of rise above the floor immediately above the level on fire. Note the rapid increase in gases with increase in height. If gases have to rise through one upper level plus a further higher level to allow people in it to move freely, it can be seen from Figure 8C that the extraction from the ceiling reservoir must be considerably greater than 200 kg/s—a very large extraction rate. It is large enough to suggest that a smoke control system for more than 3 to 4 levels is not a practical proposition unless the highest level or levels can be allowed to become smoke logged without affecting means of escape.

This fact is more recently confirmed in research work in atrium buildings where it is concluded that "through flow" smoke ventilation will rarely allow escape routes to be open to the atrium above the fourth or fifth floor (Morgan and Hansell 1987).

Air Inlets

If venting is to be effective, it is necessary for cool air to flow into a building to replace the hot air flowing out through the roof vents. Therefore, adequate inlets for cold air are a necessary design consideration.

In a shopping center or mall, it may be necessary for low level doors or louvered systems to open automatically on a signal from the smoke detector system.

In a single-story building of a factory, normally existing doors or windows can be relied on although the available area should be checked at the design stage. In very large buildings with a number of roof compartments, vents and other openings in the roof some distance from the fire zone can be opened to act as inlets.

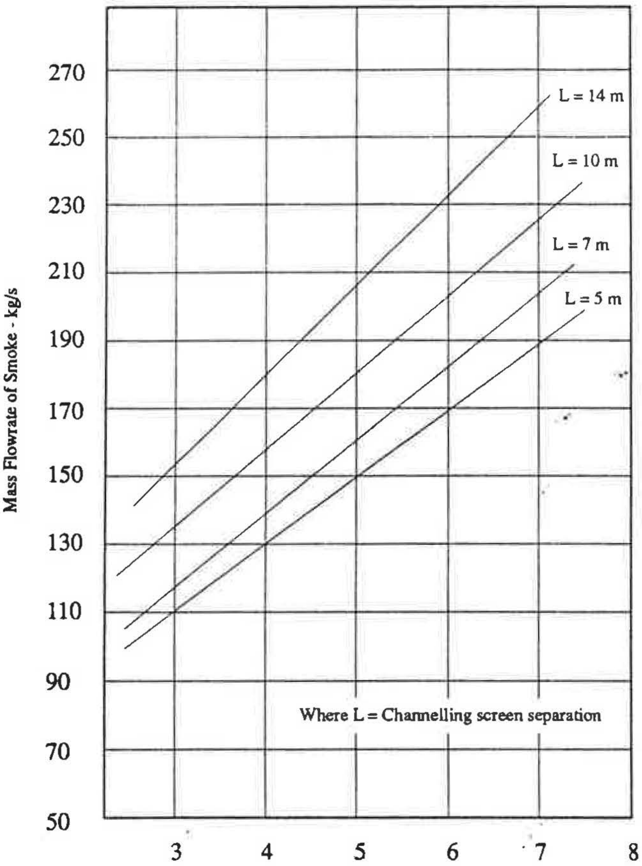


Figure 8C *Mass of smoke entering ceiling reservoir from 5 MW fire—large voids*

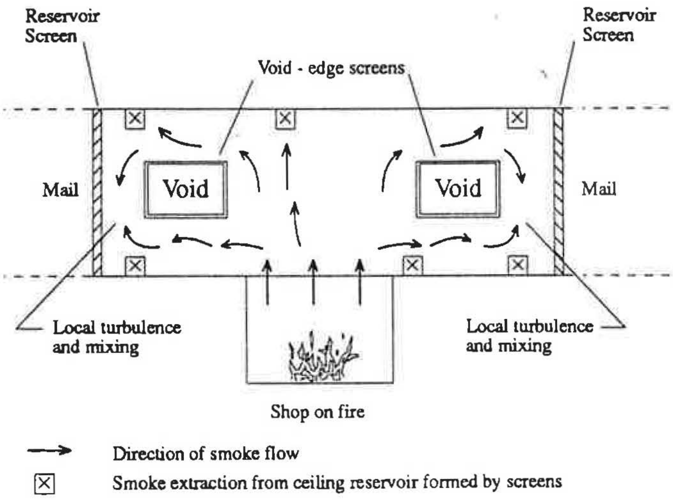


Figure 9A *Schematic plan of multistoried mall with smoke reservoir on each level*

The area of inlet opening for smoke exhaust ventilators to operate efficiently must approach twice that of the exhaust or the efficiency of the exhaust system will reduce dramatically. For example, 1:1 equal inlet to extract will result in exhaust ventilators operating as low as 70% efficiency.

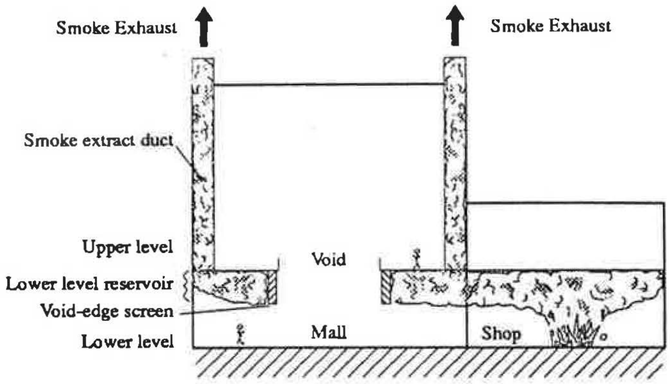


Figure 9B *Schematic section of two-story mall with smoke reservoir on lower level*

Control

Whenever a smoke ventilation system is designed to protect life, it should operate automatically on the first detection of smoke.

