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PRESSURISATION OF ESCAPE ROUTES IN BUILDINGS

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by

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SUMMARY

This paper reports the results of studies made to provide specific design requirements for mechanical ventilation systems (often called "pressurisation" systems) for keeping escape routes in buildings clear of smoke and toxic gases.

The contract was placed and originally supervised by the Directorate of Research and Information of the Ministry of Public Building and Works, supervision being transferred to the Fire Research Station following the creation of the Department of the Environment.

KEY WORDS: Escape means, pressurisation, building, smoke, movement, air.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
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INTRODUCTION

1.

It is common to think of mechanical ventilation as simply a process for providing fresh air and removing contaminated air. The process can be and is used in more sophisticated applications, for example in the control of airborne bacteria in hospitals and obnoxious fumes in laboratories. The application of ventilation to the control of the movement of smoke in the event of a fire has also been practised, in particular it has been applied to the removal of smoke from fires below ground level. More recently the use of mechanical ventilation has been advocated for keeping escape routes in buildings clear of smoke and toxic gases in the event of a fire and such schemes are now in existence. This technique has a number of advantages but this is an application where the safety of life is at stake and the ventilation system serving this purpose must meet this obligation under emergency conditions. The design, constructional and operational requirements for such systems needs then to be clearly defined.

The technique of keeping escape routes clear of smoke and toxic gases by mechanical ventilation as discussed in this paper has acquired the title of "pressurisation" and the systems performing this function are being called "pressurisation systems". This terminology arises because the flow must always be away from the escape routes and to achieve this they must be at a higher pressure than surrounding areas.

The Joint Fire Research Organisation (JFRO) and others have demonstrated that uni-directional air flow in buildings can control smoke movement; the application of this to buildings requires a knowledge of all the forces that can influence air distribution patterns under emergecy conditions. The HVRA became involved in an ad hoc way in this problem through our studies of air movement in tall buildings under the action of wind and buoyancy (stack) effects. At this time proposals were being advanced for putting mechanical pressurisation systems in new buildings and a need for more specific design requirements for these seemed apparent. The HVRA put to the Department of the Environment a proposal to study pressurisation and prepare a set of design requirements for pressurisation systems. The DOE accepted this proposal and this study was undertaken between October 1970 and July 1972 under the terms of Research Contract CR 10248.

In carrying out this task we have looked at the following problems:

(i) The pressures acting on and in buildings which can influence the internal air flow patterns and hence the efficacy of pressurisation.

(ii) The influence of mechanical ventilation plant, other than pressurisation systems, on internal air flow patterns.

(iii) The air leakage characteristics of building construction so that the air supply requirements for pressurisation could be determined.

(iv) The requirements of air distribution plant for pressurisation to achieve the design objectives.

(v) The reliability of pressurisation systems.

We tackled (i) and (ii) by theoretical means using an HVRA computer program, CRKFLO, to study the behaviour of buildings under the actions of wind, stack and fire effects and also of ventilating or air conditioning plant. For item (iii) we have checked published data on air flow around closed doors, windows and through masonry structures and we amplified this information with site measurements in typical situations. We have examined the technical and economic requirements for distributing air to pressurised escape routes and have drawn on our own studies of plant reliability to comment on the probable availability of mechanical pressurisation plant and standby needs in an emergency. We have visited completed buildings which have pressurisation systems installed and have measured their performance and compared these with the specification.

The results of our study of these problems are set out in this report and we have concluded the report with a concise set of design requirements for pressurisation systems.

1.1 *Principles of Pressurisation*

Recognition of smoke and toxic gases as major hazards to life in building fires (1,2) has contributed to current attitudes towards controlling smoke movement, alongside more traditional ideas of limiting fire spread. Movement of air, under the influence of temperature and pressure, is the vehicle for smoke spread. Pressurisation therefore involves the control of air movement such that flow is always away from areas required to be maintained smoke-free.

In practice this may be achieved by the use of mechanical ventilation plant to inject sufficient air to maintain the area at a higher pressure than adjacent zones, relying on natural leakage through gaps around doors to non-pressurised zones to create an outward air flow from the pressurised area. Generally escape routes are the areas required to be kept smoke free so that flow should typically be from stairwells to lobby or corridor to accommodation space and atmosphere. The excess pressure necessary for pressurisation is deemed to be that providing protection when adverse conditions induced by external and internal influences, e.g. wind and fire pressures, act against the needs for air movement to be always outwards from the escape routes.

The principles behind pressurisation are established procedure in other fields which require controlled air movement, such as explosion protection in hazardous industries and prevention of cross-infection in hospitals. In fact the first known feasibility study in Britain by DOE Fire Branch in 1959 was based on the earlier work of James Ferguson and Ian Mackenzie, DOE engineers engaged on the control of radio-active contaminated atmosphere through doors and other openings.

1.2 *Background to HVRA Contract*

During the late 1950's and early 1960's, a rapid increase in the number of high rise buildings highlighted the inadequacy of existing "means of escape" regulations. Following the lead of London County Council the lobby approach staircase gained acceptance as a means of providing both a bridgehead on each floor for fire-fighting operations and an added precaution against smoke entering the staircase.

This trend placed severe restrictions on architects who, wanting to put available letting space to the best economic use, were instead confined to staircases and lobbies on external walls for the provision of the necessary natural ventilation. Against a background of economic pressure for internal staircases, various ideas for mechanical or natural ventilation as an alternative were tried. This led to natural vent shafts or mechanical extraction from staircases but these posed the problem of encouraging smoke movement towards the staircases. Consequently the idea of pressurisation of escape routes by the mechanical introduction of air was evolved.

Meanwhile parallel developments in Canada, Australia and U.S.A., where concern over the evacuation time required for tall buildings was felt, were serving as guidelines for new techniques being introduced in the U.K. Some tests at a new department store (3) involving JFRO showed that positive pressurisation of a staircase was a feasible means of keeping such an escape route clear of smoke. Following this, investigations by JFRO using a four storey tower building demonstrated the practicability of pressurisation in a real fire situation. A report of this work (4) was included in a Symposium on The Movement of Smoke on Escape Routes, at Watford, 1968, which stimulated interest in pressurisation.

On the basis of JFRO's work, some new buildings were constructed incorporating pressurised staircases but a lack of design information for the mechanical ventilation systems required was apparent. Uncertainty as to the relevancy of Canadian methods and design information in this country led to the commencement of this study by HVRA under contract to DOE in 1970.

1.3 *Objectives of HVRA study*

These were to produce such information as would enable pressurisation systems to be accurately and economically designed, and to show that this information could lead to satisfactory designs in practice.

To achieve these objectives, the proposed study was to include the following aspects:

1) Collection of data on air leakages through doors and structural elements so that the air flow requirements for pressurisation can be established. A search of available literature and other sources of information was proposed to obtain air leakage characteristics of such building components that are likely to be found in lobbies and stairwells.

2) Site tests to establish air leakage characteristics of actual lobbies. The purpose of these tests was to assist in relating information from 1) above to actual situations.

3) Study methods of distributing air vertically in buildings and to compare their technical and economic aspects. (This would include an assessment of the contribution that may be made by ventilation plant installed for occupants or equipment in buildings).

4) Examine, using computer techniques, the effect of temperature differences and wind pressures on the performance of pressurisation systems. This would show how temperature and wind may affect the distribution of air from a mechanical system.

5) An assessment of the reliability of different methods of operating pressurisation systems and advising on the need for standby plant.

6) Investigation of the site performance of two or three systems in operation to assess their behaviour in the light of information collated by this study.

1.4 *Survey of other work on pressurisation*

Prior to the commencement of study of the aspects listed in 1.3, a survey was made to determine the existing state of knowledge and practice of pressurisation both in this country and abroad. Further information also came to light later in the course of the project. A summary of this information given below represents the bulk of published and unpublished work from the United Kingdom, USA, Canada and Australia, though studies of smoke control problems have been made in other countries, including Japan and France.

1.4.1 *United Kingdom*

Preliminary experiments with pressurisation were carried out by the Joint Fire Research Organisation and the Building Research Station (3) on the 3-storey staircase of a new department store. Pressurisation of the staircase was varied and, using a portable smoke generator, it was found that a pressure difference of just under 0.03in. wg (7.5 N/m^2) was sufficient to prevent the entry of smoke through the door gaps. It was suggested that this value be increased to 0.05 in. wg (12.5 N/m^2) to cater for poor fitting doors, and that higher values yet would be required for systems coming into operation on demand, to ensure fairly rapid clearance of smoke already in the escape route.

In subsequent tests at JFRO on an experimental four storey building, Butcher et al (4) demonstrated the effectiveness of pressurisation in preventing smoke from an actual fire entering the staircase. In addition they measured the pressure differential developed across the top of the staircase door, while smoke and hot gases flowed into the staircase. It was concluded that pressurisation of 0.1 - 0.2 in. wg (25-50 N/m^2) was necessary to override pressure differences produced by both this and adverse weather conditions.

1.4.2 *U.S.A.*

In 1964, the San Diego and Los Angeles Fire Department investigated the use of mechanical ventilation in smoke-proof enclosures (i.e. lobby approach staircases). They found that the best system was to pressurise the stairshaft to 0.05 in. wg (12.5 N/m^2) above atmospheric pressure, with the lobby maintained at a pressure not less than 0.1 in. wg below that of the stairshaft. A minimum discharge of 2500 cfm is required from the top of the stairshaft to ensure adequate air movement. These provisions were subsequently written into the Uniform Building Code (7) and are illustrated in Fig. 1. The lobby is designed to act as a smoke- and heat-trap.

Further tests were carried out by the Los Angeles Fire Department (8), which resulted in their adding refinements to the above system (9). These include provision for a minimum exhaust of 2500 cfm from each of three lobbies while the doors from them to the staircase are held open, and mechanical devices to control the air flow in the lobby. The Los Angeles system has been criticised recently (10) as being unnecessarily complicated.

1.4.3 *Canada*

An extensive programme of research into problems of smoke control in tall buildings has been undertaken by the National Research Council of Canada. A critical look at the evacuation time required in the event of fire in such buildings in relation to the speed of smoke spread (11) highlights the concern felt. Full scale measurements of the pressure differences caused by wind (12), temperature differences (13,14) and mechanical ventilation (13) were made in several buildings, the air leakage characteristics of which were derived. From experience gained in these measurements, a computer analysis of pressurisation (15) and smoke movement (16) under various conditions was made. It was concluded from the latter that the major influence on smoke spread in the event of a fire was stack effect which, because of the very low temperatures sustained in Canadian winters, could produce smoke logging of upper floors within a short period of time. In addition to the work on mechanical pressurisation, studies have been made of the use of natural venting to control smoke movement (17,18).

The culmination of the Canadian work was an explanatory document (19) setting out the principles of smoke control, and the requirements for seven alternative methods of achieving them in practice. These range from natural ventilation to fully pressurised buildings. Pressurisation requirements are given in terms of the air supply necessary, but the general aim is to provide a pressure difference of 0.1 in. wg (25 N/m^2) across closed doors (20). Since an emergency opening of at least 20 ft^2 ($2m^2$) is required at the bottom of stairwells, the air flow rates needed to pressurise stairwell enclosures are rather large. Where the lobbies adjoining stairwells are pressurised instead however, the vent serves to keep the lobbies at a higher pressure than the stairs.

1.4.4 *Australia*

Although no work appears to have been published, the Commonwealth Experimental Building Station (21) has carried out some experiments with pressurisation in a test building similar to that used by JFRO. In addition a draft document (22) of the Standards Association of Australia lays down requirements for pressurisation systems. These provide for a positive pressure difference between an escape route and adjacent areas of not more than 0.2 in. wg (50 N/m^2) when all doors to the escape route are closed and secondly an average air velocity of 250 fpm (1.3 m/s) through the doors, when not less than 10% of them are open.

1.5 *Current trends in pressurisation design in the U.K.*

At the start of the contract several new buildings incorporating pressurisation systems were under construction and two of these, a tall office block in Cardiff and new legal offices in London, came into operation shortly afterwards. In both of these, staircases in a central service core were pressurised at two levels, a continuous low level for normal operation, boosted to a higher one under emergency conditions. In the first case the design was based on empirical air change rates, not related to any specific pressure difference. The staircases at the law courts building were designed to be pressurised to 7.5 N/m^2 continuously during the day and boosted to 25 N/m^2 in an emergency, the latter figure to be achieved while one of the doors to the staircase was held open.

Several other buildings with pressurisation have reached completion more recently. Performance tests on three of these are described later. In general the design pressurisation of staircases, lobbies or both was 50 N/m^2 under fire conditions. Design figures were based on the work of JFRO, whose advice was usually sought by the local fire authority in the initial stages of development.

2. **PRESSURES ACTING ON AND IN BUILDINGS**

2.1 *Major influences on pressures*

The four main influences on pressure which provide the motive force for air movement within buildings are fire, stack effect, wind and mechanical ventilation. It is necessary to consider the effect that each of these, or a combination, will have on the pressure distribution within a building in order to assess the requirements for an economical pressurisation system.

The building can be considered as a series of spaces each at a specific pressure with air movement between them from areas of high to areas of low pressure. While in practice it is possible for pressure gradients to exist in large vertical spaces such as stairwells, the significant pressure differences can generally be considered as occurring across the major separations of the building structure, i.e. doors, windows, walls and floors. This is due to the resistance to air flow through them and hence the pressure differences need to be significant to sustain the air flow.

The function of pressurisation is to establish an excess pressure in the area to be protected from smoke, such that air movement into the area under adverse conditions due to the factors mentioned is prevented. It is convenient to consider the pressure differences produced by such conditions, so that the pressurisation finally selected will be high enough to override them.

2.2 *Pressure differences arising from temperature differentials*

2.2.1 *Stack effect*

Stack or chimney effect are the names given to the air movement resulting from the difference in density between two interconnected columns of air at different temperatures. The buoyancy of the warmer air in one column causes it to rise, colder more dense air being drawn in at the bottom from the other column to replace it. A building fits this configuration, in winter the building contains the warm column of air and the atmosphere the cold column. In such a system the air pressure in the cold column is greater than in the warm one at the base and is less at the top. Thus a pressure gradient is set up across the barrier separating the two columns. At some intermediate point between top and bottom the pressure is the same in both columns, and this is called the neutral pressure plane. The position of this plane, which depends on the distribution of openings in the barrier with height, is given by McGuire (23) as

$$\frac{h_2}{h_1} = \frac{A_1^2}{A_2^2} \cdot \frac{T}{T_o}.$$

A_1 and A_2 are the areas of openings whose heights from the neutral plane are h_1 and h_2 respectively (see Fig. 2). T is the absolute temperature of the warm column, T_o the absolute temperature of the cold column.

Applying this concept to a heated building in winter gives rise to a system of air flows and pressures illustrated in Fig. 3. It will be seen that in practice A_1 and A_2 consist of several openings to each floor below and above the neutral plane respectively. Vertical air movement within the building occurs principally in vertical shafts, i.e. lift and stairshafts, air flowing into the shaft at the bottom and out at the top. In the summer when external air may be warmer than internal air, the pattern of air movement can be reversed.

The height of the neutral plane is determined by the relative leakage areas of the buildings structure at high and low levels. Generally these are about equal in typical buildings so that the neutral plane is at or near mid-height.

It is possible by providing sufficiently large openings at the top or bottom of a building to shift the neutral plane close to the position of the opening. This is the underlying principle behind natural venting to control smoke movement. Assuming winter stack conditions, the pressure in a top vented shaft will be less than that on each floor of the building. Air flow is into the shaft at all levels and out of the vent, so forming a smokeshaft. Similarly the pressure in a bottom vented shaft is higher than that in the rest of the building, and air flow from stack effects is always from the shaft to accommodation areas. Smoke is prevented from entering the shaft, which is effectively pressurised. The success of such methods is obviously dependent on there being favourable weather conditions.

2.2.2 *Temperatures - U.K.*

The design outside temperatures for heating and ventilating installation given by the IHVE Guide are $-1^{o}C$ in winter and up to $28^{o}C$ in summer. An internal temperature of $21^{o}C$ is common practice for design purposes. Clearly the largest temperature differential is likely to occur in winter. The winter design figures are optimistic when considering stack effect since instantaneous temperatures should be considered rather than the daily average temperature as a suitable basis for designing systems whose purpose is to preserve life of building occupants. The range of mean minimum monthly temperatures is given by Quenzel (35) as $-10^{o}C$ to $+29^{o}C$. A survey of minimum temperatures from Met. office data appeared to bear out the use of the more critical winter temp. ($-10^{o}C$) as a suitable basis for calculating likely extremes of temperature difference between inside and outside of buildings in the U.K.

2.2.3 *Pressure differential due to stack*

The pressure difference due to stack is given in the IHVE Guide as:

$$\Delta p \;=\; 3462\, h \left(\frac{1}{T_o} - \frac{1}{T} \right) \; N/m^2 \qquad \text{—— 2.1}$$

where h = distance from neutral plane, m.

T_o = absolute temperature outside, ^{o}K.

T = absolute temperature inside, ^{o}K

For a temperature difference of $31^{o}C$ ($T_o = 263^{o}K$, $T = 294^{o}K$) the pressure gradient caused by stack is 1.4 N/m^2 per metre vertical distance from neutral plane.

It can be seen that the maximum pressure difference across the enclosure due to stack effect can be doubled if the neutral plane is moved from mid-height to the top or bottom of the building.

The pressure differential due to stack distributes itself across the external and internal separations in proportion to relative flow resistances.

2.3 *Pressure developed by a fire*

2.3.1 *Expansion*

Air movement in the neighbourhood of a fire is produced by two mechanisms, expansion due to temperature rise and stack effect. Firstly as the temperature within a fire compartment rises, the gases expand in direct proportion to their absolute temperature. Two to three volumes of hot gases may be displaced from the room depending on the maximum temperature attained by the fire. Increases in pressure are small in comparison to absolute pressure since the expansion process is relieved by the flow of gases out through the normal leakage paths of the room. In an explosive situation, the pressure rise would be much larger and fairly rapid and would clearly result in windows and doors being blown out.

2.3.2 *Stack effect*

For doors separating escape routes from corridors and accommodation areas the pressures developed due to expansion can be neglected in relation to the second mechanism, stack effect. This is because expansion of gases from the fire zone can take place into the remaining area of that floor of the building producing a minimal pressure change. If the fire developed fully over the floor area the high temperature may lead to failure of the external facade, alternatively the natural leakage of the facade would relieve the internal pressure. The stack effect also acts across separations like closed doors where the two sides are at different temperatures; this happens when a fire occurs on one side of the door. Typically smoke and hot gases flow out of the gap at the top of a door to be replaced by cool air, drawn in through the gap at the bottom. The adverse pressure difference developed at the top of the door is proportional to the distance from the neutral pressure plane, as given by equation 2.1. The maximum value which can be attained in a single floor is obviously limited very much by the height of the compartment. For an 800^{o}C temperature differential (fire temperature 1100^{o}K), the pressure difference at the top of a normal door could theoretically reach 17 N/m^2 if the neutral pressure plane were at floor level. In practice however, only about half this value will be obtained since the neutral plane is likely to be nearer the centre of the door. Higher temperature differences do not alter this figure significantly.

Some practical measurements have been made of the pressures developed by fires. In Los Angeles a series of experimental school fires were made (24) in 1959. The maximum pressure increase in a stair enclosure was 37.5 N/m^2, corresponding to 12.5 N/m^2 per storey height or 6 N/m^2 at the top of a door. This value was considerably reduced when windows or doors were open to the atmosphere. More recently Butcher (4) found that the pressure difference across the top of a door to a stairway due to fire on one side never exceeded 7.5 N/m^2. The temperature reached by the fire was 800^{o}C and at this stage the top of the door was beginning to burn away, increasing the size of the gap there.

The stack effect for underground buildings at normal temperatures is negligible.

2.4 *Wind Effects on Buildings*

2.4.1 *Nature of Wind*

The surface of the earth gives rise to frictional drag on wind and hence the wind speed near the surface is considerably reduced and a boundary layer is formed giving a vertical gradient of wind velocity. The height of the boundary layer is reached when the frictional drag forces of the earth's surface are balanced by the movement due to the earth's rotation. The gradient height and velocity profile depend on the roughness of the underlying terrain, the gradient height varies from about 300m in flat open country to about 500m in urban areas.

Opinion is divided on the best mathematical expression for variation of windspeed with height (25), the use of a power law being the simplest, i.e.

$$\frac{V}{V_{10}} = \left(\frac{h}{10}\right)^{\alpha} \qquad \text{——— 2.2}$$

where V_{10} is the meteorological windspeed usually quoted for a standard height of 10m above ground. The value of the exponent α depends on the type of terrain and also the windspeed averaging time used. Many estimates of suitable values for α have been made, and are given for example in the IHVE Guide. Appropriate values of α for mean windspeeds in U.K. are 0.17 and 0.35 for open country and urban areas respectively (26,27).

2.4.2 *Design Wind Speed*

As with temperatures, the averaging time of meteorological observations is an important factor in the choice of a design figure. The maximum hourly windspeed and 3-second gust speed exceeded once in 50 years are commonly used. These are relatively infrequent and for present purposes, the mean annual maximum hourly windspeed is more appropriate. Values are given for over 70 sites in the U.K. (28), mostly in open country, and these do not generally exceed a figure of 20 m/s (45 mph) at 10 metres above ground (apart from some of the more exposed coastal sites). Mean windspeeds in urban areas are somewhat lower than in corresponding country area, although this difference becomes less marked with increasing height. A reduction of 4 m/s (10 mph) has been suggested at 10 m height (26) and is borne out by recent results of Helliwell for London (29).

Although providing some guidance for average situations, figures given in preceding paragraphs should be used with caution. Maximum hourly windspeeds may be much higher for coastal or mountainous areas. Although mean windspeeds are reduced by wooded and built-up areas funnelling effects in valleys and between buildings can produce high local velocities. When buildings are being considered in such localities it is advisable to consult the Meteorological Office.

2.4.3 *Wind pressures on buildings*

The slowing down of wind by an obstruction, i.e. building, in its path creates a build up of pressure on the windward face. The wind is deflected and accelerated around the sides and over the roof of the building, creating an eddy behind the building and exerting a negative pressure or suction on all areas other than the windward face(s).

The pressure distribution on the surface of a building due to wind is far from uniform and depends on such factors as direction of wind, shape and height of building, shielding effects of local obstructions to flow. The distribution is conveniently expressed in terms of pressure coefficients Cp, which relate the actual pressure on the surface to the velocity or 'dynamic' pressure of the wind, i.e.

$$\text{wind pressure} = Cp \times \frac{\rho v^2}{2} \quad N/m^2 \qquad \text{——— 2.3}$$

where ρ = density of air, kg/m^3

v = wind velocity, m/s

The pressure around tall buildings is difficult to predict accurately. Average pressure coefficients for the main surfaces of a building are given in the B.S. Code of Practice on Wind Loads (30). Model and full scale tests are increasingly used to obtain a more detailed picture of wind effects on buildings (31,32,33). From these it appears that the maximum pressure difference across a building is approximately 1.2 times the velocity pressure, consisting typically of coefficients for the windward and leeward faces of +0.8 and -0.4 respectively.

