SMOKE CONTROL IN ATRIUM BUILDINGS USING DEPRESSURISATION

Part 1 : Design Principles

G. O. Hansell and H. P. Morgan*

Fire Research Station

Building Research Establishment

Borehamwood Herts WD6 2BL, U.K.

(Received, November 3, 1990)

ABSTRACT

Smoky gases in an atrium can pass through leakage paths in an atrium facade to affect adjacent accommodation and its escape routes. It is possible for the designers of smoke control systems to take advantage of thermal buoyancy due to the fire to prevent such infiltration, by using a technique known as depressurisation.

This is Part 1 of a two-part paper in which equations are derived for the design of smoke control systems using either natural or powered depressurisation. The influence of wind pressures on the building is included in design formulae.

It is shown how depressurisation and 'throughflow' smoke ventilation can be combined in a hybrid system, either to keep the atrium smoke layer at a specified height, or below a specified temperature.

The limits beyond which depressurisation cannot be used are explored.

1. INTRODUCTION

The modern atrium is usually a very tall open space within a multi-storey building. It is often centrally placed but can abut an outer wall. It is roofed over and can be very large in area. The underlying concept is to create an 'ideal' external environment indoors¹.

The resulting enclosed large, undivided space can present problems both of fire spread and smoke spread – indeed, many rooms adjacent to the atrium are often only separated from it by glazing or are open to the common space to provide a pleasant working environment.

Means of escape from such buildings in the event of fire should not be adversely affected by smoke spreading from that fire.

Smoke ventilation is an obvious technique to apply to such a large undivided volume. Here the

buoyancy of the smoky gases from the fire is useful to hold those gases in a layer above all the regions to be protected.

Smoke is extracted from the layer at the same rate (or greater) than it enters from below. Successful design of such a system depends on the correct specification of a 'design fire', and on calculation of the entrainment of air into the gases as they rise toward the buoyant layer beneath the atrium ceiling. This approach has been discussed elsewhere^{2,3,4} (see also Nelson et al⁵), and is an important way of protecting escape routes (and accommodation spaces) open to the atrium. The earlier work concluded that it is not usually feasible to design smoke ventilation systems able to keep the base of the atrium's buoyant smoke layer more than 8 m to 16 m above the fire room opening. Either the extract rate becomes impractically large, or the layer temperature falls too low for the layer to remain stably stratified – it mixes

*Colt International Ltd.

downwards.

It would be premature to reject the atrium concept completely for taller buildings. Other approaches are possible. One is the 'sterile tube' approach where the atrium boundary (or facade) is sealed and fire-resisting, and no significant fire load is allowed in the atrium itself⁶. This raises problems of materials specification (eg fire-resisting glazing which is aesthetically pleasing and cheap) and of maintenance. This approach is also necessarily very limiting to the architect, since the atrium is essentially only a fire-resisting light-well.

Greater architectural freedom becomes possible if the atrium facade need not be sealed, but can be allowed to be leaky even if the upper atrium is filled with smoke.

Examples of such 'leaky facade' design might include hotel bedrooms having doors onto 'decorative' balconies (ie not access or escape routes) small enough to be evacuated through the doors in a few seconds; where unsealed windows are used for simplicity and cheapness; or where small ventilation openings allow air to circulate between the accommodation spaces and the atrium. Clearly there must be no escape routes *open* to the upper atrium. It is possible to prevent smoke passing from the atrium into adjacent spaces, consequently requiring a simultaneous evacuation from all floors and thus adding to the pressure of use on escape routes elsewhere in the building. This is likely to be a particular problem where there is a 'sleeping risk' eg in atrium hotels. It will also be a problem for fire fighters, since they may feel the need to search all accommodation on all floors to ensure that no-one remains at risk. Such a search would be much quicker if all accommodation is kept free of smoke.

