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FIRE DRAINAGE: A NEW APPROACH TO FIRE SAFETY

by

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PREFACE

During the past several decades we have been witnessing an unprecedented evolution in the exterior and interior design of buildings. Changes are often introduced with the purpose of serving the convenience of the occupants and reducing the cost of construction. Unfortunately, in an attempt to achieve these objectives, some problems of public safety during emergencies are often overlooked. This is especially true with respect to the safety of occupants in the case of building fires. Because of rapid advances in building technology, many conventional methods of providing fire safety have become ineffective and not adaptable to the new conditions.

The Fire Section of the Division of Building Research has always regarded as prime objectives, the following of technological changes in the building industry and the devising of better approaches to fire safety under the changed circumstances. The "fire drainage" system described in this report is a new, unorthodox approach. It offers a comprehensive solution to fire safety and is compatible with all modern trends in building technology.

The report is a detailed theoretical treatise on the new fire safety system. It should be especially useful for engineers and architects who wish to consider using it. For the reader not interested in rigorous mathematical proofs and design formulae, a shortened version of this report will be published in one of the journals specializing in building design.

Ottawa
July 1974

C. B. Crawford
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ABSTRACT

The presently used measures of fire protection have been built around the standard fire test practices and are directed against hypothetical fires spreading by hypothetical mechanisms. The available knowledge indicates that fires burning at large excess air are very short and relatively harmless. By the installation of vertical "fire drainage" ducts the energy of the fire can be utilized partly to make the fire develop at large excess air in a controlled manner and partly to create a depression in the space on fire and thus prevent the spread of fire to neighboring spaces.

The theory of the fire drainage system is presented. Its design is illustrated by a numerical example. Some technical solutions are described for the various components of the system. The cost-benefit aspects of the system are discussed in the conclusion.

Even though the understanding of the basic characteristics of building fires has substantially improved during the past decade, it is doubtful whether the solution to fire safety in buildings is any closer now than it was ten years ago. Advances in the fire science seem to have been consistently outpaced by the emergence of newer problems which tend to make fire potentially more dangerous than ever before. The increasing popularity of high-rise buildings, the use of large, undivided areas in commercial and office buildings or maisonettes in apartment buildings, the introduction of a multitude of plastics to replace wood or metal both in furniture and in building components are only a few of the problems today's building officials have to cope with.

Conventional solutions that seemed to serve the objective of fire safety reasonably well ten years ago, have become ineffective. It appears now that instead of trying to adapt these conventional solutions to new, changed conditions, it would be more advantageous to take a new look at the whole problem area and develop a new system of defence against fire right from the basic principles.

In this paper an attempt will be made to outline the theory and some practical aspects of a new comprehensive approach. Although some other practical aspects still remain unsolved, there seems to be no major technical difficulty in realizing this approach in the foreseeable future.

THE CONVENTIONAL CONCEPT ON FIRE

The classical theory of fire protection is based on the assumption that fire spreads through a building by either of two mechanisms: (i) conduction of heat through the boundaries of the space on fire, followed by the ignition of the combustibles in the neighbouring spaces, (ii) collapse or partial failure of a boundary element of the space on fire and subsequent direct penetration of flames into the adjoining space. Consequently, to check the spread of fire, the boundary elements of all constituent spaces have been required to exhibit specified "fire resistances", that is, proven abilities to resist heat conduction and structural damage for specified periods.

It is conceivable that fire occasionally does spread by the mechanisms assumed by the conventional concept. The results of fairly recent surveys concerning the combustible contents of buildings (1, 2, 3), when evaluated in the light of this author's findings (4, 5), clearly show, however, that if fire could spread only according to the two mechanisms assumed, 90 to 95 per cent of all fires in modern buildings would die down in 20 to 30 minutes in the room in which they originated, without causing major structural damage.

It has been recognized for some time that the spread of flaming combustion is, in fact, primarily a convective-radiant process. The flames are driven by pressure differences from one building space to another either horizontally through gaps around doors or through left-open doors and other openings, or vertically through ducts, shafts, openings in ceilings, and by flames issuing from the windows and jumping to the next floor above. (In fact, structural failures are usually the results, not causes, of the unchecked expansion of fire.) The spread of fire, in other words, ignition by the advancing flames, occurs by a combination of direct contact with a combustible material and by irradiation by relatively short-range fluxes emanating from the flames.

Occasionally, fire may also spread to a neighboring space by long-range thermal radiation originating from a mass of flames through areas of communication between the space on fire and its environment.

Realizing tacitly that dividing a building into fire resistant compartments is not the complete answer to the problem of fire safety, today's building codes prescribe, in addition to fire resistance requirements, a host of other requirements to combat the spread of fire through buildings.

The approach to fire safety taken in this paper is different from the conventional ones. Instead of devising a system of defence against a hypothetical fire, the present approach is more concerned with the fire itself. The techniques to be described are directed toward ensuring that, if fire occurs, it will develop in a controlled manner and cause minimum damage to the space on fire and to the surrounding spaces.

Even with these new techniques, spread of fire may occasionally occur but it occurs very slowly and can be checked easily by people not trained in fire fighting techniques.

CONTROLLING THE FIRE

The essence of the new technique is a controlled admission of air to and withdrawal of gaseous products from the area affected by fire. These operations can be accomplished either by mechanical, or by "natural" means, i.e. by relying completely on the energy provided by the fire itself. Although mechanical operation may sometimes offer certain advantages, to keep the length of this paper within reasonable bounds only the natural means of operation will be discussed in detail in this paper.

Venting fires has long been regarded as an effective tool in controlling fires, primarily from the point of view of improving the visibility for fire fighting and rescue in certain industrial, mercantile and assembly occupancies. The theoretical aspects of fire venting were dealt with by Yokoi (6) and Thomas and co-workers (7, 8) and the practical aspects have been outlined in NFPA Standard No. 204 (9).

Although all work in this field has so far been related to large, single-area, single-storey buildings, a few cases are known in which the concept was applied to two-storey structures. No consideration has so far been given to fire-venting multi-storey buildings of residential, institutional or business occupancies, for which the concept would, in fact, offer some extra advantages.

The suggestion of venting building spaces on fire sounds somewhat paradoxical at first. Venting is usually accompanied by significant increase in the air flow and, possibly, by an increase in the rate of burning. Over the years people have become accustomed to the idea that the principal objective of fire fighting is the early suppression of fire and any measure that results in increasing the rate of heat evolution would seem to work against this objective. The facts, however, do not support this notion. As will be shown later, the inflow of cool air (above a certain "critical" rate) not only helps to keep the temperature down in spite of the increased rate of burning, but also reduces the duration of the fire. In reality, fires occurring in poorly ventilated spaces, such as basements, theatres, ships, etc., are usually the most destructive ones.

The fact that well vented fires are less severe than the poorly vented ones is, however, only one reason for providing each individual building space with venting facilities. If the withdrawal of the gaseous products takes place through a vertical duct in a manner coordinated with the air supply, the column of hot gases in the duct will create a depression in the space affected by fire sufficiently great to prevent the convective spread of fire to other spaces.

Since the potential energy of the hot gaseous products is exploited to render the fire relatively harmless (by providing good ventilation) and to confine it to the affected space (by creating depression), it seems appropriate to refer to this method of fire protection as the "fire drainage method."

TYPES OF BUILDING SPACES

Discussion in this paper will be restricted to such buildings whose constituent spaces can be classified as belonging in one of the following four groups[1]:

1. Rooms: relatively small spaces of single-storey height (7 to 10 ft), communicating with other rooms or with group 2 or 3 spaces through doors and, as a rule, with the outside atmosphere through windows.
2. Uncompartmented spaces: large spaces of single-storey height, communicating with Group 1, 3 or 4 spaces through doors and, as a rule, with the outside atmosphere through windows.
3. Corridors: routes of single-storey height for the horizontal movement of people and goods, communicating with Group 1, 2 or 4 spaces through doors.

[1] The fire drainage system for other buildings can be designed by the judicious application of the principles derived in this paper.

4. Shafts: spaces for the vertical movement of people or goods, extending over the entire height of the building, communicating with Group 2 or 3 spaces through doors.

Shafts had to be included in the above grouping because of the important part they play in the functioning of the building. They will not be regarded, however, as sources of building fires.

The grouping of the first three types of spaces has been made from the point of view of the types of problems encountered in designing the appropriate fire drainage system. Their design will be based on the following considerations:

Since rooms are relatively small spaces, fires occurring in them will probably become "total" fires, in other words, will expand to more or less the entire unit. One can expect, therefore, that the fire will dislodge the window panes from the "effective" window openings which then become available for the inflow of fresh air.[2] Because the total area available for the inflow of air is relatively small, the accompanying pressure drop is usually substantial. Thus, utilizing the suction created by the drainage duct, the pressure in a room can be kept below that of its environment without difficulty.

With the fire drainage system in operation, fires occurring in large, uncompartmented spaces tend to remain localized. Because of the presence of large, unobstructed spaces around the burning region, however, vast amounts of air can move toward the fire under the effect of very small pressure differences. Consequently, to create a depression in the fire area, substantial enough to effectively combat the spread of fire to other areas, it is advisable to supplement the fire drainage ducts by other devices.

Corridor fires, like those in uncompartmented spaces, will also tend to remain localized with the use of the fire drainage system. Again, because of the presence of large, unobstructed spaces adjoining the burning area it is recommended that fire drainage ducts be supplemented by other facilities.

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[2] The "effective" window area is, in general, the breakable part of the total window area. The practical design of windows to be used in buildings equipped with a fire drainage system will be discussed later in detail. It will also be shown that the absence of windows presents no major difficulties in the design of the fire drainage system.

Groups 1, 2 and 3 spaces, equipped with fire drainage system, are shown schematically in Figures 1, 2 and 3, respectively. The room shown in Figure 1 is a typical hotel room in a multi-storey building. All rooms, 1, have two windows, 2, parts of which represent the effective openings, 3. From each room a door, 4, leads to a corridor. A small washroom, 5, is attached to the room. A built-in closet, 6, serves the convenience of the occupant. The fire drainage ducts, 7, 8, extend vertically along the entire height of the building. The room shown is served by two ducts. In turn, each duct usually serves two adjacent rooms on each floor through openable gates, 9, 10, installed near the ceiling. These gates are shown in a closed position. They open wide on the build-up of heat in the room. (Some components of the spaces shown in Figures 1, 2 and 3 will be further discussed later.)

In Figure 2 a large uncompartmented office space is shown. Two solutions are possible. The one illustrated in the figures is the recommended solution. The ceiling area is divided into a large number of rectangular areas by a series of retracted fold-up curtains, 1, made of light gauge metal or some heat-resistant, metal-reinforced material and equipped with a weightier bottom piece. The purpose of these curtains is twofold. First, they restrict the spread of flames and hot gases during the growth period of fire when the drainage ducts are not yet operative. Secondly, when activated by the fire, they slide down in the grooves, 2, of posts 3, to floor boards, 4. In this way they surround the area affected by the fire, leaving only four openings, 5, for the entrance of air. Doing this they not only ensure controlled burning conditions, but also help the drainage duct to produce a substantial depression in the fire area. The main purpose of the floor boards is to prevent people from placing furniture or other objects below the fold-up curtains where their presence may interfere with the operation of the curtains.

Obviously, even though the occupants may have an unobstructed view over practically the entire area, the uncompartmented space is, in effect, subdivided into a number of elementary areas, 6. Windows, 7, are located at the peripheries of the space. The drainage ducts, 8, are located at the center of each elementary area, and can be conveniently combined with the building columns, 9. The ducts extend along the entire height of the building, and have four heat-activated gates, 10, next to the ceiling on each floor.

A simpler but less effective solution is also possible. This could be obtained from the figure shown by the omission of items 2, 3, 4 and 5, and by the replacement of the fold-up curtains by ordinary curtain boards. With this solution only a slight depression can be produced in the fire area by the operation of the drainage duct and, therefore, the spread of flames and hot gases to the neighbouring areas may not be completely checked.

Figure 3 shows a section of a corridor, also equipped with fire drainage facilities. Again, the figure illustrates only a recommended solution. Fold-up curtains, (made of light-gauge metal or metal reinforced heat-resistant material and equipped with a weightier bottom piece), 1, are again used with a twofold purpose; to limit the spread of flames and hot gases while retracted, and to control the rate of burning and the pressure after their activation by the heat. To fulfil these functions, these curtains slide down in the provided grooves, 2, to a predetermined distance from the floor, leaving an area available for the inflow of air. The location of the curtains determines the area of the corridor"elements", 3. The corridor communicates through doors, 4, with rooms on both sides. Each corridor element is generally served by one drainage duct, 5, and each duct communicates with a number of corridor elements located above each other, through heat-activated gates, 6, 7.

Again, a simpler but less effective solution can be obtained by the omission of items 2 (curtain guiding grooves) and the replacement of the fold-up curtains by curtain boards. The shortcomings of this solution are similar to those already mentioned in connection with uncompartmented spaces.

In Figure 4 the operation of the fire drainage system in case of fire is shown for the three types of building spaces discussed; rooms (Figure 4a), uncompartmented spaces (Figure 4b) and corridors (Figure 4c). On the basis of the previous description, the reader can now identify the various components of the system. It is seen that all drainage gates are closed, except those of the space on fire and the "release gates" located at the top of the drainage ducts. (The way the hot gaseous products achieve the opening of the gates needed in the drainage of fire will be discussed in a later section.) Fires occurring in a building equipped with fire drainage system will develop near a temperature level determined by the design and, as will be pointed out in the next section, will last less than 30 minutes.

An 11-storey office building is shown schematically in Figure 5a. It has five rooms, 1, an uncompartmented space, 2, and a T-shaped corridor, 3, on each floor, and four shafts, 4. (Washrooms normally contain very little combustible material and, therefore, need not be discussed in the design of the fire drainage system.)

The fire drainage duct system for the building is shown in Figure 5b. It consists of six ducts, 5 and 5a, serving the rooms (five on each floor), ten ducts, 6, serving the uncompartmented spaces, and two ducts, 7, serving the corridors. The ducts usually extend above the roof level, so that, as shown in the figure[3], $H_1 > H$. (The design of the fire drainage system for this building will be discussed later in the section "Numerical Example of Design.")

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[3]See list of nomenclature at the end of the paper.

THE THERMAL CHARACTERISTICS OF FIRE

It has been customary to investigate the characteristics of building fires by experimental fires built in "isolated" model rooms that have perfect communication through their entire window openings with the outside atmosphere and no communication whatever with the other parts of the building. These models can be regarded as fairly realistic as far as the thermal characteristics of fires are concerned, but inadequate from the point of view of spread of fire.

While research relating to fires in these model rooms received prime attention and produced very valuable results, little attention has been paid to fires occurring in other types of building spaces, such as large, uncompartmented areas and corridors. Since, as will be pointed out later, the design of the fire drainage system is not too sensitive to the accuracy of the input data, the information obtained for isolated model rooms will be used in this paper as the basis of discussion of fires occurring in any type of building space.