Natural smoke ventilators, many of which will normally be closed, should *not* operate solely on fusible links since they take far too long to operate in large areas. Pneumatic systems that provide opening when air pressure is released are commonly used. These are activated by smoke and/or heat detectors. If sprinklers are present, the system should be linked to flow switches and linked to the fire alarm system. Manual override must be included for testing or inspection purposes.

Powered smoke systems require electrical control that must be independently dedicated to the operation of the ventilators in the event of a main electrical supply. In this case, a standby emergency generator will usually be required.

Atrium Buildings

Atria today are designed to create very large undivided volumes within a structure, creating visually and spatially the ideal external environment indoors.

Modern atrium buildings are designed with the atrium creating a feature that can be appreciated from within the adjacent rooms. Thus the room/atrium boundary is usually either glazed or completely open. When compared to conventional buildings, this architectural/aesthetic requirement imposes additional problems of life safety during a fire as smoke, hot gases, and even flames may travel from one (or more) rooms into the atrium and hence affect areas that would not be affected in the absence of an atrium.

Recent experience of fires in atrium buildings in the United States has shown the problem of flame travel internally through the atrium to be minor in comparison to the hot and toxic gases accumulating and building down in the atrium. There has been a need for a properly designed smoke control system in atrium buildings, and the most recent research by U.K. Fire Research Station has produced design considerations (Morgan and Hansell 1984, 1987).

The smoke control systems in most cases required exhaust ventilation, the type depending on the building arrangement.

1. "Sterile tube" atrium (Figure 11). This is an atrium that is separated from the remainder of the building by

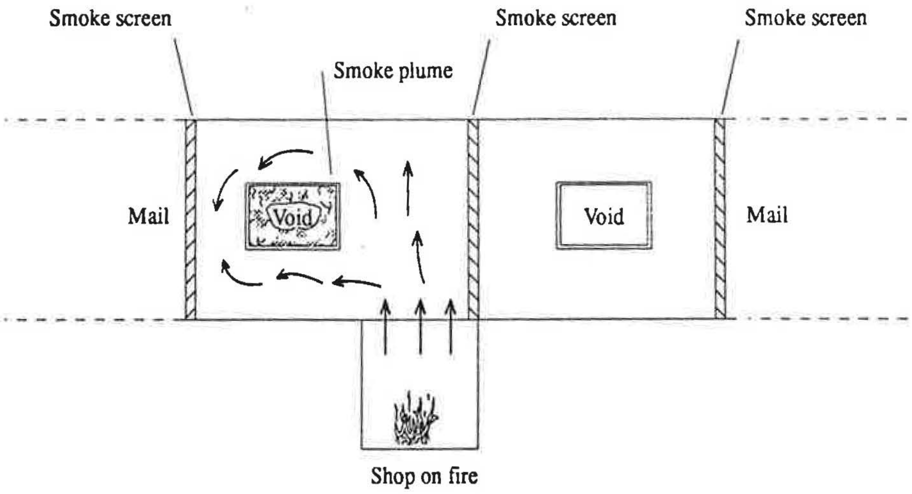


Figure 10A *Plan view of smoke circulation pattern below upper deck (with smoke-restraining screens)*

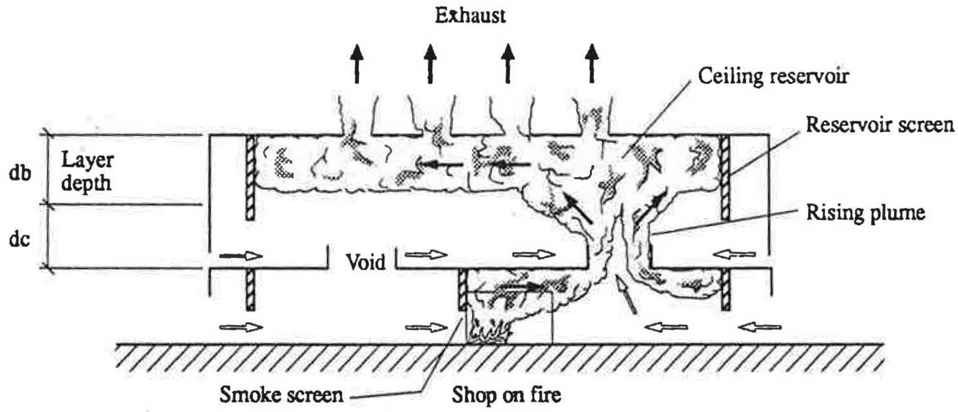
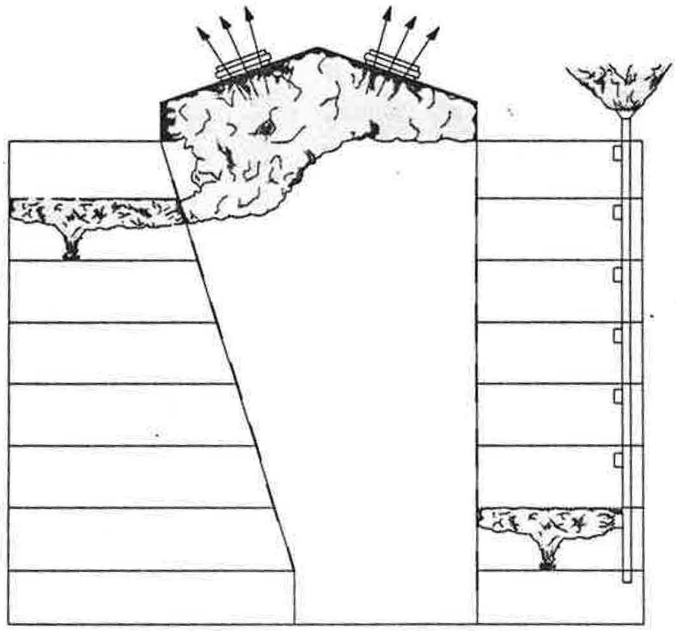


Figure 10B *Smoke and air movements in two-story mall with small connecting voids*



Atrium separated by fire rated glass
1. Direct vent of compartments.
2. Depressurization of atrium space (only if fire rated screen breaks or fire on atrium floor)
Smoke cannot break back to other floors.
Inlet low level doors.