An analogous, if more severe, fire problem exists in 'proscenium-arch' theatres, where the scenery often constitutes a serious fire load. The traditional solution^{7,8,9} has been to combine a vent (a 'hay stack light') at the top of a tower above the stage, with a heavy safety curtain to close off the

stage from the auditorium. The buoyancy of the fire gases below the vent reduces the pressure below the external ambient levels. This puts the safety curtain at a lower pressure on the fire (ie the stage) side than in the auditorium. Hence neither flames nor smoke leak past the safety curtain, since air is drawn into the stage from the auditorium through all the available leakage paths. This in turn allows the audience to escape. It should be recognized that the technique does not protect the stage at all. It protects the adjacent space in the auditorium. This concept of reducing pressure in the fire affected space in order to protect adjacent spaces can be described as 'depressurisation'.

The same concept can be applied in principle to an atrium, where the atrium itself becomes full of smoke without endangering adjacent spaces.

In the present paper we set out a theoretical analysis of such applications, both for the relatively simple case where one opening to the atrium (usually the entrance to the atrium floor) is much larger than all others and for the more complicated case where many of the inlet leakages are comparable in size, requiring a flow-network analysis. This paper describes a two-dimensional flow network for simplicity, although three-dimensional networks could of course be used in more detailed design calculations. The theory is here developed for buildings with no significant vertical leakage other than the atrium. This condition is likely to apply where there are good horizontal compartmentation and enclosed stairwells. Office, hotel (and other) atria often have these features.

It also explains how depressurisation can be combined with a smoke-ventilation design approach (such as Morgan and Hansell²) in a 'hybrid' design combining advantages of both. This would allow tall atria to have large openings on their lowest storeys and 'leaky' facades higher up. Alternatively it would permit the use of facade materials that cannot withstand high gas temperatures (eg float glass).

Extremely tall atria could present problems to a depressurisation system and any inherent height

Figure 1. Depressurisation - basic concept.

limitations are also investigated.

The gas temperature in the atrium is a very important factor in all these calculations (as well as being a vital parameter in specifying materials for the facade). In Part 2 of this paper*, a calculation technique for estimating the layer temperature in glazed-facade atria is set out in Section 6, along with many other practical applications of the atrium smoke control design principles outlined in this Part.

2. DEPRESSURISATION OF AN ATRIUM WITH A SINGLE DOMINANT INLET

2.1 No external wind

Consider an atrium as shown in Figure 1, with one dominant leakage path from the exterior (eg access doors) but smaller leakage paths between the atrium and accommodation and the exterior. This approach is useful as a simple way to explore the principles and their consequences. It is also of direct practical use where a single dominant

leakage path is obvious. Wherever no single dominant leakage path is obvious, it is necessary to carry out a flow network analysis such as that described in Section 3. Each case needs to be considered separately. Smoke fills the atrium down to a depth, D . Since we can take the air below this layer to be at ambient temperature, we can take the inlet opening A_I to be the sum of all openings, and the pressure in the atrium to be everywhere the same, below the layer's base. Note, however, that it is quite possible for the atrium to be entirely filled with smoke, in which case $D = h$. If smoke is to be prevented from leaking into an adjacent space, the atrium pressure at that height must be less than the external pressure, so that air is drawn into the atrium through that adjacent space. The height in the atrium at which the pressure is equal to the external air pressure (ie the 'neutral plane') must therefore be above the highest leakage path needing protection. It is assumed throughout this paper that the leakage paths on each storey lead ultimately to the exterior at the same storey. Large vertical flow-paths can only be treated by a full three-dimensional flow analysis.

It is a straightforward task to calculate the

*Hansell and Morgan "Smoke Control in Atrium Buildings using Depressurisation Part 2. Considerations Affecting Practical Design" Fire Science and Technology (1991), Vol ____, No ____, Pages ____.

position of this neutral plane¹⁰, giving the result that for the neutral plane to be above a depth ϕ ;

$$\frac{\phi}{(D-\phi)} \geq \frac{T_a}{T_1} \left(\frac{C_I A_I}{C_V A_V} \right)^2 \quad (1)$$

This expression can be rearranged, by defining

$$\xi = \frac{T_1}{T_a} \left(\frac{C_V A_V}{C_I A_I} \right)^2 + 1 \quad (2)$$

to give

$$D \leq \xi \phi \quad (3)$$

If the neutral plane falls – the higher storeys may be endangered. This could happen if a single dominant opening is created in an atrium with relatively small leakage paths, where for example the fire brigade or others might have opened access doors onto the atrium to investigate the severity of the fire.