It has been known for some time (10) that the rate of burning of room fires (that is the thermal decomposition of the combustible materials and the subsequent combustion of the decomposition products) depends, to a large extent, on two factors; the mass flow rate of air into the room, U_a, and the free surface area of the combustible materials, A_f. The former quantity is often referred to as the "ventilation" of fire, and is a function of the connecting areas and pressure differences between the room on fire and its surroundings. The latter can be expressed as[4]

$$A_f = \varphi F A_F \qquad (1)$$

For conventional furniture usually $0.55 < \varphi < 0.90$.

The nature of the fire depends on whether the ratio U_a/A_f is lower or higher than a critical value; about 28 lb/hr ft^2. At lower values of this ratio the rate of burning R, during the "fully developed" period of fire is determined by the rate of air flow; the fire is "ventilation controlled". At higher values, on the other hand, the rate of burning becomes roughly proportional to the free surface area of the combustible materials; the fire is "fuel-surface controlled".

By utilizing eq (1), the following equation can be written for the "critical" air flow, that is for the flow rate of air at which, with increasing ventilation, the fire becomes fuel-surface controlled:

$$(U_a)_{cr} = 28\varphi F A_F \qquad (2)$$

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[4]Most of the discussion presented in this section of the paper is a summary of the results developed in Reference 11.

It seems convenient to introduce an "air flow factor", ξ, and with it write the mass flow rate of air as

$$U_a = \xi(U_a)_{cr} = 28\varphi F A_F \xi \tag{3}$$

Obviously, if $U_a = (U_a)_{cr}$, the air flow factor is equal to 1, and

the fire is ventilation controlled if $\xi<1$ (4)
the fire is fuel-surface controlled if $\xi\geq1$ (5)

A multitude of experimental data revealed that the following two equations satisfactorily describe the rate of burning of room fires:

$$\text{if } \xi < 1 \qquad R = 0.163\, U_a \tag{6}$$

$$\text{if } \xi \geq 1 \qquad R = 4.57\, \varphi F A_F \tag{7}$$

In the second of these equations eq (1) has been utilized. The mass flow rate of gaseous products can now be obtained as

$$U_g = U_a + R \tag{8}$$

The rate of heat evolution during the period of fully developed fire, Q, can be expressed as

$$Q = R\,(0.932\beta\Delta H_v + 0.068\Delta H_c) \tag{9}$$

where β is the fraction of heat released by the combustion of the volatile decomposition products inside the room.

To calculate β, first the length of the flames, ℓ, has to be estimated, with the aid of the following equations:

$$\text{if } \xi < 1 \qquad \ell = 0.366\, U_a^{1/3} \tag{10}$$

$$\text{if } \xi \geq 1 \qquad \ell = 1.11\, (\varphi F A_F)^{1/3} \tag{11}$$

Then β is obtained as

$$\text{if } \ell \leq h \qquad \beta = 1 \tag{12}$$

$$\text{if } \ell > h \qquad \beta = (h/\ell)^{3/2} \tag{13}$$

Three parameters have been introduced to characterize the "severity" (destructive potential) of fires:

i. the duration of fully developed fire, τ,

ii. the average temperature of gases in the room during the period of fully developed fire, T_g, and

iii. the "effective heat flux", that is the heat flux available for penetrating the boundary elements of the room, also during the period of fully developed fire, q_E.

Of these three parameters the duration of fully developed fire can be calculated from the following equations:

$$\text{if } \xi < 1 \qquad \tau = 5.75 F A_F / U_a \tag{14}$$

$$\text{if } \xi \geq 1 \qquad \tau = 0.205/\varphi \tag{15}$$

The finding that the duration of fuel-surface controlled fires (i.e. $\xi \geq 1$) is independent of the total amount of combustible materials in the room, and depends only on the specific surface of the combustibles, is extremely important from the point of view of design of the fire drainage system. Since, as mentioned earlier, usually $0.55 < \varphi < 0.90$, eq (15) indicates that the fully developed period of fires burning at high air admission is not expected to be longer than 0.37 hr (22 min).

Finding the values of T_g and q_E consists of a trial-and-error solution of the following equations[5]:

$$T_g = \left\{\frac{q_E}{\sigma\eta} + \left[T_i + \frac{q_E}{k}\left(\frac{2\kappa\tau}{\pi}\right)^{1/2}\right]^4\right\}^{1/4} \tag{16}$$

$$q_E = \frac{1}{A_t}\left[Q - U_g c_g (\zeta T_g - T_e) - \sigma A_r (T_g{}^4 - T_e{}^4)\right] \tag{17}$$

where η and ζ are constant factors defined in the Nomenclature, and the average specific heat of the gaseous products, c_g, can also be regarded as constant.

In connection with the problems to be discussed in this paper, the average temperature of the departing gaseous products, T_d, rather than T_g is of primary interest. T_d is defined as

$$T_d = \zeta T_g \tag{18}$$

[5] Eq (17) is presented here in a form applicable to the problems to be discussed, and is slightly different from its form given in Reference 11.

Using eqs (3) and (6) to (15), Q, U_g and τ can be eliminated from eqs (16) and (17), so that they become expressions of T_g (or T_d) and q_E, respectively, in terms of four groups of variables:[6] (i) the air flow factor, ξ, (ii) variables relating to the combustible materials in the compartment, F and φ, (iii) variables relating to the geometry of the compartment, A_F, h, A_t and A_r, and (iv) the variables relating to the thermal properties of the lining materials, k and $\varkappa$.

SIMPLIFYING THE THERMAL PROBLEM

If the fire drainage system is designed to operate in fire under fuel-surface controlled conditions (in other words, if high air flow to the affected area is ensured), not only the duration of the fully developed period of fire will be short (about 20 min) and the temperature relatively low, but also the operation of the system will be stable and self-adjusting. This means that the system will respond to changes in its operating conditions by a shift toward restoring the original conditions. For example, if the fire temperature rises for some reason, the pressure at the entrance of the drainage ducts will drop slightly because of the increased suction exerted by the hotter gases. This, on the other hand, will result in an increase in the flow of cool air to the fire area and a subsequent reduction of the fire temperature.[6] It is obvious, therefore, that one need not be overly pedantic in defining the fire characteristics and the design can be based on a set of nominal (but realistic) data. For this reason, it seems justifiable to simplify the calculation procedure by eliminating a number of variables from eqs (16) and (17), either by replacing them with constant values, or by the use of approximate expressions.

The most obvious choices for elimination are the properties of the lining materials, k and $\varkappa$, which are rarely known at the time of design, the initial temperature of the room, T_i, and the temperature of the environment communicating with the fire, T_e, which are incidental variables. The following constants will be used here for their values: $k = 0.3$ Btu/hr ft R, $\varkappa = 0.01$ ft^2/hr, $T_i = 535$ R (75 F) and $T_e = 460$ R (0 F) (winter temperature of the outside atmosphere) in the case of rooms or $T_e = 535$ R in the case of undivided spaces and corridors.

It is desirable to retain a single variable, A_F, to characterize the geometry of the space on fire. A_F will be interpreted as the total floor area when dealing with rooms, or the elementary floor areas lying under the retracted curtains (see items 1 in Figures 2 and 3) in the case of uncompartmented spaces and corridors. By assuming that $\beta \approx 0.75$, i.e. that 75 per cent of the heat of combustion of the volatile decomposition products is released within the compartment, the compartment height, h, is eliminated from the calculations. A_t can be expressed, (in a crude way)

[6]This can be seen from Figure 7, to be discussed later.

in terms of A_F as follows:

rooms	$A_t = 2(A_F + 18A_F^{1/2})$	(19)
uncompartmented spaces	$A_t = 2A_F$	(20)
corridors	$A_t = 5A_F$	(21)

Finally, A_r can be approximated as follows:

rooms	$A_r = 0$	(22)
uncompartmented spaces	$A_r = 36A_F^{1/2}$	(23)
corridors	$A_r = 108$	(24)

The derivation of eqs (19) to (24) is explained in Figure 6. Taking $A_r \approx 0$ for rooms is justifiable on the ground that the areas of openings through which heat can be lost by radiation (windows, doors) represent only a small fraction of the total surface area, A_t.

The curtains and floor boards are generally very light constructions and are not expected to absorb any appreciable amount of heat. Their temperature will probably closely approximate the average temperature of the fire in the surrounded space. Consequently, the area of radiant heat transmission to the surroundings from elements of uncompartmented spaces and corridors can be estimated as approximately equal to the total boundary area not formed by floor, ceiling or wall. This consideration is reflected in eqs (23) and (24).

The two variables characterizing the combustible materials can also be replaced by constants. For conventional furniture $\varphi \approx 0.65$. In the lack of more detailed information this value will be used for all three types of building spaces.

The fire load is, in principle, fully determined by the type of occupancy. In practice, it has to be estimated by the designer. Fairly recent surveys (1, 2, 3) revealed that the fire load is much lower now than it used to be 20 to 30 years ago. It appears that for residential and office occupancies the following values may be selected: F = 5 lb/ft^2 for rooms and uncompartmented spaces, and F = 1.25 lb/ft^2 for corridors.

After eliminating T_g, Q, U_g, τ, A_t and A_r from eqs (16) and (17) with the aid of eqs (3), (6) to (9), (14), (15), and (18) to (24), and using the above given constants for k, $\varkappa$, T_i, T_e, β, φ and F, the following equations will finally be obtained for the average temperature of the departing gaseous products and the effective heat flux:

for ventilation controlled fires, $\xi < 1$,

$$\frac{T_d}{100} = 1.05\left\{6.49q_E + \left[5.35 + 14.9\frac{q_E \times 10^{-4}}{\xi^{1/2}}\right]^4\right\}^{1/4} \tag{25}$$

for fuel-surface controlled fires, $\xi \geq 1$,

$$\frac{T_d}{100} = 1.05\left\{6.49q_E + \left[5.35 + 14.9q_E \times 10^{-4}\right]^4\right\}^{1/4} \tag{26}$$

for ventilation controlled conditions, $\xi < 1$,
rooms:

$$q_E = \frac{\xi A_F}{2(A_F + 18A_F^{1/2})}\left\{89,000 - 2910\left(\frac{T_d}{100} - 4.6\right)\right\} \tag{27}$$

uncompartmented spaces:

$$q_E = \frac{\xi}{2}\left\{89,000 - 2910\left(\frac{T_d}{100} - 5.35\right) - \frac{6.167}{\xi A_F^{1/2}}\left[0.823\left(\frac{T_d}{100}\right)^4 - 819\right]\right\} \tag{28}$$

corridors:

$$q_E = \frac{\xi}{5}\left\{22,250 - 728\left(\frac{T_d}{100} - 5.35\right) - \frac{18.5}{\xi A_F}\left[0.823\left(\frac{T_d}{100}\right)^4 - 819\right]\right\} \tag{29}$$

for fuel-surface controlled conditions, $\xi \geq 1$.
rooms:

$$q_E = \frac{A_F}{2(A_F + 18A_F^{1/2})}\left\{89,000 - (2502\,\xi + 408)\left(\frac{T_d}{100} - 4.6\right)\right\} \tag{30}$$

uncompartmented spaces:

$$q_E = \frac{1}{2}\left\{89,000 - (2502\,\xi + 408)\left(\frac{T_d}{100} - 5.35\right) - \frac{6.167}{A_F^{1/2}}\left[0.823\left(\frac{T_d}{100}\right)^4 - 819\right]\right\} \tag{31}$$

corridors:

$$q_E = \frac{1}{5}\left\{22,250 - (626\xi + 102)\left(\frac{T_d}{100} - 5.35\right) - \frac{18.5}{A_F}\left[0.823\left(\frac{T_d}{100}\right)^4 - 819\right]\right\} \qquad (32)$$

Utilizing eqs (25) to (32), the variation of T_d with ξ has been calculated[7] for the following values:
rooms: A_F = 50, 100, 200, 400 and 500 ft^2; elements of uncompartmented spaces: A_F = 400, 500 and 700 ft^2; and corridor elements: A_F = 100, 200 and 300 ft^2. The results are presented graphically in Figure 7.

PRESSURE DISTRIBUTION IN BUILDINGS

Since convection has been recognized as one of the two major mechanisms of spread of fire in buildings, it is advisable to devote a short time to the discussion of the causes of convective fire spread, namely the pressure differences that exist between various spaces in the building. As a rule, these pressure differences are larger when large differences exist between the temperature of the interior and the outside atmosphere, in other words, during the winter heating season.[8]

The pressure differences that exist in heated multistorey buildings have been studies by Tamura and Wilson (12, 13). Based on their findings, the following approximate equation is introduced to describe the pressure at any part of such buildings[9].

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[7] As a by-product of these calculations, information on the variation of q_E with ξ was also obtained. This information is, however, of little value from the point of view of the subject area discussed in this paper and, therefore, will not be reported here.

[8] In warmer climates somewhat lesser problems may arise during the summer season when the buildings are air-conditioned. Although this situation is not discussed in this paper, the applicable design procedure can be developed by the judicious application of the formulae to be intoduced.

[9] For convenience, pressures are expressed as lb/ft hr^2. To obtain values in inches of water, multiply values in lb/ft hr^2 by 4.61 x 10^{-10}.

$$p = p_a - g(\rho_a - \rho_i)(b - z)\chi \tag{33}$$

where p_a, the pressure of the outside atmosphere is

$$p_a = -g\rho_a z \tag{34}$$

provided that its value at the z = 0 level is taken as reference pressure level.

If $\chi = 0$, eq (33) obviously describes the pressure of the outside atmosphere. With $\chi = 1$ the variation of the pressure in the vertical shafts of the building is obtained. For other spaces $0 < \chi < 1$; its actual value depends both on the "air-tightness" of the building and on the resistance to air flow between the respective space and the nearest shaft. Usually $\chi \approx 0.8$ for rooms. For uncompartmented spaces and corridors a nominal value of $\chi \approx 0.9$ may be used.[10]

According to eq (33), if $z = b$, $p = p_a$, i.e. the pressure in the building is equal to that of the outside atmosphere and, therefore, there is no air exchange between the building interior and the atmosphere. b is usually referred to as the elevation of the neutral pressure plane. For buildings not equipped with a ventilation system the neutral pressure plane is usually located at the mid-height of the building, i.e. $b \approx H/2$. Mechanical ventilation generally causes the neutral pressure plane to descend to a lower level.

From the point of view of convective fire spread the pressure differences between the area affected by the fire and its environments are of particular interest.

[10] Since, as will be pointed out later, the operation of the fire drainage system may substantially distort the original pressure distribution, one need not be very pedantic in selecting the values of χ and b.

The word "environment" is used in this paper in a specific sense. Each space that has a different temperature or pressure, or both, and can communicate with the space on fire through one or more openings or passages, is regarded as a separate environment. In a building equipped with a fire drainage system any space on fire has at least two environments, one of which, namely the outside atmosphere at a pressure prevailing at the release gates (see Figure 4), is always the same irrespective of the location of the fire area. The other environment, from which the air supply is received, will be referred to in this paper as the "horizontal" environment of fire. In general, a space on fire may have two or more horizontal environments. For example, a burning room can communicate with the outside atmosphere (at a pressure prevailing at the elevation of the room) through broken windows, and with a corridor through a left-open door. However, as will be discussed later, it is always advisable to reduce the number of horizontal environments to one by the use of special devices.

