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SOME NOTES ON THE CONTROL OF SMOKE IN ENCLOSED SHOPPING CENTRES

by

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SUMMARY

This note considers ways in which the spread of hot gases and smoke from a fire in an enclosed shopping centre may be limited. If the shop fronts are fire resisting the hot smoky gases may be confined to the shops of origin. Otherwise the size of the fire and hence the rate of 'production' of hot smoky gases must be limited (preferably by sprinklers) and it is then possible to confine the hot smoky gases to a stratified layer beneath the ceiling while the air beneath them is relatively cool and clear. The extent of the layer should be limited by dividing the space beneath the ceiling into smoke reservoirs by screens extending part of the way towards the floor. Screens by themselves are ineffective; hot gases must be extracted from a smoke reservoir at at least the same rate as they flow into it while fresh air must be introduced or allowed to flow into the building to replace the extracted hot gases. Theoretically the principle can be used to confine hot smoky gases to the space beneath the ceiling of the shop of origin but the rates of extract required can seldom be achieved on practice in the confines of a small shop and it is generally necessary to allow the smoky gases to flow into smoke reservoirs beneath the ceiling of the mall. The requirements of both natural and powered systems for extracting smoke from the smoke reservoirs are considered.

It is essential that smoke control measures should be considered at any early stage in the design of the building as they may be difficult to incorporate as a later modification.

KEY WORDS: Shopping mall, smoke, ventilation, vents.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
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1. INTRODUCTION

The designs of many town centre development and redevelopment areas include shopping centres with pedestrian malls or concourses which may be partly or entirely roofed over. Should a fire occur in such a shopping centre, smoke and other combustion products could spread through the covered malls and possibly fill the entire shopping centre. These smoky gases can hinder escape and endanger the lives of the occupants of the building; they can also restrict and even prevent effective fire-fighting by the brigade.

It is important that measures to prevent or alleviate smoke logging should a fire occur are incorporated in the building and this feature should be considered at an early stage in the design of the complex as a whole. In multi-level developments the layout of building rising above the podium deck is frequently an important factor limiting the possibility of obtaining effective smoke control by the use of vents or shafts.

The problem of the control of smoke in covered shopping centres is being investigated by the Joint Fire Research Organization. This note is based on the results so far obtained in that work and on the results of experience with roof venting of single storey buildings. Some revision may have to be made to the recommendations in the light of results which may be obtained in the future.

2. THE PROBLEM OF HOT GASES AND SMOKE

2.1. The production of hot smoky gases by a fire

Above the burning materials in a fire there rises a column of flames and hot smoky gases; because of their upward motion the surrounding air is entrained and mixed into them; flames occur when this air reacts with combustible gases produced by the decomposing fuel. At the height of the tips of the flames the column of rising hot gases generally contains much more air than is required for the complete combustion of the fuel gases[1].

When the hot smoky gases reach the ceiling they spread out and form a layer[2]; because of the difference in density between the layer of hot gases and the underlying cool air there is not much mixing between them. The rate of production of hot smoky gases is approximately the rate at which air is entrained and contaminated by the rising column of hot gases and flames; this depends on the perimeter and heat output of the fire and on the effective height of the column i.e. the distance between the floor and the bottom of the layer of hot gases beneath the ceiling (y in Fig. 1). The mass rate of production of hot gases by fires of different sizes is given approximately in Fig. 2 and (by a 3 m x 3 m fire) in Table 1 (assuming the heat output of the fire is to be such that the flames extend into the layer of hot gases).

TABLE 1

Rate of production of hot smoky gases by a 3 m x 3 m fire

Height of clear layer m	Rate of production kg/s
2	6
2.5	9
3	12
4	18
5	25
6	33
8	51
10	71

(Rates of production may be converted to other units by making use of Fig. 3)

The volume occupied by these hot gases depends on their temperature; close to the fire, where the temperature may be as high as 500°C, 1 kg of gas will occupy about 2 m^3 but a long way from the fire where the gases may have cooled to only slightly above ambient temperature 1 kg will occupy about 0.8 m^3. The flow rates may be converted to other units by making use of the chart given in Fig. 3.

2.2. Spread within a shop

Since the amount of combustible materials in a mall is generally small compared with that in a shop, the most likely place for a potentially serious fire to start is in a shop or its ancillary accommodation. A layer of hot smoky gases will form beneath the ceiling and will spread outwards because of its buoyancy. This flow of hot gases away from the fire will be balanced by a return flow (near the floor) of cool air being drawn towards the fire (Fig. 1). Eventually the layer of hot gases will reach the walls of the shop and, if there are no openings through which hot gases can flow out of the shop, the layer will become deeper until after a time, depending on the size of the fire and the size of the shop, the layer will extend to below head level. The time taken for a fire 3 m x 3 m in area with flames about 3 m high to fill shops of various sizes to 3 m from the ground have been calculated approximately (Table 2).*

TABLE 2

Approximate times for a 3 m x 3 m fire to fill a shop to 3 m from the floor

Height	Times (min) for shops having areas of		
m	100 m^2	1000 m^2	10,000 m^2
4	0.1	0.7	7
5	0.1	1.2	12
6	0.2	1.5	15
8	0.2	2.0	20
10	0.2	2.3	23
15	0.3	2.9	29

Except for large shops($\gg$1000 m^2 in area) the times do not exceed a minute or two.

When the bottom of the layer of hot gases extends below the level of the top of the highest openings communicating to the mall (for example an open door or an open shop front) hot gases will flow out of the shop into the mall. The times given in Table 2 suggest that even if the fire size is no greater than 3 m x 3 m the delay between the fire attaining this size and smoke penetrating to the mall is unlikely to be sufficiently long to ensure evacuation of the mall except, possibly, when the fire occurs in a very large shop.

*The times are based on the assumption that the time taken for hot gases to spread over the ceiling is very short in comparison with the time taken for the subsequent deepening of the layer. The mean layer temperature is taken to be 300°C. Because of mixing actual times may be shorter.

2.3. The flow of hot gases into a mall

If the fire occurs in the mall itself the same considerations apply as to a fire in a shop; the rate of flow of hot gases will be that given in Fig. 2 or Table 1.

The rate of flow of hot smoky gases from a fire in a shop in to the mall depends on the sizes of the various openings into the shop. If the shop front is open and there are no other significant openings into the shop, all the hot gases produced by the fire must flow into the mall. Generally the hot gases will have to flow beneath a fascia; at this point further mixing may occur between the hot gases and the cool air beneath so that the hot gases are cooled and their volume is increased. Thus the volume of hot smoky gases to be extracted from the mall is generally greater than the volume originally produced by the fire. However, as will be explained later in this note, fascia boards should not be omitted on that account as they frequently play an important part in a smoke control system.

If the area of the openings in the shop is small, the depth of the layer of hot gases within the shop will increase and recirculation of hot gases back to the fire will occur so that the shop becomes effectively full of hot gases. Smoky gases can flow out of leaks in the shop front on to the mall; this will be caused by two mechanisms.

Firstly the increase in temperature of the gases within the shop will cause an increase in pressure[3] according to the gas laws. Theoretically a temperature of 500°C within the shop could result in a pressure of nearly three atmospheres but very small areas of leakage, such as occur in even the best constructions, are sufficient to relieve these pressures (unless the fire grows at an almost explosive rate when windows etc may be blown out). In relieving the pressure nearly two-thirds of the mass of air within the shop will be expelled as hot gases, probably containing dense smoke. Whether these gases are expelled into the mall or out through other openings in the shop depends on the relative leakage areas to the mall and the open air and the relative pressures in the mall and the open air.

Secondly the difference in density between the hot gases in the shop and the air in the mall leads to a distribution of pressure in the shop; the pressure near the ceiling will be above that in the mall the pressure near the floor will be below that in the mall, and there will be a 'neutral plane' over which the inside and outside pressures are the same

(Fig. 4). Hot gases will flow out of the shop above the neutral plane and cool air will flow in below the neutral plane. The rates of flow of hot gases out of some openings are given in Table 3.

TABLE 3

Rates of flow out of a compartment full of hot gases through a vertical opening

Temperature in shop °C	Height of opening m	Flow through openings (kg/s) with areas of 0.01 m^2	0.1 m^2	1 m^2	10 m^2
50	0.1	0.001	0.013	0.13	1.3
	0.5	0.003	0.025	0.25	2.5
	1	0.004	0.036	0.36	3.6
	2	-	0.050	0.50	5.0
	3	-	0.061	0.61	6.1
	5	-	0.080	0.80	8.0
500	0.1	0.002	0.018	0.18	1.8
	0.5	0.004	0.041	0.41	4.1
	1	0.006	0.058	0.58	5.8
	2	-	0.082	0.82	8.2
	3	-	0.101	1.01	10.1
	5	-	0.130	1.30	13.0

Flow rates for narrow openings are approximate only.

(Rates of flow may be converted to other units by making use of Fig. 3).

Pressures due to winds may modify the above picture and increase or decrease the amount of hot smoky gases flowing from the shop into the mall. The rates of flow at pressures which might be generated by winds are shown in Table 4.

TABLE 4

Rate of flow of air under pressure through an opening

Pressure mm water gauge	Rate of flow (kg/s) through opening with an area of			
	0.01 m^2	0.1 m^2	1 m^2	10 m^2
0.03	0.006	0.06	0.6	6
0.1	0.011	0.11	1.1	11
0.3	0.019	0.19	1.9	19
1	0.034	0.34	3.4	34
3	0.059	0.59	5.9	59
10	0.108	1.08	10.8	108

(Rates of flow may be converted to other units by making use of Fig. 3)

Hot smoky gases flowing out of small openings such as ventilators or cracks around doors will rise towards the ceiling and in doing so will mix with considerable volumes of the surrounding cool air before they form a layer beneath the ceiling of the mall.

2.4. The flow of hot gases along a mall

The hot gases flowing onto the mall will form a layer beneath the ceiling. The velocity of advance of the front of this layer[4,5] depends on a number of factors, principally the width of the mall and the amount of heat contained within the layer of hot gases; with an open fronted shop the velocity is typically of the order of 1 m/s (i.e. a good walking pace). Air will flow in towards the fire beneath this outward flowing layer of hot gases; thus both flows are channelled within the relatively small cross section of the mall. Under some circumstances a slow moving smoky layer forms between the hot and cool flows. Any smoke which mixes into the return flow of relatively cool air towards the fire will itself flow back towards the fire.

As the front of the layer of hot gases moves away from the fire it cools so that it becomes less buoyant, its velocity decreases slightly, and it becomes deeper. Because the difference in temperature and therefore density between the hot and cool layers is lower at a distance from the fire than close to it there is a greater tendency for mixing to occur between the layers; such mixing can be caused by disturbing the boundary between the layers by draughts[6].

If there is a general air flow through the mall, caused for example by the wind, the layer of hot gases will travel against this air flow (although at a reduced velocity) unless the velocity of the air flow is greater than the buoyancy induced velocity of the hot gases.

Eventually the advancing layer of hot gases will meet the end of the mall which may be either closed or open. If the mall is closed the hot gas layer will, on arriving at the closed end, approximately double in depth and smoke will flow back towards the fire (Fig. 5). If the end of the mall is open, hot gases will flow out of the upper half of it but any draughts will cause a large amount of mixing of smoke into the return flow of air towards the fire (Fig. 6). Thus complete smoke logging of the mall can occur whether the end is open or closed.

3. SMOKE CONTROL MEASURES

Ideally, smoke control measures should be aimed at keeping the malls free from smoke by confining the hot smoky gases to the shop of origin. However this may frequently be impracticable and it may be necessary to allow the hot smoky gases to flow onto the mall, and to take measures to ensure that they do not hinder the escape of people. Generally this is achieved by confining the smoke to a layer well above head height and keeping the air beneath cool and relatively smoke free.

3.1. The initiation of smoke control measures

Because of the speed with which smoke can spread, smoke control measures should be brought into operation automatically at the earliest possible stage of the fire.

By the time a fire has become large enough to actuate a fusible link it will frequently be producing considerable volumes of smoke and hot gases so that fusible links and similar devices are seldom if ever satisfactory; they are particularly futile when situated in the mall because a fire in a shop may have to achieve a considerable size before the temperatures of the gases passing along the mall are high enough to operate fusible links.

Smoke detectors are a suitable means of initiation of smoke control devices. They should preferably be situated in the individual shops and this is necessary when the devices are intended to restrict the hot smoky gases to the shop of origin. Otherwise it may be satisfactory for them to be sited in the mall if the shops are only small so that hot smoky gases spill onto the mall soon after the fire has started.