It is difficult to give a simple general rule to identify when a building may be regarded as having a single dominant inlet. Nevertheless, it may be sufficient to adapt a guideline¹¹ from the related field of 'infiltration', so that one can assume a dominant inlet if the total area of all openings below the layer base is more than twice the total area of all openings above the layer base (excluding the area of the ventilators themselves).

It can be seen from equation (1) that an increase in A_I (ie opening the access doors) will result in an increase in ϕ , so the 'neutral plane' will fall. A successful depressurisation design should be able to prevent smoke infiltration into adjacent spaces on the higher floors even in this condition.

Another possible scenario is where the fire has caused breakage of windows on both the external facade and the atrium facade of a room adjacent to the atrium. In this case the broken areas can act as a 'dominant' leakage path from the exterior. The designer of a depressurization system must assess such fire-created leakage paths in the light of the circumstances applying to each separate building.

In both cases, of course, the storeys below the fire floor will necessarily be below the neutral plane, even if the atrium fills completely.

2.2 With an external wind

Buildings are usually exposed to winds, causing each leakage path to experience either a pressure rise or fall at the exterior of the building. Such wind pressures have been frequently studied in connection with wind-induced structural loading of buildings (see for example Baines¹²), and detailed design advice is available¹³. In much of this work the effect of the wind is specified in terms of a wind-pressure coefficient (C_p) defined at a specified point on the building's external surface by the relationship

$$\Delta p_\Omega = C_p \frac{\rho_1}{2} V_\Omega^2 \quad (4)$$

where Δp_Ω is the change in pressure at that point from the pressure at the same point in the absence of wind. Note that C_p is defined to take a positive value for an increase in pressure. C_p will also have different values at any given point for changes in the wind direction, but not for changes in wind strength. It is usual to define all wind pressure coefficients (C_p) in terms of the wind velocity v_Ω at a single height, typically at the top of the building in question.

In a practical design, values of C_p should be identified and assigned to the building exterior for each leakage path (usually for each floor). This can either be done by locating a published study of a building of similar geometry or, if necessary by wind-tunnel studies of the proposed design. It should be remembered that the wind velocity varies with height in practice, and the chosen study should have modelled this profile.

In practice, there is usually a wide variation in C_p on the upwind side, with relatively little variation on the downwind¹². The overall effect is to raise the pressure on the exterior of the building to windward, and to reduce it to leeward. Hence the height at which the pressure in the atrium equals the pressure on the windward exterior is higher than for no wind, while it is lower on the leeward side. Hence we can no longer identify a single 'neutral plane' in the atrium. We can instead identify a 'Windward Neutral Plane' and a 'Leeward Neutral plane'. In a successful

Figure 2. Depressurisation, showing wind effects.

depressurisation design, it is desirable for the Leeward Neutral Plane to be above the highest leakage path needing protection (see Fig.2).

The first leakage path affected by smoke will usually be the highest leeward leakage path in view of the minor variation in leeward C_p values, and where the dominant inlet is on the windward side where the positive values of C_p result in a rise in the overall atrium pressure.

As in 2.1 above, we can treat the air below the main layer as being effectively at the same pressure. We can extend the method of Appendix One of Thomas et al¹⁴ (which derived an expression for natural venting by comparing pressure drops at inlet and vent with the buoyancy of the smoky layer) by summing all departures in pressure from a no-wind ambient value, along a flow-line through the dominant inlet, up to the height (inside the atrium) of the highest leeward leakage path.

ie at a depth ϕ^L below the vent, on a flow-line through the inlet

$$\Delta p_{\phi I} = \Delta p_{\Omega I} - \Delta p_I + \Delta \rho_a g (D - \phi_L) \quad (5)$$

Similarly, on a flow-line through the vent,

$$\Delta p_{\phi V} = \Delta p_{\Omega V} + \Delta p_V - \Delta \rho_a g \phi_L \quad (6)$$