Figure 11 *Sterile tube atrium*

fire or heat-resistant glazing. The atrium space generally has no functional use other than as a transit area.

The methods of smoke control that may be employed are:

a) Direct ventilation of the compartments.
b) Depressurization ventilation of the atrium space.

The only time depressurization ventilation will be deemed necessary is if it can be assumed that the fire rated glass onto the compartment will shatter, thus allowing smoke and hot gases to flow into the atrium or if a fire could occur on the atrium floor.

2. Closed atrium (Figure 12). This is an atrium that is separated from the remainder of the building by ordinary (nonfire-resisting) glass. The atrium space may well be functional (cafeterias, restaurants, recreational, etc.).

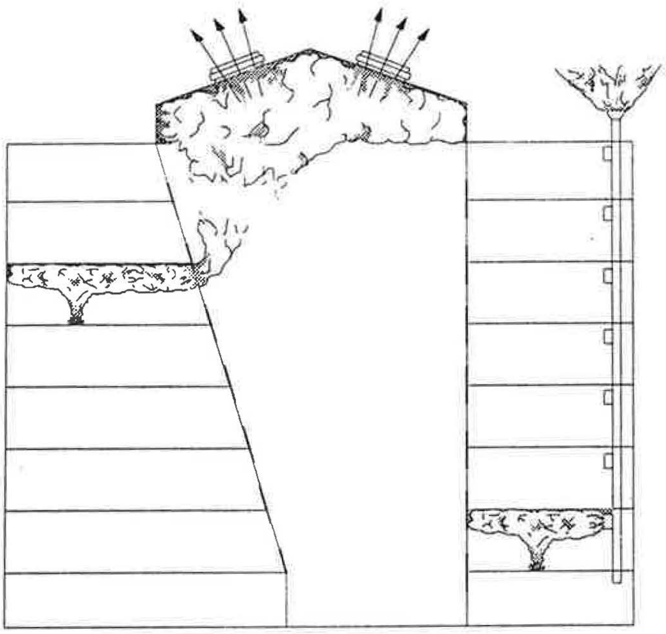
The methods of smoke control that may be employed are:

a) Direct ventilation of the compartments.
b) Throughflow ventilation of the atrium space.
c) Hybrid ventilation of the atrium space.

3. Partially open atrium (Figure 13). This is an atrium which has some lower levels open to the atrium and the remaining levels closed off by glazing.

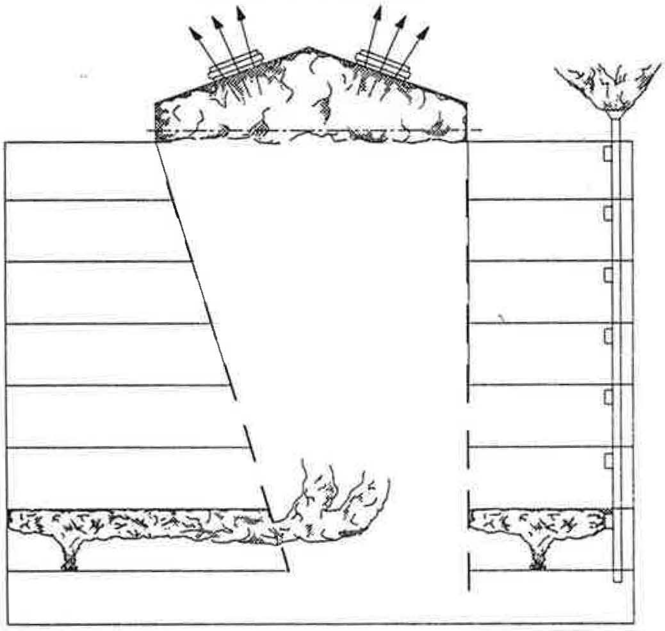
The methods of smoke control that may be employed are:

a) Direct ventilation of the compartments.



Atrium separated from remainder by ordinary (non-fire rated) glass.
1. Direct vent of compartments.
2. Through flow vent of atrium space.
3. Hybrid vent of atrium space.

Figure 12 *Closed atrium*



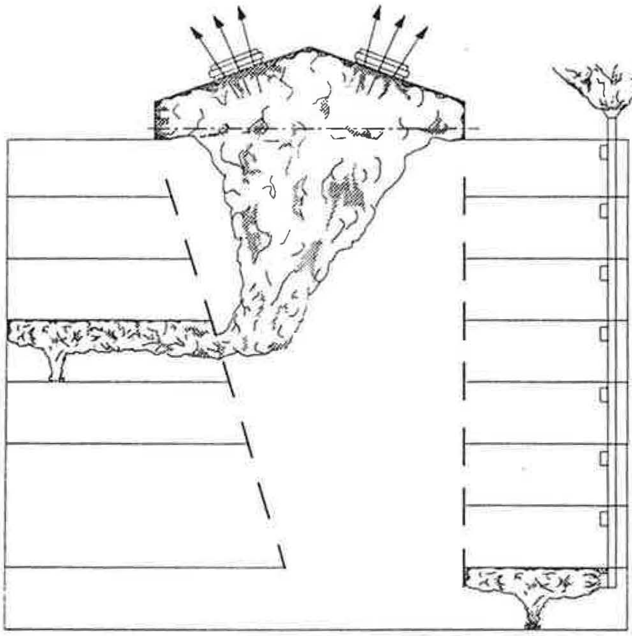
Some lower levels open to atrium.
Remaining levels closed off by glazing.
1. Direct vent of compartments.
2. Through flow of atrium space.
3. Hybrid vent of atrium space.