Fig. 4 shows the pressure distribution on tall rectangular buildings in an urban area from the results of an earlier study (34) in terms of the velocity pressure of the wind at the height of the top of the building. The primary effect of such a distribution on internal air movement is to produce a horizontal air flow through the building from windward to leeward. Some vertical movement also occurs in the building due to increasing pressure on building faces with height and negative pressure on the roof.

The wind effects on underground buildings are limited to pressures on openings and vents at or above ground level.

2.5 *Ventilation system pressures*

Air movement produced by mechanical ventilation sets up pressure differences in a building in a similar manner to and superimposed on those due to natural forces.

In addition the building as a whole may be at a greater pressure than ambient air due to the current practice of supplying air at a higher rate than it is extracted (or the reverse may occur in certain applications). It is becoming more common for buildings to be pressurised, i.e. at a positive pressure with respect to external conditions, particularly with the increasing use of sealed windows. This has the advantage of limiting air infiltration caused by wind and stack effects.

3. AIR LEAKAGE CHARACTERISTICS OF BUILDINGS

3.1 *Importance of air leakage characteristics*

Reference has already been made (section 2.1) to the resistance to air flow through the major separations of a building which results in zones of different pressure being set up. Air flows from high pressure to low pressure through leakage paths and the amount of air moving will depend on the resistance offered by the separations. In practice the separations are doors and windows and the leakage paths are the gaps around these. Leakage flow can also occur through floor and wall constructions where these are of a pervious nature. To pressurise a particular zone in a building to a specified level by means of mechanical ventilation the rate of input air is determined by the resistance of the leakage paths, hence a knowledge of the behaviour of these leakage paths is the prime requirement for estimating the capacity of pressurisation systems for buildings. This section covers existing knowledge of the leakage characteristics of doors, windows and building construction and sets out the results of some site tests which extend the published data.

3.2 *Nature of air leakage*

A general expression relating leakage flow rate Q to the static pressure differential across an individual leakage component is:

$$Q = K (\Delta p)^{\frac{1}{N}} \ \ell/s \qquad \text{—— 3.1}$$

where Δp is in N/m^2

K is the leakage coefficient of the component i.e. it is the value of Q when Δp is 1 N/m^2. It is more commonly quoted in terms of the "crack coefficient" C for unit length of crack (ℓ/s per metre per N/m^2) multiplied by the crack length L, i.e. K = CL.

For small leakage openings as represented by cracks and pervious structures the value of N varies between 1 and 2. For very small dimensioned openings the Reynolds No. ($\frac{Vd\rho}{u}$) is low and the flow resistance is mainly due to viscous forces, hence N will approach 1. For larger openings the Reynolds No. increases (since it is proportional to the characteristic flow dimension d) and the resistance will be mainly due to inertia forces in the turbulent flow and N will approach 2. In practice this means that the following values of N are typical of normal construction,

Leakage component	N
Brickwork	1
Window crackage	1.6
Door crackage	2

The leakage characteristic of a component can also be expressed in terms of an equivalent area of opening A. If the coefficient of discharge for the opening is taken as 0.65 (IHVE Guide, Section A.4) then for ambient conditions equation 3.1 becomes

$$Q = 827 \ A \ (\Delta p)^{\frac{1}{N}} \ \ell/s$$

If leakage through pervious structures is ignored and N is approximated to 2 then this becomes

$$Q = 827 \ A \ (\Delta p)^{\frac{1}{2}} \ \ell/s \qquad \text{—— 3.2}$$

Where several leakage components are in parallel and the pressure drop across each is the same the total rate of air flow is given by

$$Q = 827 \ \Sigma \ A \ (\Delta p)^{\frac{1}{2}} \ \ell/s \qquad \text{—— 3.3}$$

where $\Sigma A = A_1 + A_2 + A_3 + \ldots\ldots\ldots$

and $A_1, A_2, A_3, \ldots\ldots\ldots$ are the equivalent areas of opening of the individual leakage components.

For several components in series, as often occurs, the air flow through each is the same, i.e.

$$Q = 827 A_1 (\Delta p_1)^{\frac{1}{2}} = 827 A_2 (\Delta p_2)^{\frac{1}{2}} = \ldots\ldots$$

The total pressure drop $\Delta p = \Delta p_1 + \Delta p_2 + \Delta p_3 + \ldots\ldots$

Thus the effective equivalent leakage area A of components in series is given by

$$\frac{1}{A^2} = \frac{1}{A_1^2} + \frac{1}{A_2^2} + \frac{1}{A_3^2} + \ldots\ldots\ldots \qquad 3.4$$

For just two components in series

$$Q = 827\left[\frac{A_1 \times A_2}{(A_1^2 + A_2^2)^{\frac{1}{2}}}\right] \Delta p^{\frac{1}{2}}$$

From equation 3.4 it can be seen that the effective equivalent area A is strongly dependent on the smallest of the individual openings that are in series and it is always less than this, the smallest value. If the smallest of the openings in series is less than one quarter of any other opening then only the smallest need be considered and equation 3.2 can be used.

It is possible to produce more general relationships between Q, A and Δp using particular values of K and N but since nearly all internal building flows are controlled by door and window cracks the above equations are sufficiently accurate for most applications where manual calculations are used.

3.3 *Literature survey on air leakage data*

An extensive survey, including a literature search and enquiries to appropriate bodies, was made with a view to assembling existing data on air leakages into a comprehensive guide. The survey was less fruitful than anticipated however and the results are summarised below under the three main categories of component, windows, doors and structures. Leakage studies seem to have traditionally been orientated towards assessing heat losses due to the infiltration of cold air, and have consequently concentrated on windows. External wall construction and doors have been considered to a lesser extent.

3.3.1 *Windows*

Early studies of air infiltration through windows were made in the U.S.A. (36,37,38,39,40,41), and more recently further work has been reported (42,43). In the U.K. Dick and Thomas (44) investigated the effect of gap size on window leakage and in recent years this has been followed up at the Princes Risborough Laboratory of the Building Research Establishment (49). With increasing emphasis being placed on the performance of individual building elements, a standard for testing the weather-tightness of windows now exists (45). A draft standard for the grading of window performance (46) recommends that air leakage rates should not exceed 3.3 ℓ/s/m at 100 N/m^2 pressure difference.

Two sources (47,48) containing the most comprehensive test results were selected for more detailed analysis, in view of the wide range of window types and figures reported. To simplify the presentation the data was grouped firstly into that for windows with weatherstripping and without weatherstripping, and secondly according to the type of opening arrangement, as follows:

(i) pivoted windows, non-weatherstripped
(ii) pivoted windows, weatherstripped
(iii) sliding windows, non-weatherstripped
(iv) sliding windows, weatherstripped.

There was found to be no significant difference between groups (iii) and (iv) and these were subsequently combined. Leakage rates varied between maximum and minimum values observed by a factor of approximately 15 for non- weatherstripped and 40 for weatherstripped windows. Typical figures are given in Table 3.1.

Two difficulties experienced in making this analysis should be mentioned. Firstly a constant value of N was assumed for equation (3.1). In practice this is often only true over a limited pressure range since gap size may vary with pressure difference across the window. Secondly infiltration data was used. Recent studies have shown that centre pivoted windows excepted, leakage in the direction of opening (usually exfiltration) is approximately five times leakage against the direction of opening.

3.3.2 *Doors*

Existing experimental data on air leakage through doors was found to be very limited. Test results on full scale door cracks are reported by Min (50). From earlier work on stack effect in high buildings (13,14), Tamura (16) has estimated the equivalent leakage areas of stairwell doors (single leaf) and lift doors as 0.022m^2 (0.2 ft^2) and 0.054m^2 (0.5 ft^2) respectively. Tests at Princes Risborough Laboratory (53) on external doors with sills indicated a leakage rate of 11 ℓ/s/m at 50 N/m^2, or about five times that of unsealed windows. The equivalent leakage area deduced from the latter tests by equation 3.2 is 0.0019 m^2/m length.

In view of the lack of experimental information, it is appropriate to consider existing standards relating to the permissible sizes of gaps around doors. For fire-check doors to BS 459 (51) the width of the gap between door edge and frame should not be more than 3mm ($\frac{1}{8}$"). No regulation of gap between door and floor, which is usually the largest, is made however. BS 2655 (52) for lifts requires any gaps in landing entrance doors to be not wider than 5 mm (3/16"). Leakage rates based on these clearances are included in Table 3.1.

3.3.3 *Structure*

Based on work by Houghton and Larson et al (54,55,56,57), the ASHRAE Handbook of Fundamentals (58) gives details of air leakage through various types of wall construction. Figures for brick walls, which are the most appropriate to the U.K., show that leakage is greatly influenced by both quality of materials and workmanship. In addition the leakage through brickwork which has a plaster finish is approximately 1% of that through untreated brick, while the reduction due to painting one surface may be only 50% or less.

From studies of tall buildings in Canada, Tamura and Wilson (14) have measured leakage rates through several types of external curtain wall construction with sealed glazing. Figures have also been derived for some internal walls and floors(16).

3.3.4 *Results of Survey*

Windows are fairly well documented as regards air leakage rates. Such information as exists for doors and structures suggested that, in most practical situations where walls are plastered on at least one side, air leakage through them could be neglected in

Table 3.1 Summary of air leakage data for building components taken from various sources

Component	Description	Reference source	Average leakage in ℓ/s for Δp = 25 N/m²	Value of Index N	Remarks
Windows	Pivoted	47,48	1.60 per metre crack	1.6	Leakage range 0.42-5.7
	Pivoted & weatherstripped	47,48	0.22 per metre crack	1.6	Leakage range 0.035-1.5
	Sliding	47,48	0.61 per metre crack	1.6	Leakage range 0.15-2.3
	Proposed exposure grade				
	Sheltered	46	1.40 per metre crack	1.6	
	Moderate	46	1.08 per metre crack	1.6	
	Severe	46	0.91 per metre crack	1.6	
Doors	Single stairwell door	16	75	2	
	Lift door	16	200	2	
	Ext. door with sill	53	8 per metre crack	2	
	Standard fire stop door with ⅛" (3mm) gap	51	13 per metre crack	2	computed value
	Lift door with 3/16" (5mm) gap	52	21 per metre crack	2	computed value
Brick and Masonry	8½" (216mm) plain brick	58	0.76 per m²	1.15	
	8½" (216mm) plain brick with plaster	58	0.0068 per m²	1.15	
	13" (330mm) plain brick	58	0.68 per m²	1.15	
	13" (330mm) plain brick with plaster	58	0.0034 per m²	1.15	
	External walls	14	1-2 per m² for curtain wall	2	The leakage through completed structures is assumed to be through cracks, hence value of N = 2
	Internal walls	16	200 per floor unplastered 40 per floor plastered	2	
	Floors	16	1 per m²	2	

relation to that through door cracks. A need for more reliable information on the magnitude of door leakages to be found in practice was indicated, and this aspect was consequently investigated in some detail in subsequent site tests.

Typical air leakage rates arising out of the survey are given in Table 3.1.

3.4 *Air leakage site tests*

The purpose of these tests was to establish the air leakage characteristics of actual lobbies, stairwells and corridors, emphasis being placed on the measurement of leakage rates for doors since the literature survey findings showed that this was where confirmatory data was most needed.

It was not practicable under site conditions to measure leakage rates through individual components directly. Such information was obtained however by a method of differences, i.e. successively sealing off individual components and observing the resultant difference in pressurisation when using a known air supply to the enclosure.

3.4.1 *Test method*

Pressurisation of a selected enclosure was achieved by use of a portable centrifugal fan rated at 570 ℓ/s (1200 cfm). The restriction on the fan size arose from the requirement of being portable and being operated from a single phase 13 amp 230 v supply. The size of enclosure which could be satisfactorily pressurised with this size of fan was limited by the number of doors forming leakage paths from the enclosure. This did not prove to be too serious a limitation but did mean that the tests were mainly carried out on lobbies with only a few on corridors and stairwells. A temporary door, erected in one of the entrances to the enclosure, was fitted with the inlet orifice for the pressurisation air supply (Plate 1).

The rate of air supply could be varied over the fan output range and the volume flow was measured from the static depression at a 60° conical inlet to BS 848 positioned on the fan inlet. Precautions were taken to minimise unwanted air leakage from the fan rig and temporary door (Plate 2).

During the tests the static pressure difference across each door was measured by means of an electronic micromanometer and a probe specially designed to fit round a door (Plate 3).

Analysis of the test results into a logarithmic form of equation 3.1 gives a linear relationship between Q and Δp, from which values of K and N for each test run are more easily derived, i.e.

$$\log Q = \log K + \frac{1}{N} \log (\Delta p)$$

Providing the resistance to air leakage beyond each door from the enclosure was relatively small, the static pressure difference was nearly the same across each door. This condition could be obtained by opening a few windows in the appropriate places, and ensured that the resistance measured was that of the doors only. In the lobby or similar situation where the doors are acting as parallel leakage paths, the leakage rate of a particular door can be deduced from the difference in the value of K obtained before and after sealing the door cracks.

3.4.2 *Test results*

Tests were carried out in five buildings giving leakage rates for a total of thirty doors. The mean leakage rates and the range of results are shown in Table 3.2 for four fairly distinct categories. All single and double leaf doors had rebated frames.

Office doors were found to have substantially lower leakage than other single leaf swing doors, indicating a generally better fit in their frames. This is probably due in part to the fact that they are retained in the shut position in closer proximity to the frames by the action of the door catch. In the limited sample tested, no significant difference in leakage was observed between double leaf doors with a centre rebate and those without one. The value of the exponent N ranged from 1.5 to nearly 2, with an average value of 1.7.

It is interesting to compare the leakage rates per unit length of crack with those obtained in the literature survey. Test values correspond closely to the maximum gap, or slightly above, allowed by the relevant British Standards. Office doors are a significantly better fit although there is no present standard for these. Other single door and lift door figures are in reasonable agreement with total leakage rates calculated from Tamura's eqivalent leakage areas.

Whilst the agreement between the measurements obtained from the site tests with the data of Tamura (16) and that implied in the British Standards (51, 52) is good this does not automatically ensure that in practice actual situations will always accord with the mean data. There is no apparent control during building construction to ensure that these leakage data will be typical, yet it is not economic to size a pressurisation system after a building is complete and its "leakiness" assessed. Hence the control of the fit of these doors (and windows) which play a part in the effectiveness of pressurisation in controlling smoke movement forms an integral part of pressurisation system design. This point must not be lost sight of in specifying pressurisation system performance.

Table 3.2 Results of air leakage tests on installed doors

Door type	Mean leakage rate ℓ/s at Δp = 25 N/m^2	Range of measured leakage rates	Standard deviation of measurements ℓ/s	Mean leakage per metre of openable joint ℓ/s.m	Computed gap width mm	Equivalent leakage area m^2
Single leaf door						
(a) office door with catch	44	30 - 61	7	8	1.9	0.01
(b) doors without catch	86	79 - 98	7	15	3.7	0.02
Double leaf (with or without centre rebate)	123	94 - 164	29	13	3.2	0.03
Lift landing entrance	195	157 - 255	29	24	5.9	0.05

4. REQUIREMENTS FOR PRESSURISATION

4.1 *Introduction*

This section deals with pressure differentials, air flow rates and venting requirements for pressurisation systems, which can be summarised as follows:

(i) Pressure differentials

An excess pressure must be maintained in an escape route so that flow is always outwards, preventing the entry of smoke under adverse conditions.

(ii) Air flow rates

The rates of air flow from the escape route necessary to achieve the pressure differences of (i) must be determined from the leakage characteristics of the escape route, so that the capacity of the mechanical ventilation plant required can be correctly determined.

(iii) Venting

The air introduced for pressurisation must be able to escape from the building after leaking from the escape route. There will be a minimum leakage area in terms of window leakage rates or special vent sizes required to ensure the release of a given quantity of pressurisation air to the atmosphere.

A study has been made of these requirements using a computer and the results are described below.

4.2 *Computer study of pressurisation requirements*

A digital computer program (CRKFLO) has been developed at HVRA for an earlier study of natural ventilation in tall buildings (34). It was equally suited to the present study in that it enabled a variety of specific ventilation conditions and their effect on pressurisation in a building to be investigated.

Air movement within a building is simulated by the CRKFLO program as a pipe network problem. Air flow paths between a series of inter-connected nodes or spaces in the building are represented by a set of non-linear simultaneous equations of the form equation 3.1. Values of K and N are specified for each path in the data input. A solution is approached by making successive approximations to the unknown pressures, starting from known values, until a flow balance is achieved. "Inflow" or "outflow", representing net air supply and extract rates for mechanical ventilation, may also be specified in the data input at any node for which the pressure is not known. The print-out of results of the computer calculation includes the flow rate and direction and pressure loss for each path.

Using this program, the sensitivity of a pressurisation system to the following parameters was investigated:

(i) building plan
(ii) leakage characteristics of building structure
(iii) external weather conditions
(iv) other mechanical ventilation
(v) open windows and perimeter venting

The study was made in two parts, firstly considering a single floor of a building to look at aspects (i) and (ii) and then using a multi-storey model to consider the remaining aspects. Heights of 6, 18 and 30 storeys were used for the latter. In the main the study looked at pressurisation in vertical escape routes, i.e. stairshafts, but guidance is given concerning the application of the results to horizontal escape routes.

4.2.1 *Building plan*

Two hypothetical building plans (see Fig. 5) both having centrally situated service cores but incorporating a number of different lobby/staircase arrangements were devised for the study. Pressurisation was simulated in the staircases in each plan and in the main lift lobby of Plan 2. The computer analysis showed that these pressurised areas were not equally sensitive to changes in leakage parameters (see 4.2.2) or to the external climate. The general air movement pattern in these buildings is an outward one from the central core to atmosphere via the accommodation area. Any increase in the leakage resistance of external or corridor walls (or the introduction of internal walls into an open plan building) tends to push more pressurisation air towards the lift shafts, reducing the effective pressurisation of staircases adjacent to them (see Table 4.1). Positive wind or stack pressures on the outside of the building produce a similar effect. Since lift shafts, which are normally associated with staircase cores, can act as pressure relief points, their position on the building plan should be considered with regard to their possible effect on pressurisation.

Building plan and leakage characteristics are closely interlinked in their influence on air movement within a building. The overall pattern is determined by the resistance to flow of components in series and parallel with each other in the total building network.

4.2.2 *Leakage characteristics*

Table 4.1 shows the change in pressurisation produced by varying individual leakage rates of windows and doors over approximately the same range of values described in section 3, other factors remaining constant. These results relate to the pressure difference between escape route and corridor. This value is less than that across the door immediately protecting the escape route in the event of air flowing into the lift shaft via the lobby.

In plan 2, (Fig. 5) window leakage is the most significant parameter affecting pressurisation in stair A and lift lobby C. This is not surprising since a much wider range of leakage rates exists for windows than for other components. The pressurisation of lobby C is similarly affected by changes in lift door leakage.

In plan 1 (Fig. 5) the main lift shaft is not protected by a pressurised lobby. Thus air is able to escape freely into the lift shaft and pressurisation of the stairs is insensitive to changes in window and lift door leakages. Opening door F in plan 1 (Fig 5.) results in a large flow of air round one limb of the corridor, adversely affecting the pressurisation of the opposite stair/lobby arrangement.

Table 4.1 The effect of varying leakage parameters on pressurisation

Parameter varied	Leakage rate (from range in Section 3)	% change in pressurisation				
		Stair A	Stair B	Lift lobby C	Stair D	Stair E
Windows	10% open	+ 17	0	+ 62	+ 4	+ 2
	max.	+ 14	0	+ 55	+ 3	+ 1
	min.	- 63	0	- 107	- 3	- 2
Office Doors	max.	0	0	+ 5	+ 1	+ 1
	min.	0	0	- 8	- 1	- 1
Lift Doors	max.	- 2	0	- 44	- 2	0
	min.	+ 4	0	+ 97	+ 3	0
Lobby Door F	open	- 3	0	+ 4	- 3	- 21
	min.	+ 1	0	0	+ 2	+ 17

In Table 4.1 pressurisation of stair B is independent of changes in the various leakage parameters since excess air has no other means of egress from the staircase than through the lobby. Cumulative leakage areas on the floors of a multi-storey building would determine the proportions of air flowing through each lobby in practice.

The main conclusion from the computer analysis was that window leakage is essential for the release of pressurising air to the atmosphere unless alternative means of egress are provided. In addition doors to escape routes have a direct influence on pressurisation; a 50% increase in leakage area approximately halves the pressurisation attained by a given supply rate. This indicates a need for stricter control over the fit of doors in their frames.

4.2.3 *External climate*

The computer program was used to investigate the pressure differences produced by the external climate, i.e. wind and stack forces within buildings of varying heights with the same plans used in 4.2.1. Extremes of meteorological conditions, as discussed in section 2, were used in this study, that is a meteorological windspeed of 20 m/s and an external winter temperature of $-10^{\circ}C$. Wind and stack forces were considered both separately and together, though such a combination would occur very infrequently.

Pressure differences due to wind and stack are shown diagrammatically in Figs. 6(a) and (b) for a 30-storey building. The results given are average pressures over 5 storeys and show a maximum adverse pressure difference for the staircase of 12 N/m^2 due to stack effect and 7.5 N/m^2 due to wind. Fig. 7 summarises the results of the computer analysis, showing the maximum adverse pressure difference across a stair door on any individual floor. It was found that stack effect generally predominated over wind effect in tall buildings; the pressure differences are entirely due to stack for buildings over 90 m high in Fig. 7. Below 90 m the combined influence of wind and stack is greater than that of stack alone, due to a significant upward movement of air within the building caused by negative wind pressures on the roof. For instance wind forces contribute 5 N/m^2 and 3 N/m^2 to the total pressure difference for buildings of 25 and 50 m height respectively.

The above figures were computed for buildings with windows of average leakage, i.e. 0.12 ℓ/s.m.N/m^2. In view of current trends towards better weather seals and window design generally, it is expected that pressure differences will be lower than these in modern buildings.

Horizontal and vertical escape routes

The pressure differences due to the external climate given above apply to vertical escape routes and to lobbies giving access to them only. Other horizontal escape routes, i.e. lobbies and corridors, are affected differently by climatic forces, in that they can be seriously affected by wind pressures but are relatively insensitive to stack effect. The pressure differences across a door due to stack effect in a single storey does not exceed 1 N/m^2 for normal temperature differences (i.e. excluding fires).

Horizontal escape routes can form a "through route" for wind induced air movement from the windward to the leeward side of a building, e.g. stair lobby in plan 1, and are particularly prone to wind action when the lobby or corridor present the path of lowest resistance to air flow across the building. This aspect was not studied in great detail in the computer analysis, but the pressure difference across a door to a "through route" due to wind can be calculated approximately from the relative leakage areas of internal and external walls and the total pressure head of the wind.

i.e. $$\Delta p = P \left(\frac{A}{A_D}\right)^2$$

where Δp = pressure difference developed across lobby door
P = total pressure head due to wind (see section 2)
A = effective leakage area of walls and doors in series across the building (see section 3)
A_D = leakage area of lobby door.