Equation (5) becomes

$$\Delta p_{\phi I} = C_{pI} \frac{\rho_1}{2} v_{\Omega}^2 - \frac{\rho_1}{2} \frac{V_I^2}{(C_I A_I)^2} + \rho_1 \frac{\Theta_a}{T_a} g (D - \phi_L) \quad (7)$$

and Equation (6) becomes

$$\Delta p_{\phi V} = C_{pV} \frac{\rho_1}{2} v_{\Omega}^2 + \frac{\rho_a}{2} \frac{V_v^2}{(C_V A_V)^2} - \rho_1 \frac{\Theta_a}{T_a} g \phi_L \quad (8)$$

Since the pressure at a depth ϕ below the vent has a single value regardless of the different flow-lines followed from the same point outside the building

$$\Delta p_{\phi I} = \Delta p_{\phi V} \quad (9)$$

The change in pressure from the no wind condition on the building exterior at the highest leeward leakage path is

$$\Delta p_{\Omega L} = C_{pL} \frac{\rho_1}{2} v_{\Omega}^2 \quad (10)$$

No smoky gases will pass across the atrium facade when the pressures are such as to drive air into the atrium.

$$\text{ie we require that } \Delta p_{\phi} \leq \Delta p_{\Omega L} \quad (11)$$

Continuity of mass requires that

$$V_v = V_I \frac{T_a}{T_1} \quad (12)$$

Note that in the above V_V is defined positive for a flow out of the atrium, while V_I is defined positive for flow in.

From equations (7), (8), (9) and (12) we have

$$(C_{pI} - C_{pv}) \frac{\rho_1}{2} v_\Omega^2 - \left(\frac{\rho_1 V_v^2}{2(C_I A_I)^2} \left(\frac{T_1}{T_a} \right)^2 + \frac{\rho_a V_v^2}{2(C_v A_v)^2} \right) + \rho_1 \frac{\Theta_a}{T_a} g D = 0 \quad (13)$$

Which yields

$$V_v^2 = \frac{(C_{pI} - C_{pv}) v_\Omega^2 + \frac{2\Theta_a}{T_a g D}}{\left[\left(\frac{T_1}{T_a C_I A_I} \right)^2 + \frac{T_1}{T_a (C_v A_v)^2} \right]} \quad (14)$$

From equations (8), (10), and (11) we have

$$\frac{(C_{pv} - C_{pL}) v_\Omega^2}{2} + \frac{T_1}{T_a} \frac{V_v^2}{2(C_v A_v)^2} - \frac{\Theta_a}{T_a} g \phi_L \leq 0 \quad (15)$$

Substituting equation (14) into equation (15), and using equation (2), we get

$$(\xi - 1) C_{pv} - \xi C_{pL} + C_{pI} \leq 2 \frac{\Theta_a}{T_a} g \frac{(\xi \phi_L - D)}{v_\Omega^2} \quad (16)$$

Equation (16) can be used by designers, since ϕ_L , A_v , A_I , C_{pL} and C_{pI} can be chosen for design.

The values of D and Θ_a (and hence T_a and ξ) can be specified using Morgan and Hansell² and Section 6 (Part 2 of this paper). C_{pv} can vary according to the position and angle of inclination of the roof vents, but in general equation (16) can be used to compare a required value of C_{pv} with achievable values given by the same wind-pressure data used to identify C_{pL} and C_{pI} .

Some simplifications of equation (16) can be made. v_Ω^2 is necessarily positive, and equation (3) tells us that, for a system to be successful even at $v_\Omega = 0$, the right hand side of equation (16) will always be positive. Hence for successful depressurisation for *all* wind speeds up to $v_\Omega = \infty$,

$$(\xi - 1) C_{pv} - \xi C_{pL} + C_{pI} \leq 0 \quad (17)$$

$$\text{ie } C_{pv} \leq \frac{(\xi C_{pL} - C_{pI})}{(\xi - 1)} \quad (18)$$

The significance of equations (16) and (18) can be shown by an example. Consider the simplified two-dimensional building shown in Fig.3, where C_{pI} and C_{pL} are based on Baines C_{pL} and other

Figure 3. An example of depressurisation in an atrium.
What vent wind pressure coefficient is needed to prevent smoke infiltration into the topmost leeward storey?