Figure 13 *Partially open atrium*

b) Throughflow ventilation of the atrium space.
c) Hybrid ventilation of the atrium space.

4. Fully open atrium (Figure 14). This is an atrium that has some upper or all of its levels open to the atrium.

The methods of smoke control that may be employed are dependent on the vertical information of levels within the atrium.



Some of all upper levels open.
Methods of smoke control depend on vertical formation of levels:
A. Compartments in line or stepping back
   1. Direct vent of compartments.
   2. Through flow vent of atrium space.
B. Compartments stepping into atrium.
   1. Vent of compartments direct.

Figure 14 *Fully open atrium design*

a) Compartment boundaries vertically in line with each other or stepping back from the atrium as it rises.
   i) Direct ventilation of the compartment.
   ii) Throughflow ventilation of the atrium space.
b) Compartment boundaries stepping into the atrium as it rises.
   i) Direct ventilation of the compartment.

Direct Compartment Ventilation

This is done in order to prevent hot smoke and gases from entering the atrium. It may be achieved by either a dedicated smoke exhaust system or by adapting and boosting an air-conditioning or ventilation system. If the compartment is open to the atrium, then the compartment must have either a downstand barrier to create a reservoir within the compartment, or a high-powered exhaust slot at the boundary edge to achieve a similar effect.

If the compartment is glazed, then some provision will need to be made for an inlet air supply. In general, inlet air may be supplied from the atrium via roof ventilators.

Throughflow Ventilation of Atrium

This is the steady-state vent system familiar to most. It is used when the fire is in the same space as the people, contents, or escape routes being protected, without it filling that space. The intention is to keep the smoke in the upper reaches of the building, leaving the clean air near the floor to allow people to move freely. This stratification or layering of the smoke is made possible by the buoyancy of the hot smoky gases produced by the fire, and it follows that to be most successful, the high-level smoke layer must remain warm. Smoke ventilation is therefore only suitable for atria where fires can cause smoke to enter the atrium space. Such fires can either be fuel-bed controlled fires at the base of the atrium, or fires in adjacent spaces (rooms) that allow smoky gases to enter the atrium.

Depressurization Ventilation

This is a special case of pressurization where gases are removed from the smoke affected space in a way that maintains the desired pressure differences and/or air speeds across leakage openings between that space and adjacent spaces. Note that depressurization does not protect the smoke-affected space in any way. Instead it protects the adjacent spaces. In the circumstances of an atrium, it is sometimes possible to use the buoyancy of the smoke gases themselves to create the desired depressurization effects. Depressurization will generally apply only in closed atria.

Hybrid Ventilation

This technique employs a combination of throughflow ventilation to create a distinct layer for some purpose and the depressurization concept of raising the building neutral pressure plane to a higher level to protect smoke sensitive stories. This form of smoke control is the one most frequently employed in designs.

Practical Design Considerations Other than Throughflow Ventilation

Although it is not practical to detail the calculations of the mixing into the rising plume, Figure 15 shows examples of the output curves that can be produced.

As may be seen from the examples, the mass flow rates generated by the entrainment into the rising plume is very large, and hence the plume cools quickly with height. This large increase in mass flow with increase in height tends to suggest that there may be some cutoff point in the rise of the plume above which it might become economically impracticable in terms of a smoke control system. Experience suggests that this often is true for flows larger than 150 to 200 kg/s.

Another effective limit may also occur if the temperature of the gas layer forming in the roof void is too low, perhaps below 10 or 20°C above ambient, as the stability of the layer may be affected by internal day-to-day heat gains in the atrium or adverse air currents (drafts) due to ventilation, air conditioning, or weather conditions. There is very little information available on the destabilization of cool buoyant layers, so a precise limiting temperature cannot be given. Further research is desirable in this area.

Which limit is reached first will depend on the situation being considered, *i.e.*, the type of fire considered, the construction of the compartment, the construction of the atrium, the mode of ventilation, etc.

Experience suggests that one or other limit is usually reached when the height of rise above the fire room opening exceeds 18 to 20 m. It follows that it does not usually appear to be practicable to design a continuous (steady state) ventilation system requiring more than 4 to 5 stories (sometimes less) to be kept free of smoke, regardless of whether it is powered or natural smoke ventilation.

This limitation would appear to pose a serious threat to the design of interesting atria.

Smoke Ventilator Selection

Smoke can be ventilated mechanically or naturally. The choice will depend on the nature of the fire and on the