The value of Δp is not likely to exceed 10% of the total head providing windows are kept closed in the building.

It is concluded that pressures in horizontal and vertical escape routes are affected mainly by wind and stack forces respectively, though wind cannot be neglected in relation to vertical shafts. The leakage resistances to horizontal and vertical air movement determine the extent to which pressurisation systems are influenced by prevailing weather conditions. The approximate ratio of 1:2:5 for staircase, external and internal wall leakage areas used in the computer analysis is felt to be typical of the sort of building studied, though inevitably a wide range of values will exist in practice.

4.2.4 *Open windows and perimeter venting*

Windows opened at random in a building can unbalance a pressurisation system by allowing air to flow more easily through one entrance of the escape route at the expense of the pressurisation across the other entrances. This depends on the prevailing weather conditions and also the relative leakage of closed windows in the rest of the building. Openings at low level in winter increase the adverse effect of stack (Fig 6c), unless the windows are well sealed (Fig. 6d). If the latter condition is met, venting can be used to aid pressurisation and therefore smoke control. By venting the fire space adequately the outflow from the staircase on that floor would be increased, with a reduction on other floors. This gives added protection to the escape route on the fire floor. Since the behaviour of occupants is often unpredictable, the design of pressurisation systems must allow for an adverse arrangement of open windows to exist in the event of a fire. The worst situation, windows open at low level in winter, can give rise to an adverse pressure difference of 10 N/m^2 at the bottom of a pressurised staircase for a building height of 100 m with an opening 1% of the storey wall area.

4.2.5 *Other mechanical ventilation*

The computer analysis showed that ventilation to the accommodation areas at a net supply rate of 1 or 2 air changes per hour (i.e. supply rate less extract rate) does not affect pressurisation adversely. These rates are typical of present practice. A necessary proviso is that, should the extract system shut down, the supply ventilation could create pressurised zones in direct competition with those of the escape routes.

Uncontrolled opening of windows would also be a serious problem with normal ventilation running. Fig. 6(e) shows how venting at low level upsets the balance of the pressurisation system in favour of the vented floor.

4.2.6 *Use of normal mechanical ventilation to control smoke movement*

Fig. 6(f) illustrates that without staircase pressurisation, continued running of normal supply fans in conjunction with venting specific floor areas could control smoke movement. By venting the fire space the mechanical ventilation may be sufficient to maintain this space at a lower pressure than the remainder of the building, so that air movement is always towards the fire. With well sealed windows, a supply rate of 2 air changes per hour produces an "effective pressurisation" of lift and stair shafts of 30 - 40 N/m^2 on the vented floors.

This suggests that building pressurisation and smoke control may be achieved by normal air conditioning plant. The limitation on developing such schemes is the requirement for the sustained integrity of the system in the event of a serious fire. The idea is attractive but a detailed study of system requirements and construction is first necessary.

4.3 *Pressure requirements*

Under fire conditions pressurisation must be sufficient to overcome pressures developed in the building by fire, wind and stack effects. Further it must be sufficient to overcome the possible application of all three effects acting against pressurisation at the same time so as to maintain outward flow from the escape route. The pressure developed by a fire across the top of a closed door was discussed in section 2, the pressures developed by wind and stack effect in section 4.2.3 (Fig. 7). The overall pressure requirement for stairwells extending through the height of the building, with a safety margin to include the adverse effects on pressurisation of random window opening, is given in Table 4.2. It will be noted that the recommended pressurisation levels have been rounded off to two values, 25 and 50 N/m^2. This is because an increase in pressurisation from 25 to 50 N/m^2 constitutes only a 40% increase in the air flow requirement, and hence further subdivision would result in very marginal increments in air flow. Underground buildings would normally fall into the lower pressure category (25N/m^2) since the stack and wind effects in these buildings should be small.

Table 4.2

Minimum pressures required for pressurisation of stairwells in buildings

Building height m	Fire pressure N/m^2	Wind and stack effect N/m^2	Recommended total pressure including safety margin N/m^2
5	8.5	8	25
25	8.5	10.5	
50	8.5	13	50
100	8.5	19.5	
150	8.5	29.5	

It is important that pressurisation should not hinder the opening of doors on to escape routes during evacuation. Whilst an average adult can apply a force of about 180N (40 lbf) to open a door (71), some people would not be able to exert this force and a recommended maximum opening force of 90N is suggested. Allowing for a pull of 45N to overcome the door's self-closing mechanism then the force available to open a door against pressurisation is 45N. This is equivalent to a uniform pressure of about 50 N/m^2 on a typical door and this is recommended as the maximum level for pressurisation.

Various methods for countering stack effect and hence reducing the pressure requirements for smoke control have been suggested. Two of these are:

(1) the subdivision of vertical shafts to limit the total compartment height over which stack effect can act. Canadian practice is to divide stairshafts into 5 storey compartments, under UK winter conditions the equivalent limitations would be about 7-8 storeys. Limiting stack effect by compartmentalisation cannot normally be applied to lift shafts.

(2) use of separate pressurisation systems to serve each floor of a building. The economic aspects of this form of system are discussed in section 5.

4.4 *Air flow requirements*

4.4.1 *Closed doors*

The air flow rate for pressurisation will normally be assessed on the pressure differences required across closed doors and the associated leakage rates. During the normal passage of people through a doorway, the momentary loss of pressurisation does not seriously reduce the effectiveness of the pressurisation system. It has been found that smoke tends to be held back by the outflow of air through the open doorway and pressurisation air quickly clears small amounts of smoke which do filter through when the door is closed again (5).

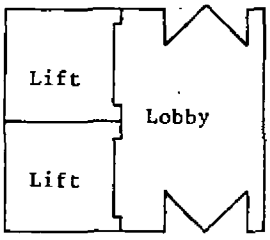
4.4.2 *Large openings*

Smoke and hot gases can infiltrate onto an escape route against an outward flow of air due to the action of buoyancy forces across a large opening e.g. an open doorway (72). Such infiltration can be curbed by maintaining an outward velocity of sufficient magnitude to overcome the buoyancy effect, the required velocity being proportional to the temperature difference across the opening (see Fig. 8). Although it has previously been stated that pressurisation design will be based on closed door leakage rates the above relationship can be used to assess whether smoke will be kept back in the event of a door being opened. A velocity of 1 m/s, corresponding to a 20°C temperature difference, should meet most purposes during the evacuation period, though it may not be sufficient to counteract flows arising from building wind and stack effects. It should be noted that the flow stratification of hot gases and backflow in a corridor is considerably more complex and cannot be treated in this simple way.

4.4.3 *Calculation of air flow rates for pressurisation systems*

In the straightforward case of a lobby or staircase, the air flow rate is simply the sum of leakage allowances at the desired pressurisation. Two examples are given below of more complicated situations occurring quite frequently.

Example 1 Pressurised lift lobby on each floor of a 5-storey building



Design pressurisation = 25 N/m^2

Leakage rate into the lift shaft depends on the leakage area of ventilation opening to the shaft and the lift doors in series.
Vent area = 0.1 m^2 per lift
Lift door leakage area = 0.05 m^2 per door
Total leakage area into each shaft = 0.25 m^2

From equation 3.4, the effective leakage area of each shaft is

$$\frac{1}{A^2} = \frac{1}{(0.25)^2} + \frac{1}{(0.1)^2}$$

A = 0.093 m^2 (Note: For 8 or more storeys, A would be approximately 0.1 m^2 i.e. just the area of the vent)

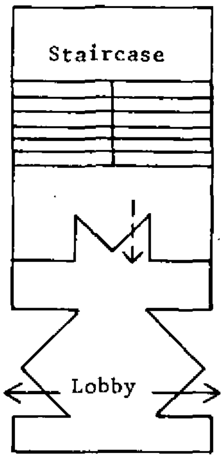
Air leakage per shaft at 25 N/m^2 = 827 x 0.093 x $(25)^{\frac{1}{2}}$ (Eqn 3.2)
= 385 ℓ/s or 77 ℓ/s per floor.

Leakage rates per lobby:

Double leaf doors	=	2 x 123	=	246 ℓ/s
Lift shafts	=	2 x 77	=	154 ℓ/s
Total			=	400 ℓ/s

Total air supply rate per lobby required for pressurisation
= 400 ℓ/s

Example 2 Two systems serving to produce different pressures in adjacent areas



10 storey staircase, adjoining lobby on each floor,
Design pressurisation: staircase 35 N/m^2
lobbies 25 N/m^2

a) Staircase

Pressure difference between staircase and lobby
= 10 N/m^2
Leakage rate per double leaf door at 10 N/m^2 = 78 ℓ/s

Total staircase supply rate = 78 x 10 = 780 ℓ/s

b) Lobby

Leakage rate from lobby:
2 double leaf doors at 25 N/m = 123 x 2 = 246 ℓ/s
Leakage rate into lobby from stairs = 78 ℓ/s from (a)

Total lobby supply rate required = 246 - 78
= 168 ℓ/s per lobby

4.5 *Venting requirements*

Fresh air introduced into the building for pressurisation must escape again otherwise the complete building becomes pressurised and the internal air flow patterns and hence smoke movement are no longer under control. The high and low pressures would no longer be clearly defined. The venting of pressurisation air is then as an important part of pressurisation as the controlled supply of air.

The position of pressure relief points is also important in controlling the internal air flow pattern. Vents must be provided to relieve pressure from each floor served by a pressurised staircase or from each room served by a pressurised corridor to ensure that the required pressure differentials are achieved across all entrances or exits of the escape route.

4.5.1 *Methods of venting*

Practical methods by which air may egress from buildings incorporating pressurisation systems are:

(i) leakage past cracks formed in openable (but normally closed) windows

(ii) vents in the external walls

(iii) mechanical extract systems

(iv) natural ventilation systems.

4.5.2 *Window leakage*

The leakage characteristics of windows were discussed in section 3. In naturally ventilated buildings there is normally sufficient leakage past window frames for the pressurisation air to escape and further venting measures may not be necessary. An assessment can be made as to whether there is sufficient window crackage to provide the required peripheral leakage area. Using typical window leakage rates from section 3, Table 4.3 gives the required crack length in terms of the net volume rate of pressurisation air supplied to the floor Q_N ℓ/s. Q_N will be less than the total pressurisation volume rate where lift shafts and other defined routes contribute to the total leakage from the building.

Table 4.3 Recommended minimum window crackage to relieve pressurisation systems

Window type	Typical air leakage rate ℓ/s. m. N/m^2	Recommended crack length in metres
Pivoted	0.21	1.2 Q_N
Sliding	0.082	3.0 Q_N
Pivoted and weather-stripped	0.030	8.3 Q_N

Non-weatherstripped windows will normally provide sufficient crackage for peripheral leakage. The figures in Table 4.3 indicate that additional venting by one of the methods described below will be necessary to supplement leakage through weather-stripped windows, where these provide insufficient crackage on their own. Use of sliding windows may also necessitate extra venting, since they normally incorporate some form of weatherstripping.

In assessing the required crackage per building floor, window crackage on one side of the building should be discounted to allow for the possibility of adverse wind conditions.

4.5.3 *Peripheral vents*

In this proposal vents are spaced uniformly in the external walls and these are released in the event of the pressurisation system being activated. These vents would be more effective if they had non-return characteristics to prevent back flow under adverse wind conditions. This method achieves the leakage requirement when the building facade is particularly airtight, e.g. when the glazing is sealed. The effective open area on a floor to be provided by the vents has been shown by the computer analysis to be $Q_N/2500$ m^2 where Q_N is the net volume rate in ℓ/s of pressurisation air to the floor as defined in 4.5.2. The effective area is that which can be considered unaffected by wind pressures, hence vent areas on a windward face must be discounted. In assessing the minimum vent areas required the above criteria must be met with the vents on any one side of the building not being effective.

4.5.4 *Mechanical extract*

If the mechanical extract system in an air conditioned or mechanically ventilated building can be run in the event of a fire then this is an effective way of removing pressurisation air from the accommodation.

The minimum extract required on each floor is the pressurisation supply to that floor if the air conditioning or ventilating supply is stopped. If the extract rate on the fire floor can be increased over that on other floors in a sealed building then this has a considerable advantage in reducing the fire floor to a minimum pressure area. The extract points must not be positioned within pressurised areas nor in such areas adjacent to pressurised areas that would prevent flow to the accommodation (e.g. internal toilets).

There are practical difficulties involved in this method of venting. The extract system must be able to handle very hot gases (although the temperature will be reduced by dilution with air extracted from other floors). Heat or smoke actuated fire dampers must be omitted otherwise the venting would be stopped when most needed. Such an arrangement would conflict with present regulations but it is possible that shunt duct connections on each floor might be an acceptable way of preventing fire being transmitted to other parts of the building by the extract duct. Electrically operated dampers under the control of the fire brigade are another alternative.

4.5.5 *Natural extract systems*

This is an alternative to the above and has a potential application in sealed buildings of open plan layout. The most economical arrangement is likely to be a vertical vent shaft running the height of the building with openings to each floor. These openings would normally be closed by a damper but in the event of a fire the damper would be opened on the fire floor. This opening could be achieved by an automatic smoke detector system. Alternatively it could be made by the release of a fusible link although this is less satisfactory since considerable smoke could be generated before the damper is released.

The only openings to the shaft that occur are at the top of the shaft and on fire floors. The size of the opening to a fire floor must be sufficient to vent all the pressurisation air supplied to that floor plus some pressurisation air from other floors. This is to ensure a general air movement to the fire floor. The sizing of the vent and shaft shall be as follows:

Net vent area (room to shaft) $A_v = \frac{Q_N}{2000}$ m^2

where Q_N = net pressurisation floor supply ℓ/s
Vertical shaft size = $3\ A_v\ m^2$
The area of the opening at the top of the shaft shall not be less than the area of the shaft itself.

4.6 *Underground Buildings*

Pressurisation can be applied to underground buildings and in the case of extensive or deep accommodation it is perhaps the only practical measure for smoke control.

Stack effects are negligible underground and apart from the possibility of wind-induced cross flow near ground level the wind effects are not great. The pressures required are then only those for low level buildings, i.e. 25 N/m^2.

Venting of potential fire spaces is essential and is normally achieved by natural ventilation shafts (4.5.5.). These need not be sited at the periphery. These vent shafts can be smaller than those normally specified for naturally smoke vented underground buildings since the pressures developed by the plant can aid egress through the shafts.

Care is necessary in the design of the terminal to the shafts to ensure adverse wind pressures are not generated.

5. MECHANICAL PRESSURISATION SYSTEMS

The objective of a pressurisation system is simply to provide sufficient clean air at the required pressure level to the escape routes to keep them clear of smoke and toxic gases. It needs to perform this function in the event of a fire for a sufficient length of time for the occupants to escape or seek a safe refuge and to aid the fire-fighting team in their attack on the fire.

The mechanical design of a pressurisation system should meet all the technical requirements needed for this objective as economically as possible. The economics will be influenced by the schedule of operation of the system, that is whether the plant is idle except for an emergency or whether it runs continuously and if so at what level of performance. The operational requirements are discussed in detail below.

5.1 *Operational schedules for pressurisation systems*

The three basic modes of operating pressurisation systems are:

(a) pressurisation plant normally off. In the event of a fire the plant is switched on to its full duty.

(b) pressurisation plant runs continuously at full duty during all hours of occupancy.

(c) pressurisation plant runs continuously at reduced capacity during all hours of occupancy with a boost to full duty in the event of a fire.

The advantages and disadvantages of these three modes are discussed in detail in the following notes.

5.1.1 *Plant off except in an emergency*

The strict requirement for pressurisation is fully met by this mode of operation. The basic weakness is that there can be a delay between the start of a fire, its discovery and notification and the starting of the pressurisation plant. During the early stages of a fire it is possible for large quantities of smoke to be generated through incomplete combustion and hence the operation of pressurisation during the early stages is important. If an automatic smoke detector system is installed and the alarm also initiates the pressurisation plant this weakness is met. This is not likely to be the case in typical office accommodation which constitutes the bulk of tall buildings. Whilst site tests have shown (5, 6) that pressurisation can quickly and effectively clear escape routes if smoke does infiltrate on to them this could still be a hindrance during the early stages of evacuation. This mode will then rely on an early discovery of a fire for the system to fulfil all its duties.

5.1.2 *Plant running continuously*

This meets the objective of the availability of pressurisation during the early stages of a fire but this mode has the disadvantages of relatively high running costs and of difficulty in providing adequate environmental conditions on the escape routes during normal occupancy.

The high running costs arise through:

(i) continuous running of the pressurisation fans

(ii) supply of heat to temper the pressurisation air in cool weather

(iii) in air conditioned buildings the use of refrigeration to counteract the direct introduction of outside air into the building.

It was apparent from the site visits to existing installations that the environmental conditions in pressurised areas were distinctly uncomfortable when the pressurisation systems were operating at full duty. The causes were strong draughts and excessive noise and these were due to the substantial air volumes being circulated in the stairwells and the lobbies. These existing systems were not intended to operate continuously and it would be feasible, but difficult, to disperse the momentum of the supply air without causing objectionable draughts if continuous running was requested. The modifications needed to reduce the possibilities of draughts and noise would add substantially to the system costs. There are special cases where continuous running of the pressurisation would be warranted, an example is a building where known toxic gases would be generated by a process if a fire occurred. Otherwise the additional costs are excessive to cater for the possibility of some smoke infiltration onto escape routes prior to the alarm being raised.

5.1.3 *Plant running continuously at reduced capacity except in an emergency*

This mode seeks to overcome the objection of possible smoke infiltration on to escape routes before the fire alarm is raised by supplying sufficent air to limit the smoke movement towards the escape routes and to dilute any smoke that does actually enter them. The cost saving of operating pressurisation schemes at reduced capacity is quite substantial.

A particular reason for advocating running the pressurisation systems continuously at reduced capacity is that they would serve the dual purpose of some smoke control facility at all times and of providing the normal fresh air ventilation requirements for internal spaces. The ventilation requirement for internal corridors as recommended in the IHVE and ASHRAE Guides is 1.3 ℓ/s per m^2 of floor area. Considering a typical pressurised lobby of 50 m^2 floor area with two double exit doors and two lifts, this would need an input of about 500 ℓ/s, that is 10 ℓ/s per m^2, to produce a pressure differential of 25 N/m^2. In this case the level of pressurisation produced by the normal ventilation requirement is,

$$\left(\frac{1.3}{10}\right)^2 \times 25 = 0.42 \ N/m^2$$

This is insignificant in terms of commonly occurring pressure fluctuations within a building, hence the ventilation needs do not contribute to the pressurisation requirements. However a common system to serve both needs is quite feasible.

A more realistic estimate of the level of pressurisation needed during the very early stages of a fire (before the alarm is raised) should be based on the following:

(i) pressures developed in the early stages of a fire
(ii) wind and stack effects that are not commonly exceeded
(iii) smoke dilution capabilities of the pressurisation air.

In section 4 it was shown that a fully developed fire on one side of a closed door could produce a pressure differential at the top of the door of 8.5 N/m^2. If the fire is not fully developed then the pressure differential is less. A typical test (73) indicates that the room temperature is likely to reach about 200°C during the early stages of a fire. The pressure difference developed across the top of a closed door at this condition is about 4.5 N/m^2.

In the analysis of wind and stack effects in section 4 extreme climatic conditions have been assumed to exist when a fire develops. In fact for most of the year the wind and stack effects are significantly less. The IHVE Guide, Book A, gives 90% of all days at temperature of 4°C and above and coincident wind speeds at the low temperature are rarely above 7.5m/s (for London). Hence a stack effect arising from an outside temperature of just 4°C, inside temperature 21°C, and neglecting the wind effect would cover eventualities on 90% of all days. The stack effect for this condition is a function of the building height as given below.

Building height m	Stack effect N/m^2
5	0.5
25	2.5
50	5.5
100	10.5
150	16

Hence the pressure and flow conditions given in Table 5.1 would meet most conditions occurring during the early stages of a fire whilst operating at a lower level of pressurisation.

Table 5.1 Recommended reduced pressurisation levels

Building height m	Reduced fire pressures N/m^2	Reduced stack effect N/m^2	Reduced pressurisation level N/m^2	Recommended levels N/m^2	Approx. % reduction in flow over full capacity
5	4.5	0.5	5.0	7.0	50
25	4.5	2.5	7.0		
50	4.5	5.5	10.0	15	45
100	4.5	10.5	15.0		
150	4.5	16	20.5	20	40

The operating costs for a system running at half capacity are about one third of those for continuous operation at full capacity.

5.1.4 *Application of operating schedules*

The choice of preferred operating schedule will be influenced by the probability of early detection of a fire. Automatic smoke detector systems or a reasonably dense occupancy level should ensure early detection, but where sleeping accommodation is involved or the occupancy density is very low detection could be delayed and the operation must take this into account. The following arrangements of operation are suggested.

Table 5.2 Economic duct velocities in vertical ducts (m/s)

Building Occupancy	Alarm System	Mode of Operation
Typical office accommodation	Manual or automatic	Plant normally off. Operates on alarm being raised
With sleeping accommodation	Automatic smoke detectors	Plant normally off. Operates on activation of alarm.
	Manual alarm	Plant at reduced capacity. Boost to full capacity on alarm being raised.

5.2 *Basic Mechanical Systems*

The component parts of a pressurisation system are:

(1) Plantroom, housing fresh air intakes
fans and associated controls
heater batteries and filters
interconnecting ductwork

(2) Distribution systems comprising ducting supply systems
terminal diffusers
venting arrangements

(3) Building venting arrangements (see section 4).

5.2.1 *Plantroom*

Certain specific requirements apply to the plant, its positioning and its protection in case of fire. The major requirements are:

(i) that the air intake shall be in a position free from smoke logging and physical obstruction

(ii) the plantroom shall be constructed of materials giving a minimum one hour fire resistance

(iii) the reliability of the plant items shall be high.

A plantroom at or near ground level has the advantages that the intake should be relatively free from smoke logging (since hot smoke and gases rise) and also it is readily accessible to the fire-fighters. An additional point is that power supplies need not be run extensively within the building.

Past practice has shown a preference for positioning plantrooms at roof level (see section 7). This position presents a possibility of smoke and toxic gases being drawn into the air intake since these contaminants will tend to cling to the building facade while rising and, depending on the wind direction, some can be trapped over the roof. The possibility of this influencing the quality of the fresh air intake can be reduced by providing two intakes spaced apart and facing different directions. This arrangement is recommended for all plantrooms placed at high level.

The air intakes should be ducted to the fan inlet. This measure is necessary to prevent the pressurisation fan reducing the pressure in the plantroom below atmospheric pressure and hence inducing flow from the building towards the plantroom.

The reliability of the plant items are discussed in section 6.

Where an emergency power supply is provided (other than from batteries) then the pressurisation fan should also be connected to this supply. The load that can be taken on the emergency power supply may influence the sizing, and hence the power requirements, of the pressurisation fan.