3.2. The shop front as a smoke barrier

The preferred method of smoke control is to prevent smoke escaping from the shop of origin. The most obvious method is to fit a shop front (of a type which will remain in position during the fire) which is pierced only by self-closing fire doors. Unfortunately there is generally some leakage around fire doors and through joints in shop fronts, frequently ventilation openings are unavoidable. As explained in the previous section, smoke will then penetrate to the mall and this may be sufficient to cause smoke logging. The pressure difference between the shop and the mall near the top of a door due to buoyancy effects alone may be about 0.5 mm water gauge[7]. To prevent smoke penetrating to the mall it is recommended that a pressure difference of from 2.5 - 5 mm water gauge (opposing the pressure difference due to the hot gases) be maintained across the shop front; this allows for pressures to both to the winds and the fire. The pressure difference may be developed by exhausting air from the shop (Fig. 7) or possibly by supplying air to the mall (Fig. 8). The former method requires a much smaller air supply but the fans and ducting need to be able to withstand the hot gases. The latter method might be considered for closed malls although the possible loss of pressure due to people escaping through doors leading from the malls and thus keeping them open must be taken into account. Vents would have to be provided at the rear of shops and in the event of fire it would probably be advantageous if all the vents except those in the shop on fire were closed, thus reducing the loss of pressurizing air.

Which-ever method is adopted it is essential that the doors and any ventilation openings to the mall of the shop on fire be closed (except to allow the passage of people escaping); preferably by automatic door closers and fire dampers. Failure of the shop front would of course lead to the rapid spread of smoke in the mall and thus the shop front should be fire resisting or have fire resisting back-up walls unless sprinklers are fitted.

If sprinklers are fitted in the shops the possibility of a fire becoming large enough to cause failure of the shop front is greatly reduced although it is not at present certain that failure can be prevented. Unless it is certain that the sprinklers will prevent failure of the shop front provision should be made for ventilating the mall as described later in this report.

3.3. Dilution of smoke

It is in theory possible to mix sufficient air with hot smoky gases to reduce their temperature, the concentration of toxic or irritant gases in them and the smoke density to tolerable levels. Generally, diluting the hot smoky gases sufficiently to reduce the density of the smoke to a tolerable level will also ensure that the temperature and concentrations of toxic gases are tolerable[8]. If large quantities of some types of materials such as chlorinated plastics are involved in fire toxicity may be the limiting factor.

It has been suggested that the gases from a fire should be diluted by a factor of at least 100[9]; the suggested maximum allowable optical density is 0.1 m^{-1} (1 dB m^{-1}) which according to Rasbash[8] corresponds to a visibility of about 8 metres.

This visibility seems rather low for the purpose of ensuring easy escape from an enclosed shopping mall without any possibility of panic; a lower visibility could certainly not be tolerated. The air flow required to dilute the gases from a fire to give a visibility of even 8 m may be large[10]. About 1 kg of air is required for every gram of relatively non-smoky materials (for example dry wood) which is burnt and roughly 10 kg of air for every gram of smoky material (for example rubber or polystyrene). A freely burning wood fire on a base 3 m x 3 m in area and with flames about 5 m high would be burning at a rate of about 0.5 kg/sec and would require 50 kg/sec (40 m^3/sec) of air to dilute the smoke to give a visibility of 8 metres. A smoky fire burning at the same rate might require 10 times this air flow.

The smoke percolating through leaks in an otherwise intact shop front is likely to have been produced by a starved (ventilation controlled) fire. Assuming an air fuel ratio of 5 : 1; on the basis of the figures given in the previous paragraph this smoke would require to be diluted by a factor of from 170 - 1,700 depending on the materials burning. If the rate of leakage was about 0.1 kg/sec (through for example an opening 0.1 m^2 in area and 3 m high) an air flow of from 17 to 170 kg/sec, would be required.

It is difficult to thoroughly mix hot smoke and cool air because of the tendency for the hot smoke to float on top of the cool air; it would be better to make use of this tendency for stratification to assist in maintaining clear air near the floor rather than to attempt to dilute all the smoke to an acceptable density.

4. THE MAINTENANCE OF A LAYER OF CLEAR AIR NEAR THE FLOOR IN LARGE SHOPS AND CIRCULATION AREAS

4.1. General principles

The remainder of this note will be concerned with measures for confining the hot smoky gases to a layer beneath the ceiling and ensuring that the air beneath them is relatively cool and clear[11,12]. These measures are applicable to shops (although they may only be practicable in large ones) and may be used to prevent smoke from flowing onto the mall. However it is expected that they will more generally be used to keep the lower part of a mall free from smoke. The general principles are the same in both cases.

The lateral spread of the layer of hot smoky gases is restricted by screens extending downwards from the ceiling towards the floor so forming 'smoke reservoirs' while its depth is restricted by extracting the hot smoky gases at the same rate as they are produced by the fire (Fig. 9). Fresh air to replace the extracted hot gases must be allowed to flow in or be introduced beneath the layer of hot gases in such a way that the boundary between the layers is not disturbed sufficiently to cause mixing between them.

4.1.1. <u>The necessity of limiting the fire size.</u>

The rate of production of hot smoky gases by even a small fire is large compared with normal ventilation flow so that the extraction of sufficient hot gases to maintain a mall sufficiently clear of smoke for it to be an escape route is only possible while the fire is relatively small, unless the spread of fire and hot gases outside the shop of origin is restricted by a fire-resisting shop front. Most of the figures quoted in this note refer to a fire occupying a floor area no greater than 3 m x 3 m. The time taken for a fire to grow to this size from a small beginning such as a fire in a waste paper basket may only be about a minute or two, if readily flammable materials, for example in the form of thin sheets or foam are involved[13]. Should a fire approach flashover in an open fronted shop (or one in which the shop front has failed) the mall may rapidly become untenable because of heat, particularly if the height of the mall is limited[14].

The size of fire may, in theory, be restricted by strict control of the amount, nature and disposition of the combustible contents of the shop but in practice sprinklers are probably the only viable method.

4.2. Smoke reservoirs

4.2.1. The importance of smoke reservoirs and smoke extracts

The formation of a layer of hot gases beneath a ceiling can only be prevented by having a very large vent immediately above the fire through which all the hot smoky gases produced by the fire can flow. Generally the presence of a layer of hot smoky gases beneath the ceiling is inevitable. The presence of this layer need not be an obstacle to escape provided its temperature is reasonably low (this should be the case when the fire is held in check by sprinklers) and the air beneath is clear of smoke.

Although mixing between the layers is small it is not entirely absent and is increased by any factors tending to disturb the boundary between the layers (such as draughts from ventilators). The larger the extent of the layer the cooler its outer parts become and the greater the tendency for mixing. Thus the greater the extent of the layer of hot gases the more smoky will the air beneath become. It is therefore necessary to restrict the extent of the layer of hot gases by dividing the space beneath the ceiling into smoke reservoirs by screens extending from the ceiling part of the way towards the floor. These screens should be reasonably air tight (although small leaks for example round pipes are unimportant) and made of a material which is able to remain in position at least until one side has been licked by flames for 15 minutes tentatively.

Provision must be made for extracting hot gases from the smoke reservoir at a rate equal to the maximum rate at which they are likely to flow into it. The presence of screens without this provision for extraction of hot gases would seldom result in any delay between the time when the front of an advancing layer of hot gases reaches the screen and the time when hot gases start to spill beneath it. If gases are extracted from a smoke reservoir at a rate less than that at which they are flowing into it there will be a delay before hot gases spill over the edge of the screen but this delay may not be very great. For example if the rate of extraction is half of that necessary to keep the gases within a smoke reservoir having a depth equal to one third of the ceiling height, the time before gases spill beneath roof screens will be about 70 per cent longer than when there is no extract.

4.2.2. Minimum ceiling heights and depths of smoke reservoirs in shops and malls

The presence of a layer of smoke and hot gases beneath the ceiling will inevitably cause apprehension to the occupants of the shopping centre even though the air beneath is clear. To minimize this apprehension and prevent the possibility of panic the bottom of the layer of hot smoky gases should be as high as possible above people's heads. There is probably a minimum depth for the layer of gases and this may be as much as one third of the ceiling height; certainly it is unlikely to be less than 1 metre. If the shop or mall is 4 m high this means that the bottom of the layer of hot smoky gases will be only about 2.7 m from the floor. This is the absolute minimum height necessary with no factor of safety. Thus generally the ceiling should be much higher than 4 metres. It is tentatively suggested that the smoke reservoir should be at least 1 m deep and preferably should have a depth equal to one third of the height of the ceiling above the floor.

4.2.3. Smoke reservoirs in shops

It is, in theory, possible to make the spaces beneath the ceilings of shops into smoke reservoirs, thus preventing hot gases from flowing onto the mall, even if the shop is open fronted or the shop front cannot be relied upon to remain intact during a fire. Unfortunately, if the shop is small, the rate at which hot gases have to be extracted is many times the capacity of the normal ventilation system for the shop and if natural ventilation is utilized the area of vents required is a substantial proportion of the area of the shop. Thus the system may only be practicable with larger shops (possibly of the order of 500 sq.m or more in area).

With shops less than roughly 1000 m^2 in area the smoke reservoir would be enclosed by the walls of the shop and a deep fascia over the shop front. With shops much larger than this it is tentatively recommended that the space beneath the ceiling of the shop should be sub-divided by screens into smoke reservoirs each not exceeding 1000 m^2 in area.

4.2.4. Smoke reservoirs in malls

If the ceiling of the mall is higher than the ceiling of the shops and the difference in height is sufficient (tentatively at least 1 m and preferably $\frac{1}{3}$ of the total height of the mall) the space beneath the ceiling of the mall may be used as a smoke reservoir (Fig. 10). When the difference in height is not sufficient a smoke reservoir must be formed by fitting fascias above the shop fronts (Fig. 11). These will confine the hot gases to the mall and prevent them from flowing into shops other than the one on fire. Not only will this facilitate the escape of people from nearby shops but will also reduce the extent of smoke damage.

Long malls must be sub-divided by screens across them; it is tentatively suggested that these screens should be at distances apart not exceeding 60 m with a maximum area of smoke reservoir of 1000 m^2. Open malls should also have screens at their ends. It may be best for these screens to be situated several metres inside the mall; this should reduce mixing between the hot gases and the inflowing cool air caused by winds blowing across the ends of the mall.

4.2.5. Suspended ceilings and smoke reservoirs

Suspended ceilings are frequently fitted in malls and shops in a shopping centre; they may or may not be fire resisting but they are probably seldom air tight. Unless they are both fire resisting and sufficiently air tight to prevent substantial smoke leakage it is necessary for ceiling screens to be continued up through the space above the suspended ceiling (Fig. 12a, b, c).

If the area of leakage in the suspended ceiling is small the smoke reservoir is in effect wholly below the suspended ceiling and the roof screens must extend downwards beneath the suspended ceiling for tentatively at least 1 m or preferably $\frac{1}{3}$ of the height to the false ceiling (Fig. 12a). Smoke should preferably be extracted through ducts leading through the space above the suspended ceiling.

If the leakage area is large (tentatively 10 per cent or more of the ceiling area) the ventilation openings can be in the space above the false ceiling and it may be possible to regard the space above the false ceiling as contributing to the smoke reservoir so that the depth of that portion of the screens below the suspended ceiling may be reduced although it would be unwise to eliminate all the screens below the suspended ceiling (Fig. 12b).

If the suspended ceiling has an open type of construction with a large leakage area (tentatively, 50 per cent or more) it should be possible to confine the smoke reservoir entirely to the space above the suspended ceiling (providing this is deep enough) so that screens need not extend below the ceiling (Fig. 12c).

If the suspended ceiling is both air tight and fire resisting and the services in it are protected against heat if necessary, the space above could be used as a horizontal duct for smoke venting purposes (Fig. 12d). The use of ducts for smoke venting will be considered later in this report.

4.3. Extraction of smoke from reservoirs

In order to prevent smoke spilling beneath the roof screens out of a smoke reservoir it is necessary to extract the hot smoky gases at the maximum rate at which they are likely to flow into it[2]. Fresh air to replace the hot smoky gases flowing out must be introduced or allowed to flow into the compartment. The smoke must be discharged from the building in such a way that, even if a wind is blowing, the inflowing air will not be contaminated by smoke.

Possible methods of removing smoke from smoke reservoirs include powered extract systems (allowing fresh air to flow into the compartment, powered inflow systems (allowing hot smoky gases to flow out through vents) a combination of powered extract and inflow systems and systems making use of the flow induced by the buoyancy of the hot gases (roof venting).