According to eq (33) the pressure in the horizontal environment of the fire can be described as follows:

$$p_e = p_a - g(\rho_a - \rho_i)(b - z)\,\chi_e \qquad (35)$$

If there are several horizontal environments, naturally

$$p_{e1} = p_a - g(\rho_a - \rho_i)(b - z)\,\chi_{e1} \qquad (35a)$$

$$p_{e2} = p_a - g(\rho_a - \rho_i)(b - z)\,\chi_{e2} \qquad \text{etc.} \qquad (35b)$$

In the upper floors of the building (above the neutral pressure plane) the highest pressures always prevail in the shafts. They drop moderately across each internal obstacle (door, partition) toward the boundaries of the building and produce horizontal air flow from the shafts through the internal obstacles to the exterior walls and finally to the outside atmosphere. Obviously, if fire breaks out on these upper floors of a building, the main direction of the spread of fire will be toward the outside boundaries of the building. If the floors are reasonably fire resistant and the flames can be prevented from jumping to the next floor above through broken windows,[11] there is a chance that the fire will die out on reaching the exterior walls even without special protective devices. Vertical leakage currents (not discussed here in detail) would, however, result in the smoke contamination of a few floors above the fire floor.

[11] Investigations in Australia (14) indicated that projections wider than about 4 ft are capable of preventing the spread of fire along the facade of buildings.

Unfortunately, the conditions are not so favourable in the floors below the neutral pressure plane. Here the lowest pressures prevail in the shafts. The general direction of the spread of fire is therefore, toward the shafts of the building (if it is not equipped with a fire drainage system), although thermal radiation may result in unexpected turns. The major problem is, however, not so much the spread of fire as the spread of combustion products which are carried through the shafts by the air currents to the upper floors and, as Tamura and co-workers pointed out (15, 16), cause dangerous conditions there long before the flames can reach the shafts.

THEORETICAL CONSIDERATIONS

As mentioned earlier, with the use of a fire drainage system the potential energy of the hot gaseous products is expoloited in two ways: (i) to draw air to the space affected by fire in quantities sufficiently large to render the fire relatively harmless, and (ii) to keep the pressure in the space on fire below that of its environment.

Before engaging in further discussions on how to achieve these, a decision has to be made with respect to the density of the gaseous products in the drainage ducts. The density of air and gaseous products can be expressed with the aid of the gas law as

$$\rho = \frac{B}{T} \tag{36}$$

where B = 39.74 lb R/ft^3. Unfortunately, the definition of the average temperature of the gases in the drainage ducts, T_D, is somewhat problematic. Normally, one could expect some temperature drop along the ducts. There is a strong possibility, however, that this drop will be partly or fully compensated by the temperature rise produced by the continuing combustion of some of the volatile decomposition products. (The reader is reminded that, according to earlier assumptions, about 25 per cent of the heat of combustion of the volatile decomposition products is expected to evolve outside the space affected by fire.) It seems reasonable, therefore, to interpret T_D as approximately equal to the temperature of the gaseous products leaving the space, in other words, that

$$T_D \approx T_d \tag{37}$$

This interpretation of T_D also implies that

$$\rho_D \approx \rho_d \tag{38}$$

If the space affected by fire receives air mainly from one "dominant" horizontal environment, the mass flow of air can be written as

$$U_a = \lambda \delta A_C \rho_e v_C \tag{39}$$

where δ, the "orifice constant" can be taken as approximately equal to 0.7 when the flow occurs through contracted openings (windows, doors). Otherwise $\delta = 1$. The factor λ has been introduced to take account of possible minor air flow from a secondary environment.

As mentioned earlier, it may occasionally happen that the air is received from more than one environment. In this case the total air flow is

$$U_a = \delta A_{C1} \rho_{e1} v_{C1} + \delta A_{C2} \rho_{e2} v_{C2} + \ldots \tag{39a}$$

If the fire drainage system is correctly designed, all gaseous products will leave through the drainage ducts and the mass flow of gases can be expressed as[12]

$$U_g = A_D \rho_d v_D \tag{40}$$

Again, it may occasionally happen that some of the gaseous products will be released toward one or more horizontal environments of the space on fire. In such cases

$$U_g = A_D \rho_d v_D + \delta A_{C1} \rho_d v_{C1} + \delta A_{C2} \rho_d v_{C2} + \ldots \tag{40a}$$

An examination of eqs (6)to (8) reveals that the ratio U_g/U_a is constant and equal to 1.163 for ventilation-controlled fires and varies only slightly, between 1 and 1.163, in the regime of fuel-surface controlled fires. In the following discussions it will be assumed that a unique relation exists between U_g and U_a:

$$U_g = 1{\cdot}163\, \psi U_a \tag{41}$$

where the factor ψ has been introduced primarily to account for the possible leakage of air into the drainage duct along its height.[13]

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[12]In all equations A_D means the "nominal" cross sectional area of the drainage ducts. As mentioned in connection with Figure 1, it can often be arranged to have each space be served by two drainage ducts and, in turn, to have each duct serve two adjacent spaces. If this can be done, the actual cross sectional area of the drainage ducts is only half of the nominal duct area.

[13]Even though the factor 1.163 already includes a certain margin of safety, it is believed that under certain conditions this margin may not be sufficient. Consequently, it is wise to select $\psi \geq 1$.

The pressure in the space affected by the fire can be expressed in terms of pressure losses along the various routes of communication between this space and its environments. To simplify these expressions, the frictional pressure losses and those associated with changes in the direction of flow, will be combined with the entry and exit losses. Thus, it will be assumed that the total pressure loss for the drainage ducts is equal to α times two velocity heads, half of which occurs at the entry and half at the exit of the gases. The flow of air to the fire area through contracted communication routes (windows, doors, etc.) will be modeled as flow through an orifice (17) and described in terms of a hypothetical orifice velocity which yields a pressure drop of one velocity head across the contraction. Thus

$$p_{\phi} - p_e = -\frac{1}{2} \rho_e v_C^2 \tag{42}$$

The earlier introduced orifice constant, δ, compensates for the errors originating from the use of this hypothetical velocity in flow rate calculations.

A not too complicated situation which, nonetheless, shows all essential details to be considered in a general calculation scheme, is shown in Figure 8. The space on fire receives air from environment e1 through communcation route C1 (orifice-type) and discharges gaseous products partly to the atmosphere through a drainage duct, D, and partly to environment e2 through communication route C2 (also orifice type). Because of the presence of three communication routes, the pressure in the space on fire, p_{ϕ} can be expressed by three equations:

$$p_{\phi} - p_a = (p_{e1} - p_a) - \frac{1}{2} \rho_{e1} v_{C1}^2 \tag{43}$$

$$p_{\phi} - p_a = -g(\rho_a - \rho_d)(H_1 - z) + \alpha \rho_d v_D^2 \tag{44}$$

$$p_{\phi} - p_a = (p_{e2} - p_a) + \frac{1}{2} \rho_d v_{C2}^2 \tag{45}$$

In situations like this, that is when the fire area communicates with two or more horizontal environments, it may be rather time-consuming to find the rates of flow of air and gaseous products. The general procedure is as follows: (i) Assign tentative values to the air flow factor, ξ, and to $(p_{\phi} - p_a)$. (ii) From Figure 7 find the value of T_d that corresponds to the selected value of ξ, then calculate ρ_d, (iii) Calculate the three velocities, v_{C1}, v_D and v_{C2}, from eqs (43), (44) and (45). (iv) Calculate U_a and U_g from the applicable forms of eqs (39a) and (40a). (v) Calculate ξ with the aid of eqs (2) and (3), and determine the ratio U_g/U_a. (vi) If ξ is sufficiently close to the value selected earlier, and U_g/U_a to 1.163ψ (see eq (41)), the task is completed. Otherwise assign supposedly more accurate new values to ξ and $(p_d - p_a)$ and repeat the procedure.

As mentioned earlier, it is part of the design procedure to reduce the number of horizontal environments to one "dominant" environment, sometimes with the use of special devices. In this case there are only two communication routes, one with the outside atmosphere through the drainage duct, and the other with the dominant environment through an opening or passage.

By combining eqs (39) and (40) with eq (41) a relation is obtained between the velocity of gaseous products in the drainage duct and the air velocity in the route of communication with the dominant environment:

$$\frac{v_D}{v_C} = 1.163\psi\lambda\delta\frac{A_C}{A_D}\frac{\rho_e}{\rho_d} \tag{46}$$

The area of communication with the dominant environment is normally represented by (a) the area of effective window opening in the case of rooms, (b) the area of the four openings left in the floor boards (see item 5 in Figure 2) in the case of uncompartmented spaces, and (c) the area of two gaps left between the floor and the edges of the released fold-up curtains, in the case of corridors. (See also Figure 6.) To have the fire drainage system operate satisfactorily, these areas must be determined by the designer. Formulae for their evaluation will be presented later. At this time A_C will be regarded as a known quantity.

By combining eqs (35), (42) and (44), the following correlation is obtained between v_D, v_C and the elevation of the fire floor, z:

$$\frac{1}{2}\rho_e v_C^2 + \alpha\rho_d v_D^2 = g(\rho_a - \rho_d)(H_1 - z) - g(\rho_a - \rho_i)(b - z)\chi_e \tag{47}$$

Furthermore, by combining this equation with eqs (36) and (46), the velocity of air in the route of communication with the dominant environment is obtained:

$$v_C = \left(2g\,\frac{\left(\frac{T_e}{T_a} - \frac{T_e}{T_d}\right)(H_1 - z) - \left(\frac{T_e}{T_a} - \frac{T_e}{T_i}\right)(b-z)\chi_e}{1 + 2\cdot705\alpha\psi^2\lambda^2\delta^2\frac{T_d}{T_e}\left(\frac{A_C}{A_D}\right)^{1/2}}\right)^{1/2} \tag{48}$$

Once v_C is known, the air flow factor, ξ, can be calculated by utilizing eqs (3), (39) and (36), as

$$\xi = \frac{\lambda\delta}{28\varphi F} \frac{A_C}{A_F} \frac{B}{T_e} v_C \qquad (49)$$

and the pressure in the space affected by the fire can also be determined with the aid of eqs (35), (36) and (42) as

$$p_\phi - p_a = -B \left[\frac{v_C^2}{2T_e} + g \left(\frac{1}{T_a} - \frac{1}{T_i} \right) (b-z)\, \chi_e \right] \qquad (50)$$

BASIC DESIGN FORMULAE

As discussed earlier, the pressures in the lower storeys of a building always stay below the pressure of the outside atmosphere during the winter heating season. Because of this, it is more difficult to ensure that the fire drainage ducts will create a depression in any space in relation to all of its horizontal environments. These difficulties are, obviously most pronounced on the ground floor level (i.e. at $z = h/2$) where, as eq (33) indicates, the lowest pressures prevail. It is advisable, therefore, to start the design of the fire drainage system with deliberations concerning the operation of the system on the ground floor during the winter season. (It is obvious that a design based on summer conditions is considerably less restrictive.)

By assigning a value to $\hat{\chi}_\phi (0 \le \hat{\chi}_\phi \le 1)$ to characterize the pressure in the fire area [see eq (33)], the following equation can be written for the pressure difference betweeen the space on fire and its dominant horizontal environment ($z = h/2$):

$$\hat{p}_\phi - \hat{p}_e = -g\,(\rho_a - \rho_i)\,(b - \frac{h}{2})\,(\hat{\chi}_\phi - \hat{\chi}_e) \qquad (51)$$

The condition of air flow from the dominant environment is, naturally, $\hat{p}_\phi < \hat{p}_e$ and, therefore, $\hat{\chi}_\phi > \hat{\chi}_e$. Fulfilling this condition alone is, however, rarely sufficient. In general, the fire area also communicates, even though in a minor way, with one or more secondary environment. (For example, for a burning room the outside atmosphere is usually the dominant environment, but it may also communicate with a corridor through some gaps around the door.)

If the pressure in the secondary environment is characterized by $\hat{\chi}_e^*$, the condition of confining the flames to the space on fire is $\hat{\chi}_\phi \ge \hat{\chi}_e$ and also $\hat{\chi}_\phi \ge \hat{\chi}_e^*$. If $\hat{\chi}_e^* > \hat{\chi}_e$, it is practical to select $\hat{\chi}_\phi = \hat{\chi}_e^*$ in the design.

The pressure difference between the fire area and its dominant environment can also be expressed, analogously to eq (42), in terms of the (hypothetical) velocity of air in the area of communication with the dominant environment.

$$\hat{p}_{\phi} - \hat{p}_e = -\frac{1}{2}\rho_e \hat{v}_C^2 \tag{52}$$

By combining eqs (51) and (52), $\hat{v}_C$ is obtained as

$$\hat{v}_C = \left[2g\frac{\rho_a - \rho_i}{\rho_e}(b - \frac{h}{2})(\hat{\chi}_{\phi} - \hat{\chi}_e)\right]^{1/2} \tag{53}$$

Substituting this expression of $\hat{v}_C$ in eq (47) (as applied to the z = h/2 level) and making use of eqs (36) and (46), the following equation can be arrived at for the ratio $\hat{A}_C/\hat{A}_D$:

$$\frac{\hat{A}_C}{\hat{A}_D} = \frac{1}{1.163\psi\lambda\delta}\left\{\frac{1}{2\alpha(\hat{\chi}_{\phi} - \hat{\chi}_e)}\left[\frac{\left(\frac{T_e}{T_a} - \frac{T_e}{\hat{T}_d}\right)\left(H_1 - \frac{h}{2}\right)}{\left(\frac{\hat{T}_d}{T_a} - \frac{\hat{T}_d}{T_i}\right)\left(b - \frac{h}{2}\right)} - \frac{T_e}{\hat{T}_d}\hat{\chi}_{\phi}\right]\right\}^{1/2} \tag{54}$$

Finally, an expression for the air flow factor at z = h/2, $\hat{\xi}$, can be obtained by combining eqs (3), (36), (39) and (53):

$$\hat{\xi} = \frac{\lambda\delta}{28\varphi F}\frac{B}{T_e}\frac{\hat{A}_C}{\hat{A}_F}\left[2g(\hat{\chi}_{\phi} - \hat{\chi}_e)\left(\frac{T_e}{T_a} - \frac{T_e}{T_i}\right)(b - \frac{h}{2})\right]^{1/2} \tag{55}$$

A_F and A_D are usually kept constant along a vertical section of the building (see e.g. Figure 5a), so that $A_F = \hat{A}_F$ = const and $A_D = \hat{A}_D$ = const. The only possible variation of A_F and A_D is that both can be subdivided simultaneously into two roughly equal areas. Such a situation is shown in Figure 1, where on one floor a normal room is subdivided by the use of a partition, 11, into two smaller rooms, 12 and 13. It is seen that these smaller rooms are served by one drainage duct only, while all bigger rooms are served by two.

A_C (for example, the effective area of window openings) may be selected to vary along the height of the building, although selecting $A_C = \hat{A}_C$ = const may be advisable from a practical standpoint.

Once the cross sectional areas for the ground floor level, $\hat{A}_C$ and $\hat{A}_D$, are known, the designer has to check whether the fire drainage system would work satisfactorily if fire breaks out on other floors. This can usually be done with the use of eqs (48) to (50).