5.2.2 *Distribution arrangements*

The purpose of the distribution system is to convey the air to the escape routes in the event of a fire and to do this economically. The escape routes in general consist of lobbies and staircases and these invariably repeat themselves at the same position at each floor level for at least a number of successive floors. Distributing to these areas with a minimum length of ducting can be achieved by:

(a) A single plant serving a vertical duct with short horizontal branches to each floor.

(b) System (a) but with plants at various levels so as to restrict the length of duct run served by a single plant.

(c) Individual plants serving each floor.

These methods are shown schematically in Fig 9.

If arrangements (a) and (b) are compared it is apparent that (b) does not present any particular economic advantages unless the building is very tall and ducting is a major part of the system cost. Taking the cost of the vertical ducting as uniform per unit surface area and the cost of the horizontal branch connections and fittings being 25% of the total ducting cost then the capital cost ratios are approximately:

No. of plants and vertical ducts	Relative distribution costs	Relative plant room costs
1	1.0	1.0
2	0.89	1.6
3	0.82	2.1

These figures do not take full account of the floor space saved by running smalled ducts vertically when more than one plant is used.

There is a technical reason for limiting the vertical distance served by any one pressurisation system. This is the need for a design which inherently meets the requirement for uniform (or set) discharge at intervals along the vertical length. This is more easily achieved as the number of branch outlets is reduced (section 5.2.4).

It is more difficult to quantify the cost comparison between systems (a) and (c). Provided system (a) has branches of limited length and complexity this method will almost always be cheaper in the case of a multistorey building since the recommended requirements for (c) would, in the case of internal pressurised areas, include:

(i) individual fan units with controls duplicated at building entrance

(ii) horizontal ducts spanning the building width so that air intakes could be in two alternative positions

(iii) enclosure of fresh air ducts to give them the necessary fire resistance.

The advantages of (c) are that the vertical shaft is eliminated and net floor space can be increased.

5.2.3 *Ductwork construction*

The constructional requirements of ducting are for integrity in the event of a fire and long life at a minimum cost.

These properties for common duct materials are summarised qualitively in Table 5.2.

Table 5.2

Duct material	Maximum operating temperature °C	Resistance to atmospheric corrosion	Relative cost
mild steel	500	poor	1.00
galvanised mild steel	500	good	1.25
aluminium	250	good	1.60
P.V.C.	60	excellent	1.90
stainless steel	600	excellent	9
brick or concrete	1000	good	low since structural shaft is normally required. Extra cost is for sealing.

The economic choice is between galvanised mild steel ducting and builders work. The latter is probably slightly cheaper (Appendix A), but the necessity for completely sealing the surfaces, and preferably the internal surface, of builders work ducts is very important. Brick ducts should not be used for pressurisation without an internal lining or rendering of the surface. Experience has shown that without sealing the loss through leakage can be high (20 - 50%).

The cost of rectangular sheet metal duct is significantly influenced by the design operating condition, that is with fan operating at maximum capacity. Current constructional specifications (67, 68) distinguish between low velocity ducting at pressures up to 500 N/m^2 and high velocity ducting at pressures over 500 N/m^2. The latter is approximately 25% dearer (61). Since ducting constitutes about 50% of the total system cost, the difference represents about 12% on capital costs. For circular sheet metal ducting there is little difference in cost between low velocity and high velocity ducting.

Pressurisation ducting must be run in a protected shaft but it does provide a vertical duct connecting with all floors. Whilst this would normally require fire dampers it is recommended that these be omitted so as to eliminate the possibility of a malfunction of a damper shutting down the pressurisation system in an emergency. With the system running at full capacity the pressure developed by a fully developed fire would not be large enough for the fire to enter the duct and hence spread of fire through the duct would be prevented.

5.2.4 *Duct sizing*

Experience gained from the site visits (Section 7) indicated that many systems were initially well out of balance and considerable adjustment at the terminals was necessary to approach the discharge conditions specified. In one case the system was incapable of being balanced in its installed form. This situation is not acceptable when the correct distribution of air is a prime requirement for the system. The mal-distribution, which was common, need not arise if suitable procedures are adopted to size the distribution system. Two design procedures which produce an inherently balanced distribution system for long ducts with uniformly spaced outlets are:

(a) the static re-gain method for variable section ducts

(b) the manifold design method for constant section ducts.

(a) Static regain method

The design pilosophy of this method is that for a duct with multiple outlets spaced along its length the static pressure at entry to each branch shall remain constant. This can be achieved by balancing the static pressure gains and losses between the branch take-offs, i.e.

Static pressure regain due to lowering of velocity after a branch = friction plus other losses in main duct up to and including next branch.

The method sizes the duct so that this equation balances. Provided that the velocity pressure in the main duct does not contribute significantly to the flow in the branch this method of duct sizing should ensure approximately uniform outflow.

Standard charts (69) are available for computing the size of ducts to achieve this balance. The method has one particular limitation, if a main duct of constant cross-section is chosen then the design solution gives an equivalent duct diameter of about $\frac{\ell}{200}$ where ℓ is the duct length. This solution may be neither practical nor economic.

(b) Manifold design method

The solution to sizing ducts of constant cross section appears in many texts, a simplified solution which can be readily adapted to sizing pressurisation systems for multistorey buildings where the flow to each floor is equal is given by Haerter (70). A balanced flow situation can be achieved if:

(i) the main duct is made very large in relation to the branch ducts

(ii) the resistances of the branches are relatively high.

Where the equivalent diameter of the main duct does not exceed $\frac{\ell}{70}$

then these two requirements can be quantified by the equation,

$$nA_b < 0.7 \; A \; \sqrt{C_b}$$

or

$$A_b < \frac{0.7 \; A \; \sqrt{C_b}}{n}$$

where A_b = c.s. area of each branch duct, m^2

A = c.s. area of main duct, m^2

n = number of branch ducts

C_b = total resistances factor for branch duct

$$C_b = \frac{\text{total resistance of branch duct, N/m}^2}{\text{velocity pressure in branch duct, N/m}^2}$$

Total resistance of branch duct = branch entry loss + branch duct friction loss + branch duct fittings loss + terminal loss.

This simplified solution to sizing of main and branch ducts is not valid if the take-offs at each floor differ substantially.

5.2.5 *Economic duct velocities*

The economic duct velocity is that velocity which produces the lowest annual operating cost for the pressurisation system. The cost factors involved in conveying air for pressurisation through buildings are:

(i) plant capital costs
(ii) ducting costs
(iii) plant operating costs
(iv) space costs.

A simplified analysis of these costs is presented in Appendix A. Considering only the main vertical distribution duct this analysis (equation 8) gives the mean values of Table 5.2 for a typical distribution system handling 1 - $10 m^3/s$.

Table 5.2 Economic duct velocities in vertical ducts (m/s)

Annual plant running hours	Duct space rental £/m²/Annum		
	0	20	50
2600	12	17	21
0	20	27	33

6. RELIABILITY OF PLANT FOR OPERATING PRESSURISATION SYSTEMS

6.1 *Introduction*

The reliability of mechanical ventilation in comparison to natural ventilation is one of the main points in favour of pressurisation. The possibility of a breakdown occurring in mechanical plant must however be considered since safety of life may be dependent on the plant. A separate study has been made by HVRA of the reliability of heating and ventilating equipment (62) and use has been made of data collected in this study to assess the likely performance of pressurisation systems. The need for standby plant has been considered in the light of failure rate data and the frequency of fire outbreaks in buildings. The type of standby plant, where it is required, has also been considered.

6.2 *Concept of reliability*

Reliability is the probability that an item will perform a required function under stated conditions for a stated period of time. If n items out of N are still serviceable after this period, the reliability $R = \frac{n}{N}$. Hence if no failures occur, R = 1. R can be related exponentially to the failure rate λ (number of failures per unit time), making the simplification that λ is constant with time.

The criterion of reliability can be used to assess the performance of systems. Where the plant is run continuously, the criterion is the probability of a failure within a given period of time. Alternatively where a system only operates at any required instant, e.g. emergencies, then availability (ratio of time in working condition to total time) is the correct criterion.

6.3 *Failure rates for mechanical plant*

Items of plant to be considered in an assessment of reliability of pressurisation systems are fans and their motors, various controls including switches, failure sensing devices where standby plant is to be provided, filters and ductwork including grilles. Failure rates where available and estimates of the useful life of these items are given in Table 6.1. Failure rates are given as the average number of faults per year requiring unscheduled maintenance action. A failure rate of 0.5/yr is equivalent to one failure every two years. Electrical faults include power failures due to power cuts, although the HVRA survey did not include data for the two winters 1970/71 and 1971/72, when extensive power cuts occurred. No data was available on the reliability of standby generators.

6.3.1 *Fan systems*

It can be seen from Table 6.1 that fans and motors are the major sources of failure, and rates are independent of size (motor kw) and the ratio of operating/calendar hours. Common causes of failure are bearings in both fan and motor, and drive belts for centrifugal fans. A direct driven axial fan has a greater inherent reliability than a centrifual fan due to the elimination of some fan bearings and the drive belts. Not all faults result in total loss of capability, the percentage that do being considerably greater for axial fans than centrifugal (68% as opposed to 23%). This is due to the difficulty of regularly inspecting installed direct driven axial fans. The average time to repair a fault is 12 hours for both types.

6.3.2 *Controls*

Failure rate data for controls is rather scanty. The figures given in Table 6.1 are not specifically for ventilation plant. Electrical faults in starter switches, etc. are included in the fan motor rates. 15% of all centrifugal fan faults were electrical ones in the data used.

Table 6.1 Failure rates for mechanical ventilation plant

Item	Failure rate/yr.	Estimated useful life years
Axial fan	0.052	15 - 20
comprising fan	0.002	
motor	0.05	
Centrifugal fan	0.5	15 - 20
comprising fan	0.25	
motor	0.25	
Controls		
pneumatic	0.68	15
electrical		15
Automatic filters	negligible	10
Ductwork	negligible	Life of building
Grilles, diffusers	negligible	15 - 20
Fresh air screens and louvres	negligible	15 - 20

6.4 *Fire statistics*

The probability of an outbreak of fire per building per unit time is the frequency of outbreaks divided by the number of buildings at risk. The frequency of outbreaks in buildings of various occupancies are published in the annual fire statistics for the U.K. (63). The number of buildings in these groups can be obtained from rating information (64), also available annually. An estimate of the probability of a fire outbreak for some building occupancies has been made along the lines used by Baldwin (65) but using data from these 2 sources for 1968 (see Table 6.2).

Table 6.2

Occupancy	Probability of an outbreak of fire per building per year.
Offices	0.0016
Private dwellings	0.0023
Shops	0.0056
Hotels	0.025
Education establishments	0.039
Industrial	0.089
Local government	0.39

Fire statistics used are based on the number of fires large enough for a fire brigade to be called. In some buildings several outbreaks may be experienced in one year, in others none at all. The occupancy classification varies slightly between the 2 sources, as the population is not strictly the same. Nevertheless the figures serve as a useful approximate guide. In this light office buildings present relatively low risk, hotels medium and local government buildings high.

6.5 *The need for standby plant*

Provision of both main and standby plant for pressurisation systems is an obvious way of increasing system reliability. To provide a rational basis for deciding whether the extra expense of providing standby plant is justified, a statistical approach has been initially taken but this must be tempered by the emotional considerations associated with the safety of life in the final analysis.

The chance of a fire outbreak and pressurisation plant failure coinciding

The probabilities to be considered are that a fire may occur during breakdown or vice versa. The probability of 2 separate events occurring together is given by the product of their separate probabilities.

Consider the worst combination from the data in Tables 6.1 and 6.2, a centrifugal fan operating a pressurisation system in a local government building. The mean time the fan would be inoperative if failure occurred is 12 hours. Hence probability that fan is inoperative for any 12 hour period in a year is

$$\frac{0.5}{2 \times 365} = 6.9 \times 10^{-4}$$

Probability of fire outbreak in any 12 hour period in a local government building is

$$\frac{0.39}{2 \times 365} = 5.3 \times 10^{-4}$$

Probability of a plant failure coinciding with an outbreak of fire is therefore 3.7×10^{-7}.

This is extremely small and does not appear to justify provision of standby plant.

This is not to say that standby plant is not necessary at all, just that the need for standby plant is very small. Where lives are possibly at stake there is a strong desire on the part of authorities to ensure maximum safety. Reliability of 1 is not attainable but by providing standby plant the reliability can be improved. Various forms of operating pressurisation plant with standby provisions are considered in the next section.

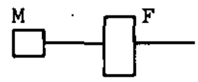
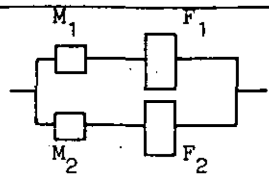
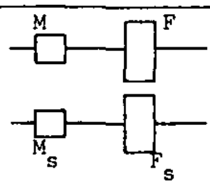
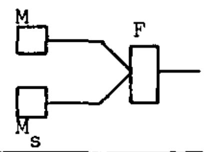
6.6 *Operation of standby plant*

Reliability figures, based on failure rates from Table 6.1, are given for the following configurations of standby in Table 6.3.

1) Single fan and motor, i.e. no standby.
2) Two fan and motor sets in parallel (both operating).
3) Fan and motor, standby fan and motor.
4) Fan, motor and standby motor.

Reliability of standby and parallel systems are given by Ireson (66).

Table 6.3

Arrangement	System M = motor (subscript s F = fan for standby)	Reliability Fan type Axial	 Centrifugal
1		0.949	0.607
2		0.997	0.579
3		0.998	0.910
4		0.996	0.758

The overall reliability figures for arrangements (3) and (4) assume reliability R = 1 for switches and failure sensing devices that operate standby plant.(this reliability is not reached in practice). These figures show that a considerable increase in reliability is gained by having a standby fan and motor, though, in the case of an axial fan, little extra is gained by having the fan itself, the standby motor being sufficient.

A parallel system where both fans operate simultaneously and one would continue to run at reduced load if the other failed, appears to be significantly less reliable than a single fan and motor of centrifugal type due presumably to a greater inherent failure rate, i.e. more components to go wrong.

6.7 *Conclusions*

Mean failure rates for mechanical plant are low, the main causes being fan and fan motor. Axial fans are more reliable than centrifugal ones. The risk of a breakdown coinciding with a fire is apparently very small, though where a life support system is concerned, reliability is of paramount importance to continuing safety of occupants and warrants the provision of standby plant. In particular a standby motor and/or fan improves potential reliability considerably. However, the general conclusion is that standby plant is not objectively necessary to achieve a high level of plant availability in the event of a fire.

7. PERFORMANCE OF EXISTING PRESSURISATION SYSTEMS

7.1 *Introduction*

At the present time there are at least ten known completed buildings in this country with pressurisation systems and undoubtedly many more are planned or under construction. None of the operational ones has been put to the test by a significantly real fire situation yet, so in a sense their design criteria and performance has not been completely proven. However smoke tests and various measurements have been made which demonstrate their effectiveness in simulated fire conditions. Two site tests have been carried out by JFRO (5, 6) using a density of smoke comparable with fire conditions, but the accompanying temperature rise has been rather small because of the practical difficulties associated with simulation of fire in completed buildings. The results of these tests are summarised below.

7.1.1 *Pearl Assurance House, Cardiff*

This 26-storey office block has a centre service core containing two staircases with a lift lobby in between them. In normal operation air is supplied to the staircases at the rate of 4 air changes per hour and to the lobbies at 8 air changes per hour. Air is extracted from the staircases, also at 4 air changes per hour, to provide a balanced ventilation system. In an emergency the staircase supply is boosted to 16 air changes an hour, extract and lobby supply remaining the same.

Although the pressurisation obtained was fairly low (5 N/m^2 across stair door and 7.5 N/m^2 across lobby door) because of the low air flow rates and the extraction from the stairs, smoke tests in both stairs and lobby showed that the system was capable of keeping smoke out of them when the doors were closed and the outside weather conditions were typical.

7.1.2 *Royal Courts of Justice, London*

This is a 14-storey block consisting mainly of office accommodation. Twin staircases in the central core were to be provided with continuous pressurisation to 7.5 N/m^2 during office hours. In the event of a fire, pressurisation was designed to be increased to a level of 25 N/m^2, this pressure being maintained while a door to the staircase was held open.

The design figures were adequately met. Smoke tests were carried out under normal and emergency conditions, smoke being generated in one of the office areas. The performance of 'normal' pressurisation was rather inconclusive, possibly due to ambient conditions at the time of the test. Emergency pressurisation was capable of preventing smoke entering the staircase and lobbies, although some smoke spread to other parts of the building, possibly via the ventilation ductwork, was observed. This was thought to be due to the air tightness of the external wall construction.

7.2 *Site test programme*

An investigation of some existing systems (other than those mentioned above) has been made to assess their performance and to examine practical problems arising in their design and operation. In the light of the previous work further smoke tests were considered unnecessary. A quantitative assessment of performance of three systems was made by the following measurements:

(i) the measurement of the air supply rate to the enclosure by the pressurisation system. Direct reading anemometers and hoods were used to measure the air flow at each inlet grille.

(ii) the relative pressures attained in the pressurised areas. Pressure differences across separating doors were measured using a micromanometer and the pitot described earlier (Plate 3).

The precision of measurement (i) was subject to certain limitations. In each case site conditions ruled out the possibility of in-duct measurements, which are inherently more accurate, for both the branch ducts and the fan discharge. Hence neither the fan performance nor duct losses could be measured. In addition the grille measurements made could have been suspect due to non-uniformity of flow at the grille face in some cases. Nevertheless some conclusions can be drawn about the standard of ductwork from a comparison of design and actual air flows.

7.3 *The buildings*

7.3.1 *Deacon House, Sheffield*

An office building forming an L-shape, one leg of which rises to 8 storeys. A design pressurisation of 50 N/m^2 was specified for the main staircase and lift lobby areas. Some openable windows were provided in these areas but these were under the control of the fire brigade. The pressurisation system is single stage, coming into operation on demand (emergency) only. See Fig. 10 and Plate 4.

Based on a leakage allowance of 75 ℓ/s per single leaf door and 550 ℓ/s per lift shaft, a design air flow of 5135 ℓ/s (10,880 cfm) was calculated. The plant room is at roof level. It contains an axial fan rated at 5665 ℓ/s and mounted at the top of a vertical builders duct which has branches to each lobby and to the staircase at alternate floor levels. The fresh air intake is in the side of the plant room and is not connected directly to the fan. The design supplies were:

staircase	225 ℓ/s at each of 4 levels
lobbies	520 ℓ/s each, except ground floor = 595 ℓ/s for combined entrance hall/lift lobby.

Apart from mechanical extraction from the toilets, the building is naturally ventilated. Air leakage from the pressurised areas is via windows in offices, stairs and lobbies, extract ducts in toilets, lift shafts and an exit door at ground level from the staircase.

Tests were initially carried out before the building was fully completed. Temporary doors were still in place and the floors were unfinished. In view of the low pressure differences obtained tests were repeated on completion of the building to see what improvements had been made.

Comments

The site measurements are set out in Tables 7.1 and 7.2. A marked improvement in pressurisation was achieved in the second set of measurements (Table 7.2). With a mean value of 60 N/m^2, the final pressure difference between lobby and offices was higher than the design figure, despite the total air flow being lower by some 40% than required. This can be explained by the fact that pressure differences across other doors, for which full allowance has been made, were considerably smaller, indicating a significant resistance to leakage of air from toilets.

Overall the pressurisation was balanced between staircases and adjoining lobbies. This is not surprising in view of the positions of the respective supply grilles on adjacent sides of the pressurisation duct at the same level. Ideally the staircase would be maintained at a slightly higher pressure than the lobbies.

Table 7.1

Deacon House: *Site measurements on pressurisation system before completion of the building.*

Floor	Staircase		Lift lobby	
	Air supply ℓ/s	Pressurisation w.r.t. lobby N/m²	Air supply ℓ/s	Pressurisation w.r.t. offices N/m²
G		+ 25 †	Not measured	
1	115	- 2.5	145	+ 20
2		- 7.5	170	+ 12.5
3	105	- 2.5	260	+ 20
4		- 5	270	+ 20
5	85	- 2.5	300	+ 30
6		- 7.5	265	+ 20
7	105	- 5	285	+ 25
*Total	410		1695	

* Estimated leakage through the toilets was 140 ℓ/s giving an apparent system supply of 2245 ℓ/s.

† Pressure difference across door to outside.

Table 7.2

Deacon House: *Site measurements on pressurisation system after completion of building.*

Floor	Staircase		Lift lobby	
	Air supply ℓ/s	Pressurisation w.r.t. lobby N/m²	Air supply ℓ/s	Pressurisation w.r.t. offices N/m²
G		+ 2.5	525	+ 30 † (+105) ¶
1	160	- 7.5	250	+ 82.5
2		- 7.5	270	+ 87.5
3	170	+ 5	190	+ 52.5
4		+ 5	305	+ 60
5	185	- 2.5	210	+ 52.5
6		- 2.5	300	+ 60
7	125	0	265	+ 32.5
*Total	640		2315	

*Estimated leakage through toilets was 100 ℓ/s giving an apparent system supply of 3055 ℓ/s.

†Across two sets of double leaf doors in series. Pressure difference across each set is half this value.

¶Across main entrance door to street

During the tests a positive airflow from the toilet next to the duct into the lobby was noticed. It was discovered that the toilet extract ducting was situated inside the builders work pressurisation duct, and that pressurisation air was leaking into the toilets as a result. The estimated leakage is thus included in the total pressurisation supply.

Due to the suction of the fan, a negative pressure difference was created across the plant room door at the top of the stairs, and is the most likely cause of the reduced pressurisation at 7th. floor level.

7.3.2. *Dyson House, Sheffield*

This is a 9-storey office building (10 at the rear), the main staircase and lift lobby enclosure forming an internal service core at the inner angle of the L-shaped block. A pressurisation system providing a positive pressure of 50 N/m^2 in the staircase and lobbies was installed and comes into operation only in an emergency.

The plant room and air intake are at lower ground level. Two axial fans, main and standby, each rated at 7360 ℓ/s (15,600 cfm) are provided to distribute pressurisation air via a single vertical riser (consisting of sheet trunking inside a builders duct) to each lobby except the lower ground and the staircase at each half-landing. In addition a smaller fan supplies warmed air via the same ducting to lobbies and staircase during normal office hours. At ground floor level a fan rated at 1040 ℓ/s (2,200 cfm) has been mounted in the external wall of the main entrance lobby to cope with the increased volume of that space. This fan is linked electrically to the main pressurisation system.

Design air supplies for the main system, based on the same allowances as Deacon House, were 1660 ℓ/s for the stairs and 5665 ℓ/s for the lobbies. No other mechanical ventilation is provided in the building. Air leakage from the pressurised areas is via windows in office and toilet areas, lift shafts, main entrance and rear exit from the staircase at lower ground floor.

Tests were carried out on completion of the building but before it was occupied. Plate 5 and Fig. 11 show the building and its layout.