The advantage of powered systems is that it is, in theory, possible to ensure the required flow rates whatever the temperature of the layer of hot gases and whatever the external wind conditions. The main difficulty lies in the large rate of production of hot gases by even a small fire. Thus to maintain a clear layer 3 m high with a 3 m x 3 m fire requires at least 12 kg of hot gases to be removed every second. If the mean temperature of the layer is about 300°C the corresponding volume rate is 20 m^3/s or 72,000 m^3/h. This corresponds to more than 14 air changes per hour in the volume beneath a smoke reservoir 1000 m^2 in area when the ceiling height is 5 m. This is much greater than the normal ventilation rates within a building and it is evident that in the event of a fire a considerable part of the normal ventilation plant would have to be mobilized to extract hot gases from the smoke reservoir. To be effective as a means of facilitating escape this would need to be done automatically and presupposes an elaborate and sophisticated control system which, upon a signal from a smoke detector, would close some dampers, open others and increase fan speeds as required. This is technically feasible, particularly with computerized control systems, although it would undoubtedly be expensive.

The great advantages of a smoke control by natural ventilation (roof venting) lie in its basic simplicity (although because of the factors listed in para 6.4, the design of an effective venting system for a complex shopping centre may involve considerable complications), the large volume of hot gases which may be extracted, the limited number of mechanical devices (i.e. those necessary to open vents and fresh air inlets in the event of fire) and its relative cheapness. Its main disadvantages lie in its great susceptibility to wind effects and its relative inefficiency when the smoky gases are at a relatively low temperature.

4.3.1. Rates at which hot gases must be removed from reservoirs

Before a smoke control system can be designed it is necessary to decide on the maximum size of fire for which it is required. In the absence of other information it is suggested that a fire 3 m x 3 m should be taken. The rate of production of hot smoky gases by such a fire with various heights of clear layer is given in Table 1. The height of the clear layer should be taken as the height to the bottom of the smoke reservoir. When the hot gases are to be extracted from the shop of origin the rate at which they must be extracted may be taken to be the rate of production given in the Table. However when the hot gases flow onto the mall there is almost certain to be some additional mixing so that the volume of hot gases to be extracted from the mall will generally be greater than the volume produced within the shop. Tentatively a factor of safety of about two is suggested but further work is being carried out on this aspect.

4.3.2. Design and position of smoke outlets

The upward movement of hot gases in smoke outlets will disturb the bottom of the layer of hot gases in a smoke reservoir and some cool air may be sucked up into the smoke outlet (Fig. 13). This can be minimized by having smoke outlets at as high a level as possible within the smoke reservoir, keeping the dimensions of individual outlets small compared with the depth of the smoke reservoir and by restricting the velocity of gases in the smoke outlet.

4.3.3. Design and positions of air inlets

The resistance of fresh air inlets must be taken into account when designing a smoke control system. Fresh air must be injected or allowed to flow in to the compartment in such a way that jets of air from the air inlets do not disturb the boundary between the hot gases in the smoke reservoir and the fresh air.

When the malls are open ended the open ends will generally be the fresh air inlets. In some developments where smoke reservoirs are formed beneath the ceilings of malls the fresh air inlet may be windows or ventilators at the rear of the shops fronting on to the mall. When these shops are fitted with shop fronts ventilation openings in them may be necessary; these ventilation openings should be as close to the floor as possible.

Forced draught air inlets should preferably be near the floor and directed downwards; this may conflict with normal ventilation practice for avoiding draughts on people and make it difficult to arrange the ventilation ducts economically. Inlets for fresh air may be in the ceiling provided all the inlets to the smoke reservoir into which hot gases from the fire are flowing are shut-off in the event of fire.

4.3.4. Powered extract systems

The advantages and disadvantages of powered systems in general have already been discussed. Powered extract has the advantage over other types of powered systems that leakage of air into compartments via doors, windows, walls, floor etc. will hardly affect the rate at which hot gases must be extracted from the smoke reservoir. The main disadvantage is that hot gases will pass through the fans which must be designed to withstand high temperatures, as must all the exhaust ducting.

The pressure within the space from which air is being extracted will be slightly lower than that outside.

4.3.5. Powered inlet systems

It is, in theory, possible to blow air into the mall or shops so that the pressure is higher than that outside and the hot gases in the smoke reservoir are driven out through vents or ducts leading to the open air (Fig. 14). The disadvantage of this system is that air will flow out of the mall and shops through all other openings as well as the hot gases blowing out through the vents and additional air must be supplied to make good this leakage. In practice this may lead to impractically large air requirements particularly if account is taken of the opening of exits doors. The air may be supplied at any position so long as it does not disturb the hot gases within the smoke reservoir.

The outside openings of vents or ducts will be subject to wind pressures and ideally the pressure within the mall and shops should be higher than the highest pressure likely to be caused by the wind. It may be necessary to restrict the area of the vents to the minimum necessary to exhaust the hot gases. Even so because of leakage it may be difficult to ensure that the pressure is always high enough to overcome wind pressures and the outlets from vents or ducts should be situated where high pressures due to wind are least likely to occur. This will be further discussed in the section on natural ventilation.

4.3.6. Powered inlet and outlet systems

Where a powered exhaust system is employed it may be advantageous to use a powered inlet system to replace or augment the natural inflow through doors, windows ventilators etc.

4.4. Smoke extraction by natural ventilation

Because the layer of hot gases is less dense than the cool air the pressure beneath the ceiling will be slightly higher than outside the building at the same level. Thus, if openings are made in the roof above the smoke reservoir, the hot gases will flow out in the same way that hot gases flow through a chimney; this principle has been employed in the 'roof venting' of large single storey buildings to facilitate fire fighting[11,12]. It may be possible to apply this to the control of smoke in shopping centres although problems arise in the latter case which do not arise in the former.

1) Venting to ensure the escape of occupants in the event of a fire must operate more quickly and probably must result in a higher degree of smoke control than would be necessary with venting for assisting fire fighting.

2) Ceilings in shopping centres are generally lower than in single storey industrial buildings so that hot gases need to be restricted to a more shallow layer in a shopping centre than in an industrial building.

3) Shopping centres frequently form part of a complex which may have tall blocks rising from it or may be in the vicinity of taller buildings. These will affect the wind patterns round the shopping centres and may result in areas of relatively high pressures near vents and consequent down draughts. Not only will these effectively reduce the capacity of the vents but they may induce mixing of smoke into the clear air layer.

4) The siting of vents may be difficult because of the layout of the upper parts of shopping centres. Ducts leading through upper floors may be necessary and these may use valuable floor space.

5) Because it is envisaged that the fire in a shopping centre will generally be controlled by sprinklers, the gases to be vented will be cooler than those which may arise during a fire in a typical industrial building.

4.4.1. Areas of vent required (ignoring wind effects)

The areas of vents required in windless conditions to confine most of the hot gases from a fire to a smoke reservoir may be calculated from the formulae and nomograms developed for the design of roof venting systems in large single storey industrial buildings[2,11,12], although the reservations in the previous section must be borne in mind and an increased area of vents may be required to allow for mixing when hot gases flow out of a shop to a mall. The theoretical vent area depends on the size of the fire, the height of the lower edge of the smoke reservoir above the floor and the 'stack height' i.e. the height of the outlet of the vents or ducts above the lower edge of the screen (Fig. 15). Some theoretical areas of vents needed for a 3 m x 3 m fire are given in Table 5. The area of vents required increases as the height to the lower edge of the screen increases and decreases with increasing stack height.

TABLE 5

Theoretical area of vents required to confine hot gases from a 3 m x 3 m fire to a single smoke reservoir

"Stack height"	Areas of vent (square metres) when height of lower edge of screens is:-					
metres	3 m	4 m	5 m	6 m	8 m	10 m
1	8.1	12	17	23	35	49
1.5	6.6	10	14	19	29	40
2	5.7	8.8	12	16	25	35
3	4.7	7.2	10	13	20	28
5	3.6	5.6	7.8	10	16	22
7	3.1	4.7	6.6	8.7	13	19
10	2.6	3.9	5.5	7.3	11	16
15	2.1	3.2	4.5	5.9	9.1	13
20	1.8	2.8	3.9	5.1	7.9	11

The figures in the table may be taken to apply to vents in smoke reservoirs within shops. The areas of vent required for smoke reservoirs within malls will be greater than the area required in the shops possibly by a factor of the order of 2. Work is proceeding on this problem.

It must be noted that these areas of vents will not generally entirely prevent the spill of hot gases beneath screens but only reduce it to a small proportion of the volume of hot gases produced by the fire. This was of little consequence in the original application but it may be important when considering the more stringent requirements of shopping centres. Work is also being carried out on this problem.

The vent areas must also be increased if the area of inlets for cool air to flow into the building is restricted or if the resistance of ducts for either the hot gases or cold air has to be taken into account. If the inlets are doors, windows, or ventilators direct to open air the vent areas must be multiplied by the factor given in Table 6.

TABLE 6

Correction factor for restricted area of inlets

Ratio $\frac{\text{area of inlets}}{\text{area of vents (from table)}}$	Multiply vent area (from table) by
.2	5
.3	3.5
.4	2.7
.5	2.2
.6	1.9
.8	1.6
1.0	1.4
1.5	1.2
2	1.1
3	1.05

The method of making corrections for the resistance of ducts etc. is more complicated and is indicated in Appendix 2.

Some increase in vent areas may also possibly be necessary to allow for the low heat output of a sprinklered fire and the possibility of additional mixing between the hot gases and the cool air beneath caused by the sprinkler discharge, this is being investigated.

4.4.2. The effect of wind on a roof venting system

A primary consideration when designing a roof venting system (or considering whether it is possible to control smoke at all by natural ventilation) must be possible wind effects. The dynamic pressure heads due to wind are compared in Fig. 16 with the pressures due to the atack effect of a layer of hot gases. The stack heights necessary to overcome some dynamic wind pressures are given in Table 7.

TABLE 7

Stack height necessary to overcome dynamic wind pressure

Wind speed m/s	Stack height (necessary to overcome dynamic wind pressure) (metres) when hot gases are at				
	50 °C	100 °C	200 °C	500 °C	800 °C
5	10	5	3.5	2.1	1.8
10	325	20	14	8	7
15			725	19	16
20					725

Because of the high pressures which may be generated by the wind it is not satisfactory to assume that the buoyancy of the layer of hot gases will be sufficient to overcome wind effects. It is necessary to so design a venting system that, as far as possible, pressures due to wind will assist the flow of gases through the vents whatever the direction of the wind. This means that the pressure inside the vented space due to the wind must always be greater than the pressure due to the wind at the mouth of the vent.

The pressures around a given building depend on wind speed and direction[15,16] and may be either positive or negative (suction) pressures. They can each be expressed in terms of the dynamic wind pressure (q) by multiplying it by a factor known as the "pressure coefficient" (C_p); that is pressure

$$P = q\,C_p$$

Pressure contours for any building can be obtained from wind tunnel tests, some mean pressure coefficients over surfaces of some simple shape of building are given in Building Research Station Digest No. 101[16].

Wind blowing across a flat or low pitched roof (less than about 30^o) produces a suction effect with a maximum when the pitch of the roof is about 15^o. The pressure coefficient may be of the order of −1 and locally at the edges of the roofs it may be as high as −2.

With windward facing roof pitches greater than about 30^o the pressure coefficient may be positive. The pressure coefficients for a low (height less than that about twice the width) square building are given in Fig. 17.

The internal pressure depends on the relative ease of inflow and outflow of the air[16]. For a building with small openings distributed on all the faces and no single dominant opening the internal pressure coefficient may be taken, for venting purposes, to be -0.2. If there is one dominant opening (for example a mall open at one end) it will largely control the value of the internal pressure coefficient which may reach a value approaching that outside the dominant opening.

The design of a venting system for a building of simple shape isolated from other buildings seldom presents any great difficulty; except for outward facing steep roof slopes, the pressure on the roof will be less than the internal pressure whatever the wind direction, provided the inlets for fresh air are evenly distributed round the building. Vents in the vertical walls are not recommended because the pressure on a windward facing wall will generally be greater than the internal pressure; an exception may be made for vents symmetrically placed on either side of a monitor type roof (see Fig. 15(b), the wind will blow through this arrangement which should be satisfactory.

The pressure distribution round a complex shape of building, particularly one with tall blocks rising from it, may itself be complex[17] and the presence of other buildings, particularly tall ones, may modify the pressure distribution round even a simply shaped building. Thus with the building shown in Fig. 18 the pressure at A, where vents will normally be placed, may well be greater than that at B, where inlets for fresh air would be expected. Ideally the pressure distribution over such a building should be investigated using a model in a wind-shear wind tunnel before designing a venting system. Possible solutions to the problem of unfavourable pressure distribution due to wind are chimneys or ducts leading to low pressure areas round the building, vents so designed that the wind causes a low pressure locally at their outlets, or possibly vents and inlets placed near together on the balanced flue principal (precautions would have to be taken against smoke recirculating from the vents into the inlets).