NUMERICAL EXAMPLE OF DESIGN

To illustrate the use of the formulae derived, the design of the fire drainage system for the 11-storey office building shown in Figure 5a will be developed here.

The area of the building is approximately 80 ft by 80 ft. Each floor is occupied by the following spaces:

5 rooms, area 300 ft^2 each, total	1500 ft^2
1 corridor, area	400 ft^2
1 uncompartmented space, area	4000 ft^2
4 shafts, total area	500 ft^2
area per floor	6400 ft^2

The height of the building is 110 ft and the height of the fire drainage ducts is selected as 118 ft. The fire load is chosen (according to earlier recommendations) as 5 lb/ft^2 for the rooms and uncompartmented spaces and 1.25 lb/ft^2 for the corridors, and the specific surface of the fuel as 0.65 ft^2/ lb.

The practical solutions described in connection with Figures 1, 2 and 3 are utilized in the design. Thus, as already illustrated in Figure 5b, each room is served by two drainage ducts, 5, and each duct will serve two adjacent rooms, except for two (marked as 5a) which will serve only one room each. With the use of fold-up curtains the uncompartmented spaces will be divided into ten elementary areas on each floor and therefore, will be served by ten fire drainage ducts, 6. Similarly, the corridors will be divided into two elementary areas on each floor, and will be served by two ducts, 7.

The fire drainage system will be designed to operate satisfactorily during the winter heating season. The temperature in the inside of the building is assumed to be 75 F (535 R) and the temperature of the outside atmosphere 0 F (460 R). The neutral pressure plane is located at the mid-height of the building.

It is possible now to summarize the basic design information:

$$H = 110 \text{ ft} \qquad T_a = 460 \text{ R}$$

$$H_1 = 118 \text{ ft} \qquad T_i = 535 \text{ R}$$

$$h = 10 \text{ ft} \qquad \varphi = 0.65 \text{ ft}^2/\text{lb}$$

$$b = 55 \text{ ft}$$

The values of A_F and F are as follows:

for rooms	$A_F = 300\ ft^2$, $F = 5\ lb/ft^2$
for uncompartmented spaces	$A_F = 400\ ft^2$, $F = 5\ lb/ft^2$
for corridors	$A_F = 200\ ft^2$, $F = 1.25\ lb/ft^2$

The design of the fire drainage system for the rooms is based on the realization that for these units the outside atmosphere is the dominant horizontal environment (from which they will receive air through the effective window openings), and the corridor is the secondary environment (to which flames may be spilled through some gaps around the doors). Thus, according to earlier discussions, $\hat{\chi}_e = 0$ and $\hat{\chi}_e^* = 0.9$. Consequently $\hat{\chi}_{\phi}$ is selected as 0.9. (With this selection the pressure in the fire room will be equal to the corridor pressure on the ground floor level and, therefore, neither will flames from the room spill into the corridor nor air from the corridor enter the room.)

The following additional information is now available for the design: $\delta \approx 0.7$ (as the air enters through windows, $\lambda = 1$ (as there is no secondary air flow), $\chi_e = 0$ and $T_a = 460$ R (as the outside atmosphere is the dominant environment), and $\hat{\chi}_{\phi} = 0.9$ (to equalize pressures in the fire room and corridor). It is assumed, furthermore, that $\alpha = 1$ and $\psi = 1$.

The design considerations start with the selection of value for the "nominal" cross sectional area of the drainage ducts, A_D. As a rule, A_D can be chosen as 2 to 5 per cent of the floor area. For reasons mentioned in footnote 12, the net loss in useful floor area will be only 1 to 2.5 per cent. Here the "nominal" cross sectional area of the drainage ducts is selected as 3 per cent of A_F; $A_D = 9\ ft^2$. Thus the actual cross sectional area of the ducts is $4.5\ ft^2$.

Furthermore, it has been tentatively decided to keep the area of communication with the dominant environment (namely the effective window area), A_C, constant throughout the height of the building and equal to that required for the ground floor level. Consequently, $A_C \equiv \hat{A}_C$, and naturally also $A_D \equiv \hat{A}_D$, and therefore, the mark ^ can be omitted from these symbols.

A_C can be calculated from eq (54). In this equation all quantities are known, except $\hat{T}_d$, the temperature of the gaseous products in the drainage ducts. Since $\hat{T}_d$ is a function of ξ, the calculations start with selecting a value for $\hat{\xi}$ and determining the corresponding value of $\hat{T}_d$ from Figure 7. After calculating A_C from eq (54), the value of $\hat{\xi}$ is determined with the aid of eq (55). This newly calculated value of ξ provides the basis for a new round of calculations. After two more trials, $\hat{\xi}$ was chosen as 2.31. With this, from Figure 7, $\hat{T}_d$ = 1595 R. Thus, from eq (54),

$$A_C = \frac{9.0}{1.163\text{x}0.7} \left\{ \frac{1}{2\text{x}(0.9-0)} \left[\frac{\left(\frac{460}{460} - \frac{460}{1595}\right)(118-5)}{\left(\frac{1595}{460} - \frac{1595}{535}\right)(55-5)} - \frac{460}{1595}\, 0.9 \right] \right\}^{1/2} = 14.39 \text{ ft}^2$$

Checking the value of $\hat{\xi}$ [eq (55)],

$$\hat{\xi} = \frac{0.7\text{x}39.74\text{x}14.39}{28\text{x}0.65\text{x}5\text{x}460\text{x}300} \left[2\text{x}4.17\text{x}10^8\text{x}0.9 \left(\frac{460}{460} - \frac{460}{535}\right)(55-5) \right]^{1/2} = 2.31$$

which shows that latest selection was correct.

The designer can proceed now to perform additional calculations that may be needed in the detailed engineering design. First the flow rate of air and that of the combustion products is determined, then the (hypothetical) velocity of air in the effective window opening is calculated, and finally the pressure in the fire room is expressed and compared to the pressure in the neighboring spaces. The results of these calculations are as follows:

from eq (3) $\hat{U}_a$ = 63,060 lb/hr

from eq (41) $\hat{U}_g$ = 73,340 lb/hr

from eq (39) $\hat{v}_C$ = 72,460 ft/hr (=20.1 ft/sec)

from eq (50) $\hat{p}_\phi - \hat{p}_a$ = -2.27 x 10^8 lb/ft hr^2 (=-0.105 in. w.)

A quick check with the aid of eq (33) will reveal that this pressure is indeed equal to the pressure in the corridor at the ground floor level.

The characteristics of fire occurring on the second to eleventh floors were subsequently calculated. The calculation covered the following three conditions: (i) the doors remain closed throughout the fire, (ii) the doors are open but the window openings are blocked during the fire (or, alternatively, the rooms are windowless), and (iii) both the door areas and effective window areas are free for the inflow of air or outflow of gaseous products.

In cases (i) and (ii) the burning room has only one horizontal environment (the outside atmosphere and the corridor, respectively). For these cases all required information can be derived from values of v_C and ξ which can be determined by simultaneously solving eqs (48) and (49).

The results of one set of calculations performed for rooms on the fourth floor (z = 35) under case (ii) conditions (door open, window blocked) are reproduced here. For this case the corridor is the dominant environment and, therefore, χ_e = 0.9 and T_e = 535 R (i.e. the temperature is equal to that of the building interior). The door area, A_C, is assumed to be 18 ft^2. Furthermore, λ = 1 and δ = 0.7.

After two trials it was assumed that ξ = 1.92. With this, from Figure 7, T_d = 1730 R. Then

from eq (48) v_C = 55,880 ft/hr

from eq (49) ξ = 1.92 (agrees with assumed value)

from eq (39) U_a = 52,300 lb/hr

from eq (41) U_g = 60,820 lb/hr

from eq (50) $p_\phi - p_a = -2.07 \times 10^8$ lb/ft hr^2 (=-0.095 in.w.)

Since pressure of the fire room is lower than the corridor pressure [as calculated from eq (33)] by 0.053 in. w, the results are satisfactory.

In case (iii) the burning room has two horizontal environments (the outside atmosphere and the corridor) and, therefore, the trial-and-error method described in connection with eqs (43) to (45) has to be employed in finding the characteristics of the burning room. The results of all calculations, covering cases (i), (ii) and (iii) are presented graphically in Figure 9. Discussion on these results is delayed until the next section.

It may be added that the average temperature in the burning rooms was found to be nearly the same in cases (i) and (ii). The air supply decreases slowly and the temperature increases with the elevation of the fire floor. The highest temperatures are reached on the two uppermost floors, about 2190 R (1730 F). These higher temperatures are associated with the fact that with the selected value of A_D fuel-surface conditions cannot be ensured if fire occurs on these two floors. In addition to these higher temperatures, the duration of the fully developed fire would also be somewhat longer, 26 min on the eleventh floor, compared to 19 min on the first to ninth floors. The designer has to make a decision whether to accept these slightly unfavourable conditions, or to increase the cross sectional area of the drainage ducts on the two uppermost floors.

For case (iii) the highest temperature develops on the seventh floor, about 1880 R (1420 F).

In another series of calculations the characteristics of fires occurring in these rooms during the summer season were examined. As expected, the air supply is somewhat lower and the temperature somewhat higher than in fires occurring during the winter.

The procedure to be followed in designing a fire drainage system for uncompartmented spaces and corridors is essentially the same as that applicable to rooms. Consequently, only a few results of the calculations will be reproduced here.

For the elements of both the uncompartmented spaces and the corridors the adjoining spaces represent the dominant horizontal environment, i.e. $\hat{\chi}_e = 0.9$ and $T_e = 535$ R. The design can be based on the restriction that on the ground floor level an element on fire must not spill flames into a secondary environment, possibly an adjacent shaft (for which $\chi = 1$), in other words, that $\hat{\chi}_\phi = \hat{\chi}_e^* = 1$. To both uncompartmented space and corridor elements the following additional information applies: $\lambda = 1$ (air flow from dominant environment only), $\delta \approx 0.7$ (air flow through contracted openings, see Figure 4), and $\alpha \approx 1$, $\psi \approx 1$. The cross sectional area of the drainage duct is selected as 2.75 per cent of A_F for uncompartmented space elements and 1 per cent of A_F for corridor elements.

With these data, the following information is obtained for the elements of uncompartmented spaces:

A_C = 56.28 ft^2 (the sum of the areas of four openings in the floor boards, see Figure 4)
$\hat{\xi}$ = 2.10
$\hat{T}_d$ = 1630 R (1170 F)
$\hat{U}_a$ = 76,440 lb/hr
$\hat{U}_g$ = 88,900 lb/hr
$\hat{v}_C$ = 26,120 ft/hr (=7.26 ft/sec)
$\hat{p}_\phi - \hat{p}_a$ = -2.53×10^8 lb/ft hr^2 (=-0.116 in. w, equal to the pressure in the shafts).

If fire occurs on the uppermost floor,

ξ = 0.905
T_d = 1890 R (1430 F)
U_a = 32,940 lb/hr
U_g = 38,310 lb/hr
v_C = 11,257 ft/hr (= 3.13 ft/sec)
$p_\phi - p_a$ = $+2.23 \times 10^8$ lb/ft hr^2 (=+0.103 in. w)

This pressure is lower than the pressure of the dominant environment by 0.002 in. w, and lower than that in the shafts by 0.014 in. w.

Some results obtained for corridor elements:

A_C = 11.05 ft^2 (the sum of the areas of two openings below the edge of fold-up curtains, see Figure 4)
$\hat{\xi}$ = 3.29
$\hat{T}_d$ = 1140 R (680 F)
$\hat{U}_a$ = 14,790 lb/hr
$\hat{U}_g$ = 17,410 lb/hr
$\hat{v}_C$ = 26.055 ft/hr (=7.24 ft/sec)
$\hat{p}_\phi - \hat{p}_a$ = -2.53×10^8 lb/ft hr^2 (=-0.116 in. w, equal to the pressure in the shafts).

If fire occurs on the eleventh floor,

ξ = 1.52
T_d = 1290 R (830 F)
U_a = 6920 lb/hr
U_g = 8040 lb/hr
v_C = 12,020 ft/hr (=3.34 ft/sec)
$p_\phi - p_a$ = $+2.22 \times 10^8$ lb/ft hr^2 (=+0.102 in. w)

The latter pressure is below that of the dominant environment by 0.003 in. w, and below that in the shafts by 0.014 in. w.

DISCUSSION OF RESULTS

Figure 9 seems to indicate that, even with the use of a fire drainage system, it may not be possible to prevent some flames from reaching through the windows, if the fire occurs higher than about 2/3 of the building height and if both the window and the door are allowed to remain open during the fire. The real conditions are, however, much more favourable. In the previous calculations it was tacitly assumed that a fire in a room would leave the corridor pressure essentially unchanged. The flow rate of air into the burning room through an open door, as calculated on the above assumption, usually turns out to be much larger (even below the mid-height of building) than the rate of total air flow entering the building through its exterior boundaries.[14] The withdrawal of large amounts of air (in the form of gaseous products) through the fire drainage duct will lower pressure throughout the building (especially on the fire floor) and move the neutral pressure plane to a higher level, perhaps up to the top of the building. Naturally, under these conditions, the

[14] In the case of uncompartmented spaces and corridors it may be necessary to provide facilities for the admission of extra air to the fire floor in order to ensure fuel-surface controlled conditions.

floor level at which flames start to issue through the window (if the door is left open) will also move toward the top of the building. Notwithstanding, it would seem a wise practice to separate the room on fire from the rest of the building with the aid of automatically closing doors, except, of course, in windowless buildings for which fuel-surface controlled (short) fires can be achieved only with a large air supply from the interior of the building.

The problem of flame issuance through the windows may also be present in the case of uncompartmented spaces if the element in which the fire occurs is adjacent to an outside wall. To prevent this from happening and to create a considerable depression on the fire floor (and also in an increased portion of the building), it would also seem a wise practice to equip uncompartmented spaces with unbreakable windows that automatically close when exposed to fire.

FIRE DRAINAGE DUCTS AND GATES

The satisfactory operation of the fire drainage system naturally stands or falls on how the related technical problems can be solved by the detailed design. The heart of these problems is the drainage duct and its gates. In this section the underlying principles of their design will be outlined. Attention is directed to Figure 10 which shows the main components of the drainage duct system.

In order to best utilize the space and to minimize the pressure losses associated with the entry of gaseous products, the use of narrow (6 to 12 in. wide) drainage ducts and gates seems to be most advantageous for rooms and corridors (see Figures 1, 3, 4 and 5). For uncompartmented spaces, ducts of roughly square cross sectional areas are recommended which, as mentioned earlier, may be combined with the building columns (see Figures 2, 4 and 5).

It is clear that the walls of the drainage ducts must be provided with sufficient insulation to prevent damage by heat transmission in all spaces located above the space on fire. The insulation requirements are, however, not excessive. It must be remembered that the fires that develop in buildings equipped with these facilities are fuel-surface controlled fires and, therefore, their fully developed period is only about 20 min. The thickness of insulation that would ensure only minor temperature rise on the outside surface of the ducts for this period can be calculated from the following formula (18):

$$a = 1.8\,\kappa^{1/2} \qquad (56)$$

In general, a 2-in. layer of some good insulating material (e.g. sprayed asbestos, fiberfrax), 1, (Figure 10) reliably attached to a lightweight concrete base, 2, of about 1-1/2 in. will yield satisfactory performance. The use of double-walled light metal ducts, filled with water between the walls, may also be considered.