Comments

A summary of the site test results is given in Table 7.3. A mean pressurisation of 70 N/m^2 was achieved in the lobbies, significantly more than required. The corresponding figure for the staircase is 17.5 N/m^2 with respect to the lobbies, so that the total staircase pressurisation is effectively the sum of these values. These figures are surprising considering that the total airflow is approximately 35% less than the design, but can be explained by two factors:

(i) the lobby and staircase entrance doors were clearly a much better fit than average. Further leakage tests which were made revealed a mean gap width about 1.5 mm, or half the average value. Carpet tiles laid on the lobby floor probably contributed significantly towards this low value.

(ii) resistance to air leakage through the toilet windows increasing pressure in toilet areas.

The size of the main duct was relatively small causing a very high air velocity (approximately 20 m/s) at entry on full flow. The effect of this was apparent from the staircase measurements where extraction of air from the stairs took place at the lower 5 grilles.

Table 7.3

Dyson House: *Site measurements on pressurisation system.*

Floor	Staircase		Lift lobbies		
	Air supply ℓ/s	Pressurisation w.r.t. lobby N/m²	Air supply ℓ/s	Pressurisation w.r.t. office N/m² Door A†	Door B†
LG	-115	Not measured*		+ 10*	
G	- 80	+ 35	350 §	+ 20	+ 52.5 (+47.5) ¶
	- 25				
1	- 80	+ 5	465	+ 75	+ 75
2	- 35	+ 2.5	460	+ 75	+ 72.5
3	90	+ 17.5	495	+ 65	+ 67.5
4	180	+ 7.5	505	+ 75	+ 77.5
5	180	+ 12.5	495	+ 75	+ 75
6	200	+ 17.5	430	+ 67.5	+ 67.5
7	175	+ 17.5	380	+ 65	+ 67.5
8	205	+ 15	400	+ 77.5	+ 77.5
Total	695		3980		

† See plan

* door to outside

¶ across main entrance door to street

§ does not include additional fan input in ground floor lobby.

The volume of the pressurised enclosure only affects the air flow requirement in so far as the leakage characteristics may be changed. It is evident from the test results that there was some justification on this basis for the installation of the extra fan in the entrance hall.

7.3.3. *Basildon Hospital*

The tests at Basildon were concerned with a tower block containing office and residential accommodation and rising 9 storeys above the rest of the hospital. A central service core contains the staircase, of which the lobby was required to be pressurised to 50 N/m² on each floor. Natural ventilation was provided for the staircase by a louvred window and a louvred door, both at the top of the staircase. Apart from pressurisation, mechanical ventilation is only provided in the toilets. Plate 6 and Fig. 12 shows details of the tower block.

The plant room for the pressurisation system is on the 8th floor. Air intakes were situated on the roof above the plant room and were sheltered somewhat by a high parapet wall. A centrifugal fan rated at 2125 ℓ/s (4500 cfm) supplies air to the lobbies via a single vertical builders work duct. The system only comes into operation in an emergency and a standby motor can be brought in manually if required.

A design supply of 235 ℓ/s per lobby was based on an allowance of just over 75 ℓ/s per single leaf door. The inlet grille is situated at low level at one end of the lobby.

Air leakage takes place through lift shafts and windows, staircase entrance and vents to the atmosphere.

Two sets of measurements were made; firstly with the stair vents open and secondly with the vents temporarily blocked off. Sealing in the latter case was not perfect by any means, but the results show some improvement over the previous situation.

Comments

The site test results are summarised in Tables 7.4 and 7.5. With the stair vent open, a mean lobby pressurisation of 19 N/m^2 was measured, considerably less than required. Total airflow was 30% less than design, which is not enough to account for the low pressurisation. A total of approximately 2470 ℓ/s or 90 ℓ/s per door is calculated to achieve 50 N/m^2. This clearly reflects on the over size of the door gap.

Air distribution from this system is fairly uniform, 9th floor being an exception. The lobby grille on this floor is almost directly opposite the fan outlet connection to the main duct, resulting in a relatively high flow to the lobby.

In view of the low pressures and the airflow into the staircase at ground level the staircase vents were blocked off and the tests repeated. The effect of this was to increase the pressure difference between lobby and corridor (mean value 24 N/m^2) at the expense of a lower pressure difference between lobby and staircase. The staircase is pressurised with respect to outside air by leakage from the lobbies to a limited extent. The higher stair pressure observed in the second tests reduces the possibility of any smoke which does enter the lobby being driven onto the stairs.

Table 7.4

Basildon Hospital: *Site test measurements with staircase vents open.*

Floor	Air supply ℓ/s	Lobby pressurisation N/m^2		
		w.r.t. stairs	w.r.t.† corridor door A	door B †
G		- 6.5*	- 6.5¶	- 6.5§
1	165	+ 23	+ 22	+ 25
2	165	+ 14	+ 16	+ 16
3	165	+ 15	+ 14	+ 12.5
4	150	+ 15	+ 17	+ 18
5	165	+ 16	+ 20	+ 18
6	175	+ 21	+ 22	+ 20
7	185	+ 26	+ 23	+ 18
8	150	+ 15	+ 10	+ 10
9	205	Not measured		
Total	1525			

† see plan

* stair door to outside

¶ stair door to main entrance hall

§ stair door to changing room

Table 7.5

Basildon Hospital: *Site test measurements with stair vents blocked*

Floor	Air supply ℓ/s	Lobby pressurisation N/m^2		
		w.r.t. stairs	w.r.t. corridor door A †	w.r.t. corridor door B †
G		+ 22*	+ 16¶	+ 16§
1	165	+ 12	+ 32	+ 30
2	165	+ 5.5	+ 21	+ 22
3	165	+ 4	+ 23	+ 21
4	150	+ 4.5	+ 21	+ 22
5	165	+ 7	+ 27	+ 25
6	175	+ 10	+ 26	+ 24
7	185	+ 13	+ 28	+ 23
8	150	- 1	+ 17	+ 18
9	205	Not measured		
Total	1525			

† see plan

* stair door to outside

¶ stair door to main entrance hall

§ stair door to changing room

7.4 *General conclusions*

A properly sized ductwork system is clearly needed to achieve the required air distribution (see section 5) and in particular to avoid the sort of suction effect near the fan (reference Dyson House). It is important that a check of the fan and system performance can be made and the system should be designed with this in mind.

Although no direct check was made, it is expected that leaky ductwork contributed to the low airflows in each case. The site tests implied that the builders ducts were the main culprits and these should be rendered if it is intended to use them unlined for pressurisation. In any case an allowance for ductwork losses should be made at design stage.

Variation in the fit of doors is a major factor in attaining a specified pressurisation. It can be seen from the site tests that high pressure differences do not necessarily correspond to areas with high air supply rates. The only way in which an accurate design can be made is by fairly precise control over the size of door gaps to the pressurised enclosure.

In two of the buildings the fan was not directly connected to the air intake and this created a negative pressure in the plant room in relation to the rest of the building. There is a danger that smoke could be drawn into the plant room and distributed with pressurisation air to the escape routes. It is recommended that a ducted connection be used from the air intake to the fan inlet.

Pressurisation of staircase lobbies can provide an effective means of keeping smoke out of the staircase too, although the staircase is necessarily at a lower pressure and this may be considered an inferior smoke control system to positive pressurisation of the staircase. Providing the staircase is not vented, leakage from the lobbies pressurises the staircase to a limited extent.

8. DESIGN INFORMATION FOR PRESSURISATION SYSTEMS

This section sets out as concisely as possible the design data required for pressurisation, which has been extracted from sections 1-7. Reference to the appropriate subsection for more detail is given wherever possible.

8.1 *Space pressurisation requirements*

The level of pressurisation should not be less than the appropriate value for the building height given in Table 8.1 or greater than 50 N/m^2 with all doors to the pressurised zone closed (4.3, 5.1.3).

Table 8.1

Building height metres	Pressurisation level, N/m^2	
	Emergency operation	Reduced capacity operation
5 or under ground	25	7
25	25	7
50	50	15
100	50	15
150	50	20

The figures in Table 8.1 do not apply to buildings on coastal or other exposed sites i.e. those experiencing minimum temperatures less than -10°C or maximum hourly wind speeds greater than 20 m/s. A pressurisation of 50 N/m^2 will normally be required for exposed sites to overcome wind effects. Meteorological data for the exposed site should be considered to ensure that local conditions are taken into account (2.4.2).

8.2 *Air leakage characteristics of buildings*

Table 8.2 contains values of air leakage rates for doors (3.4.2) and windows (3.3.4) to be used in conjunction with the pressurisation requirement in calculating air flow rates for pressurisation. The leakage rate Q at other pressure differences, Δp, can be calculated from the leakage rate K at 1 N/m^2 using the appropriate value of N in Table 8.2. from

$$Q = K \times (\Delta p)^{\frac{1}{N}} \quad \ell/s$$

Table 8.2

Component	Type	Crack length m	Leakage rate ℓ/s — Pressure difference N/m^2: 1	7	15	20	25	50	Index N	Equivalent leakage area m^2
Windows	Pivoted	1	0.21	0.71	1.14	1.37	1.60	2.42	1.6	
	Pivoted and weather stripped	1	0.030	0.10	0.16	0.20	0.22	0.35	1.6	
	Sliding	1	0.082	0.28	0.45	0.53	0.61	0.94	1.6	
Doors	Single leaf a) office door with catch	5.5	9	24	34	39	44	62	2	0.01
	b) doors without catch	5.6	17	45	67	77	86	122	2	0.02
	Double leaf (with or without centre rebate)	9	25	66	95	110	123	174	2	0.03
	Lift entrance	8	39	103	151	174	195	276	2	0.05

8.3 *Calculation of air volumes for pressurisation (4.4.3)*

Procedure

(i) Consider building layout, confirm area(s) to be pressurised and decide on system of operation (5.1) to be used.

(ii) Select pressurisation levels for emergency and if necessary reduced capacity operation from Table 8.1.

(iii) Determine the component air leakage rates from each area at the required pressurisation as follows:

a) Single components

For individual doors and windows, use the leakage rates in Table 8.2. For other openings calculate the leakage rate Q as,

$$Q = 827\ A\ (\Delta p)^{\frac{1}{2}} \qquad \ell/s$$

Where A is the effective leakage area of the opening in m^2,

Δp is the pressurisation in N/m^2.

For single openings A is the net free area. The effective leakage area of several components in series is,

$$\frac{1}{(A)^2} = \frac{1}{(A_1)^2} + \frac{1}{(A_2)^2} + \frac{1}{(A_3)^2} + \ldots\ldots..$$

and the effective leakage area of several components in parallel is

$$A = A_1 + A_2 + A_3 + \ldots\ldots..$$

b) Lift Shafts

The effective leakage area and hence the leakage rate of lift shafts should be computed from the respective leakage areas of lift doors, ventilation and other openings to the shaft using the above equations. For shafts in which the only openings are the doors and the minimum vent area of 0.1 m^2 per lift required for ventilation purposes (74), the total leakage rate into the shaft is,

$$Q_D \times K_1$$

where Q_D = lift door leakage rate from Table 8.2,

K_1 = a factor for the number of floors (i.e. number of lift doors to the shaft) from Table 8.3.

Table 8.3

Number of floors served by lift shaft	K_1
1	0.9
2	1.4
4	1.8
8 or more	2.0

c) Toilets adjacent to a pressurised zone

For toilet and other areas which are directly connected to a pressurised zone and have mechanical extract systems, the leakage rate into them is either

a) the extract rate in ℓ/s when the extract fan is running,

or b) $Q \times K_2$ ℓ/s, with the extract fan off,

where Q = the door leakage rate in ℓ/s at the design pressurisation from Table 8.2, unless specific grilles or gaps are provided for air flow, in which case

$$Q = 827\ A_D\ (\Delta p)^{\frac{1}{2}} \quad \ell/s$$

K_2 = factor from Table 8.4 for the ratio of $\frac{A_B}{A_D}$

A_D = door leakage area including air flow grilles etc, m^2. For ordinary crackage around the door, a typical value for A_D is 0.02 m^2.

A_B = Minimum cross section area of extract branch duct in m^2. Note: This may occur at a balancing device i.e. orifice or damper.

Table 8.4

$\frac{A_B}{A_D}$	K_2
4 or more	1
2	0.9
1	0.7
0.5	0.45
0.25 or less	0.25

d) Large openings (4.4.2)

Design pressurisation cannot be maintained if large openings exist between pressurised areas and neighbouring spaces. If openings arise intermittently then design pressurisation levels are not continuously maintained but smoke can be kept back from the opening for short periods of time if the egress velocity from pressurised spaces is sufficiently high. A minimum egress velocity of 1 m/s is recommended. The average air velocity through the opening can be assessed from the air supply rate to the pressurised space and the area of the opening by assuming all the air flows out through the opening.

(iv) Determine the total air leakage rate as the sum of leakage rates through single components, lift shafts and toilets (iii).

(v) Determine the total rate of mechanical extraction, if any, from the pressurised spaces (other than toilet extraction included in (iii)).

(vi) The total fan capacity required is the sum of air flow rates from (iv) and (v), plus an allowance for duct losses as given in 8.4.3.

(vii) Supply rates at terminals to individual pressurised spaces are in the proportion of leakage and extraction rates from each space to the total fan capacity.

8.4 *Plant and plantroom requirements (5.1)*

The following recommendations cover the number and extent of pressurisation systems for servicing escape routes in buildings.

(a) A separate pressurisation system should be provided for each stairwell.

(b) A single pressurisation plant and distribution system may serve a stairwell and its associated lobbies where both are pressurised.

(c) Where more than one stairwell has access to a common lobby separate pressurisation systems should be provided for each stairwell as specified in (a). All or any of these stairwell pressurisation systems may also supply the common lobby.

The recommended operating procedures for pressurisation systems are summarised in the following table.

Table 8.5

Building details		Operating schedule for pressurisation plant	
Accommodation	Fire alarm system	Normal duty	Emergency duty
Occupied buildings without sleeping accommodation	Automatic or manual	Plant off	Plant runs at full capacity
Occupied buildings with sleeping accommodation	Automatic	Plant off	Plant runs at full capacity
	Manual	Plant off in daylight hours. Plant runs at reduced capacity during silent hours	Plant runs at full capacity

The reduced capacity level for plant operation in the case of buildings with sleeping accommodation should be 50 - 55% of the full air flow duty requirement. Where an automatic fire or smoke alarm system is installed this is assumed to initiate the pressurisation system when the alarm is made.

8.4.1 *Plantroom location (5.2.1)*

The preferable location for plantrooms housing pressurisation equipment is at or near ground level. They should not be placed near potential fire hazard areas, e.g. a boiler house.

Plantrooms can also be positioned at roof level or an intermediate level but these should include dual air intakes to ensure that at least one is clear of smoke. These intakes should face in different directions and if placed near the side of the building they should have smoke operated dampers in each inlet duct to prevent smoke circulation by pressurisation systems.

A system of pressurising each floor individually is feasible but may be more expensive.

8.4.2 *Plantroom construction*

The structure of pressurisation plantrooms should be of materials having a minimum fire resistance rating of one hour. Plantroom access doors should be self-closing.

8.4.3 *Plant (5.2)*

The basic plant requirements are a fan and distribution system. If the same system is used to supply the normal ventilation requirements to pressurised areas during occupied hours a heat exchanger and filter are likely to be included. These latter items can be by-passed for emergency operation.

The required fan duty shall be assessed from the following:

Volume flow rate = Aggregated supply to all pressurised areas (see 8.3) + 10% for possible leakage.

Fan total pressure = Total resistance of distribution system PLUS emergency pressurisation level (see 8.1).

Fan static pressure = Fan total pressure - velocity head at fan discharge.

For normal applications a standby pressurisation fan should not be necessary (see section 6.).

The ductwork systems should generally conform to BSCP 413 - Ducts for Building Services.

8.4.4 *Plant supply and controls*

Where an emergency power supply is provided for the building (other than by accumulators) then the pressurisation fan should also have a connection to this supply.

The following control arrangements are recommended:

(a) The fan shall be energised from an automatic smoke or fire detector system where this is fitted. The fan shall be switched off independently of the detector system.

(b) Manual start/stop controls shall be placed in the following positions,
   (i) in the central building services control room
   (ii) in the pressurisation plantroom if this is remote from the central control room
   (iii) near the building entrance in a position agreed with the local fire authority.

8.5 *Distribution system (5.2.2, 5.2.3)*

For multistorey buildings the preferred arrangement of a pressurisation distribution system is a vertical duct running adjacent to the pressurised spaces. This arrangement has advantages of low cost and minimum exposure of ducting in the event of a fire.

The distribution ducting should generally conform to BSCP 413. For the arrangement outlined above the latest draft of this Code of Practice calls for fire dampers where the branch ducts penetrate the vertical protective structural shaft. The operating conditions for pressurisation systems during the evacuation period should not lead to closing of such dampers, but they could create a hazard in the case of pressurised lobbies if a random mechanical failure of a fusible link occurred when the pressurisation fan started. To avoid this happening it is recommended that permission be sought to omit these fire dampers (fire dampers can be avoided if the duct is situated wholly within a protected enclosure).

The recommended forms of construction of the distribution system are,

(i) galvanised mild steel ducting run in protected shafts. The sheet metal construction should be to the HVCA specifications DW/121 or DW/132

(ii) brickwork ducting used solely for air distribution and with the internal surface rendered to limit air leakage

(iii) concrete ducting used solely for air distribution with all joints sealed.

Some leakage will occur with ducting made to these specifications. The air leakage can be limited to about 10% if care is taken to seal all obvious cracks and penetrations.

8.5.1 *Duct sizing procedures (5.2.4.)*

The basic requirement is to get the correct air distribution at minimum cost. A cost factor of some importance is the time spent in balancing an installed system, hence the system should be sized to give an approximately correct balance.

The two techniques that can be used to achieve an approximately correct balance at the design stage for a vertical distribution duct are,

(i) for a stepped duct, the static regain method

(ii) for a constant section duct, a manifold design method.

8.5.2 *Static regain duct sizing method*

This method seeks to achieve a uniform static duct pressure in the vertical duct at each branch take-off. The technique is to balance the static pressure recovery after a take-off to the friction losses up to the next take-off. The duct sizes are chosen to make this balance.

Charts which simplify the computation are given in ASHRAE Guide and Data Book (69) and in other publications. These should be referred to in actual duct sizing operations and a static regain factor of about 0.75 is recommended.

Where losses are given in terms of equivalent lengths these may be obtained from the following formula,

Equivalent length of fitting = 55k x No. of duct diameters

where fitting loss = $k \times \frac{1}{2}\rho V^2$

V = duct velocity

duct diameter = $\dfrac{4 \times \text{duct area}}{\text{duct perimeter}}$

8.5.3. *Manifold sizing method*

A simplified solution to this is given in (70). If the main duct area is selected then the maximum branch area is given by,

$$A_b = \frac{0.7A\sqrt{C_b}}{n}$$

If the branch area is chosen then the minimum area of the main duct is given by,

$$A = \frac{n\,A_b}{0.7\sqrt{C_b}}$$

where A = minimum c.s. area of main duct, m^2

A_b = maximum c.s. area of branch duct, m^2

n = number of evenly spaced similar branches

C_b = resistance factor for branch duct

= summation of 'k' values for branch duct.

C_b can be determined as follows,

Branch duct element	k factor for element	Area correction factor	Area corrected k value
branch connection	k_1	1	k_1
duct resistance	$\frac{f\ell}{d}$	$\frac{a}{A_b}$	$\frac{f\ell}{d}\left(\frac{A_b}{a}\right)^2$
branch fittings	k_2	$\frac{a}{A_b}$	$k_2\left(\frac{A_b}{a}\right)^2$
terminal	$\frac{2}{\rho}\frac{\Delta p}{V^2}$	$\frac{a}{A_b}$	$\frac{2}{\rho}\frac{\Delta p}{V^2}\left(\frac{A_b}{a}\right)^2$

C_b = sum of area corrected k values

The area correction is applied if the branch duct changes its cross-sectional area (from say A_b to a).

f = duct friction factor, approx. 0.018

ℓ = duct element length, m.

d = duct diameter (or $\frac{4a}{\text{perimeter}}$), m

a = c.s. area of duct fitting or length, m^2

Δp = terminal pressure drop, N/m^2

V = nominal velocity at duct terminal, m/s.

Some loss factors for typical branch connections are shown in Table 8.6

The losses in the straight through section of a branch fitting are relatively small. Values for a typical range of fittings are given in Table 8.7.

Table 8.6 Branch losses (k) for typical duct fittings

Branch loss $k = \frac{\Delta p}{\frac{1}{2}\rho V_3^2}$

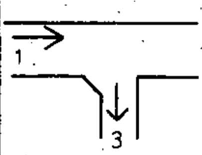
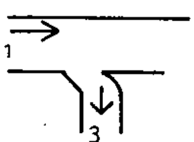
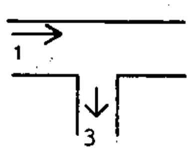
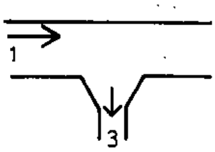
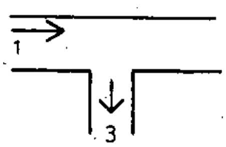
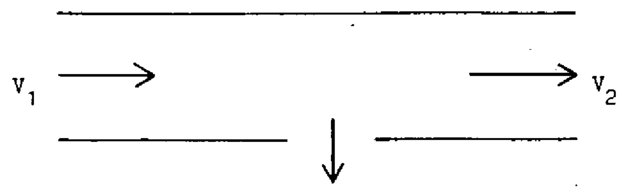
Velocity ratio	Rectangular duct fittings. Fig.Nos. refer to HVCA Duct Spec. DW/121 (67)			Circular duct fittings. Fig.Nos. refer to HVCA Duct Spec. DW/132 (68)	
$\frac{V_3}{V_1}$	 Fig.9. Branch ducts up to 400 mm wide	 Fig.10. Branch ducts over 400 mm. wide		 Fig.101. Conical tee	 Fig.113. Straight tee.
0.2	18.0		22		22
0.3	8.5		10.0	10	10
0.4	4		6.3	5	6.3
0.5	2.3		4.3	3	4.3
0.6	1.5		3.2	2	3.2
0.7	1.0		2.5	1.5	2.5
0.8	0.7		2.1	1.2	2.1
0.9	0.6		1.7	0.95	1.7
1.0	0.5		1.5	0.8	1.5

Table 6.7 Straight-through losses for typical branch fittings

$$\text{Straight through loss } K = \frac{\Delta p}{\frac{1}{2}\rho V_1^2}$$



Velocity ratio $\frac{V_2}{V_1}$	Loss factor k	
	Rectangular duct	Circular duct
0.4	0.12	0.36
0.5	0.09	0.25
0.6	0.06	0.16
0.7	0.03	0.10
0.8 0.9 1.0	0.0	0.0

8.6 *Venting requirements (4.5)*

The requirements of one of the following four methods should be used to ensure adequate venting. Alternatively, if more than one method is to be used, the requirement of individual methods may be reduced in proportion to the amount of venting provided by each one. Q_N is the net volume rate of pressurising air leakage to the floor (i.e. excluding the air leakage to atmosphere via lift shafts and toilets) in l/s.