4.4.3. Other factors in the design and positioning of vents

A satisfactory roof venting system may consist of a number of small vents evenly distributed over the area of the smoke reservoir. In practice the possible positions of vents are often dictated by the layout of floors above the shopping centre. Not only may the arrangement of the building be such that positions where vents can be placed are very limited but vents must also be placed so that exposure hazards to higher levels do not occur. It is necessary to ensure that the discharged smoke and hot gases do not enter other parts of the complex or adjacent buildings and so create a smoke hazard in them. If the shopping centre is sprinklered there should be little danger of an exposure hazard from flames out of roof vents although the possibility of this should the sprinkler system be inoperative should not be overlooked.

It may frequently be necessary to employ vertical ducts or chimneys to convey hot gases through upper levels of the building. It may be possible to employ only one such chimney in a smoke reservoir and it is likely that the gases leaving the smoke reservoir will then be at a high velocity so that cool air is likely to be sucked into the chimney together with the hot gases. Ways of overcoming this are being investigated; one possibility is to use a horizontal duct with a number of small openings in it. It may be possible to employ a suspended ceiling as such a horizontal duct.

Occasionally it may be found that there is no possibility of siting a vent immediately above a smoke reservoir and it may be necessary to convey the hot gases through horizontal ducts into the vents. The resistance of ducts must be taken into account when designing the venting system and also the loss of buoyancy of the heated gases as they are cooled by passage through the duct. This can be reduced by lining the duct with a non-combustible insulating material.

5. CONCLUSIONS

5.1. Without provision for the control of smoke in an enclosed shopping centre, even a small fire may result in its becoming rapidly smoke-logged.

5.2. Because of the rate at which smoke can spread, smoke control measures should be automatically controlled and initiated by a smoke detector.

5.3. The preferred method of smoke control is to confine the hot smoky gases produced by the fire to the shop in which the fire originates. This is only possible if there is a shop front with a self closing fire door, the door is closed (except to allow passage of persons escaping) and the shop front remains intact throughout the fire. If sprinklers are not fitted the shop front must be fire resisting. Smoke may be prevented from entering the mall by lowering the pressure in the shop with an extractor fan or possibly by pressurizing the mall.

5.4. Other methods of smoke control are only possible if the size of the fire is restricted; in general this means that sprinklers must be installed and operative. The design of smoke control systems must be based on a "design" fire - in the absence of other information one 3 m x 3 m is suggested.

5.5. Although it is theoretically possible to dilute smoky gases with air to the extent that they will not hinder escape this is seldom a practical method of smoke control.

5.6. It is possible to confine hot gases to a layer beneath the ceiling while the air beneath is relatively cool and clear. The lateral extent of the layer should be limited by dividing the space beneath the ceiling into smoke reservoirs by screens extending part of the way towards the floor. Hot smoky gases are confined to one reservoir by extracting them at the maximum rate at which they are likely to be produced while fresh air is allowed to flow in or is introduced into the building in such a way that the boundary between the hot gases and cool air is not disturbed.

This principle may, in theory, be used to prevent smoke from flowing into a mall from an open fronted shop but it is only practicable with large shops. It is expected that the principle will generally be used to keep the lower part of a mall smoke free.

5.7. Methods of extracting smoke from the smoke reservoir include powered extract, natural venting, a combination of powered inlet and extract and, possibly, pressurizing the mall while opening suitable vents.

5.8. Natural ventilation has the advantage of basic simplicity but the system must be designed so that the effects of wind will always be to enhance the flow through the vents and this may be difficult with complex building layouts. Areas of vents may be calculated using the same formulae that were developed for roof venting of single storey buildings but certain corrections have to be applied which may increase those areas considerably.

5.9. It is essential that smoke control measures should be considered at an early stage in the design of the building since they may be difficult to incorporate as an afterthought.

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APPENDIX I

Derivation of tables and graphs

Rate of production of hot smoky gases by a fire. (Table 1 and Figure 1.)

The mass (M_i) of an entrained by flames rising through a distance y is [2]

$$M_i = 0.096 \; P \; y^{3/2} \; \rho_o \; (g \; T_o/T)^{\frac{1}{2}}$$

where ρ_o is the density of the ambient air (1.22 kg/m^3 at 17^{o}C)

T_o is the absolute ambient temperature (290^{o}K)

T is the absolute flame temperature (1100^{o}K)

P is the perimeter of the fire

If P and y are given in metres

$$M_i = 0.188 \; P \; y^{3/2} \quad kg/s$$

Approximate times for a fire to fill a shop to a given depth. (Table 2)

From reference 2.

$$M_i = 0.05 \; P \; y^{3/2} \; \rho_o \; g^{\frac{1}{2}}$$

If the gases subsequently cool to 300^{o}C the volume rate of flow into the layer

$$V = 0.1 \; P \; y^{3/2} \; g^{\frac{1}{2}}$$

$$V = A_g \; dD/dt$$

where D is the depth of the layer

t is time

A_g is the area of the compartment

$D = h - y$

where h is the height of the compartment

$$t = \frac{10A_g}{Pg^{\frac{1}{2}}} \int_0^D \frac{dD}{(h - D)^{3/2}} = \frac{5A_g}{Pg^{\frac{1}{2}}} \left\{ \frac{1}{(h - D)^{\frac{1}{2}}} - \frac{1}{h^{\frac{1}{2}}} \right\}$$

Rate of flow through a vertical opening out of a compartment full of hot gases (Table 3)

Let the neutral plane be at a depth D_n beneath the top of the opening [2]

Then $$M_a = (2/3) \; C_d \; (H - D_n)^{3/2} \; W \; \rho_o \; (2 \; g \; \theta/T)^{\frac{1}{2}}$$

where M_a is mass rate of flow into the compartment

C_d is the discharge coefficient

H is height of opening

W is its width

θ is the temperature of the gases above ambient

T is their absolute temperature

$$M_b = (2/3)\ C_d\ (D_N)^{3/2}\ W\ \rho_o\ (T_o/T)(2\ g\ \theta/T_o)^{\frac{1}{2}}$$

where M_b is the mass rate of flow out of the compartment

If the fuel/air ratio is 1/5

$$6\ M_a = 5\ M_b$$

and $$M_b = \frac{(2/3)C_d\ H^{3/2}\ W\ \rho_o\ (2\ g\ \theta\ T_o)^{\frac{1}{2}}}{T^{\frac{1}{2}}\ (0.886\ T_o^{\frac{1}{3}} + T^{\frac{1}{3}})^{3/2}}$$

If $T_o = 290^oK$ $\rho_o = 1.22\ kg/m^3$

$C_d = 0.7$

$$M_b = \frac{42.85\ \theta^{\frac{1}{2}}}{(\theta + 290)^{\frac{1}{2}}\ \{5.87 + (\theta + 290)^{\frac{1}{3}}\}^{3/2}}\ H^{3/2}W$$

<u>The rate of flow of an under pressure through an opening (Table 4)</u>

$$M_c = C_d\ A\ \sqrt{2\ g\ H_w \rho_w \rho_o}$$

where M_c is the mass rate of flow

C_d is the coefficient of discharge (0.7)

A is the area of the opening

H_w is the 'head' of water in a water manometer

ρ_w is the density of water (10^3 kg/m^3)

If A is in m^2

and H_w in mm of water

$$M_c = 3.78A\ H_w^{\frac{1}{2}}\ kg/s$$

<u>The area of vents required to confine hot gases to a single smoke reservoir (Table 5)</u> From reference 2.

$$A_v = 0.13\ P\ y^{3/2}/D^{\frac{1}{2}}$$

where A_v is vent area

P is perimeter of fire

y is height of lower edge of roof screens above floor

D is depth of roof screens

Correction factor for restricted area of inlets (Table 6)

From reference 2

$$C = (1 + 1/r^2)^{\frac{1}{2}}$$

where r is the ratio of the area of inlets to the calculated vent area.

C is the correction factor to be applied to the calculated vent area

Dynamic wind pressure (Table 7)

$$v^2 = 2\, g\, H_w \rho_w / \rho_o$$

where v is wind velocity

H_w is head of water in a water manometer

ρ_w is density of water

ρ_o is density of air

$\rho_o = 1.22$ at $17^{o}C$

and $H_w = 0.062\, v^2$

APPENDIX II

MODIFICATIONS TO VENTING FORMULAE TO ALLOW FOR THE RESISTANCE OF DUCTS

The formulae in Technical Paper No. 7[2] will apply to venting through ducts if the coefficient of discharge (C_v) is replaced by $1/(\Sigma S)^{\frac{1}{2}}$
where ΣS is the number of velocity heads lost along the duct[18]

$$\Sigma S = \Sigma S_1 + \Sigma S_2 + \Sigma S_3$$

where ΣS_1 is the sum of the velocity heads lost at entrance and exit. (This may usually be taken as 1.5).

ΣS_2 is the sum of the velocity heads lost at bends, elbows, etc in the duct (this may be obtained from tables eg I.H.V.E. Guide[18] p.188).

ΣS_3 is the number of velocity heads lost due to friction in the ducts

$$S_3 = 4 f \frac{L}{D}$$

where L is the length of the duct

D its equivalent diameter.(see I.H.V.E. Guide[18] p.180)

f is the friction factor (see I.H.V.E. Guide[18] p.137)* This is a function of the Reynolds number

$$Re = \frac{vD}{\nu}$$

where v is velocity

ν is kinematic viscosity

This complicates the calculations since it is first necessary to estimate an approximate value for v and to use this to calculate a rough value for the duct area (A_v) from which is calculated a better value for v and hence an improved value for A_v. The process is repeated until the desired accuracy is attained.

Example

How many ducts having a cross sectional area of 1.5 ft x 1.5 ft and lined with riveted steel would be required to maintain a 6 ft high cool layer in a 10 ft high shop if the hot gases are at 500°F?

$C_v A_v$ may be calculated to be 5.6 ft^2.

$\Sigma S_1 = 1.5$

ΣS_2 is the number of velocity heads lost at the elbow which from p.189 in the I.H.V.E. Guide is 1.25

---

* $f = 2 \dfrac{R}{v^2}$

where R is frictional force per unit area of wetted surface. This is the factor often quoted elsewhere[19].

To calculate S_3 it is necessary to assume a value for the velocity through the duct. The mass of gas to be vented (M_v) may be calculated using Fig.9 in Technical Paper No. 7

$$M_v/C_v A_v d^{\frac{1}{2}} = 0.32 \text{ lb ft}^{-5/2} \text{s}^{-1}$$

$$\text{i.e. } M_v = 0.32 \times 5.6 \times (3.5)^{\frac{1}{2}} = 3.4 \text{ lb/s}$$

Assuming $C_v = \frac{1}{2}$

$A_v = 11.2 \text{ ft}^2$

and the velocity through the duct

$$v = \frac{M_v \quad T}{\rho_o T_o \; A_v} = \frac{3.4 \times 1000}{0.081 \times 500 \times 11.2} = 7.5 \text{ ft/s}$$

The equivalent diameter D of one duct (from p.180 of the I.H.V.E.Guide) is 1.5 ft and the kinematic viscosity of the gases at 500°F

$\nu \simeq 5 \times 10^{-4}$

Then $Re = vD/\nu = 7.5 \times 1.5/5 \times 10^{-4} = 2.3 \times 10^4$

The relative roughness of riveted steel (from chart facing p.70 of Technical Data on Fuel[19]) $k_s/D = .007$

From Fig.1 on p.137 of the I.H.V.E.Guide

$f = 0.009$

Then $S_3 = 4 f \frac{L}{D} = 4 \times 0.009 \times 50/1.5$
$= 1.2$

$$C_v = \frac{1}{1.2 + 1.5 + 1.25} = 0.5$$

This is the same as the value that was assumed at the commencement of the calculation and there is therefore no need to repeat it. Then the total duct area required is 11.2 ft^2 i.e. 5 ducts each 2.25 ft^2 in area. However, no account has been taken of heat loss along the duct, a 1 in thick layer of sprayed asbestos should nearly eliminate its effects once the duct has become warm if the hot gases are at 500°F or above.

Effect of resistance of inlet duct

If the resistance of the inlet duct cannot be neglected $A_v C_v$ in the venting formulae must be replaced by the equivalent aerodynamic free vent area of the system $A_s C_s$ given by

$$\frac{1}{(A_s C_s)^2} = \frac{(\Sigma S)_d}{A_d^{\,2}} + \frac{T_o}{T} \frac{(\Sigma S)_i}{A_i^{\,2}}$$

where $(\Sigma S)_d$ is the sum of the pressure heads lost in the venting ducts
$(\Sigma S)_i$ is the sum of the pressure heads lost in the inlet duct
A_d is the area of venting duct
A_i is the area of inlet duct

The ratio A_d/A_i may be optimized for example to give a minimum cost. A discussion of this is beyond the scope of this note.