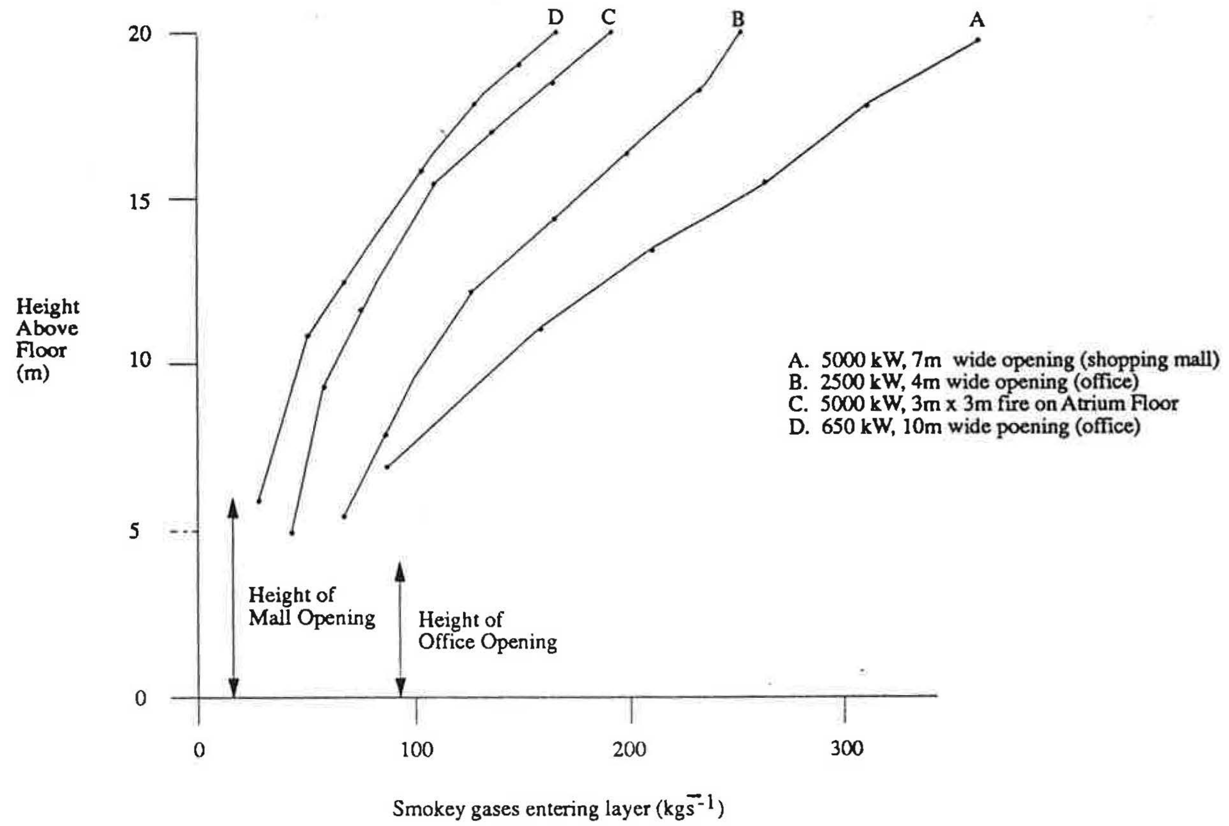


***Figure 15** Examples of smoke flows in atria*

structure in which it occurs. There are many factors common to the types of equipment.

First, ventilators must be automatic, triggered by smoke detectors so that they operate when the mains electricity is cut off. Usually, they are backed up by a link set to fuse at 70°C in case heat is felt first.

Manual control is also needed so that equipment can be activated in an area that firemen think is likely to become affected by heat and smoke. Automatic operation is essential because fires can occur at night when no one is about.

The equipment must also be capable of operation even after standing idle for years and sited in a position where maintenance is easy. If sprinklers are in use, ventilators must not be adversely affected by them.

Finally, whichever type is chosen must not present a hazard itself by, for example, allowing hot components to drop into the building, using materials that can burn, or contributing to fire spread.

Fan-powered equipment is preferred where wind can produce positive pressure across a building. It should also be considered where quantities of cool smoke are likely to be produced and where it is difficult to form openings in the building fabric.

The fan is, however, a device with a constant output, so any increase in heat from a fire will not produce increased mass flow like a natural ventilator.

Mechanical equipment in Europe is designed to operate at 400°C for 2 h.

In the United Kingdom, 300°C for 1/2 h is accepted mainly because, if a fire produces so much heat for the longer period, the building would be close to destruction. High temperatures can easily put an end to the operation of the mechanical equipment, as can the failure of any single component.

Fans must be operated by a source of electricity independent of the main supply, because this is often cut off in a fire. Sometimes, the generator for the auxiliary electrical system is so big and the wiring so costly that it is ruled out for reasons of economy alone.

Natural ventilators tend to adapt to fire size and to the quantities of heat and smoke produced, by automatically adjusting their capacity. This is, however, directly related to their coefficient of exhaust.

A simple opening has a factor of 0.6. Most louvered ventilators are close to this figure, while special designs can exceed it.

Inevitably, permanently weathered smoke ventilators will offer much more resistance to smoke exhaust than louvered units that are currently more commonly used in Europe.

The fact that natural ventilators are often employed for day-to-day ventilation purposes, has the advantage of being regularly tested by virtue of regular use. Control of a natural system can be arranged to be fail-safe.

The materials from which ventilators are made form part of the choice. Aluminum has the advantage of melting at 650°C, when it quickly vaporizes, ensuring that the opening is kept free. Iron or steel may buckle under heat and form a damper, thus defeating its purpose. Many plastics will behave in the same way or melt, allowing burning drops to fall into the building, possibly injuring fire fighters or spreading the fire.

Air inlet supplies are vital to the operation of any ventilation system. For smoke removal, natural ventilation equipment alone is unsatisfactory. Powered inlet equipment creates turbulence and can spread the fire too.

Inlet ventilation in many buildings occurs naturally, but in enclosed areas like offices, shops, and hotels, additional provision must be made. The natural ventilators used must be fitted with manual controls that can easily be handled by fire fighters, and special ventilation to blend with the building design is available.

As any equipment may not be used for years and yet must always be ready, its quality is important. A wise choice would therefore be equipment made by companies with the British *Standard* 5750 Quality Assurance Certificate and FIRTO Lost Prevention Council Approvals that can come with maintenance, service, and commissioning.

New British Standard

Standards are now set down by the British Standards Institution for the design and construction of smoke control equipment to ensure that the equipment is designed and operated correctly in fire conditions.

British *Standard* 7346 (1990) is concerned with Components for Smoke and Heat Control Systems.