Method

(a) Window leakage (4.5.2)

Table 8.8

Recommended minimum window crackage for relief of pressurisation systems

Window type	Typical air leakage rate ℓ/s. m. N/m^2	Recommended crack length metres
Pivoted, no weather stripping	0.21	1.2 Q_N
Sliding	0.082	3.0 Q_N
Pivoted and weather stripped	0.030	8.3 Q_N

In assessing the available crackage, one face of the building should be discounted because of possible adverse wind conditions.

(b) Peripheral venting (4.5.3)

Vents should be provided on all sides of the building, but one side should be discounted in assessing the effective open area to allow for adverse wind conditions. The effective open area per floor should not be less than

$$\frac{Q_N}{2500} \ m^2$$

(c) Vertical shafts (4.5.5)

The recommended minimum sizes of shaft and vents are as follows:

Net vent area (room to shaft) $A_V = \frac{Q_N}{2000} \ m^2$

Shaft size $= 3 \ A_V \ m^2$

Top vent (shaft to atmosphere) $= 3 \ A_V \ m^2$

(d) Mechanical extract (4.5.4)

The extract rate per floor should not be less than Q_N ℓ/s. Suitable precautions should be taken to ensure that the system will withstand high temperatures and that smoke will not be spread to other floors via the ducting system.

Table 8.9 Guide to the choice of venting system

Building layout	Windows	Ventilation	Venting system	
			Main method	Additional methods, if required
Open plan	Openable, non-weather stripped	Natural	(a)	
	Openable, weather-stripped	Natural or Mechanical	(a) or (c)	(b) or (d)
	Sealed	Mechanical	(c)	
Compartmented	Openable, non-weather stripped	Natural	(a)	
	Openable, weather-stripped	Natural or Mechanical	(a) or (b)	(c) or (d)
	Sealed	Mechanical	(b)	

8.7 *Site testing of pressurisation systems*

8.7.1 *General conditions of testing*

Tests should be carried out to check the performance of pressurisation systems after completion and before occupation of the building. It is particularly important that the proper doors and windows are fitted and are in the closed position before air flow and pressure difference measurements are made. Vents to vertical shafts and on the leeward sides of the building that are required for pressurisation relief should be open. Tests should not be carried out in winds stronger than 5 m/s (11 mph), since it would be difficult to allow for the adverse effects of wind on pressurisation. An allowance may be made for stack effect however as indicated in 8.7.3.

8.7.2 *Measurement of air flow rates*

Provision should be made for the measurement and regulation of the total air flow rate in the main duct near the fan and the air flow rates in the branches near each terminal in accordance with the general guidelines set out by the IHVE Commissioning Code (75). The layout of the plant room and air distribution system should be designed with these measurements in mind. It is recommended that actual air flow rates to each terminal be measured, since these are critical to pressurisation, rather than proportional measurements at the terminals suggested by the Code.

8.7.3 *Measurement of pressure differences*

Pressure differences should be measured across each floor from the pressurised zone giving access to the accommodation area. Plate 3 shows suitable portable apparatus for these measurements. The design pressurisation level should be achieved on each floor of the building. In practice however stack effect may act to modify the pressure differences. Table 8.10 gives maximum recommended values for the reduction in pressurisation due to stack effect which may be allowed in assessing whether the system meets design requirements. In winter the greatest reduction occurs on the lowest floor level of the building, becoming successively less at each floor up to the neutral pressure plane level. Above the neutral plane the actual pressure differences become successively greater than the design pressurisation at each floor.

Table 8.10

Building height metres	Maximum allowable reduction in pressurisation due to stack effect for testing purposes. N/m^2	
	Indoor/outdoor temperature difference $10^{\circ}C$	$20^{\circ}C$
5	1	1
25	2	3.5
50	3.5	6.5
100	6.5	12.5
150	9.5	19

8.7.4 *Alarm system test*

Tests should be made to ensure that the pressurisation system is brought into operation by manual and automatic alarm systems i.e. the pressurisation fan(s) are started, or are boosted to full capacity when reduced level pressurisation is provided. In addition cancellation of the alarm should not shut down pressurisation fans.

8.7.5 *Maintenance*

The operation of pressurisation systems including all starting controls should be tested, in conjunction with fire alarm tests, at regular intervals not more than 12 weeks apart to ensure that systems are maintained in working order.

9. FUTURE RESEARCH INTO SMOKE CONTROL WITHIN BUILDINGS

During the course of this project certain problems have been seen to be much deeper than the scope envisaged and problems in other related fields have also been apparent. These areas which in our opinion need further consideration and research are briefly reviewed below.

(a) An assessment of the evacuation of a building and its influence on the efficacy of a pressurisation system.

A pressurisation scheme for escape routes is most effective when there are barriers which impede the escape of the pressurising air. However, during evacuation there will be intermittent opening of doors between stairwells and lobbies and further the ground floor door leading from the stairwell may be open for a considerable period. Hence pressurisation air will be dispersed through these openings with a substantial reduction in pressurisation level. The influence of such events or the movement of smoke within the building does require further consideration. The problem is not simple, the influence of wind and stack effect with an open ground floor door could conceivably increase the pressurisation of stairwells.

(b) Use of normal air conditioning and ventilating systems for smoke control.

We have shown that with a well-sealed building facade that the excess air supplied for air conditioning or ventilating purposes is adequate to pressurise the building. It is then feasible for such systems to overcome the pressures developed by fire, wind and stack effects by simply venting (i.e. lowering the pressure) of the fire space. There are many attractions to such a scheme but much more detailed consideration needs to be given to the mechanics and protection of the mechanical systems to ensure their operation and reliability under emergency conditions.

(c) Methods of venting.

The report has high-lighted that venting is an integral part of pressurisation. Methods of venting buildings have been outlined but apart from the case of the building with a sufficient number of average quality openable windows a simple universal solution to venting potential fire spaces is not apparent. All the methods advocated (section 4.5) have limitations in application or conflict with existing regulations. There is a need for detailed consideration of methods of venting well-sealed building that will lead to hardware specifications.

(d) Unusual applications.

The design procedures put forward in this report are based on studies of buildings of simple shape and layout subjected to design wind and stack effects and as such are generally applicable to most modern building designs. The wind effects can however be different for unusually shaped buildings or special locations and this may warrant a separate study being made in such cases. The computer program CRKFLO used in this project could with some modification be made more efficient for studying the influence of a range of conditions or building parameters on the pressurisation requirements of special applications. This program would be complementary to the proposed design procedure.

APPENDIX A

ECONOMIC VELOCITIES IN VERTICAL DISTRIBUTION DUCTS

An analysis of the economic velocities in ducts was made by Swain et al (60) a few years ago and their data confirmed the then existing practice. Their analysis is repeated here using more up-to-data figures and applying the study to a simple vertical pressurisation distribution system.

The cost factors involved in assessing the economics are,

(i) amortisation of the plant costs
(ii) amortisation of the ducting costs
(iii) running costs of the plant
(iv) cost of floor space occupied by ducting.

Symbols

Air volume	Q	m^3/s
cost of ducting $/m^2$	α	£/m^2 of surface area
length of small side of duct	a	
duct aspect ratio	s	
mean duct velocity	v	
friction factor	f	
air density	ρ	
equivalent duct dia.	D	$= \frac{2as}{1+s}$
annual fan running hours	T	
unit electricity charge	ϕ	£/kwh
fan efficiency	n_1	
motor efficiency	n_2	
floor rental value	R	£/m^2
pressure drop	p	

For a given design the system factors influenced by the duct velocity are the size and resistance of the main duct since the branch conditions will be common to all floors. Hence a single length of ducting can be analysed and this has been taken as unit length. The cost factors are quantified below.

(i) Plant costs

Assume that plant costs are given by the formula

Cost = bQ + cQp, where b and c are constants.

If the pressure loss in the main duct at the branch is neglected,

$$p = \text{friction loss} = \frac{f}{D}\left(\tfrac{1}{2}\rho v^2\right)$$

$$= \frac{f\,(1+s)\rho v^2}{4as}$$

Taking $f = 0.02$ and with $a = \sqrt{\frac{Q}{vs}}$

$$\text{Capital cost } C_1 = bQ + 0.005\,cQ\left(\frac{1+s}{s}\right)\rho\left(\frac{v^5 s}{Q}\right)^{\frac{1}{2}}$$

$$\frac{dC_1}{dv} = 0.0125\,c\rho\left(\frac{1+s}{s}\right)\left(Q\,s\,v^3\right)^{\frac{1}{2}}$$

If $\rho = 1.2\ kg/m^3$

$c = £0.07$ (taken from typical plant costs),

$$\frac{dC_1}{dv} = \frac{1.05}{10^3} \left(\frac{1 + s}{s}\right) (Qsv^3)^{\frac{1}{2}} \qquad (1)$$

The amortised cost is taken over 10 years at a rate of interested of 10%, this then gives

$$\frac{1.71}{10^4} \left(\frac{1 + s}{s}\right) (Qsv^3)^{\frac{1}{2}} \qquad (2)$$

(ii) Ducting costs

The alternatives are (a) sheet metal duct in brick shaft (two extra brick walls required)

(b) concrete duct.

At current building prices,

(a) $\alpha = 5.4$ (sheet metal) + 3 (brick)
$= £8.4/m^2$

(b) $\alpha = £8.0/m^2$

Taking option (b) then ducting cost is,

$$C_2 = \alpha \times \text{perimeter}$$
$$= 8 \times 2a(1 + s)$$
$$= 16\ (1 + s) \sqrt{\frac{Q}{sv}}$$

$$\frac{dC_2}{dv} = -8\ (1 + s) \sqrt{\frac{Q}{sv^3}} \qquad (3)$$

The amortised cost is,

$$1.3\ (1 + s) \left(\frac{Q}{sv^3}\right)^{\frac{1}{2}} \qquad (4)$$

(iii) Running costs

For unit length of duct annual running cost,

$$C_3 = \frac{T\phi}{n_1 n_2} \times \frac{Qp}{1000}$$

If $n_1 = 0.7$, $n_2 = 0.8$, $T = 2600$, $\phi = £0.0087$,

$$C_3 = 0.0404\ Qp$$
$$= 0.0404\ Q \left[0.005 \times 1.2 \left(\frac{1+s}{s}\right) \left(\frac{v^5 s}{Q}\right)^{\frac{1}{2}}\right]$$
$$= \frac{2.4}{10^4}\ Q \left(\frac{1 + s}{s}\right) \left(\frac{v^5 s}{Q}\right)^{\frac{1}{2}}$$

$$\frac{dC_3}{dv} = \frac{6}{10^4} \left(\frac{1 + s}{s}\right) (Qsv^3)^{\frac{1}{2}} \qquad (5)$$

(iv) Space rental

Assume that space taken up is duct c.s. area plus 150 mm on all sides.

$$\text{Floor area lost} = a^2 s + 0.3a(1+s) + 0.09$$
$$= \frac{Q}{v} + 0.3\ (1+s) \left(\frac{Q}{vs}\right)^{\frac{1}{2}} + 0.09$$

If the floor height is taken as 3 metres then unit length has a rental value of $\frac{R}{3}$.

$$\therefore \text{ Rental cost } C_4 = \frac{R}{3}\left[\frac{Q}{v} + 0.3\ (1+s)\ \left(\frac{Q}{vs}\right)^{\frac{1}{2}} + 0.09\right]$$

$$\frac{dC_4}{dv} = \frac{-R}{3}\left[\frac{Q}{v^2} + 0.15\ (1+s)\left(\frac{Q}{sv^3}\right)^{\frac{1}{2}}\right] \qquad (6)$$

Minimum system costs occur when

$$0.163\,\frac{dC_1}{dv} + 0.163\,\frac{dC_2}{dv} + \frac{dC_3}{dv} + \frac{dC_4}{dv} = 0$$

That is,

$$\frac{1.71}{10^4}\left(\frac{1+s}{s}\right)(Qsv^3)^{\frac{1}{2}} - 1.3\ (1+s)\left(\frac{Q}{sv^3}\right)^{\frac{1}{2}} + \frac{6}{10^4}\left(\frac{1+s}{s}\right)(Qsv^3)^{\frac{1}{2}}$$

$$- \frac{RQ}{3v^2} - 0.05\,R\ \ (1+s)\left(\frac{Q}{sv^3}\right)^{\frac{1}{2}} = 0$$

$$\text{or } \frac{7.71}{10^4}\left(\frac{1+s}{s}\right)(Qsv^3)^{\frac{1}{2}} = (1.3 + 0.05R)(1+s)\left(\frac{Q}{sv^3}\right)^{\frac{1}{2}} + \frac{RQ}{3v^2} \qquad (7)$$

The solution of this minimum cost equation is not very sensitive to s. Hence assuming s = 2 then,

$$\frac{1.64}{10^3}\ (Qv^3)^{\frac{1}{2}} = (2.75 + 0.106R)\left(\frac{Q}{v^3}\right)^{\frac{1}{2}} + \frac{RQ}{3v^2} \qquad (8)$$

Using appropriate values of R and Q gives the most economical velocity in the main duct.

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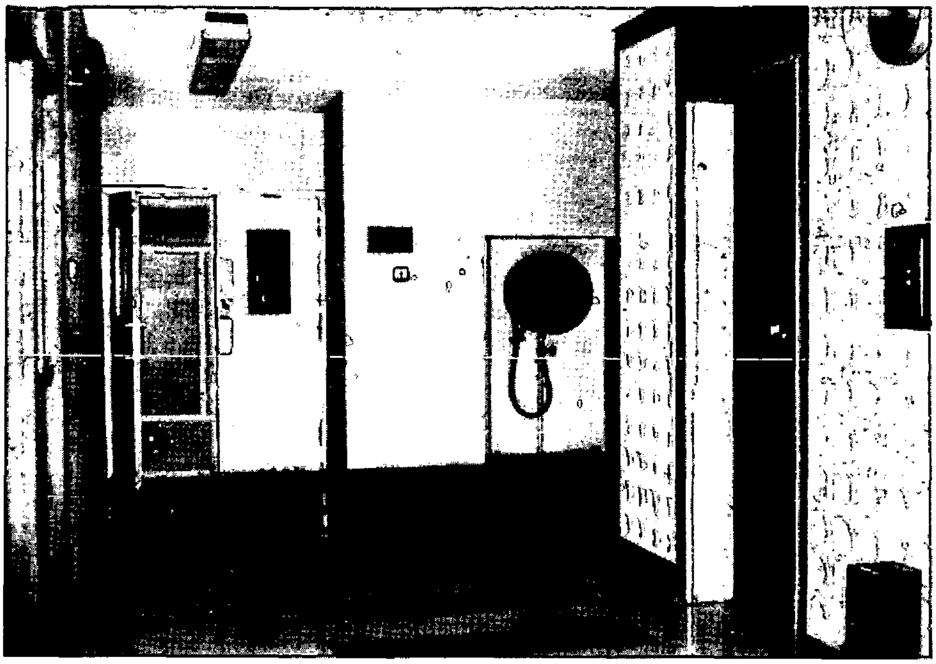