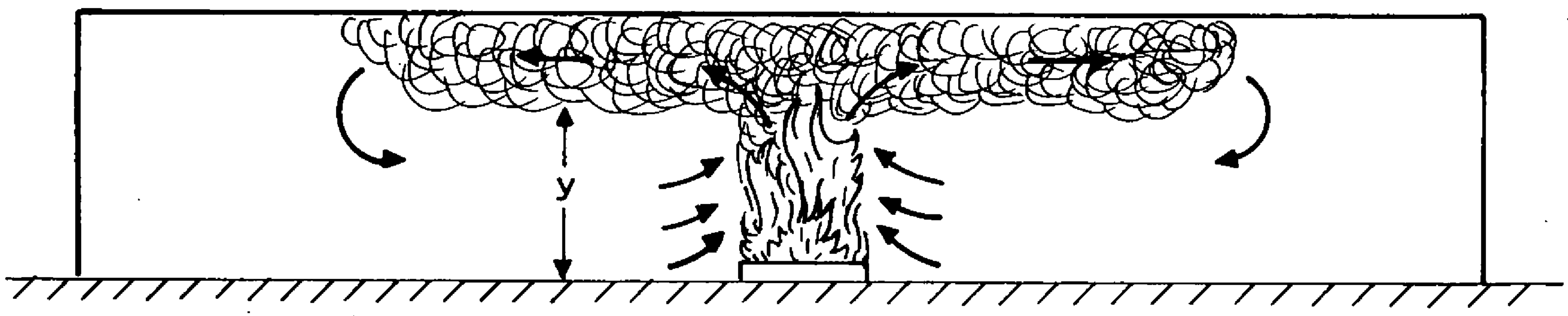


FIG.1 SPREADING LAYER OF HOT GASES

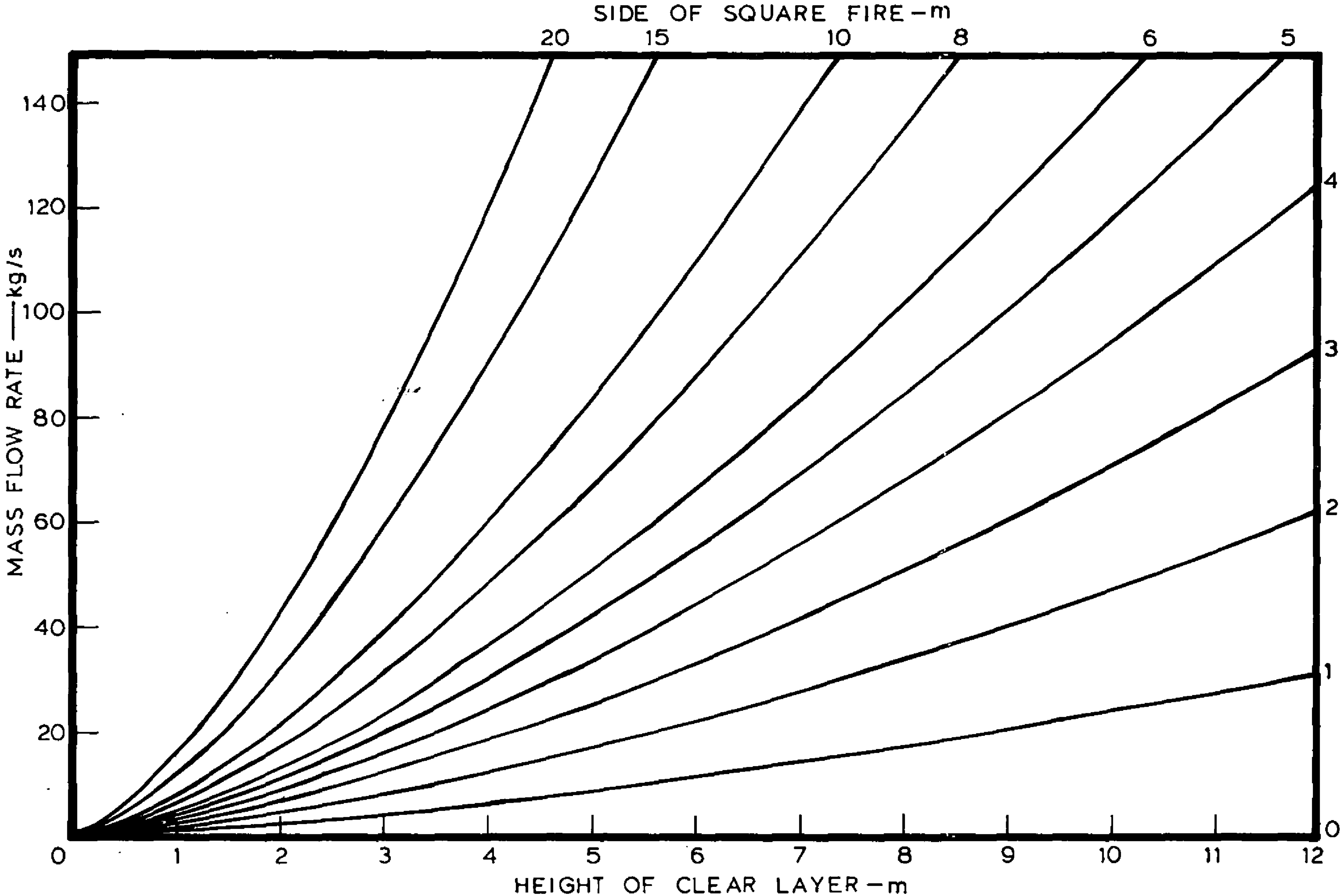


FIG.2 RATE OF PRODUCTION OF HOT GASES

A straight edge laid perpendicular to the scales intersects them at equivalent flow rates in different units