Part 1—Specification for Natural Smoke and Heat Exhaust Ventilators

Part 2—Specification for Powered Smoke and Heat Exhaust Ventilators

Part 3—Specification for Smoke Curtains

Users of this British standard are advised to consider the desirability of assessment and registration of a suppliers quality systems against the appropriate part of BS 5750 by a third party certification body.

Jack roof designs, common in Southeast Asia, can cause deflection of smoke, which, under fire conditions, might be more of a hindrance than a help (Figures 16A and 16B). A jack roof construction used for normal day-to-day

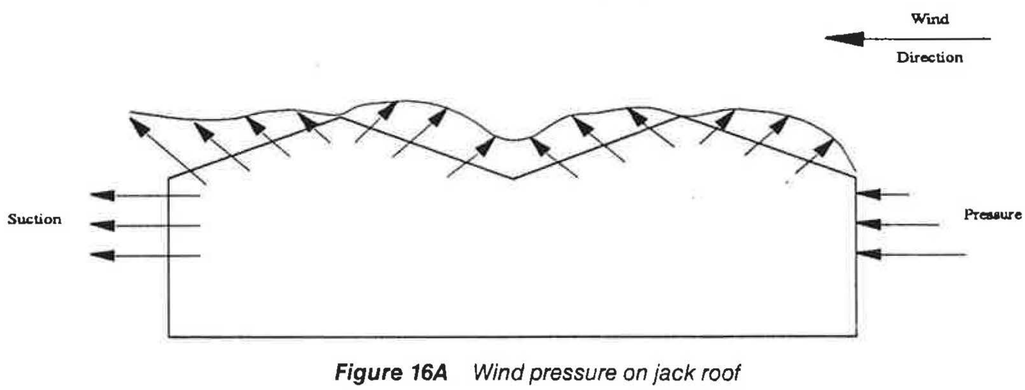


Figure 16A *Wind pressure on jack roof*

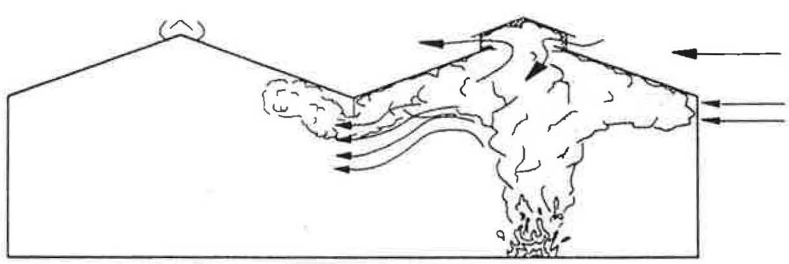


***Figure 16B** Unsatisfactory smoke flow with jack roof or ridge vent*

ventilation can react adversely under fire conditions and certain wind conditions. The inlet of air through one side of the jack roof combined with high level side wall openings will help push smoke and hot gases across the building to increase smoke logging of the building. Under such circumstances, the jack roof cannot be considered as a suitable smoke ventilation system.

Concern should always be given to wind pressures over the roof. Side wall natural smoke ventilators should not normally be considered unless with specialist advice.

Multilevel Buildings with Undivided Large Spaces

The problems associated with the spread of smoke and gases in multilevel buildings during fire is compounded.

Occupants may well try to escape all at the same time down escape routes normally designed for phased evacuations where fire control management is not strictly enforced. Those on upper floors have the furthest to travel, normally passing the fire floor. Fire fighting usually takes place from above and below the fire floor.

Smoke and gases need to be restricted to the fire floor without spread above or below, Occupants on the fire floor require time to evacuate. Where individual floors are subdivided into small compartments with fire barriers, the problems are not so critical as when the floor is a large undivided space, such as used for manufacturing or warehousing.

For life safety considerations of occupants on the fire floor, smoke must be removed at a suitable rate to maintain a clear height of visibility not less than 2000 mm.

Where smoke control is for the purpose of containment only to the fire floor, a lower smoke layer can be designed with a resulting lower exhaust rate. In each case, consideration should be given to the likely temperature of smoke and gases, which may exceed operating conditions of the control equipment.

Method of Control

Whilst practical research into smoke floor in multistory buildings is limited, the design can be considered based on calculations of mass flow from the fire as indicated in Figure 5. Each floor is considered as a single-story building and gases removed accordingly.

Smoke exhaust from a multifloor building (without connecting atria) would normally use mechanical systems, although in certain circumstances by correct design natural release (by gravity vents) is possible.

With the mass flow/temperature calculated and subsequent air volume established, this would then be the capacity of the system on the basis of a fire on one floor at any one time. Exhaust (from ceiling height) would be a shaft/duct to serve a number of floors together with individual damper control to each floor (Figures 17A, 17B, and 17C).

Operation of exhaust plant and dampers would be via signals from a smoke detection system on each floor.

Inlet

Replacement air to the fire floor should he provided by suitably sited natural or mechanical means previously described. Natural inlet by purpose design automatic opening ventilators in the side walls of the building will give advantage with air entering at low velocity (below 3 m/s) and at a level below the smoke layer. Such a system will prevent excessive air drawn from adjoining pressurized escape routes, thus reducing their effectiveness. Mechanical inlet should provide at least 80% of that exhaust with airflow designed to limit the effects of excessive air drawn from adjoining pressurized escape routes, thus reducing their effectiveness. Mechanical inlet should provide at least 80% of that exhaust with airflow designed to limit the effects of excessive air movement in the space, and could disturb the smoke layer or the fire source.

Smoke Control by Pressurization—Principles and Applications

Pressurization is the term commonly applied to mechanical smoke control systems in which a supply of fresh air to a space within a building is used to maintain that space at a slightly higher pressure than the rest of the building.