Figure 4. Critical wind speed for depressurisation failure for the building in Figure 3.

parameters have been chosen arbitrarily. In this example the atrium has been assumed to fill completely with smoke, ie $D=h$. What wind pressure coefficient is required at the vent? The solutions to equation (16) are shown in Fig.4 for two values of C_{pv} (-0.40 and -0.50). These show the serious effect of increasing wind speed in increasing ϕ if C_{pv} is not sufficiently large and negative. Fig.4 also shows that there is a critical value of $C_{pv} = -0.54$ beyond which the system works for all values of v_0 . Baines¹² shows that for the same tall building C_p values of -0.56 to -0.60 would be obtained across most of its flat roof. Hence it appears feasible to design a depressurisation system able to protect all leakage paths across the atrium facade in this particular building below 6m beneath the vent, for all wind speeds. Even where C_{pv} cannot in practice reach the values required by equation (18), Fig.4 shows that it may be possible to design a system able to protect the necessary leakage paths for all wind speeds up to some value. In the example shown here, if C_{pv} cannot go below -0.50 , a leakage path at $\phi = 12$ m will be protected for all wind speeds up to $v_0 = 30$ m s⁻¹. Use can be made of wind frequency tables (eg Reference 15) to establish the proportion of each

year the specified wind speed value will be exceeded for that building's location. If this proportion is small enough, it is possible that the risk might be deemed acceptable by the relevant Approving Authority.

Where circumstances will not allow the use of a depressurisation system using roof vents, it might be feasible to use mechanical fans to produce the same depressurisation effect. Equation 11 will apply once more.

Equations 7, 11 and 12 (with V_e replacing V_v) give

$$V_e \geq \left(\frac{T_a C_{pI} A_I}{T_1} \right) \left[(C_{pI} - C_{pL}) v_0^2 + \frac{2\Theta_a}{T_a} g(D - \phi_L) \right]^{1/2} \quad (19)$$

Where V_e is the total throughput (volume extract rate) of the roof-mounted fans in the atrium, and is assumed not to vary over the range of wind pressures likely in practice.

3. SMOKE CONTROL BY DEPRESSURISATION IN A MULTIPLE-LEAKAGE ATRIUM

The same principles can be applied as in Section 2 above, namely that the leeward neutral plane must remain above the highest vulnerable leakage path. It is now necessary, however, to recognise the effect of wind pressure, flow resistance and the atrium buoyancy (ie the stack effect) on each leakage path. Ideally, this could be done using a three-dimensional network analysis of all possible flow-paths. In the rest of this section, we will instead outline a simpler two-dimensional model to illustrate the principles.

Even this two-dimensional model might be capable of practical design application where there is good horizontal compartmentation at each floor, and where leakage paths on any single storey can be approximated as a single windward path (and a single leeward path) having single 'flow restrictions' at the exterior, in the interior of the building connecting larger spaces, and at the atrium facade. This situation might for example correspond to two open-plan offices separated by a corridor (or even one open-plan office with a negligible interior flow resistance) and with all the

exterior facade leakage openings on each storey located in a region having little variation in C_p .

It should be recognised, however, that if any other large open vertical paths exist in the building (eg unenclosed stairwells), a full 3-dimensional network is essential.

It should also be recognised that where the large leakage path between the building's interior and the atrium is not matched by a similar leakage path from the exterior to the same interior point, the following analysis will not apply. Instead the interior space in question should be regarded as being effectively open to the atrium.

The resulting idealised two-dimensional building is shown in Fig.5.