For obvious reasons, having the gates opened by the fire itself is preferred over other possible techniques. The activation of the gates shown in Figure 10 does not depend on the availability of electric power at the time of fire.[15] The entry and release gates are shown in closed position. Each entry gate consists of two panels, 3 and 4, both attached to the gate frame, 5, through hinges, 6, located near the lower inner edge of the frame. The outer panel, 4, is furnished with insulation, 7, to protect the gate assembly from heat when the duct is filled with hot gaseous products originating from a fire at a lower floor level. Both the inner and outer panels are sealed to the frame. The outer seal, 8, must be made of moderately heat resistant material, while the inner seal, 9, can be any ordinary sealant. The inner panel is locked to the inside rim of the frame with the aid of J-shaped studs, 10, and nuts, 11, made of some low-melting alloy. The nuts are thermally insulated from the inner panel with thick washers, 12, made possibly of a plastic material. A spring, 13, is compressed between the inner and outer panels. The two panels are connected with a short piece of wire rope, 14, which will prevent them from separating by more than a definite angle.

The operation of the gate is as follows. As the fire builds up in the area, the low-melting nut, 11, melts and causes the spring, 13, to swing open the inner panel which, in turn, will pull with it the outer panel, via the wire rope, 14.

The closed gates generally occupy a strip area of 8 to 12 in. wide adjoining the ceiling. They can be made indistinguishable from the surrounding areas by being pasted over with wallpaper. It is recommended, however, that some brightly coloured wallpaper be used to remind the occupants that this area must not be blocked by furniture.

The gaseous products leave the fire drainage ducts through two to four release gates of identical design. A release gate assembly consists of a frame, 15 (Figure 10) and a double-walled gate, 16, attached to the frame by hinges, 17, and sealed to its rim by an ordinary sealant, 18. The gate is locked in the frame by a small lever, 19 held in locking position by a U-shaped tongue, 20, and by the pulling force of a com-

[15] It must be emphasized that the technical solutions shown in this figure and the forthcoming figures have been selected with the view of facilitating the understanding of the principle of operation. They do not necessarily represent the best practical solutions.

bustible rope or low-melting wire, 21. If the pull ceases, a small spring, 22, removes the tongue from between the gate wall and the lever and thus allows the lever to clear the frame. Then, but its own weight, the gate falls down about its hinges. The pull on the rope or wire is exerted by a weight, 23, hanging near the bottom of the duct. Pulleys 24, are used to change the direction of the rope or wire.

Obviously, the unlocking of the release gates must be preceded by the opening of one of the entry gates along the drainage duct. The flames penetrating into the duct then burn or melt away the rope or wire, 21. The fall of the weight, 23, causes the gate to open.

A small door should be provided at the bottom of each duct for cleaning and inspection.

In designing the fire drainage ducts and gates, an important consideration is to make the system re-usable without repair (excepting, of course, the gates directly involved in the fire).

The duct-gate system could be assembled from pre-fabricated units. With mass-production of the units, the costs could be kept at a reasonable level.

WINDOWS

In Footnote 2 the effective window area was defined as the breakable part of the total window opening. In the numerical example discussed the required effective window area was found to be about 14 ft^2. Although there may be a tendency in the future toward the use of smaller windows (due to the projected world-wide energy shortage), in present practice a 14 ft^2 window opening is considered small for a room of 300 ft^2 floor area. It is imperative, therefore, to provide some additional window surfaces, made with panes that cannot be dislodged by the fire and are either non-openable or close automatically on exposure to fire.

Based on these considerations, two types of glazing must be employed; one that breaks very easily under fire exposure, and another that does not break at all or, at least, remains in place after breaking. According to B.S. CP-153 (19) ordinary annealed glass qualifies for the first type. Some further investigations may be conducted to find glasses which are even more fragile in fire, produced, e.g. by partial annealing or by the deliberate introduction of stresses. The effect of the framing material and its connection with the glass panes on the breaking characteristics of panes in fire may also be studied.

Naturally, the fragility problem could be circumvented by the use of windows that swing open under exposure to excessive heat. The design task is extremely simple and will not be discussed here further.

B.S . CP-153 describes some glazings which qualify for "fire-resistance". Thus, windows, composed of pieces not larger than 0.7 ft^2 in area, will stay in place during a fire. Wired glasses (in panes not exceeding 13 ft^2 in area) also yield satisfactory performance.

Admittedly, wired glasses have not been considered so far for use in windows of residential or office occupancy, probably because of their unattractive appearance. It is believed, however, that the appearance of wired glazings could be substantially improved by the use of thin, shiny high-strength wires and by the omission of at least some of the horizontal components of the web. Alternately, the wire web could be patterned to give a pleasing effect.

Naturally, the breakable and unbreakable portions of the window can be combined in a single unit. Such a solution is shown in Figure 11. This figure also illustrates an additional feature, namely fire-activated closure. The upper and larger portion of the window surface, 1, is made from wired glass, the lower portion, 2, from ordinary glass. The panel-frame, 3, is attached to the window-frame, 4, via hinges, 5. In addition, the breakable part of the panel is installed in a separate smaller panel-frame, 6, which is hinged to a dividing bar, 7, via hinges 8. Thus the lower panel is a separately openable part of the total panel. In the figure both the total and the lower panel are shown in open position.

The small panel is opened and closed in the conventional way. The total panel is opened with the aid of a combustible cord or girdle, 9 , the end of which is attached to an arm 10, protruding from the panel frame, 3. The cord is guided by pulleys, 11, 12, and 13, fixed to the window frame, and passes through a conventional fastener, 14. In case of fire the hot gases accumulating below the ceiling, burn away the exposed section of the rope, 9 and let the total window panel fall back into the window frame. If open, the small panel will remain open and serve for ventilating the fire. If closed, it will first crack and fall out before starting its function.

Naturally, if the requirement is to block completely the inflow of air when fire occurs, [16] the total window panel must consist of a single "fire-resistant" glazing.

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[16] This may be the requirement in case of uncompartmented spaces. See the section entitled "Discussion on the Results."

DOORS, FOLD-UP CURTAINS

As discussed earlier, it is highly desirable tc isolate the room on fire from the rest of the building with the use of automatically closing doors. Some difficulties may arise, however, owing to the depression brought about in the room by the operation of the fire drainage system. The pressure difference may be high enough to keep a conventional swinging door partially open, even if it is equipped with a closing mechanism. Alternately, with a different door arrangement, the pressure difference may make the opening of the door difficult or impossible, and thus prevent people from escaping from the room. Obviously, these difficulties could be easily overcome by the use of weight-operated, automatically closing sliding doors. Such doors are already widely used, especially in ships.

As described earlier, the fold-up curtains are used to ensure controlled burning in case of fire in elements of uncompartmented spaces or corridors. Figure 12 shows a possible practical solution. The curtain itself consists of a multitude of light metal strips, 1, which are, in turn, attached (by spot welding) to a very thin sheet, 2. This thin sheet provides the "elbows" when the curtain is folded up. To every third or fourth strip two studs, 3, are fastened at the ends. They serve as the axes for spherical rollers, 4, which are guided in vertical grooves, 5, during the unfolding of the curtain. The unfolding is achieved by a weighty bottom strip, 6. Even when completely unfolded, the curtain will retain a zig-zag form, to better resist the pressure differences that exist between the area on fire and its environment.

Two arms, 7, are attached to the base of the curtain on either side. A thin steel rope, 8, is extended between the arms. The ends of these ropes are sealed with nuts, 9, (or small melted-on balls) made from a low-melting alloy. With the aid of these nuts the rope holds the curtain up in a retracted position. Fire on either side of the curtain will melt the nut (or ball) and thus cause the curtain to unfold.

ECONOMIC CONSIDERATIONS

Equipping a building with a fire drainage system would mean saving in certain respects and extra expenditures in others. Saving would come about owing to the possible relaxation of certain requirements associated with the present philosophy of defence directed against hypothetical fires spreading by hypothetical mechanisms. Part of this defence is the use of fire resistant compartmentation.

But, obviously, there would also be extra expenditures which most probably would outweigh the savings. One type of cost increase is associated with the loss of useful area. This loss can be expected to amount to about 2.5 per cent of the overall building area, and the resulting extra expenditure to 2.5 per cent of the cost of building.

The other type of cost increase is associated with the cost of extra devices to be installed. These costs may be substantial at the beginning, but would decrease with the mass production of the components. Of course, it is rather difficult to evaluate the net increase of costs, since some of these devices may increase the intrinsic value of the building. For example, the drainage ducts could improve the sound insulation between compartments, and the sliding doors would provide added convenience irrespective of the fire aspect.

Obviously, the extra expenditures should be viewed, in the light of the extra benefits produced. Some experts believe that at present the cost of fire protection may run as high as 4 per cent of the cost of the building. In the case of tall buildings it will probably grow even higher if the requirement of having these buildings equipped with sprinklers becomes generally accepted. Sprinklering facilities are estimated to amount to about 5 per cent of the cost of building, so that the total cost of fire protection will probably top 7 per cent. It would seem reasonable, therefore, to view the costs of equipping a building with a fire drainage system against this background.

The advantages of equipping a building with sprinkler system are well known. It is a comprehensive defence system against fire and is capable of replacing a number of other protective measures. Nevertheless, it also has several weaknesses. Some of these are: (a) it requires supervision and maintenance, (b) even with constant maintenance (or sometimes because of the maintenance) it often fails to operate,[17] (c) it relies on the availability of water in large quantities at the time of fire, (d) its operation during fire may cause damages far in excess of the fire and smoke damages, and (e) false or mischievous operation of the system may also cause excessive property damage.

The fire drainage system is also a comprehensive fire protection system. Although it does not, by itself, extinguish the fire, it limits the extent of fire, controls its development and keeps the surrounding spaces relatively clean. Because of these, the fire can be easily located, closely approached, and suppressed safely by people not experienced in fire fighting, using extinguishing devices which create minimum property damage (e.g. by chemical suppressants or foam). In view of these advantages, the extra costs spent on a fire drainage system may well be justified.

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[17] Data available from the United Kingdom, indicate that the sprinkler system will fail to operate in about 14 per cent of the fires.

SUMMARY

In developing techniques of fighting the spread of fire in buildings, people have conventionally approached the problem from the defence angle. They have directed the defence measures against a hypothetical fire that propagates by thermal conduction and structural destruction. Since the true mechanism of fire spread is a combined convective-radiant process, the conventional protective measures are rarely effective.

A new concept is described which is aimed at preventing the spread of fire by controlling its development and using its energy to render it relatively harmless.

Since fires burning at large excess air rarely last longer than 30 minutes, and their temperature is relatively low, venting a fire is a wise practice. If the gaseous products withdraw through vertical "fire drainage" ducts, the pressure in the space on fire can be kept sufficiently low to prevent the penetration of the flames into adjacent spaces.

The design of the fire drainage system is discussed in detail. A numerical example is presented to illuminate the design process. The practical design of the various components of the system, such as the drainage ducts, their gates, windows with special functions, and fire-activated fold-up curtains is described. The extra expenditures associated with the construction of the system are analyzed briefly in closing.

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NOMENCLATURE

a	thickness of insulation, ft
A	area, ft^2
b	elevation of neutral pressure plane, ft
B	constant, = 39.74 lbR/ft^3
F	fire load (specific), lb/ft^2
g	acceleration due to gravity, = 4.17×10^8 ft/hr^2
h	height of storey, ft
H	height of building, ft
H_1	height of fire drainage ducts, ft
ΔH	heat of combustion, Btu/lb
k	thermal conductivity, Btu/ft hr R
l	length of flame, ft
p	pressure, $lb/ft\ hr^2$
q	heat flux, $Btu/ft^2\ hr$
Q	rate of heat evolution, Btu/hr
R	rate of burning, lb/hr
T	temperature, R
v	velocity, ft/hr
U	mass flow rate, lb/hr
z	elevation (to mid-height of storey), ft

Greek letters

α	velocity head correction, dimensionless
β	fraction of heat released by combustion of volatiles inside the room, dimensionless
δ	orifice factor, ≈ 0.7 for contracted openings, dimensionless
ζ	factor of correction for departure temperature, ≈ 1.05, dimensionless
η	factor of correction for radiation losses, ≈ 0.9, dimensionless
$\varkappa$	thermal diffusivity, ft^2/hr
λ	factor of correction for secondary air flow, dimensionless
ξ	air flow factor, dimensionless

ρ	density, lb/ft^3
σ	Stefan-Boltzmann constant, = 0.1713×10^{-8} Btu/ft^2 hr R^4
τ	duration of fully developed period of fire, hr
φ	specific surface of fuel, ft^2/lb
χ	pressure factor, dimensionless
ψ	drainage duct leakage factor

Subscripts

a	of the outside atmosphere
c	of the charring fuel (cellulosic, in general)
C	of or in the route of communication between the space on fire and its horizontal environment
cr	critical
d	of the departing gaseous products
D	of or in the drainage duct
e	of the horizontal environment
E	effective
f	of the fuel (cellulosic, in general)
F	of the floor
g	of the gaseous products (average for the space on fire)
i	of the interior of the building; initial
r	of radiant heat transfer
t	total
v	of volatile decomposition products
ϕ	of the space affected by fire