The normal applications for pressurization are corridors, lobbies, or staircases that form part of an escape route. The enclosing construction of this part of the escape route will be fire resisting and the door leading to it from the fire area will also be fire resisting, although there will be cracks around their edges large enough to allow the ingress of smoke. In a fire, one would also expect the door to be opened temporarily to permit escape of personnel.

The pressurization air must be able to escape so that pressure differentials can be established, and it will normally be able to do this by leakage through the cracks around doors, etc. Given a fairly modest input of air, a unidirectional airflow from the escape route can be achieved, thereby preventing the infiltration of smoke and hot gases from a fire.

Pressurization systems should be designed in accordance with BS 5588 Part 4 1978 Code of Practice for Fire Precautions in the Design of Buildings—Smoke Control in Protected Escape Routes Using Pressurization.

The smoke control system should be capable of producing a significantly higher pressure in an escape route

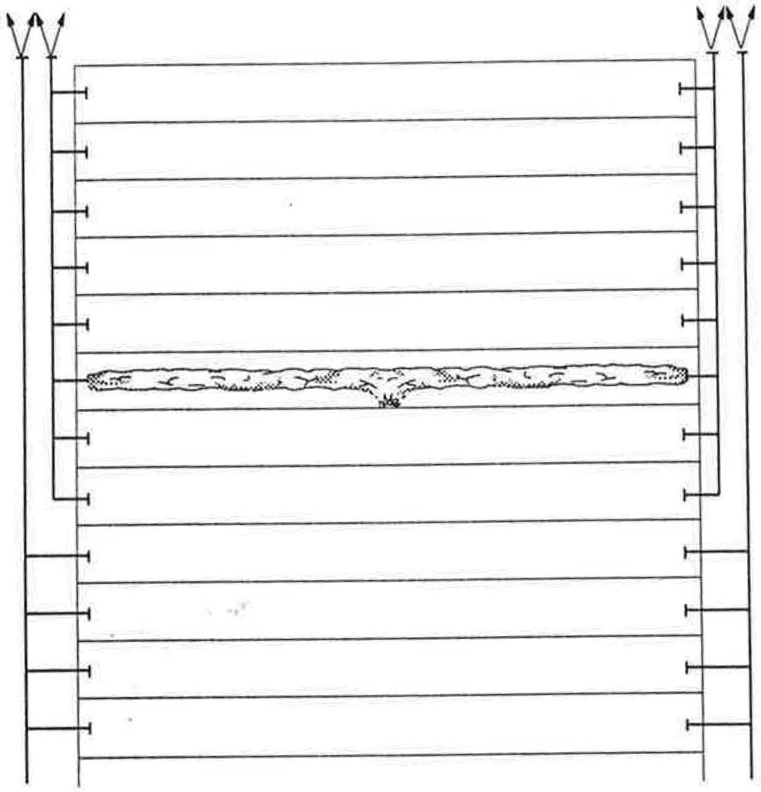


Figure 17A *Fire floor exhaust*

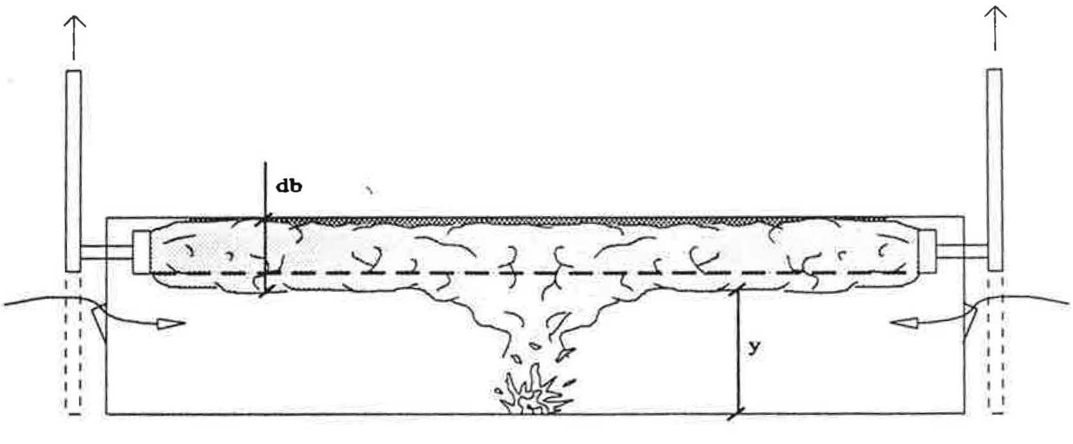


Figure 17B *Exhaust above perforated ceiling—natural inlet via windows*

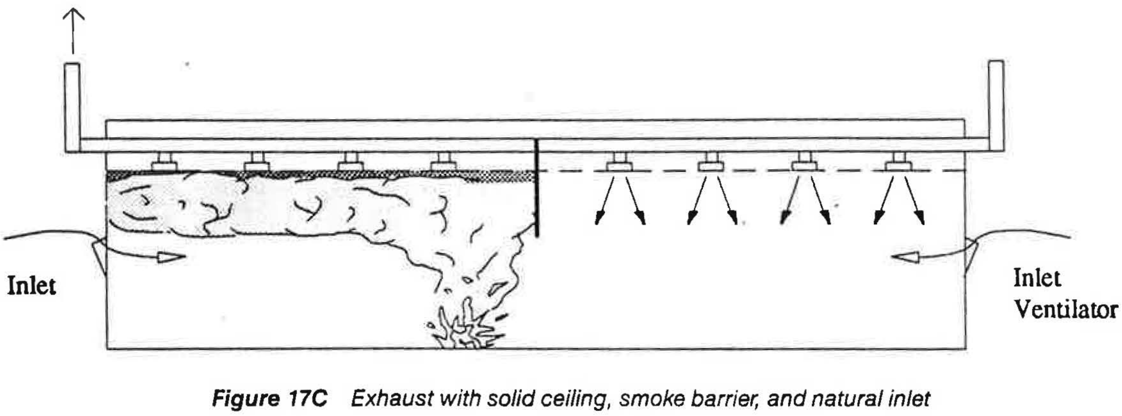


Figure 17C *Exhaust with solid ceiling, smoke barrier, and natural inlet* than in adjoining spaces in the event of a fire. Since a fire can itself produce a pressure differential of 8N/m^2 across a door, pressurization must exceed this amount to maintain an outward flow of air.