Plate 1 Temporary door installed in lobby door-way for air leakage tests

Plate 2 Fan unit used in air leakage tests

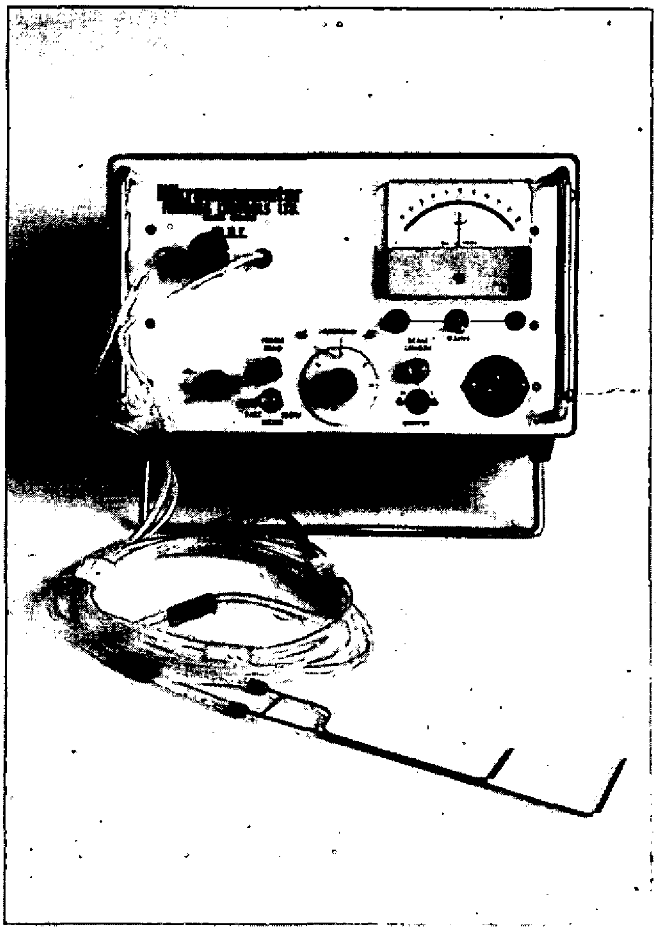


Plate 3 Apparatus for measuring pressure differentials

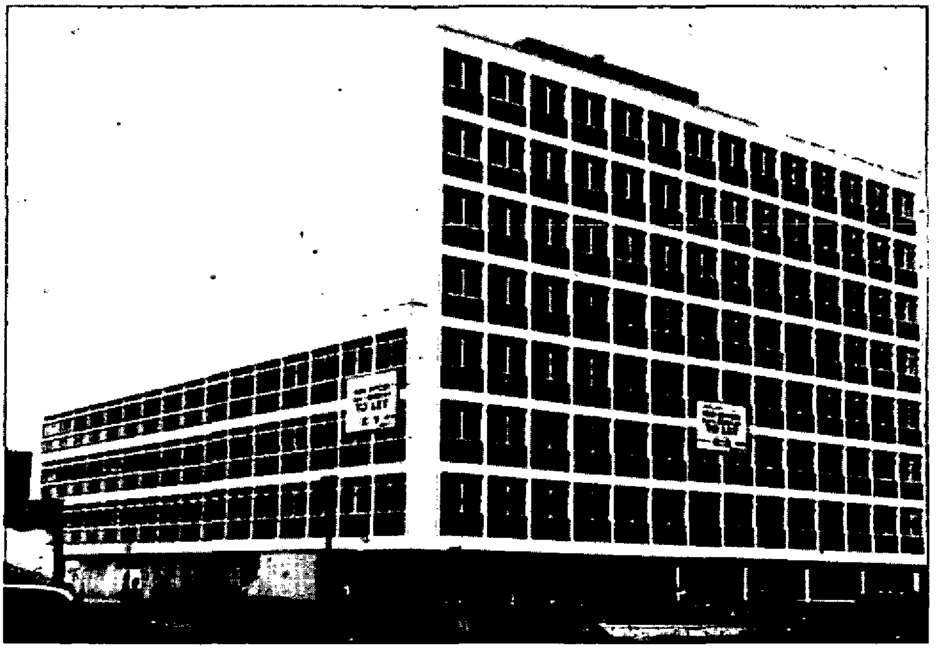


Plate 4 Deacon House

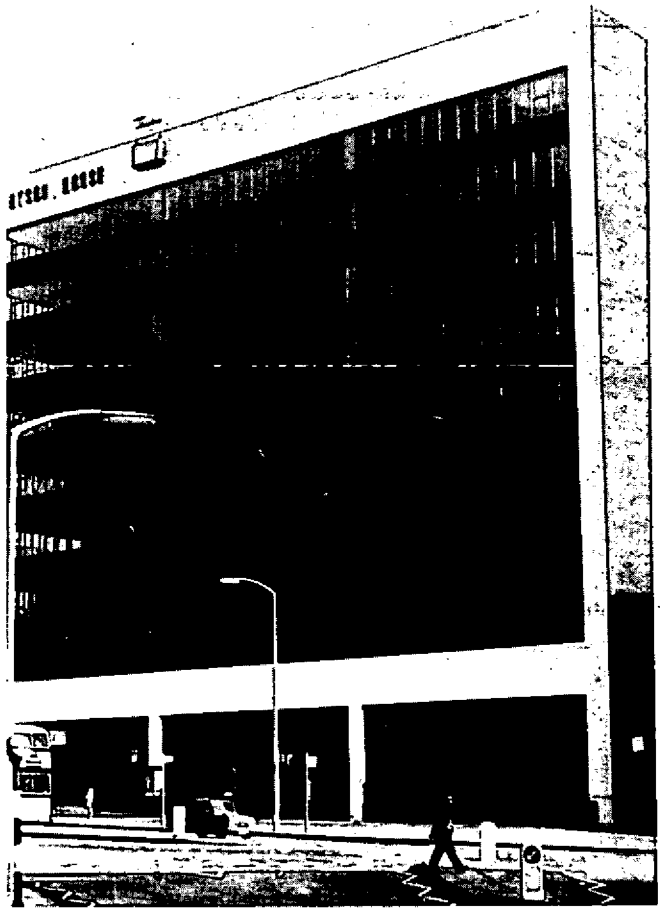


Plate 5 Dyson House

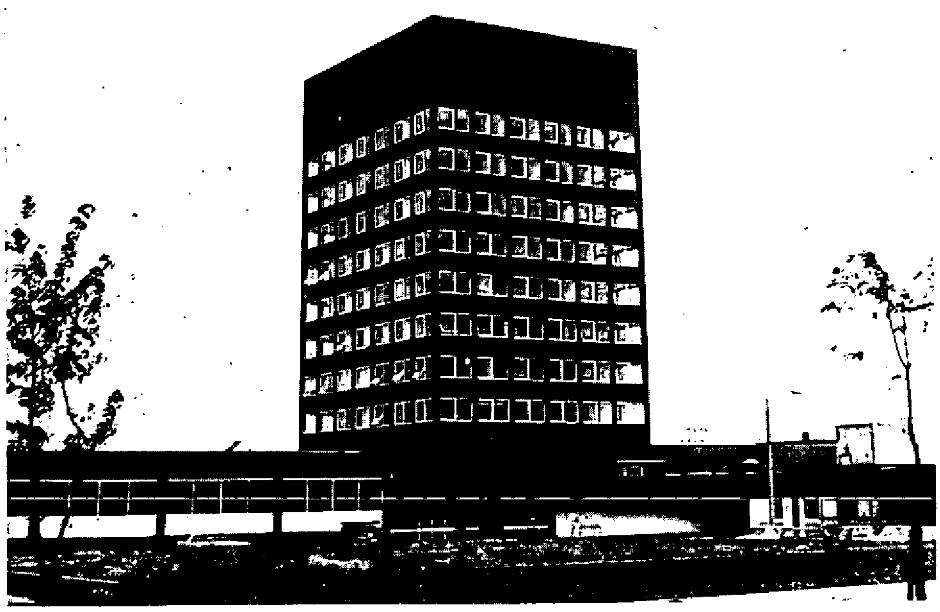


Plate 6 Basildon Hospital

FIG. 1 MECHANICALLY VENTILATED SMOKE-PROOF ENCLOSURE

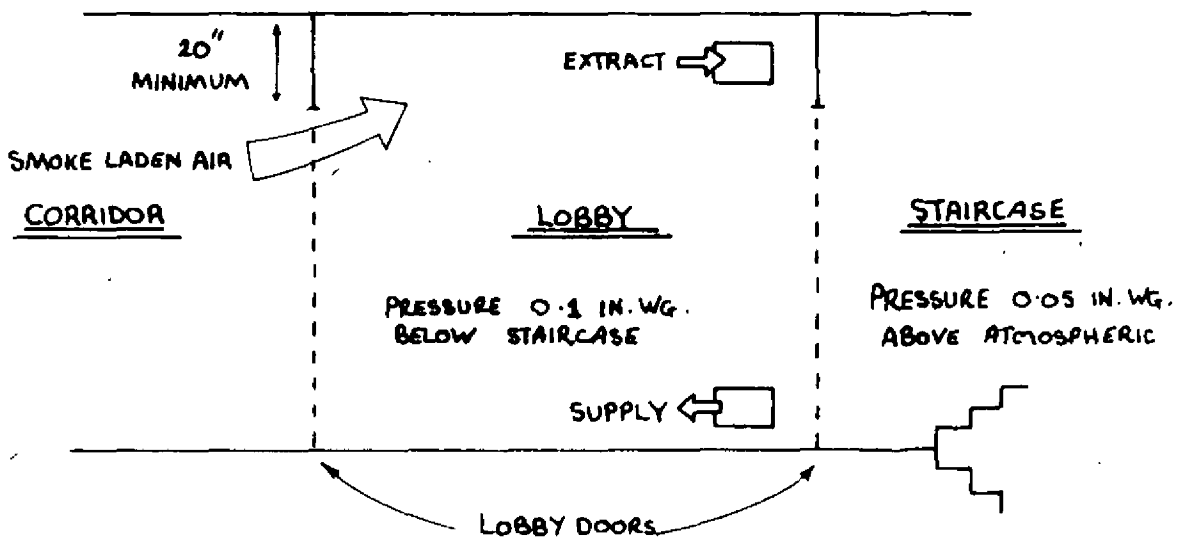
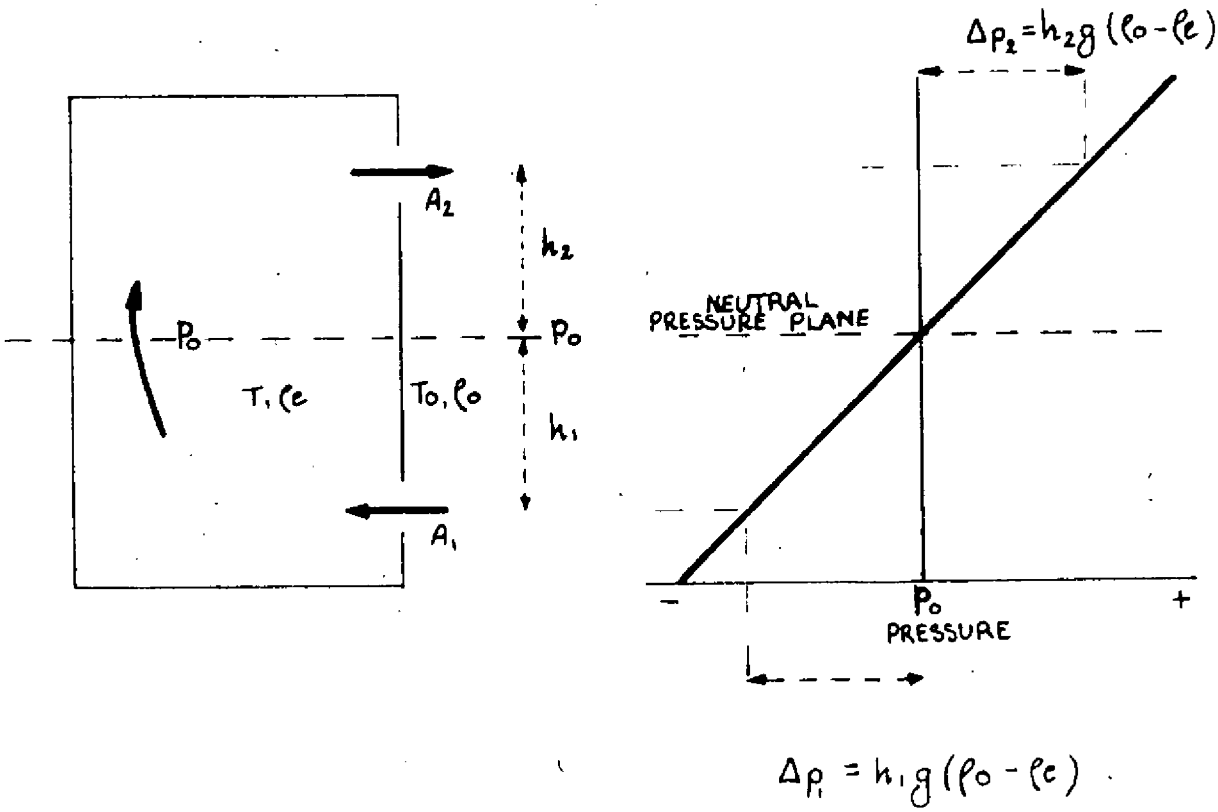


FIG. 2 MECHANISM OF STACK EFFECT



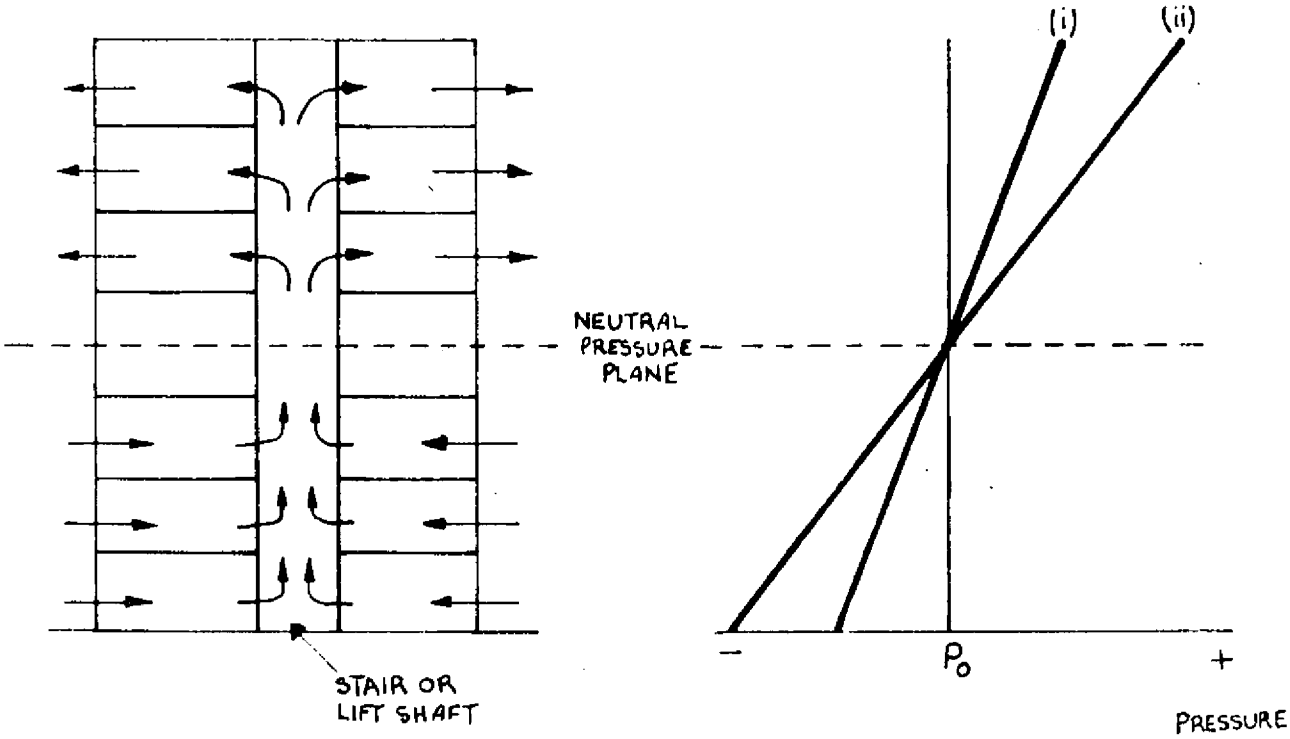
(a) AIR MOVEMENT FOR $T > T_o$

T, ρ_e = ABSOLUTE TEMP AND AIR DENSITY WITHIN ENCLOSURE

T_o, ρ_o = ABSOLUTE TEMP AND AIR DENSITY OUTSIDE ENCLOSURE

(b) PRESSURE GRADIENT IN ENCLOSURE WITH RESPECT TO OUTSIDE PRESSURE P_o

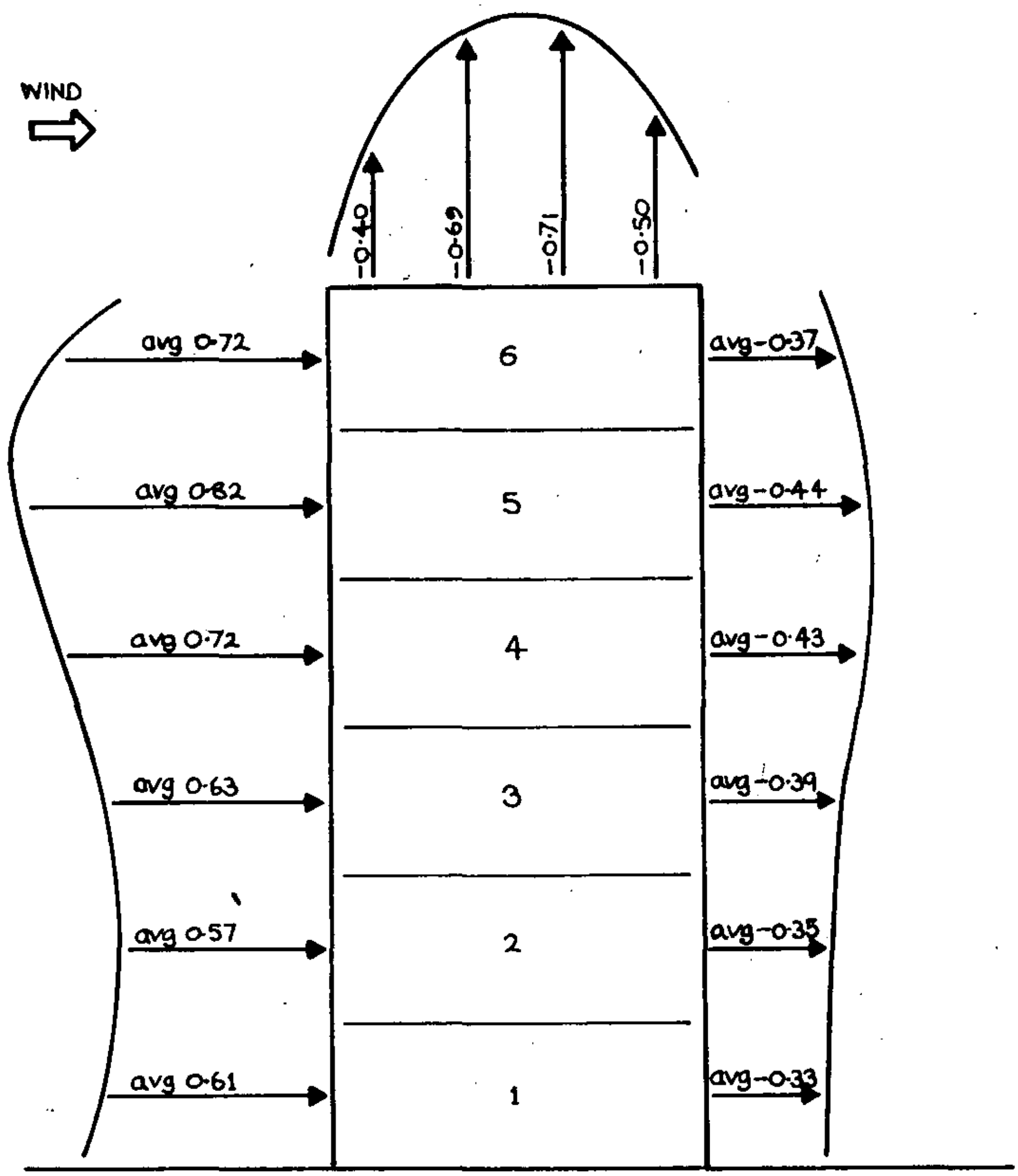
FIG. 3 STACK EFFECT IN A BUILDING IN WINTER



a) AIR MOVEMENT PATTERN

b) PRESSURE GRADIENTS (DIAGRAMATIC) WITH RESPECT TO OUTSIDE AIR PRESSURE P_o FOR
(i) FLOOR SPACES
(ii) VERTICAL SHAFT

FIG. 4 WIND PRESSURE COEFFICIENTS C_p FOR A TALL BUILDING.

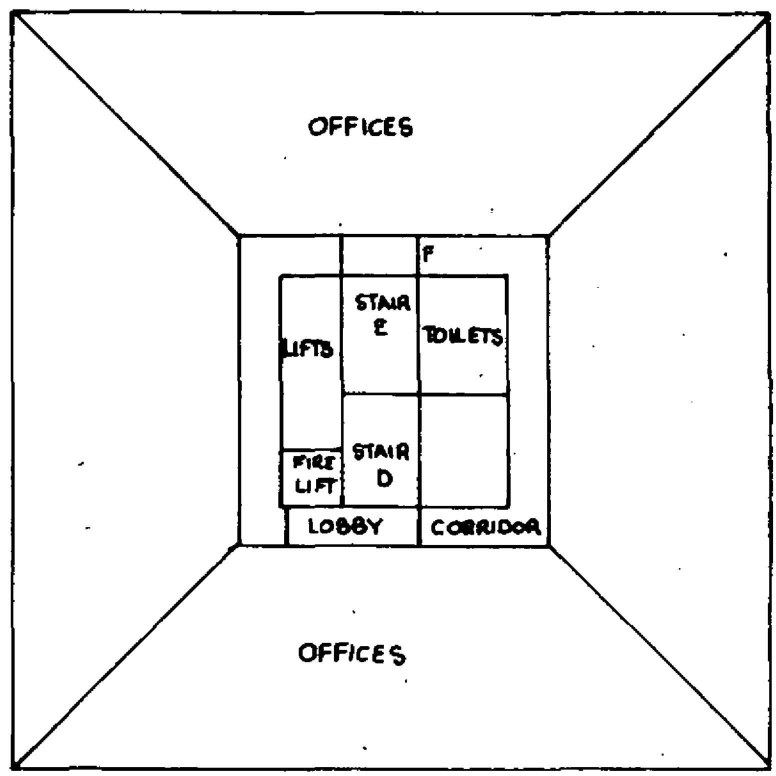


$C_p = -0.55$ FOR FACES PARALLEL TO WIND

FIG. 5.

BUILDING PLANS FOR COMPUTER STUDY

PLAN 1



PLAN 2

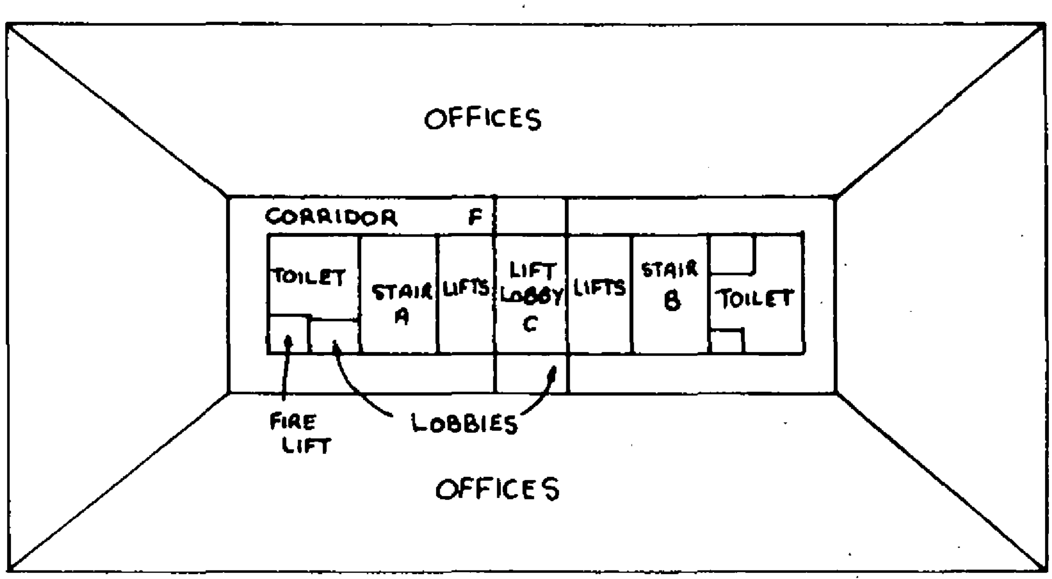


FIG. 6. PRESSURES AND AIR FLOW PATTERN IN A 30 STOREY BUILDING.

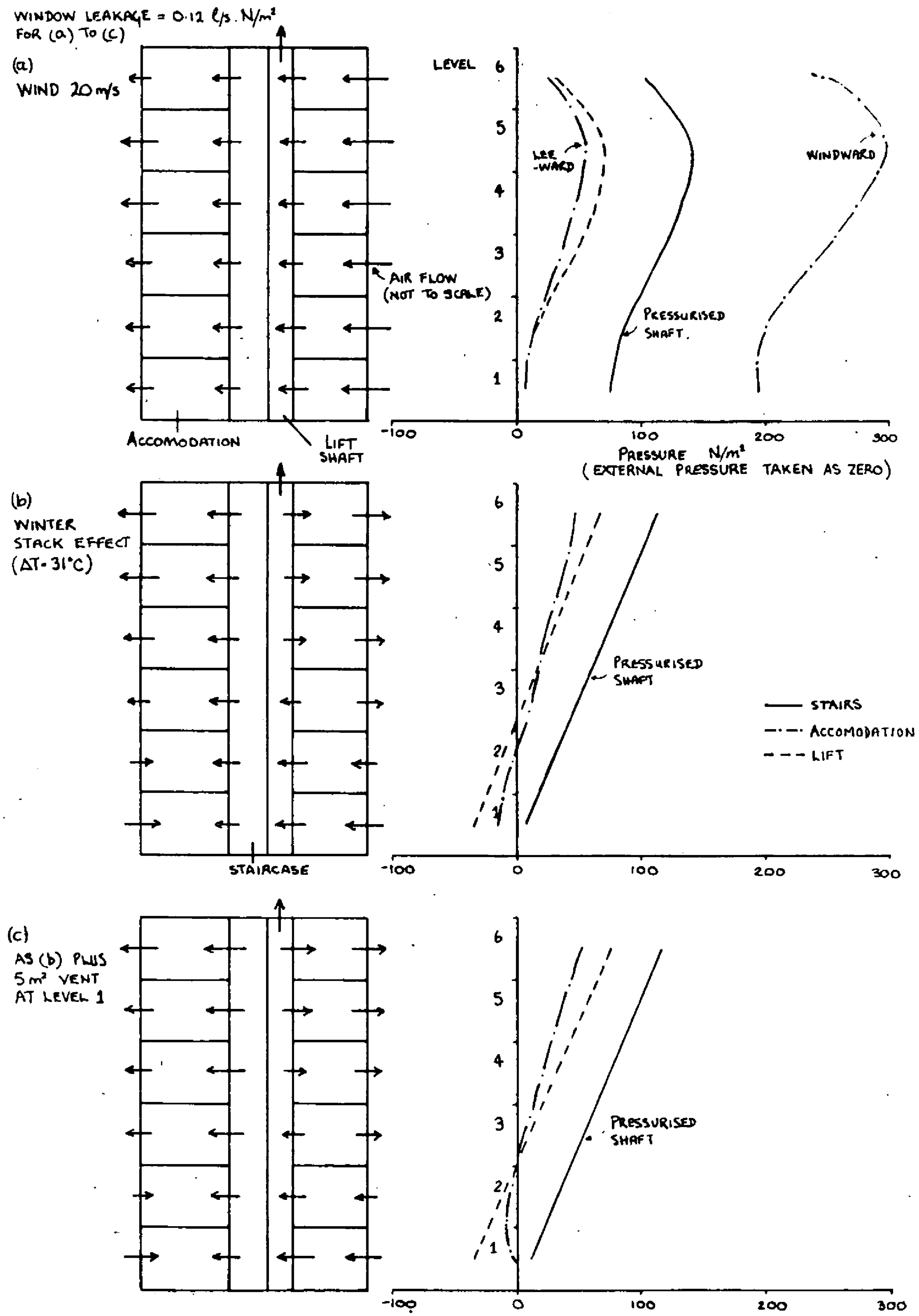


FIG. 6.