Superscripts

*	of the secondary environment
^	for the ground-floor level

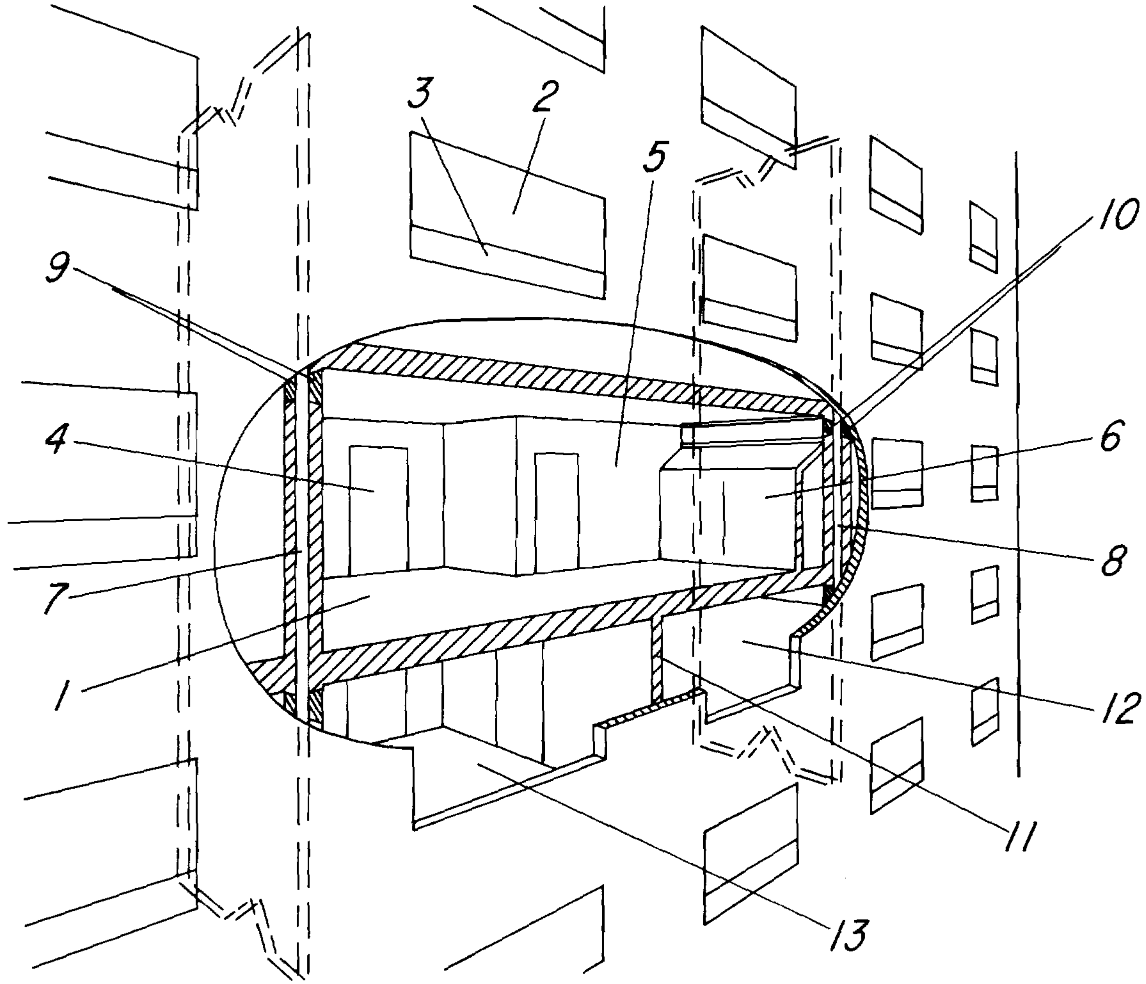


FIGURE 1

TYPICAL ROOM IN A BUILDING EQUIPPED WITH FIRE DRAINAGE SYSTEM

BR 5254-1

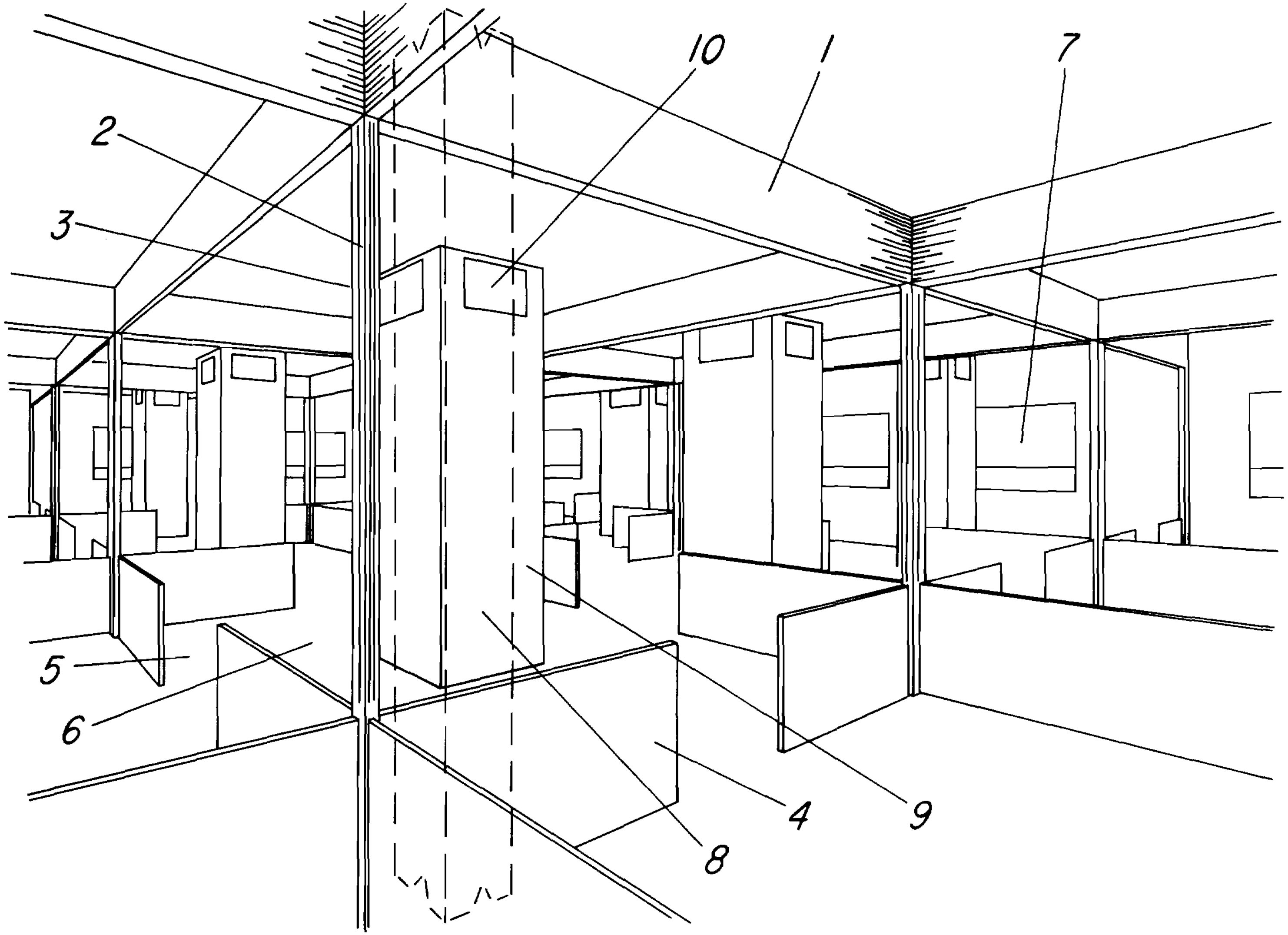


FIGURE 2

TYPICAL UNDIVIDED SPACE EQUIPPED WITH FIRE DRAINAGE SYSTEM

BR 5254-2

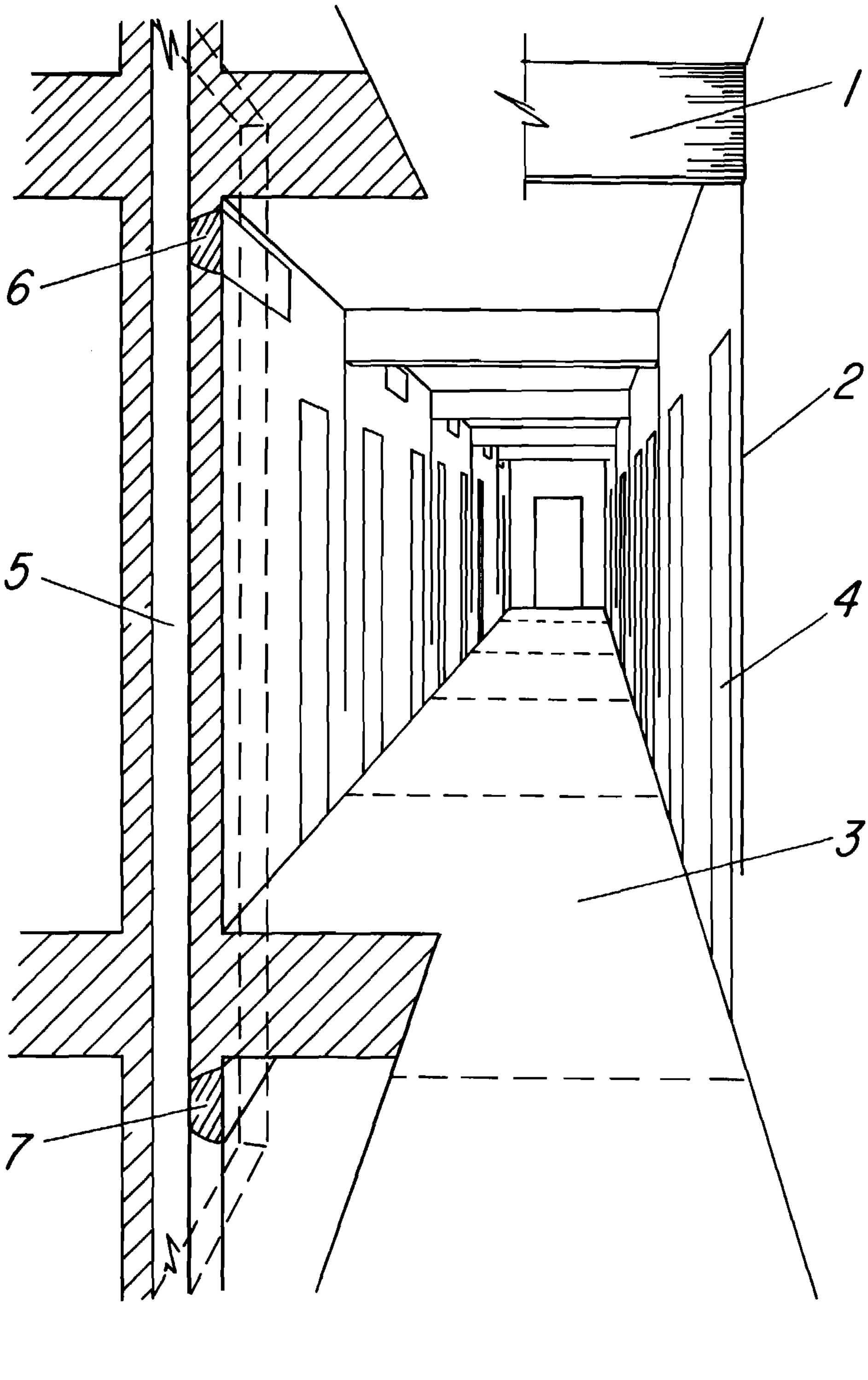


FIGURE 3

TYPICAL CORRIDOR IN A BUILDING EQUIPPED WITH FIRE DRAINAGE SYSTEM

BR 5254-3

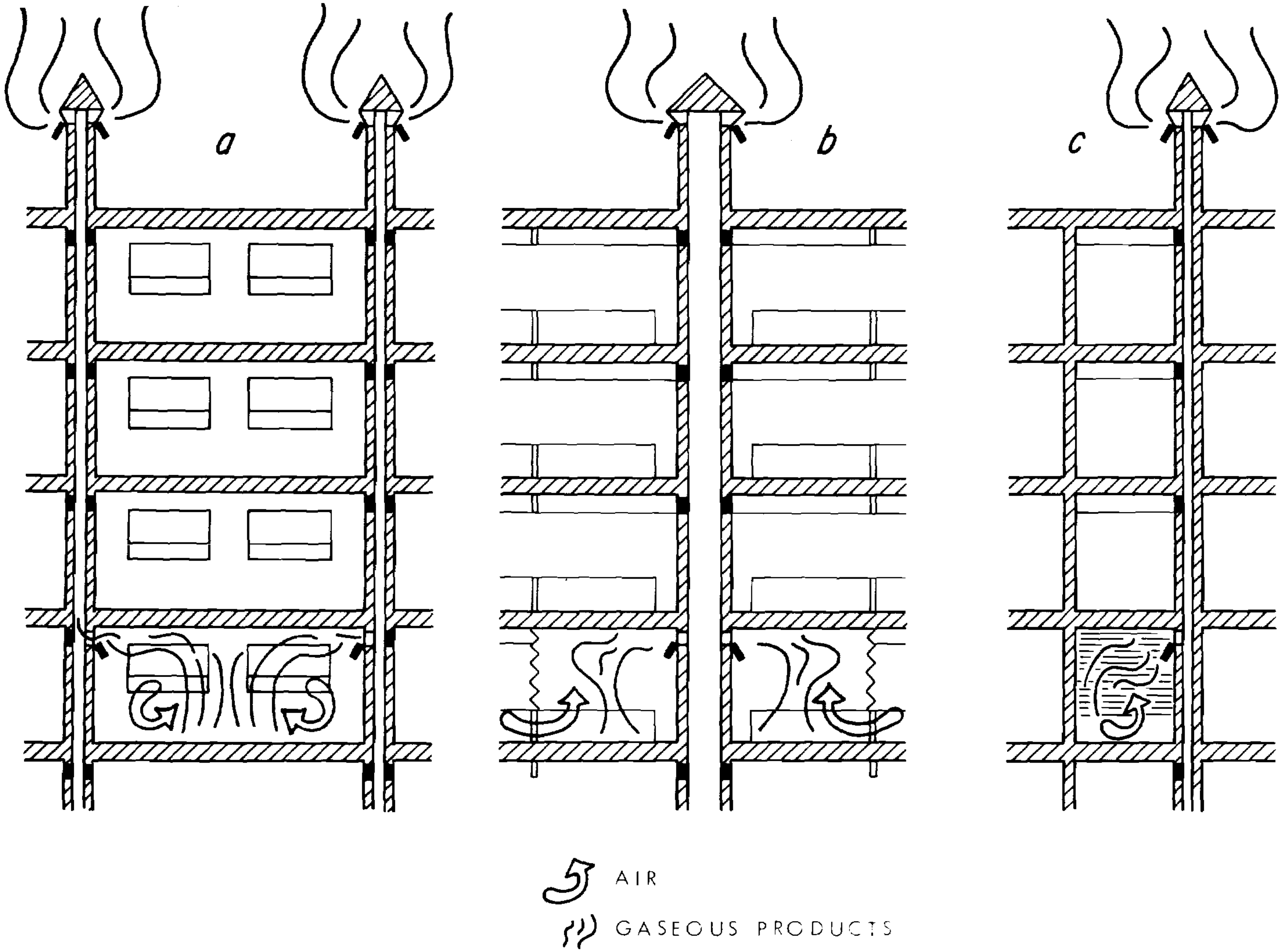


FIGURE 4

OPERATION OF FIRE DRAINAGE SYSTEM : a) ROOMS, b) UNCOMPARTMENTED SPACES, c) CORRIDORS.