Other forces are also at work in creating air movement through a building. Pressure differences from the action of wind and through stack effect must also be considered—their magnitudes both increase with building height. To cater for the worst combination of fire, wind, and stack effect, an emergency pressurization of about 25 N/m^2 is sufficient for buildings up to 25 m high and 50 N/m^2 for buildings higher than 25 m.

The air supply rate required to obtain the selected pressurization depends on the leakage characteristics of the building envelope enclosing the escape route. Intermittent opening of doors must be expected to allow the evacuation of occupants, and pressurization will drop to virtually zero when a door is open. Tests have shown that smoke is held back by pressurization from intermittent opening since all the leakage will temporarily take place here, thus protecting the weakest point in the system.

Interaction with Other Fire Suppression Systems

There is a growing awareness of the need for fire protection systems and hence new buildings are equipped with an array of such systems as sprinklers, smoke/heat detectors, smoke ventilation, first aid fire-fighting equipment, etc. Each has a vital and distinct part to play, and in combination, they provide the most effective means of protecting life and safety of the buildings' occupants and the integrity of the buildings themselves.

The sprinkler puts water on the fire to provide cooling and reduce fire spread, as well as give an alarm. The smoke detector provides early warning and is able to actuate other fire control devices.

The ventilation system removes smoke to increase visibility. If the sprinkler does or does not control the fire, it is quite likely that manual fire fighting will be required, hence visibility must be clear and smoke has to be removed for fire fighters to find and see the fire.

In shopping complexes in Europe, the provision of sprinklers and smoke ventilation is widely accepted practice, but there have been in the past questions relating to their capability in industrial buildings.

The controversy is now dispelled following the results of investigations currently being undertaken at the Fire Research Station in the United Kingdom. Commonly expressed concern relates to the possibility of ventilators directing hot gases away from sprinkler heads or preventing enough heads from opening. In case histories and fire tests, the results show that venting has little effect on the operation of sprinklers, since the ventilation system is draining off the heat that has already risen to high level and is already in contact with the sprinklers. Indeed, a sprinkler is generally only useful over the fire. If the spread of heat and smoke beyond the fire area can be prevented to reduce loss, then excessive water damage can be prevented.Research also indicates that venting is most useful where sprinklers alone might not cope with a fire.

Certain applications, such as a bus garage, would need ventilation if sprinklers cannot get to the source of the fire, for example, inside the vehicle. There is no design standard yet for integrated sprinkler and venting systems. Each case has to be taken separately in consultation with the specialist designer and fire insurer.

Air-Conditioning Systems for Smoke Control

An important smoke control strategy is to ventilate fire compartments directly, thus protecting means of escape from the compartment and restricting the spread of smoke to adjacent areas not involved in the fire.

For buildings that are air conditioned and may be of one or several stories with large open areas, the same considerations are necessary as in single-story buildings, such as restraining screens, adequate inlet air supply, and good distribution of extract points.

Where a fire compartment is to be served by a ducted air-conditioning system for general use, it is worth considering the use of the distribution network for the control of hot smoke and gases.

Australian *Standard* 1668 (1979), Part 1, Fire Precautions in Buildings with Air Handling Systems, has been the generally recognized basis for such systems in Southeast Asia. However, it must be recognized that this standard advises on the precaution and use of air-conditioning systems under fire conditions to make best use of the facility available and to prevent fire spread within the network.

Generally, the extract capacity or "smoke spill" of such systems is insufficient for smoke purposes, unless additional "boost" is incorporated with the exhaust volume designed on the method previously advised. The fans and motors must be capable of handling the elevated temperatures involved, and a suitable arrangement of fire rated dampers and ducts of the necessary specification must be incorporated.

In the event of a fire, all air supply systems to the fire area or fire floor should be stopped and purpose designed air inlets should be opened to avoid the disturbance of the thermally buoyant smoke layer beneath the compartment ceiling. The system would normally be activated automatically on smoke detection.

The common belief that the airflow on the inlet side of an air-conditioning system in an open area will form a barrier and keep back smoke and hot gases approaching the area is a misconception. Smoke movement from a fire of 1 m/s would require an abnormally high inlet capacity from the air-conditioning system to overcome the more buoyant smoke flow in any area other than a subdivided pressurized space.

CONCLUSION

Smoke control should not be restricted to just maintaining a smoke-free staircase or lobby, but in large undivided structures must center on smoke removal to maintain visibility, offering protection of life and property.

Adequately designed automatic smoke ventilation will:

- Restrict the spread of fire.
- Reduce structural damage by heat.
- Allow fire fighters to locate and extinguish the fire at the source.
- Limit water damage.
- Keep escape routes clear of smoke.

Above all, adequate smoke ventilation will gain time for everyone.

As far as the rate of success is concerned, the evidence is quite conclusive. Fire venting has stopped fires where they started, has kept damage to a minimum, reduced costs, and saved lives. It has allowed businesses to survive where otherwise the disaster might have been complete, and it has maintained production where customers might have gone elsewhere. Schemes correctly designed by experts, that are properly installed and operated have a 100% record.

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