We can describe each of the above-mentioned 'choke' points, or flow resistance, in terms of a flow resistance Z , defined by the general expression

$$\Delta p = ZV^2 \quad (20)$$

For example the pressure drop across the windward exterior flow resistance on the n 'th floor is

$$\Delta P_{nUE} = Z_{nUE} V_{nUE}^2$$

In general, the flow-rate through a leakage opening is

$$V = vCA \quad (21)$$

where C is the discharge coefficient (often about 0.6 to 0.7 for large openings such as vents and doors). The pressure drop across a leakage opening can also be written

$$\Delta p = \frac{\rho}{2} v^2 \quad (22)$$

ie, using equation (21),

$$\Delta p = \frac{\rho}{2} \frac{V^2}{(CA)^2} \quad (23)$$

Comparing equations (20) and (23), we see that

$$Z = \frac{\rho}{2(CA)^2} \quad (24)$$

In principle it will be possible to identify the area and discharge coefficient for each appreciable leakage opening in a proposed or existing building. Hence all relevant values of Z can be identified and separately calculated using equation (24).

As in Section 2.2, we can sum all the changes in pressure from an initial zero-wind ambient, along a line through the leakages on the n 'th up-wind floor into the atrium.

Figure 5. An idealised 2-D building.

The resulting pressure $\Delta p(\phi_n)$ is characteristic of the atrium gases ϕ_n below the vent. Hence the sum of all pressure changes along a line from the same initial no-wind height, through the vent and down to ϕ_n in the atrium also is $\Delta p(\phi_n)$.

$$\begin{aligned} ie \Delta p(\phi_n) &= \Delta P_{\Omega nU} - \Delta P_{nUE} - \Delta P_{nUr} - \Delta P_{nUA} \\ or \Delta p(\phi_n) &= C_{pnU} \frac{\rho_1}{2} v_{\Omega}^2 - Z_{nUE} V_{nUE}^2 - Z_{nUr} V_{nUr}^2 \\ &\quad - Z_{nUA} V_{nUA}^2 \end{aligned} \quad (25)$$

$$\begin{aligned} and \Delta p(\phi_n) &= \Delta p_{\Omega V} + \Delta p_V - \rho_1 \frac{\Theta_a}{T_a} g \phi_n \\ or \Delta p(\phi_n) &= C_{pv} \frac{\rho_1}{2} v_{\Omega}^2 + \frac{\rho_a}{2} \frac{V_V^2}{(C_V A_V)^2} - \rho_1 \frac{\Theta_a}{T_a} g \phi_n \end{aligned} \quad (26)$$

We can define at each leakage flow resistance a transformed volume flow rate V' , being the volume of that flow after it has come to the temperature of the layer in the atrium.

ie

$$\left. \begin{aligned} V_{nUE} &= V'_{nU} \frac{T_1}{T_a} \\ V_{nUr} &= V'_{nU} \frac{T_i}{T_a} \\ V_{nUE} &= V'_{nU} \frac{T_i}{T_a} \end{aligned} \right\} \quad (27)$$

Equation (25) becomes, using equation (27)

$$\begin{aligned} \Delta p(\phi_n) &= C_{pnU} \frac{\rho_1}{2} v_{\Omega}^2 - Z_{nUE} V_{nUE}^2 \left(\frac{T_1}{T_a} \right)^2 \\ &\quad - (Z_{nUr} + Z_{nUA}) V_{nU}^2 \left(\frac{T_i}{T_a} \right)^2 \end{aligned} \quad (28)$$

Giving

$$V'_{nU} = \left\{ \frac{[C_{pnU} \frac{\rho_1}{2} v_{\Omega}^2 - \Delta p(\phi_n)]}{Z_{nUE} \left(\frac{T_1}{T_a} \right)^2 + (Z_{nUr} + Z_{nUA}) \left(\frac{T_i}{T_a} \right)^2} \right\}^{1/2} \quad (29)$$

Note that a reversal of flow in this leakage path would necessarily cause a change in sign of Δp at each flow resistance (equation (20)), even though the flow rate appears in equation (20) as a squared term. The effect when solving equation (29), is that a reversal in flow would appear to give a square root of a negative number. When calculating V'_{nU} therefore, it is necessary to take

the square root of the modulus of the function between the outermost brackets of equation (29), and to assign the same sign to V'_{nU} as is carried by that function.

The analysis of the depressurisation system would then be as follows. First identify Θ^a (see Section 7 in Part 2 of this paper). Initially choose $v_{\Omega} = 0$. Choose a trial value of V_v ($V_v = 1.0 \text{ m}^3 \text{ s}^{-1}$ has proved useful).