BR5254-4

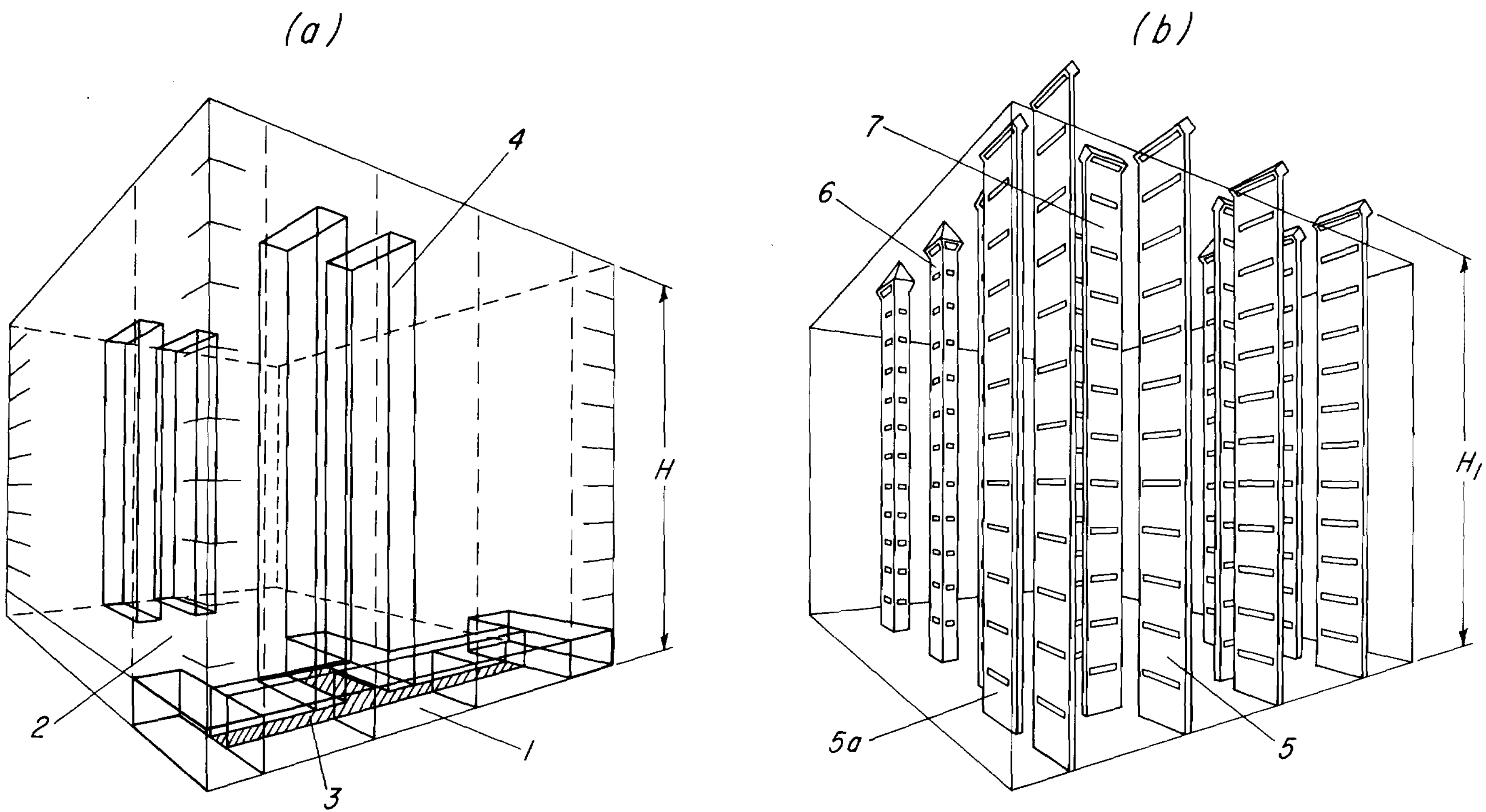
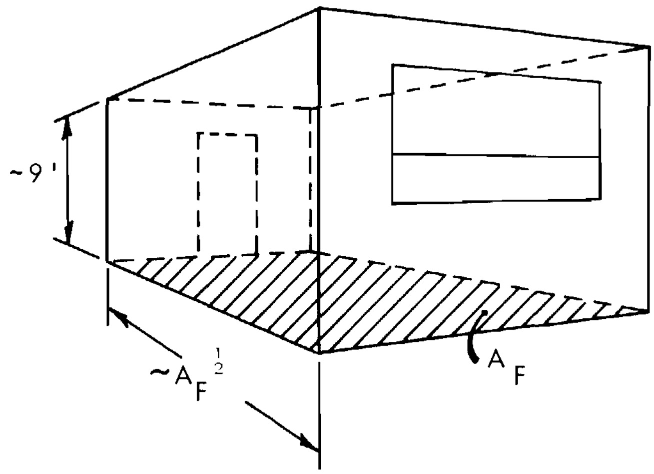


FIGURE 5
(a) OFFICE BUILDING AND ITS CONSTITUENT SPACES
(b) THE DRAINAGE DUCT SYSTEM FOR THE SAME BUILDING

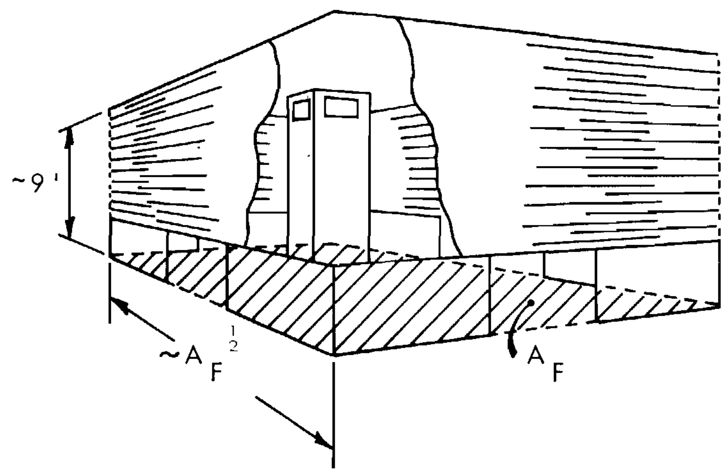
BR5254-5



ROOMS

$A_t \approx 2A_F + 4 \times 9 \times A_F^{\frac{1}{2}}$

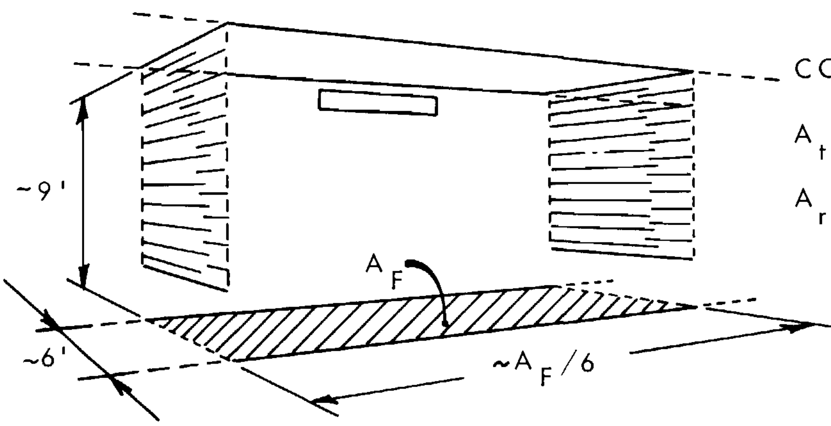
$A_r \approx 0$



UNCOMPARTMENTED SPACES

$A_t \approx 2A_F$

$A_r \approx 4 \times 9 \times A_F^{\frac{1}{2}}$



CORRIDORS

$A_t \approx 2A_F + 2 \times 9 \times \frac{A_F}{6}$

$A_r \approx 2 \times 6 \times 9$

FIGURE 6

MODELING THE GEOMETRY OF BUILDING SPACES

BR 5254-6

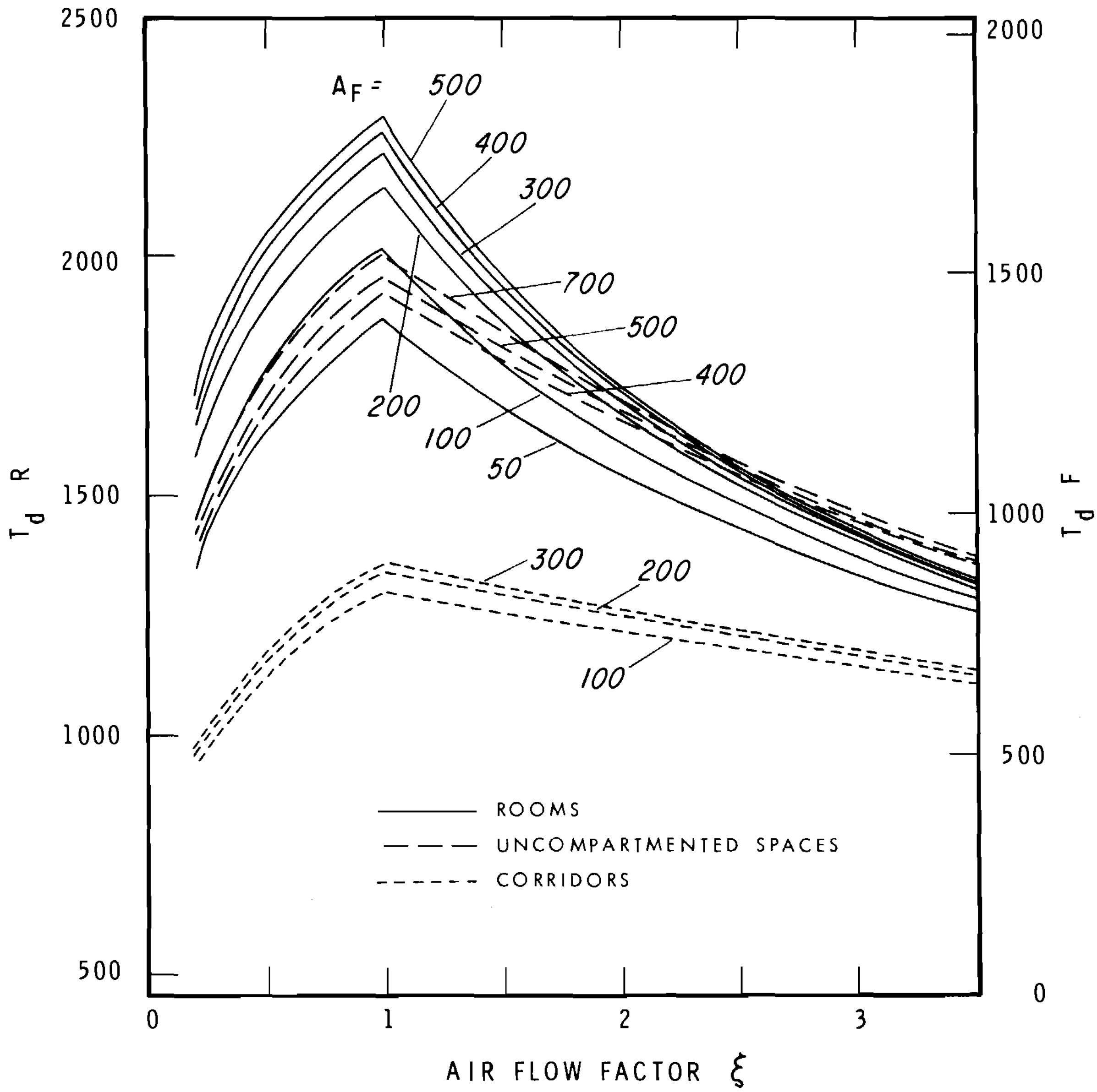


FIGURE 7

TEMPERATURE OF DEPARTING GASEOUS PRODUCTS

3R5254-7

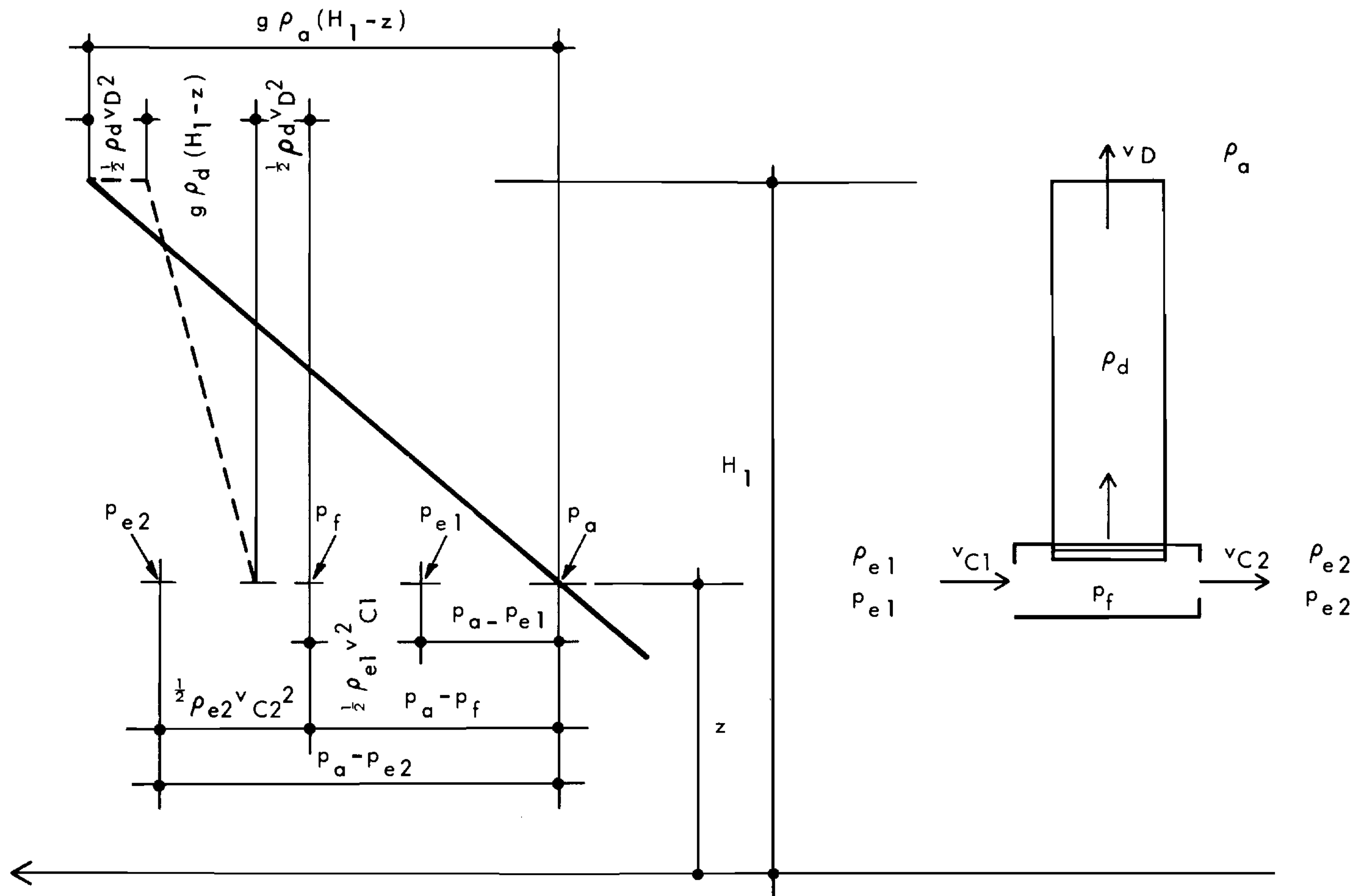


FIGURE 8

PRESSURES IN THE SPACE ON FIRE AND IN ITS "ENVIRONMENTS"