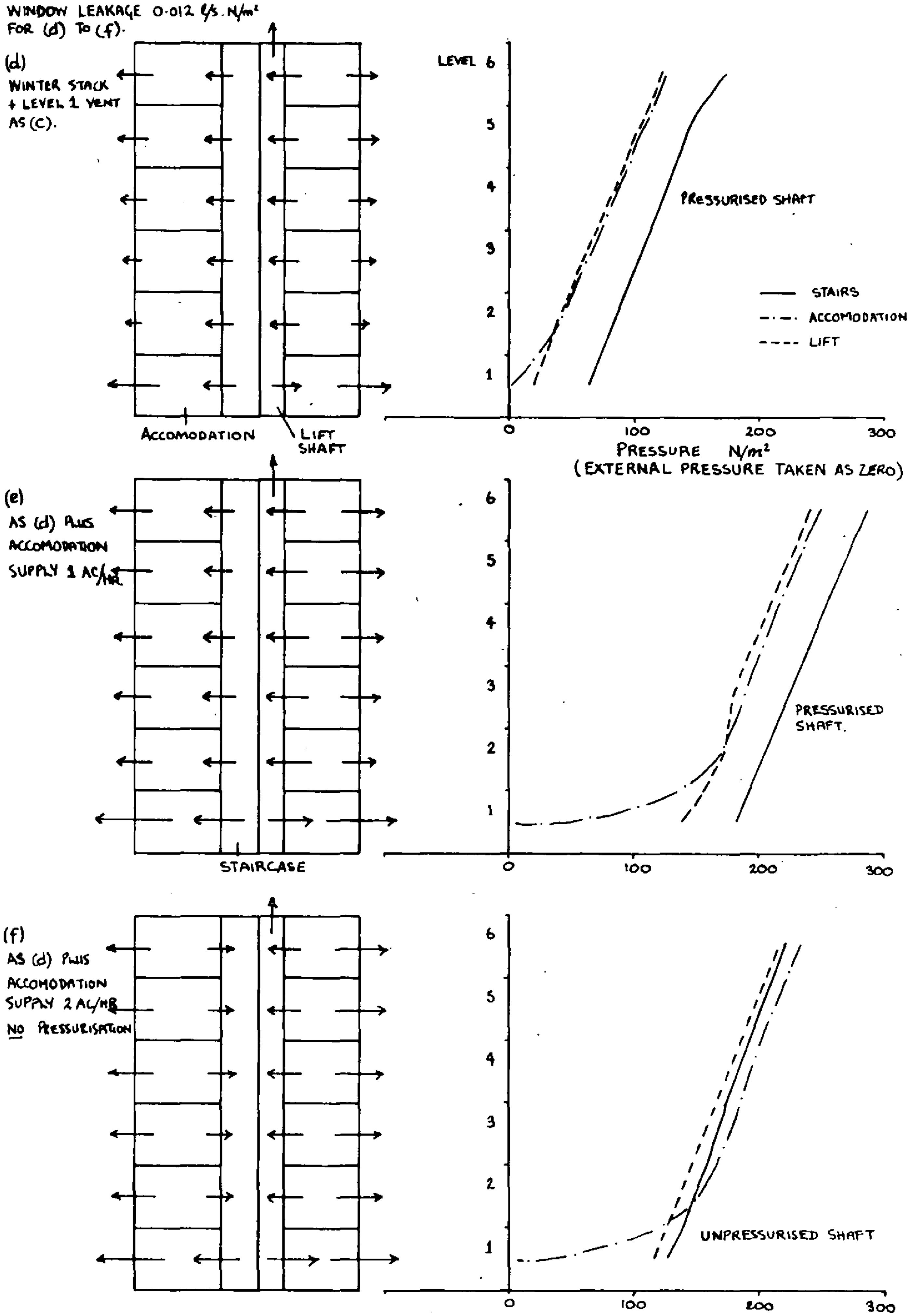

WINDOW LEAKAGE 0·012 ℓ/s. N/m²
FOR (d) TO (f).
(d)
WINTER STACK
+ LEVEL 1 VENT
AS (C).
ACCOMODATION
LIFT SHAFT
LEVEL 6
5
4
3
2
1
PRESSURISED SHAFT
STAIRS
ACCOMODATION
LIFT
0
100
200
300
PRESSURE N/m²
(EXTERNAL PRESSURE TAKEN AS ZERO)
(e)
AS (d) PLUS
ACCOMODATION
SUPPLY 1 AC/HR.
STAIRCASE
PRESSURISED SHAFT.
(f)
AS (d) PLUS
ACCOMODATION
SUPPLY 2 AC/HR
NO PRESSURISATION
UNPRESSURISED SHAFT

FIG. 7

PRESSURE DIFFERENCE ACCROSS STAIR DOOR DUE TO WIND AND STACK EFFECT

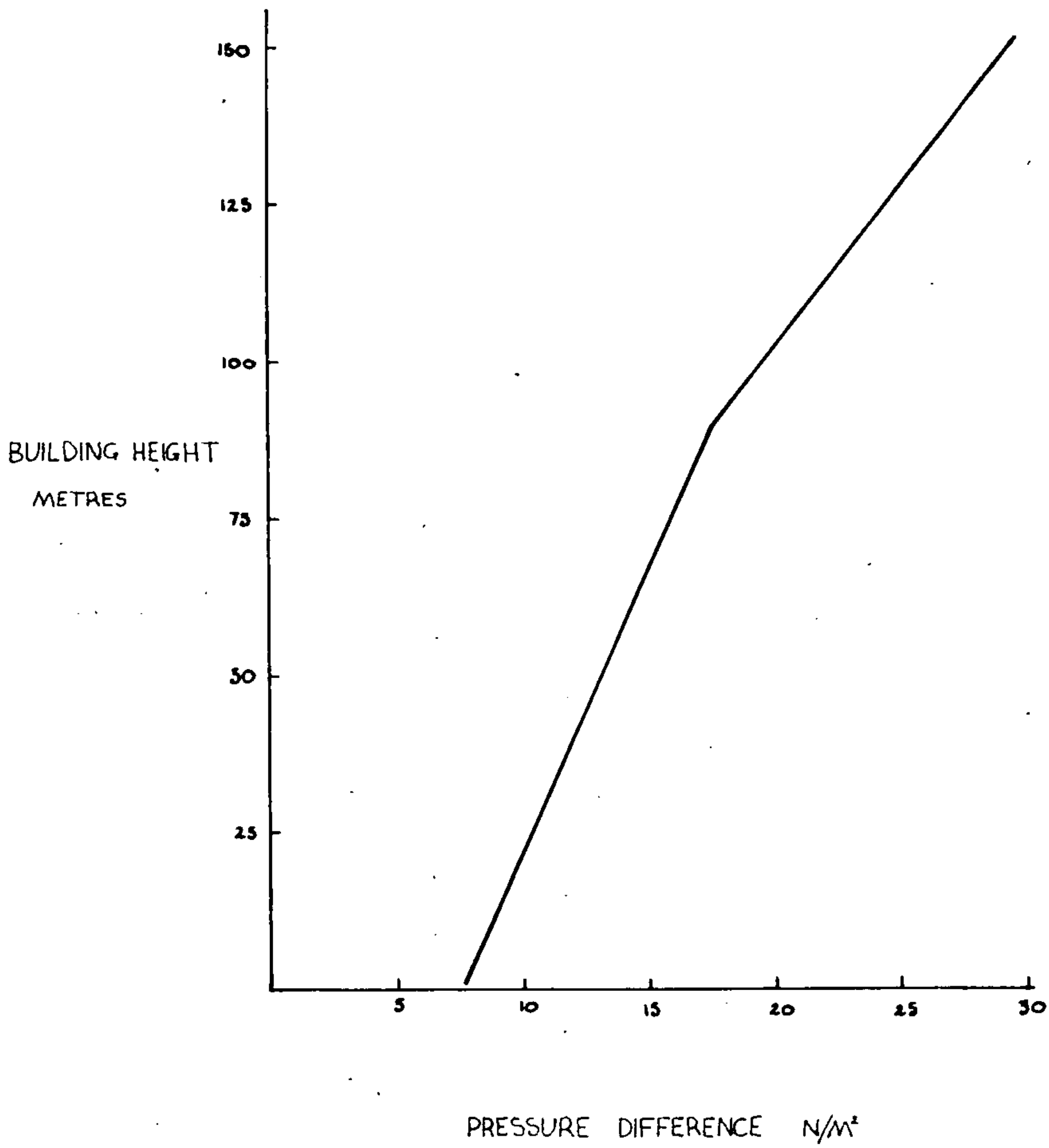


FIG 8 OUTWARD VELOCITY OF AIR TO PREVENT INFILTRATION OF SMOKE AND HOT GASES THROUGH AN OPEN DOORWAY

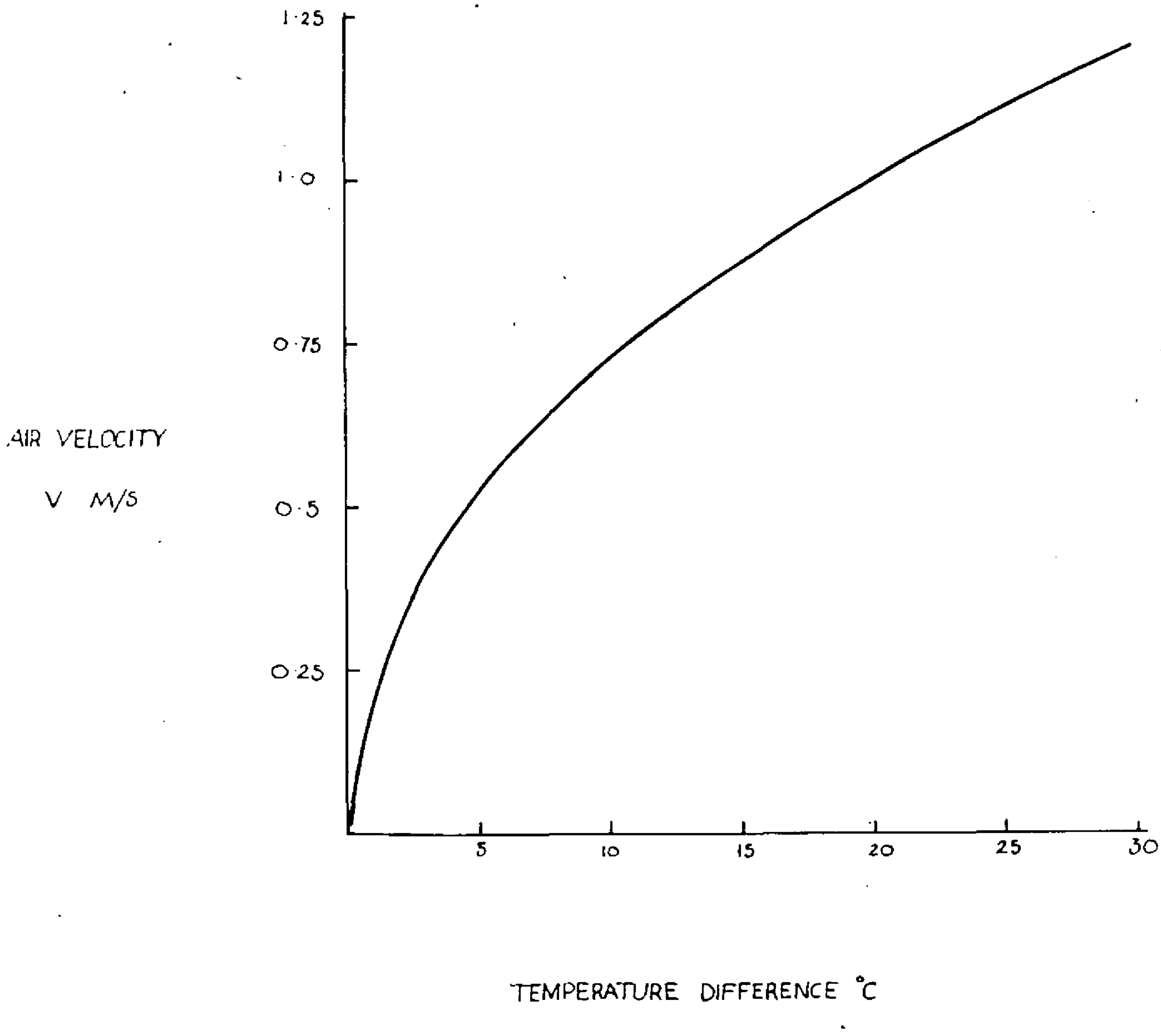
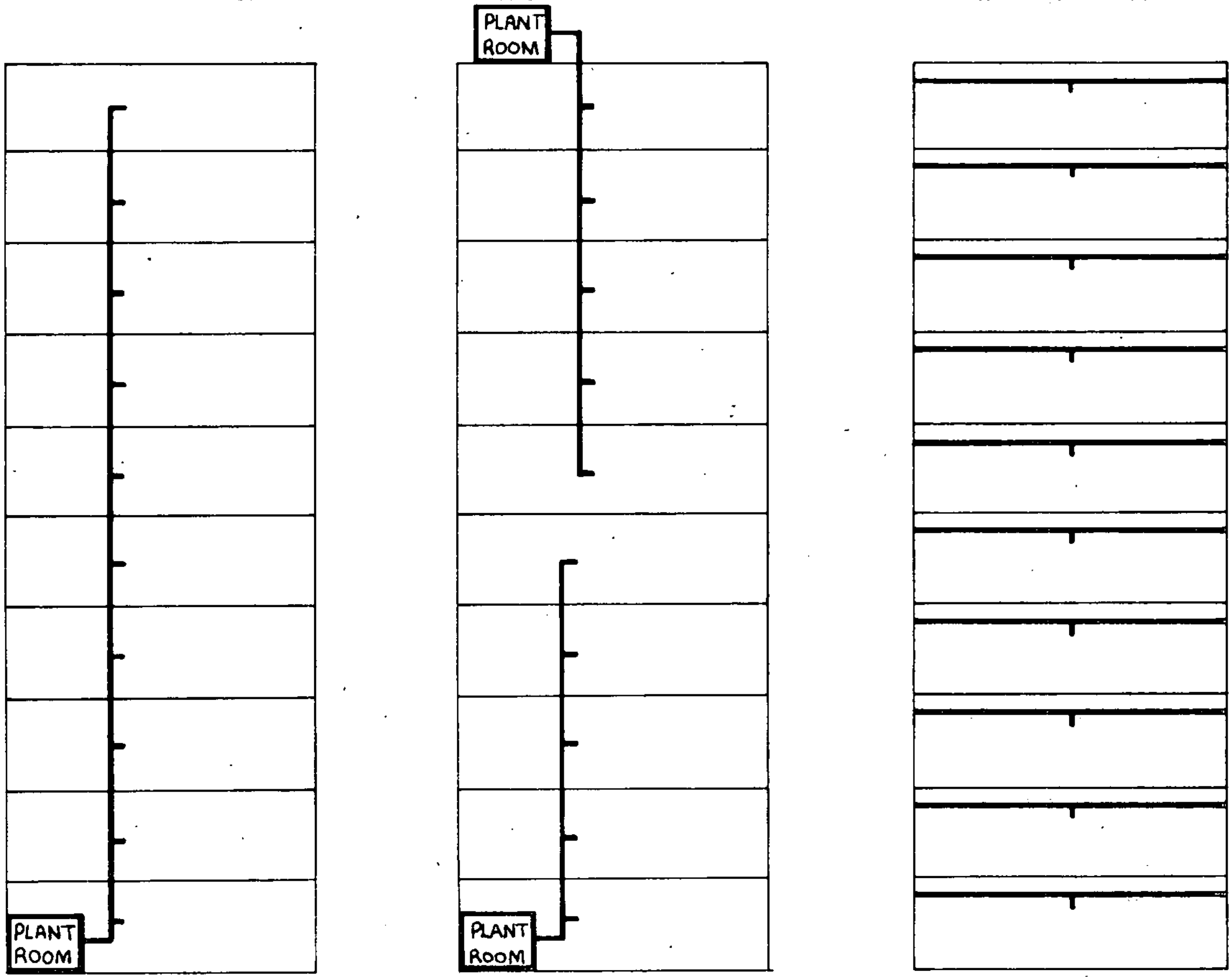


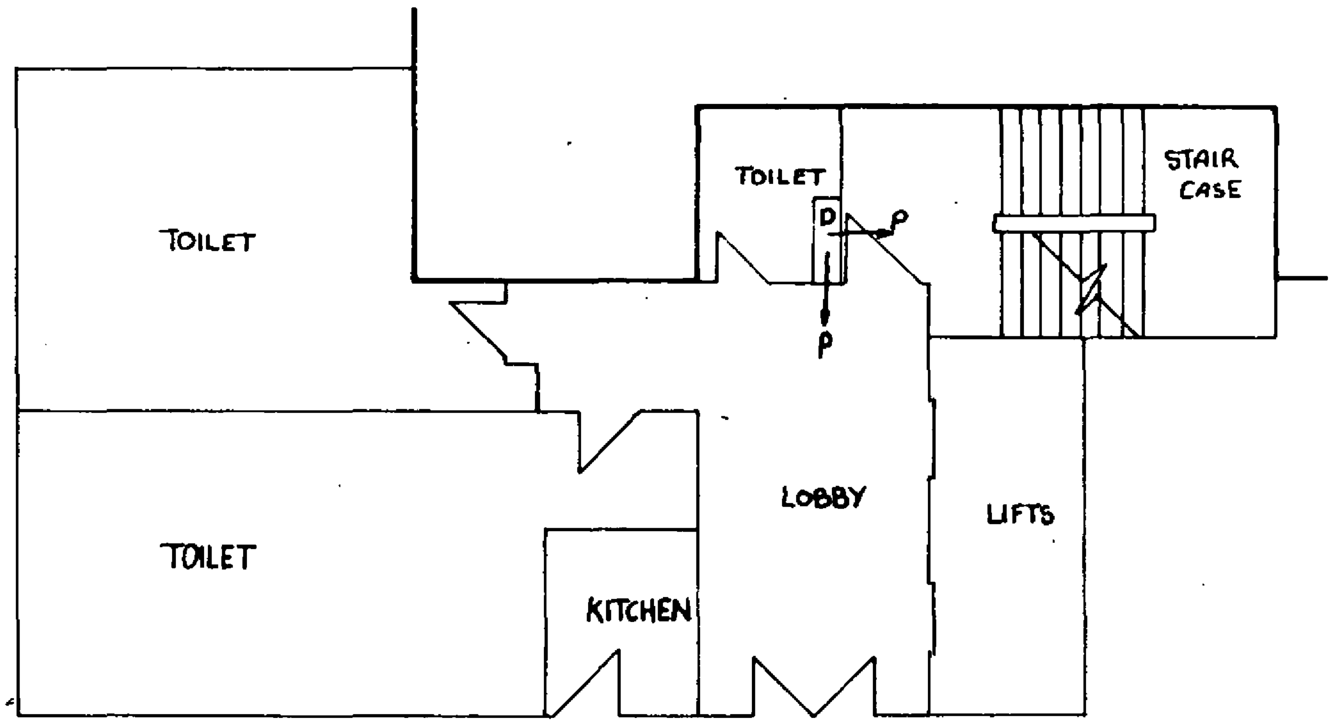
FIG. 9 METHODS OF VERTICAL DISTRIBUTION OF PRESSURISATION AIR IN MULTISTORY BUILDINGS



SINGLE PLANT AND DUCT DUAL PLANTS AND DUCTS INDIVIDUAL PLANTS AND DUCTS

FIG. 10 DEACON HOUSE

PLAN OF SERVICE CORE SCALE APPROX 1:100



D = PRESSURISATION DUCT

P = PRESSURISATION AIR INLET

BLOCK PLAN OF BUILDING SCALE APPROX. 1:2500

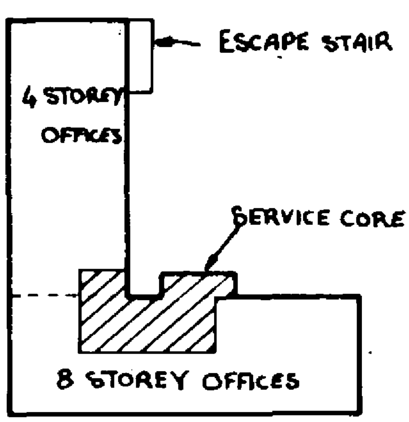
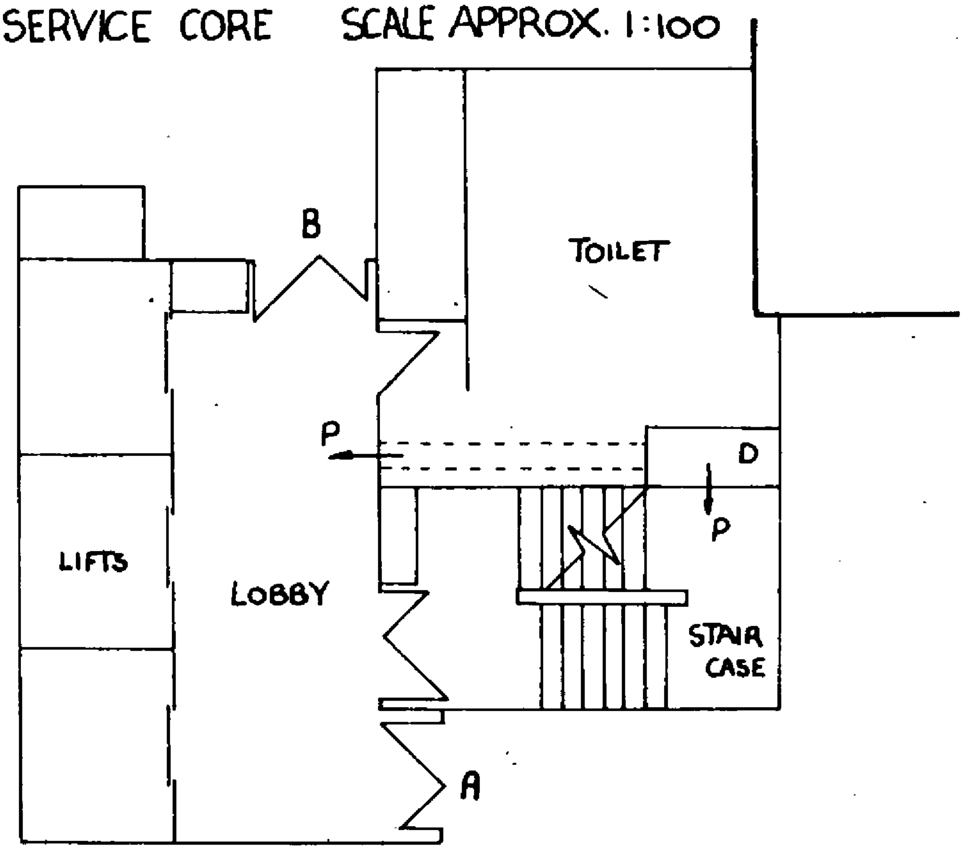


FIG.11 DYSON HOUSE

PLAN OF SERVICE CORE SCALE APPROX. 1:100



D = PRESSURISATION DUCT

P = PRESSURISATION AIR INLET

BLOCK PLAN OF BUILDING SCALE APPROX. 1: 2500

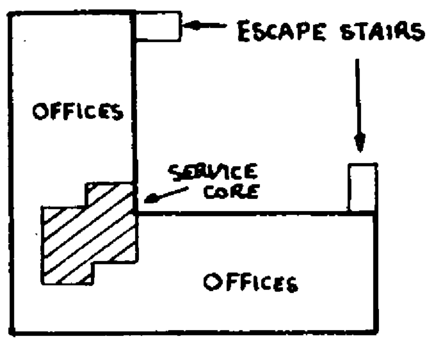
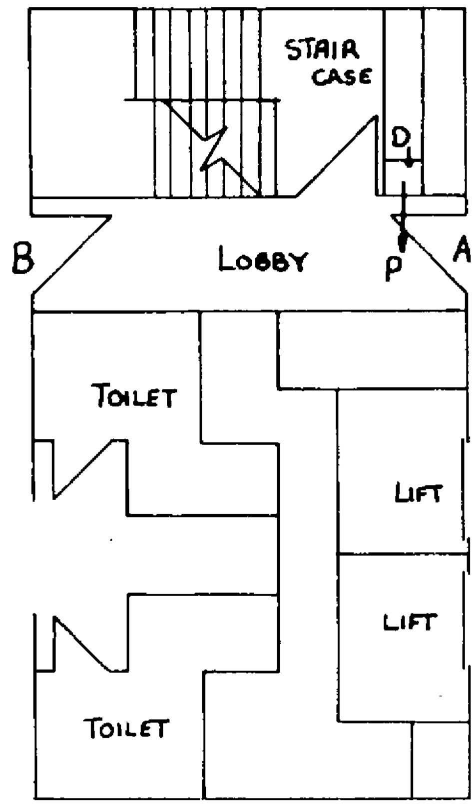


FIG. 12 BASILDON HOSPITAL

PLAN OF SERVICE CORE SCALE APPROX. 1:100



D = PRESSURISATION DUCT

P = PRESSURISATION AIR INLET

BLOCK PLAN OF BUILDING SCALE APPROX. 1:1250