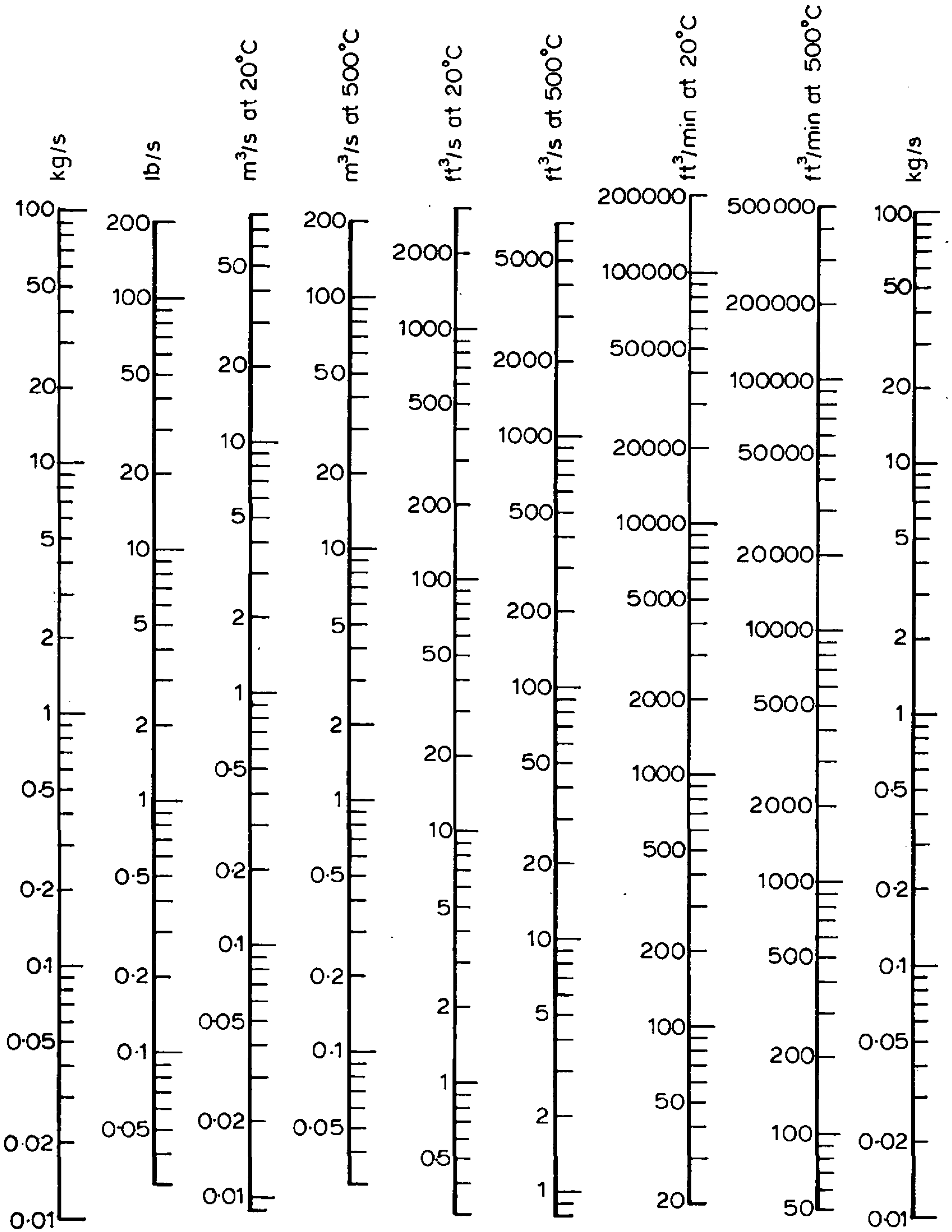


FIG.3 CONVERSION CHART FOR FLOW RATES

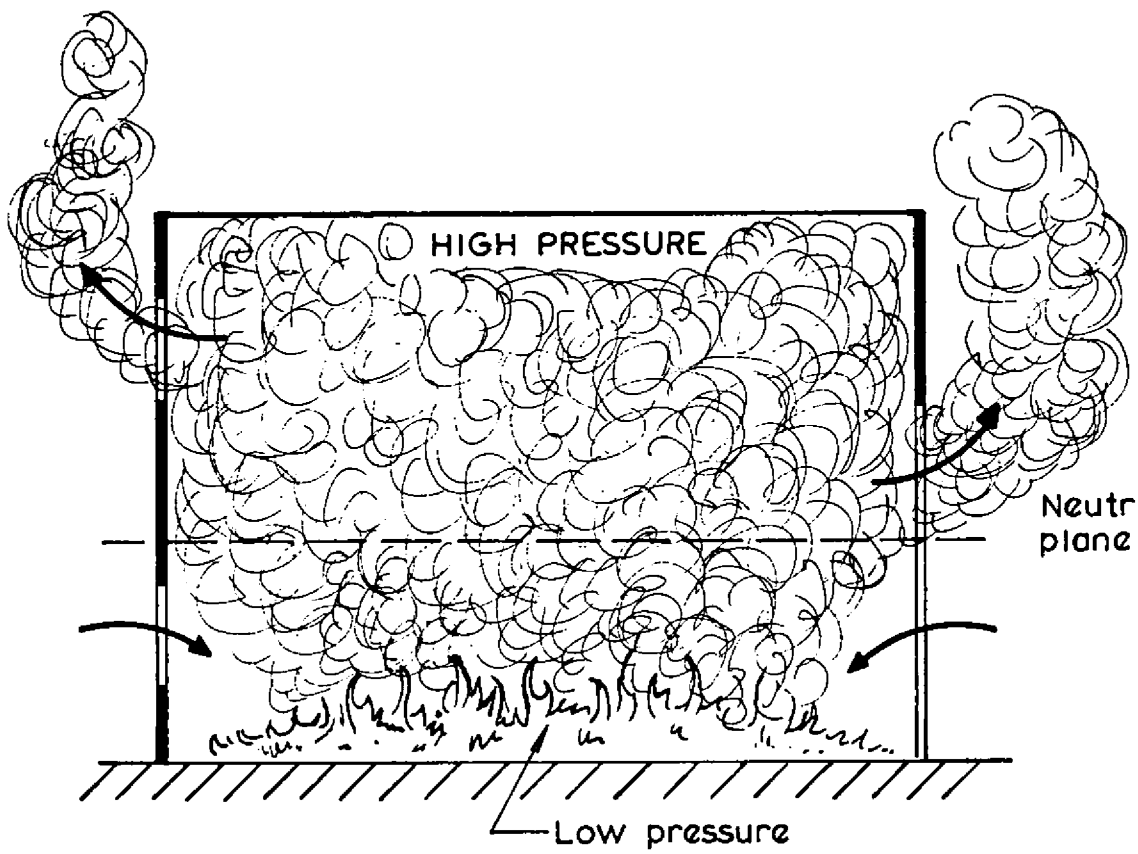


FIG.4 FLOW IN AND OUT OF A COMPARTMENT FULL OF HOT GASES

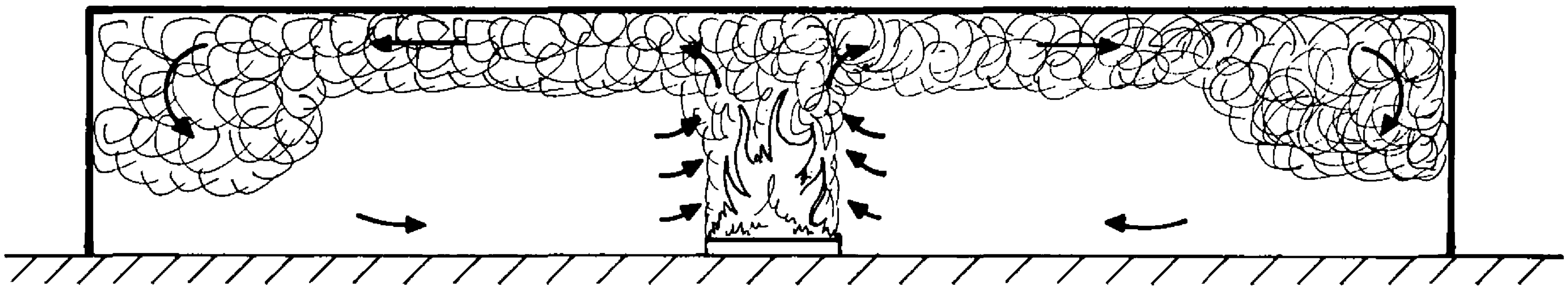


FIG.5 RETURN FLOW OF SMOKE IN A CLOSED MALL

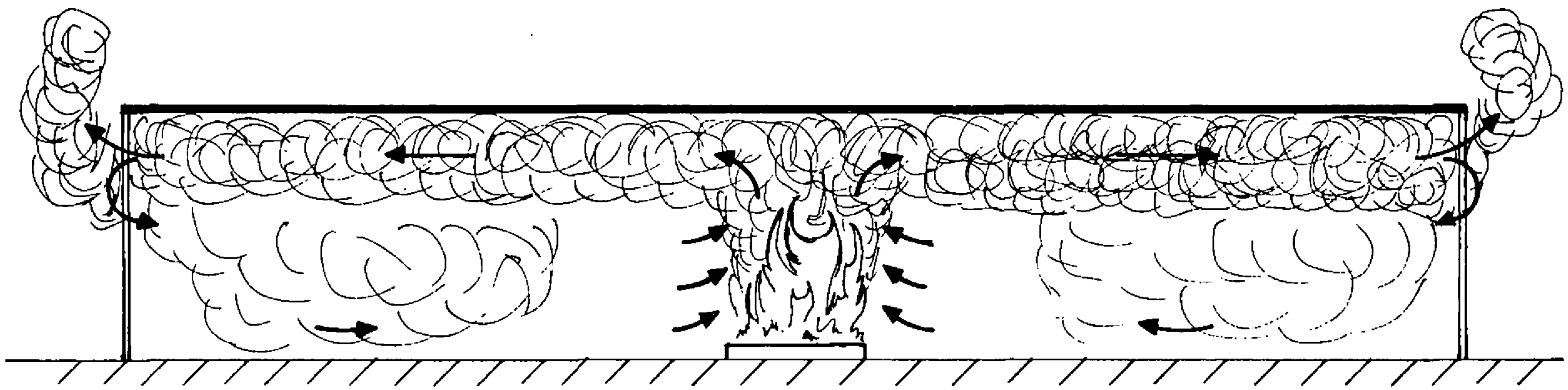


FIG.6 RETURN FLOW OF SMOKE IN AN OPEN-ENDED MALL

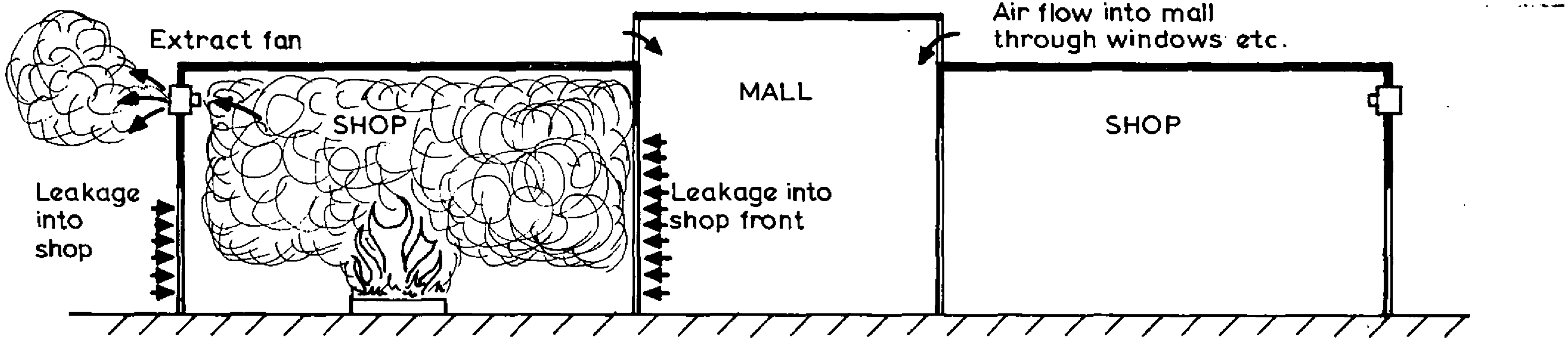


FIG.7 EXTRACTING SMOKE FROM REAR OF SHOP

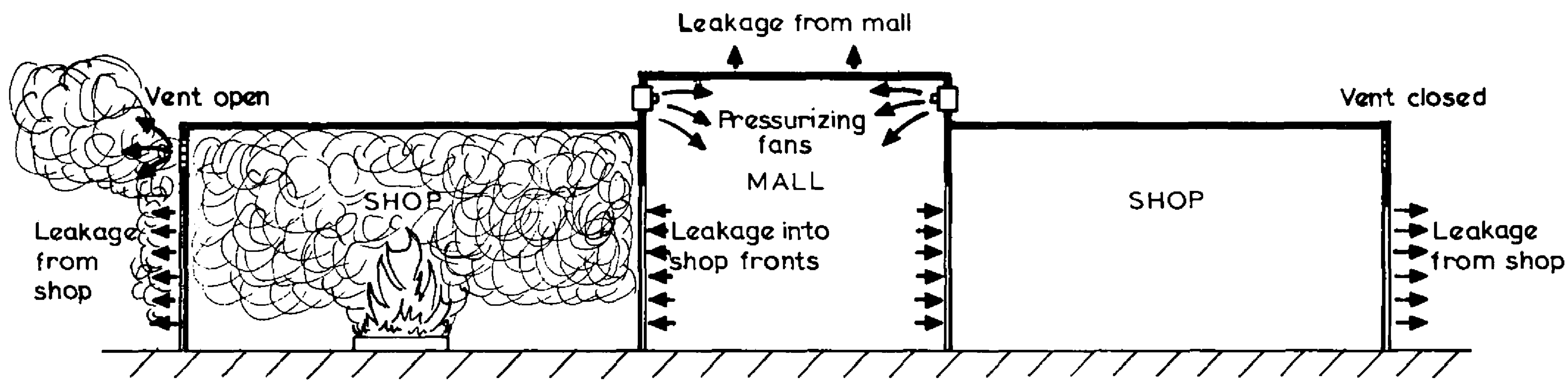


FIG.8 PRESSURIZING A MALL

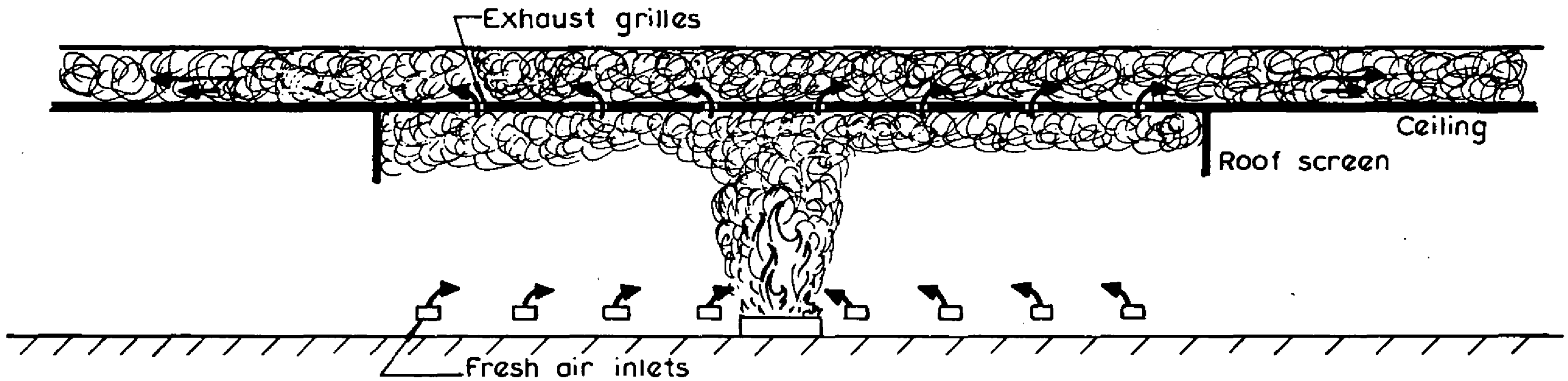


FIG. 9 PRINCIPLES OF SYSTEM TO MAINTAIN A LAYER OF CLEAR AIR NEAR THE FLOOR (USING POWERED EXTRACT)