Calculate $\Delta p(\phi_n)$ from equation (26).

Calculate V'_{nU} from equation (29), paying close attention to its sign.

Repeat for all n storeys.

Similarly calculate V'_{nD} for each leeward storey (replace subscripts 'u' with 'D' in equation (29)).

Calculate a new value of flow through the vent (V'_v)

$$V'_v = \sum_n (V'_{nU} + V'_{nD}) \quad (30)$$

[Note that this is based on conservation of mass]

Test whether V'_v is sufficiently close V^v . If not, use a new trial value for $V_v (= V''_v)$ where

$$V'_v = \frac{V_v + V'_v}{2} \quad (31)$$

the iteration can be terminated.

$$\text{when } |V_v - V'_v| \leq \frac{V'_v}{m} \quad (32)$$

where m is an arbitrary integer ($m = 1000$ has proved reasonable in practice). If all values of V_{nu} and V_{nD} are then listed, it will be immediately obvious from their signs which storeys will suffer infiltration of smoky gases from the atrium.

The entire exercise can be repeated for an incremented value of v_{Ω} . This can continue up to the highest value of v_{Ω} likely to be of practical significance.

4. DEPRESSURISATION/SMOKE VENTILATION HYBRID DESIGNS

Earlier work² has suggested that smoke ventilation can only keep a limited number of lower storeys clear of smoke, below the buoyant smoke layer formed in the atrium. The technique does in principle, however, allow those lower storeys to

have adjacent spaces, and their escape routes, open to the atrium. Sections 2 and 3 above show that it is often possible to design a depressurisation system where clean air is drawn through all significant leakage openings on the atrium facade immersed in the smoke layer. Depressurisation does not, however, protect any large leakage openings on any storey above the layer base in the atrium. Neither will it protect any escape routes on that storey open to the atrium.

It should be recognised that 'pure' depressurisation systems can exist, where there are virtually no inlet openings into the atrium (ie the vent is much larger than any inlet) and the atrium fills with smoke. Such a condition appears to have existed in the Washington atrium fire¹⁶ where at one point the atrium filled with smoke to its floor, ten storeys below the actual fire. It is interesting that there was no report of smoke infiltration into the adjacent rooms during this fire. The combination of roof venting and a replacement air provision insufficient for throughflow smoke ventilation appear to have combined in this case to effectively create a successful depressurisation system.

It will often be the case, however, that architects will want to maximise use of the atrium space, and an obvious way is to combine the smoke ventilation approach² allowing greater freedom of design on the lowest storeys with the lesser freedom of 'leaky facades' allowed by the depressurisation technique set out above. In this 'Hybrid' design the ratio of vent to fresh-air inlet areas will be determined by Section 2 or 3 above, whereas the actual values of these areas must be consistent with the necessary smoke extraction requirement². It should be appreciated that in such a hybrid design the layer temperature in the atrium, required in depressurisation calculations, is a natural outcome of the calculations for both plume entrainment and smoke extract.

5. INHERENT LIMITATIONS OF DEPRESSURISATION

5.1 Criteria for ensuring escape from the atrium

It is an inevitable consequence of a depressurisation system that the space below the atrium's smoke layer will be at a lower pressure than the air outside (ignoring wind pressures for the moment). If there are any doors opening outwards on the escape routes out of the atrium, this pressure difference will tend to hold them closed. Where such doors are open to the exterior, there will be a flow of air into the atrium. The higher the neutral plane above the base of the smoke layer, the greater will be the pressure difference or inflow velocity at the inlet.

Consider first the case where powered fans produce the depressurisation effect in the atrium. Equations (12) and (19) give for the critical design condition

$$\frac{V_I^2}{(C_I A_I)^2} = (C_{PI} - C_{PL})v_a^2 + \frac{2\Theta_a}{T_a}g(D - \phi_L) \quad (33)$$

But the velocity through the inlet leakage is v_I where

$$v_I = \frac{V_I}{C_I A_I}$$

$$\text{Hence } v_I^2 = (C_{PI} - C_{PL})v_a^2 + \frac{2\Theta_a}{T_a}g(D - \phi_L) \quad (34)$$

and does not depend on the inlet area (this is a consequence of the initial assumption that V_v is independent of the pressure drop across the fan, obviously only approximately true where A_I is not too small).