BR 5254-8

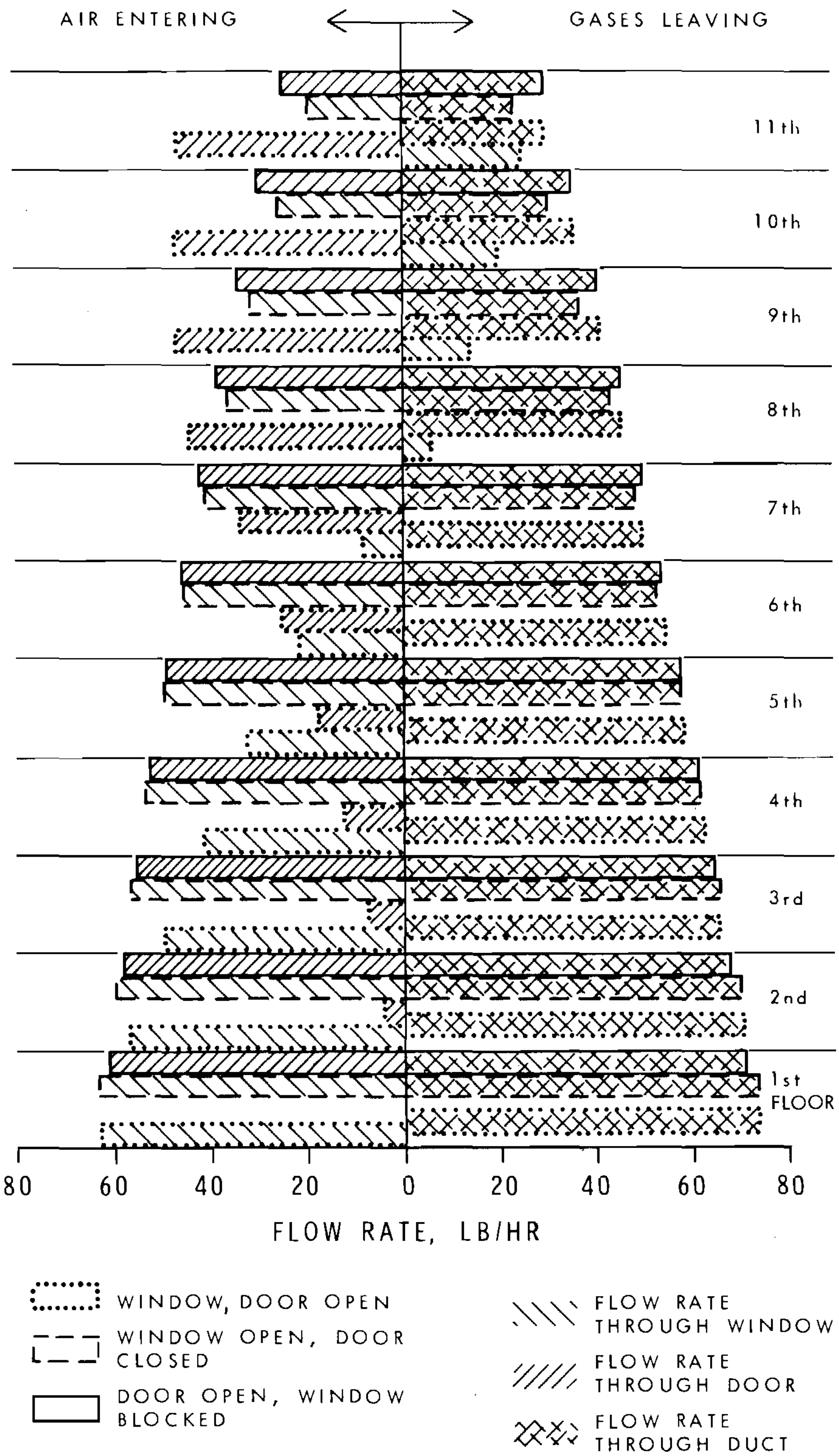


FIGURE 9

MOVEMENT OF AIR IN AND GASEOUS PRODUCTS OUT OF A ROOM ON FIRE. See text for details.

BR 5254-9

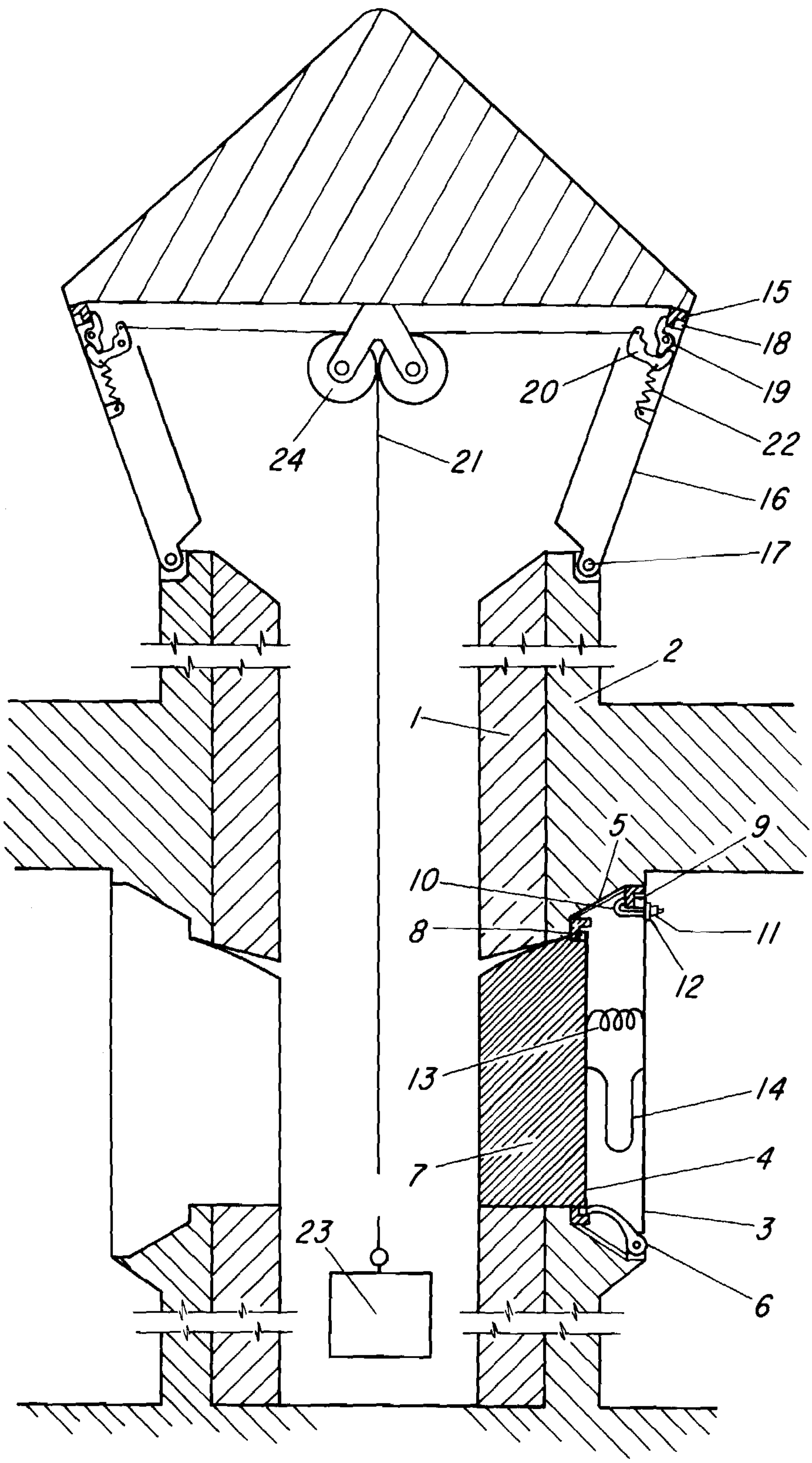


FIGURE 10

FIRE DRAINAGE DUCT AND GATES

8R 5354-10

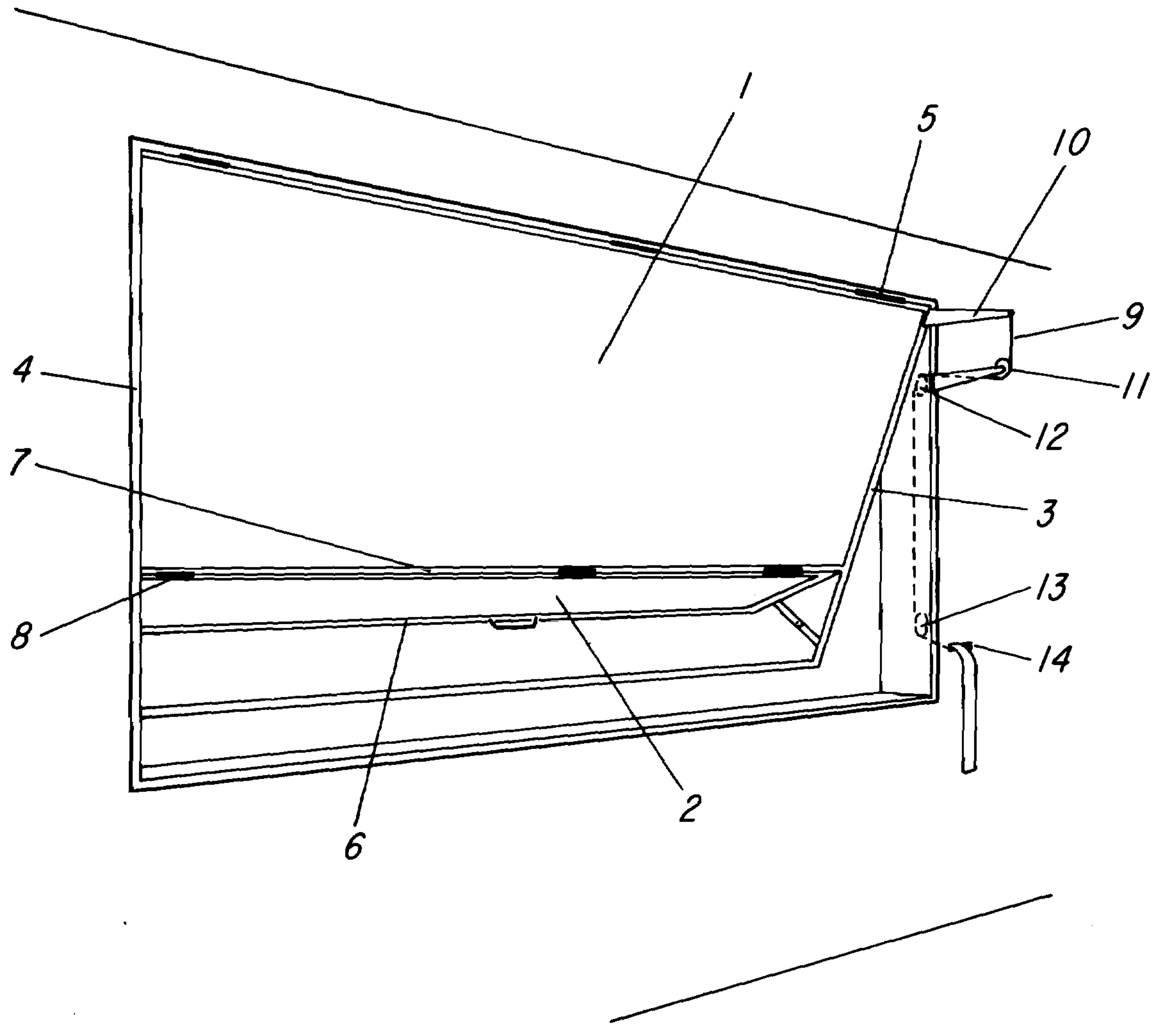


FIGURE 11

WINDOW, TO BE CLOSED BY THE FIRE

DR 5254-11

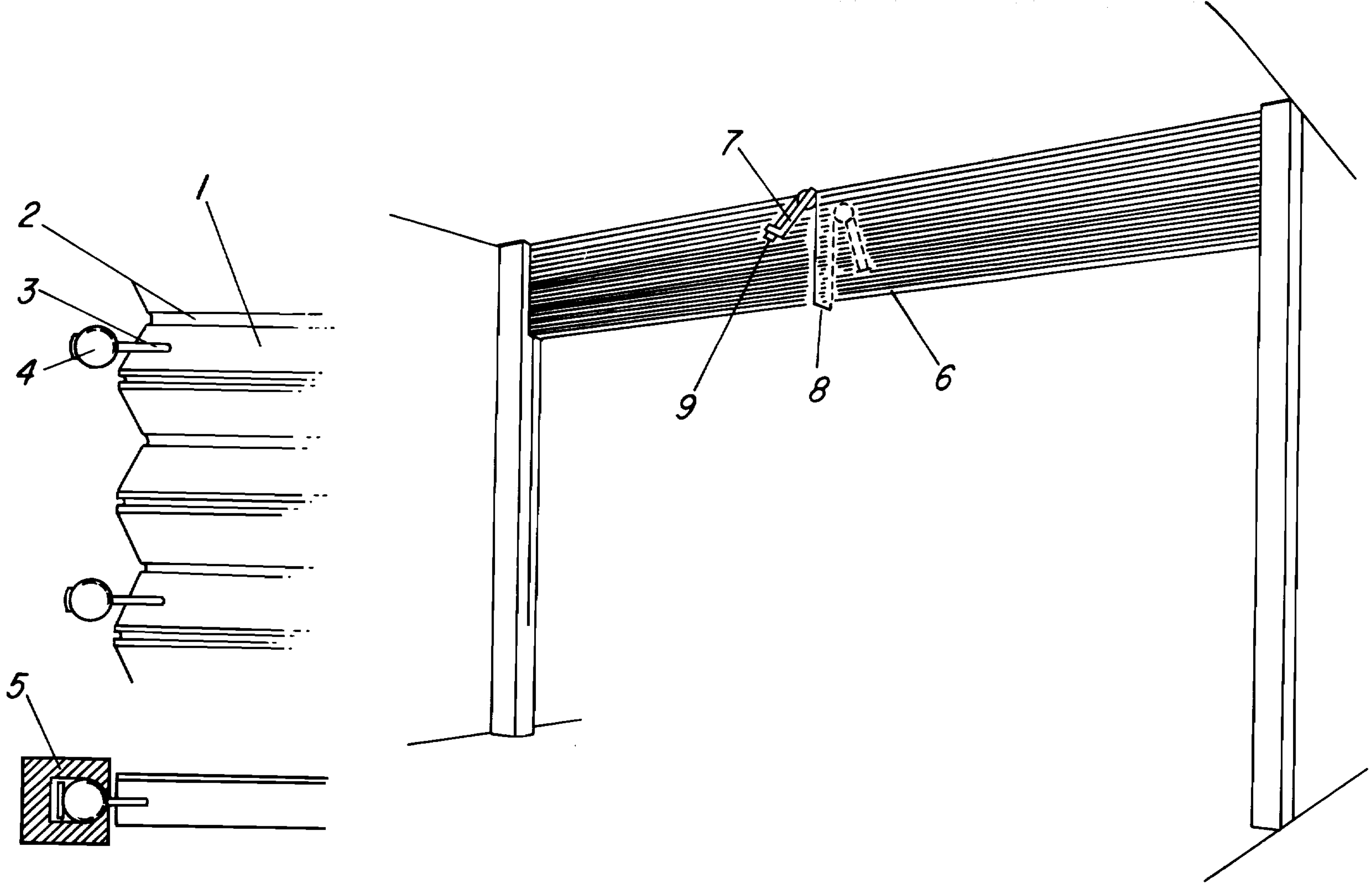


FIGURE 12 FOLD-UP CURTAIN

BR 5254-12