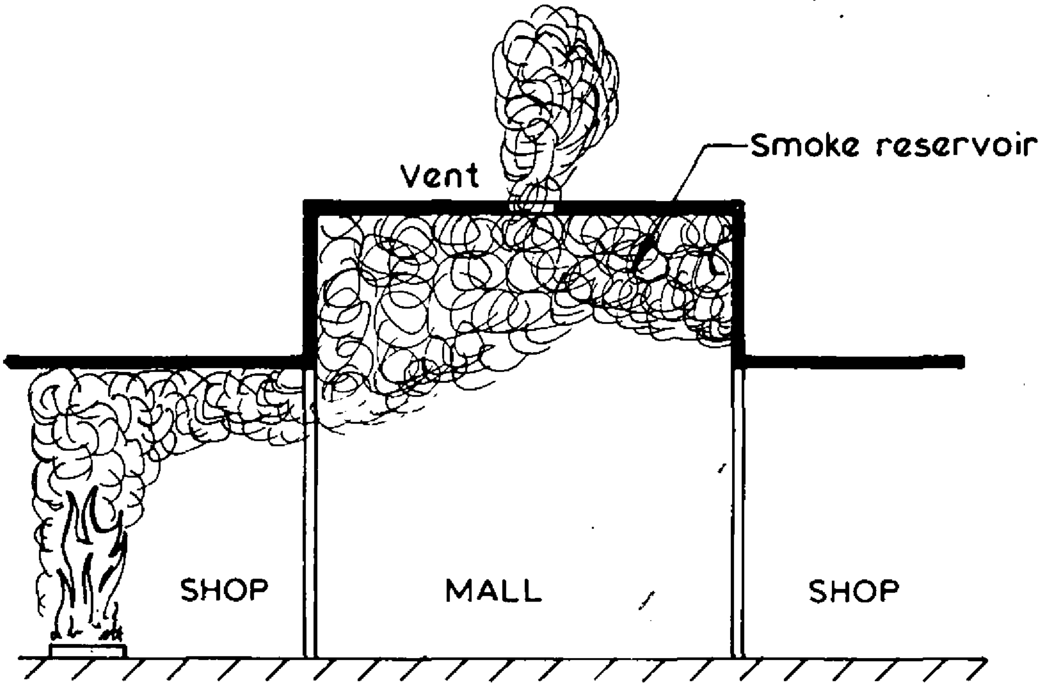


FIG.10 SMOKE RESERVOIR IN MALL WITH CEILING HEIGHT GREATER THAN THAT IN SHOPS

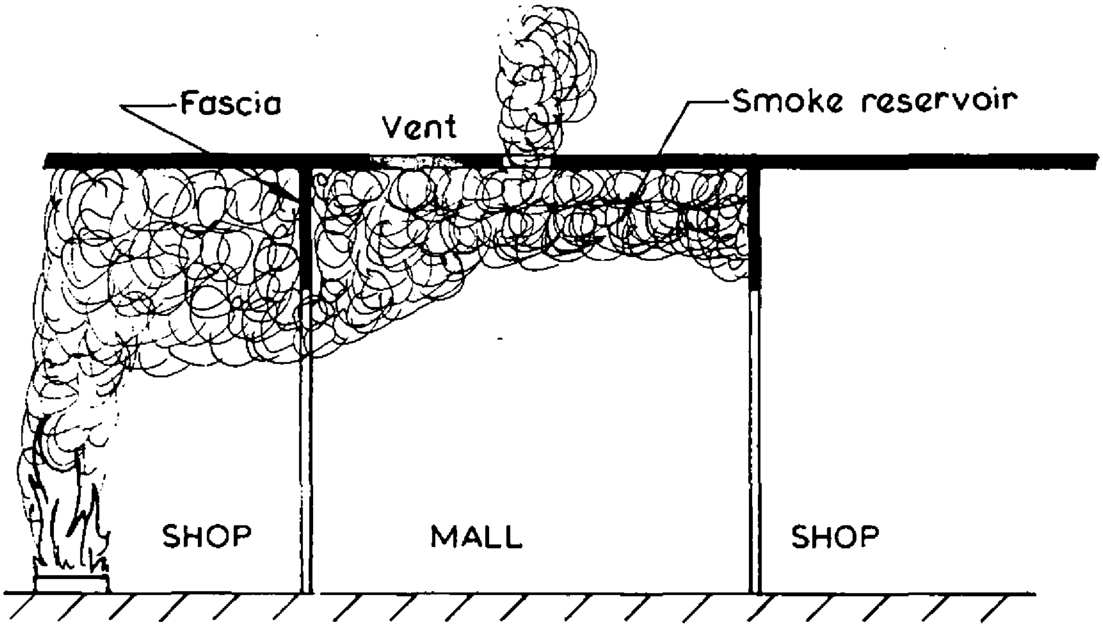
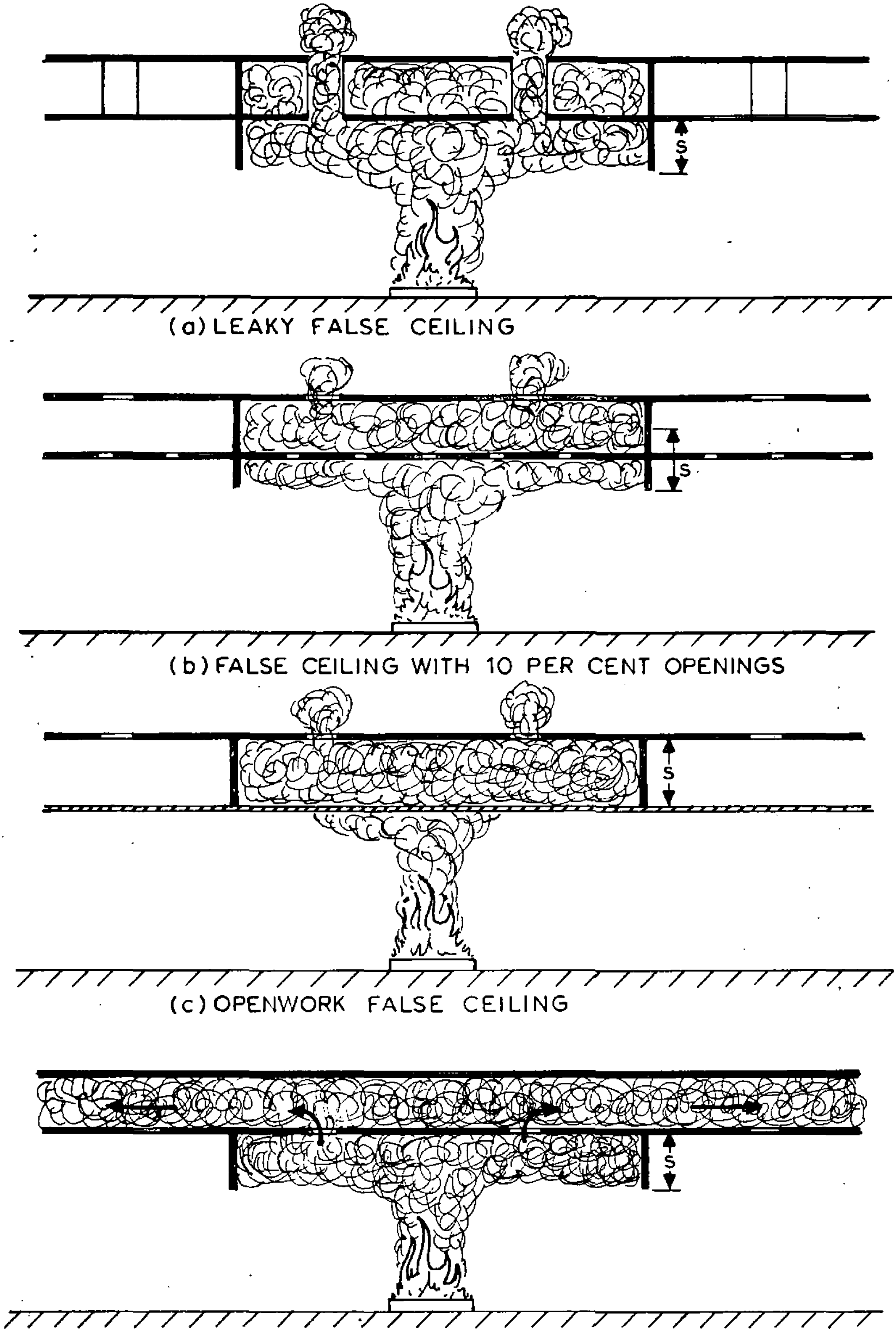


FIG.11 SMOKE RESERVOIR FORMED BY FASCIAS ABOVE OPEN FRONTS OF SHOPS



s = Effective depth of ceiling screens

FIG.12 FALSE CEILINGS AND SMOKE RESERVOIRS

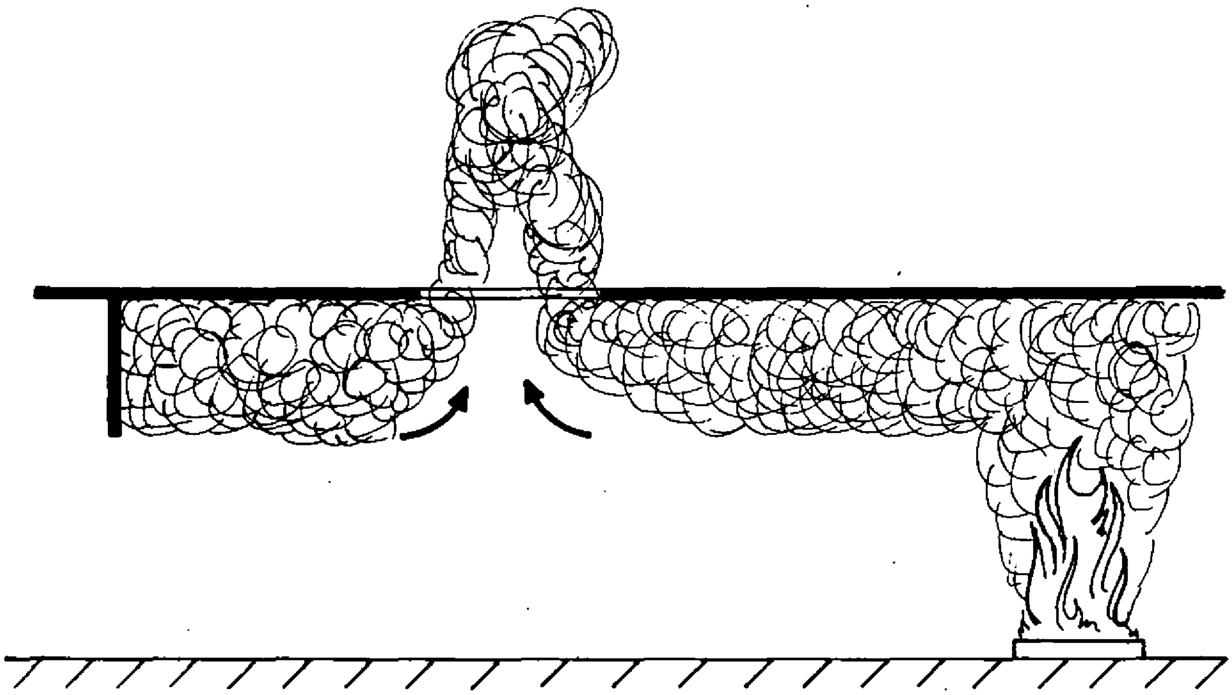


FIG. 13 FRESH AIR SUCKED INTO LARGE OUTLET

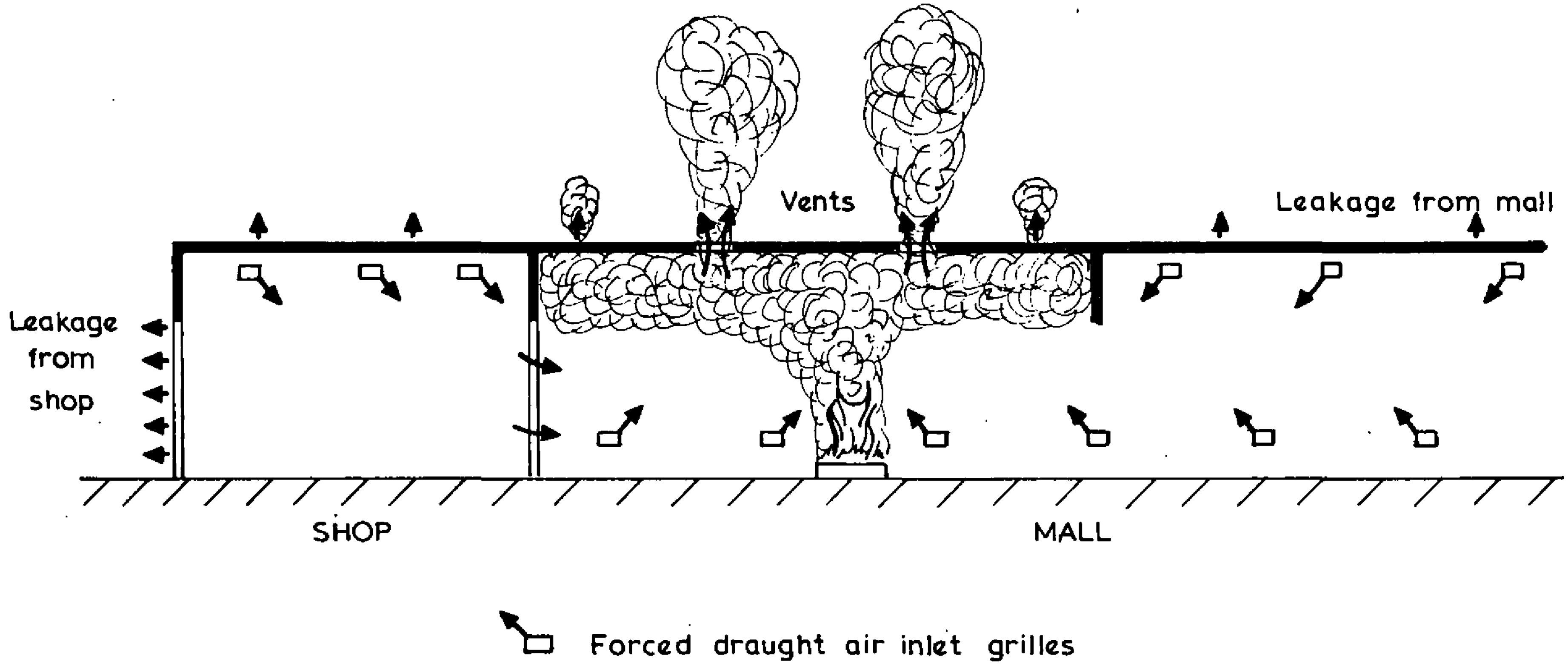


FIG.14 FORCED AIR INLET VENTING SYSTEM

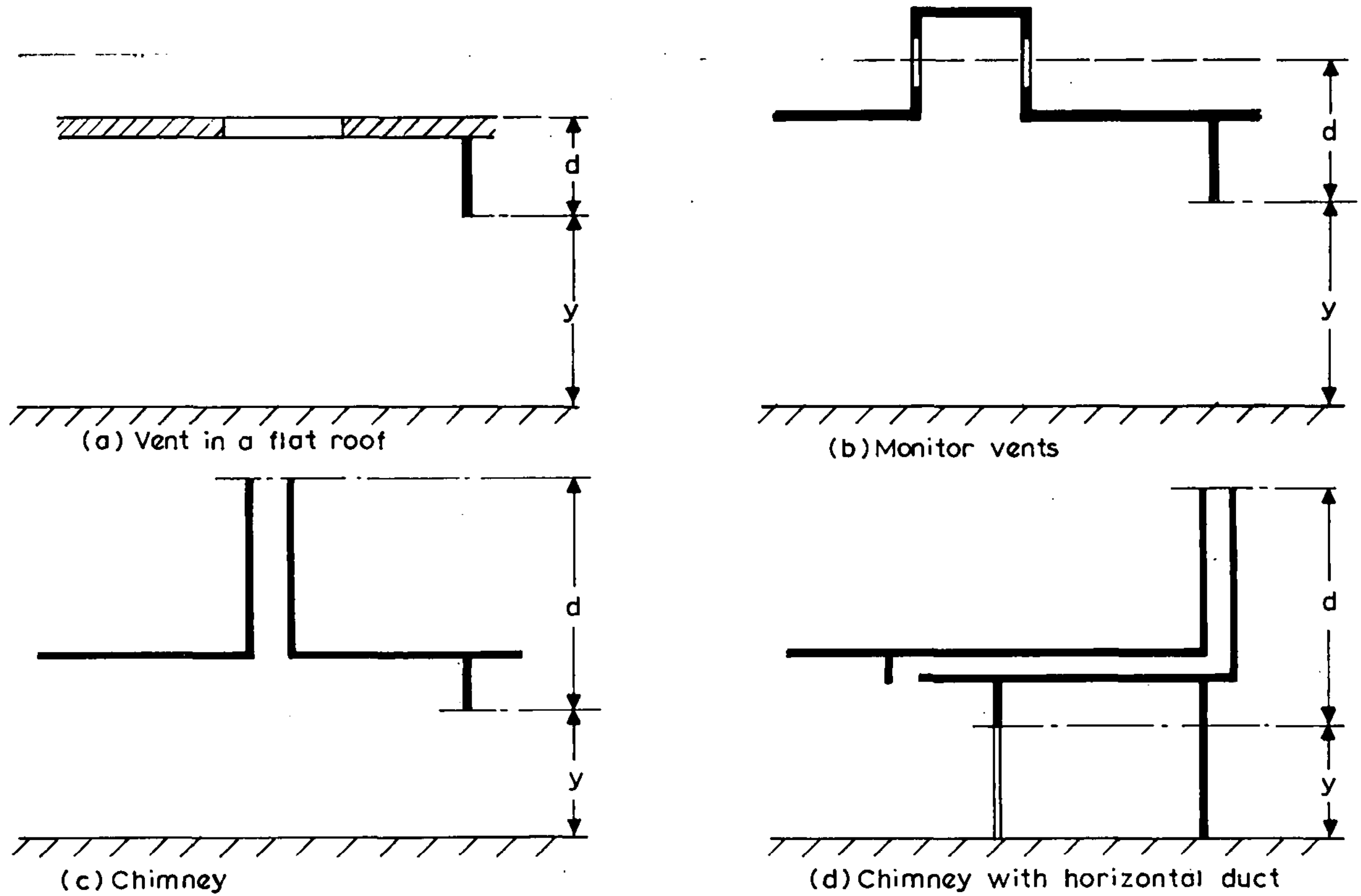


FIG. 15 TO ILLUSTRATE STACK HEIGHT (d)

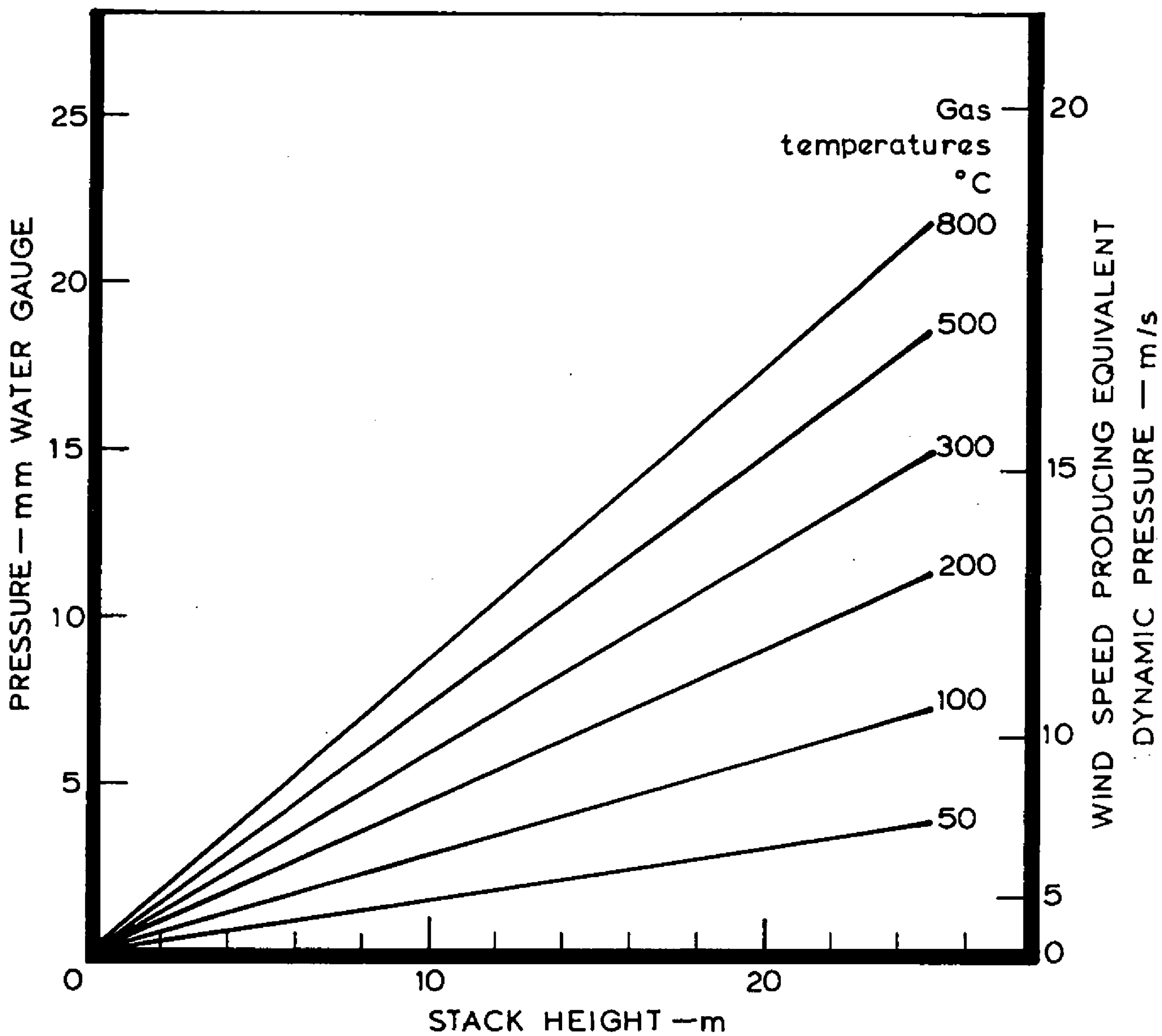
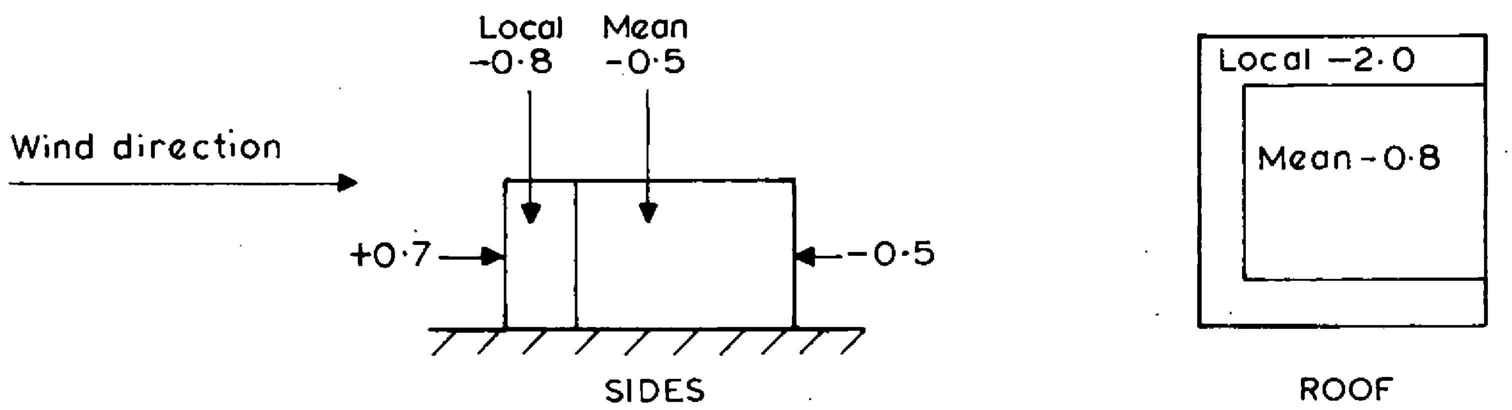


FIG. 16 COMPARISON OF PRESSURES DUE TO BUOYANCY AND WIND



If openings are evenly distributed internal pressure coefficient ≃ − 0·2

FIG.17 PRESSURE COEFFICIENTS FOR A LOW BUILDING

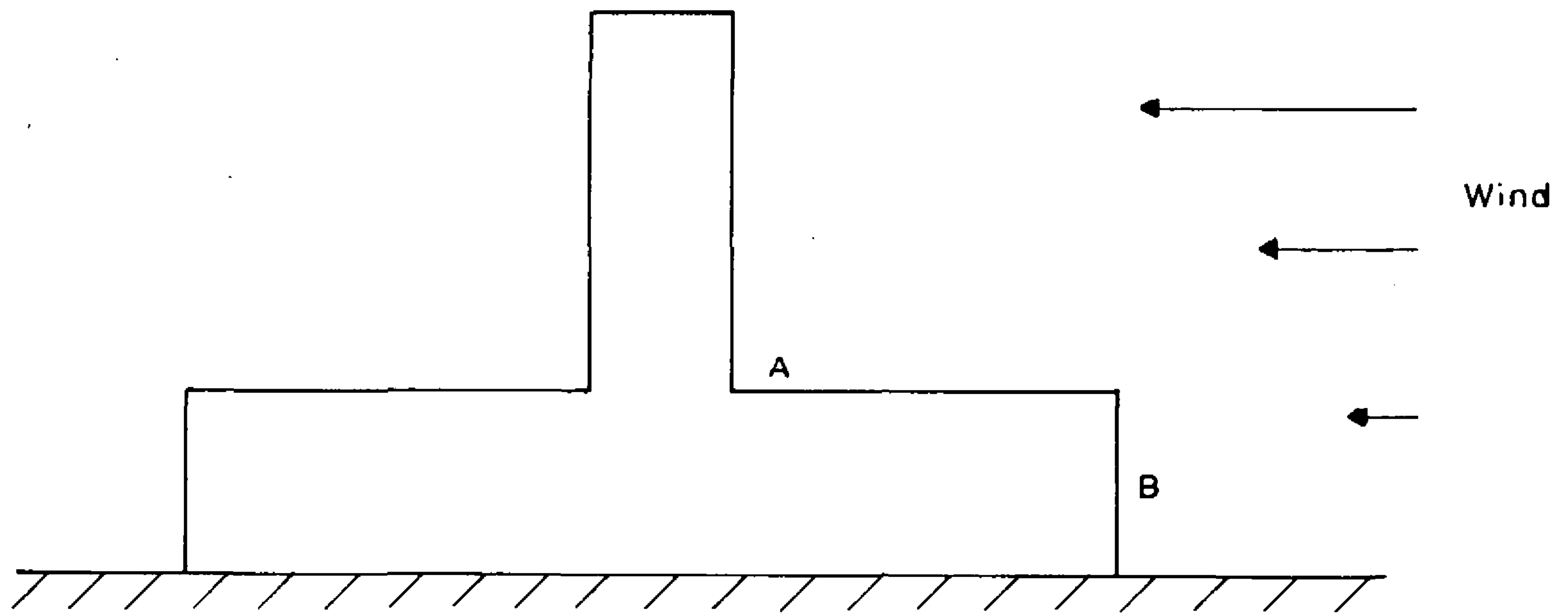


FIG. 18 LOW BUILDING WITH TALL BLOCK RISING FROM IT