The pressure difference across the inlet leakage (and hence potentially the pressure difference developed across an escape door) is given by equation (22)

Hence the pressure difference or inflow velocity at the escape exit can be found from equations (22) and (34). Note that in the absence of wind, equation (34) reduces to

$$v_I^2 = 2 \frac{\Theta_a}{T_a} g(D - \phi_L) \quad (35)$$

Next consider a naturally vented depressurisation system. V_v is given by equation (14). Clearly

V^v is not constant with change in A_f . If we consider only the no-wind condition, equation (22) again applies, and we have for the critical design condition, where $\phi_\pi = \phi_L$.

$$\frac{\rho_1 v_I^2}{2} = \Delta \rho_a g (D - \phi_L) \quad (36)$$

ie

$$v_I^2 = 2 \frac{\Theta_a}{T_a} g (D - \phi_L) \quad (37)$$

Not unexpectedly, equation (37) is the same as equation (35), showing that the same criteria will be met by a given system, whether natural or powered, in the absence of wind. The differences between equations (14) and (19) however show that natural and powered system performances diverge as v_a increases although they would be qualitatively similar.

We should now address the question of how large Δp_I or v_I should be. If the pressure difference across a closed escape door is too great, escape will be impeded. The force required to open doors, and the forces people are able to exert, have been studied elsewhere^{17,18} in connection with pressurisation of stairwells, corridors etc. It was concluded that, where the building's population may include young children or the infirm, a pressure difference of 60 Pa should be the maximum. This is also the maximum allowed in the Code of Practice on Pressurisation¹⁹. One can, however, infer from Shipp and Read's¹⁷ data that 100 Pa might be a reasonable maximum for a normally-fit adult population, while 200 Pa or even 300 Pa might be acceptable for physically-fit males under exceptional circumstances. These last might include, for example, firemen needing to open a door (perhaps not forming part of an escape route) to investigate conditions in the atrium.

Where the doorway is open, one needs to consider the largest v_I compatible with safety. The criterion usually applied in the UK to escape exits from enclosed shopping malls²⁰ is that v_I should be <3 metres per second. This is an arbitrary reduction from the airspeed found to cause inconvenience²¹ to pedestrians (c.5 ms⁻¹). It is not clear

whether either criterion ought to apply generally to all buildings, and it is perhaps better to apply a test of 'reasonableness' to each specific design in the circumstances of that building. Higher airspeeds may well be deemed acceptable under special circumstances, eg where there is only limited escape from the atrium floor. Research into the highest airspeeds acceptable on escape routes appears desirable.

5.2 Powered depressurisation – factors affecting escape criteria

Consider a building with the same wind pressure coefficients as in Figure 3, but with a powered depressurisation system. We can use equations (22) and (35) to calculate the maximum height of the neutral plane above the atrium layer's base consistent with each of the criteria set out in Table 1, in the absence of wind. The result is shown in Table 1 in each case for three representative values of Θ_a .

Similar calculations for a wind speed of 80 mph (ie 36 ms⁻¹), chosen as a rare windspeed in the UK, were carried out using equations (34) and (22), with $C_{pI} = 0.25$ and $C_{pL} = -0.55$ as in Fig.3. With this windspeed all the criteria listed in Table 1 were exceeded in all cases.

Several important conclusions follow from these results. There is obviously a need to reduce the term $(C_{pI} - C_{pL})$ in equation (19) in order to reduce the influence of the wind. Ideally $C_{pI} = C_{pL}$. This will be approximately true if the dominant inlet can be arranged to be on the leeward face of the building, where C_{pL} is (as discussed in Section 2 above) the highest leeward leakage path. There appear to be several ways of achieving this condition of $C_{pI} \approx C_{pL}$.

One would be to have several air inlets (including any escape doors from the atrium) opening onto different faces of the building, with a wind-direction sensor controlling the opening and closing of these inlets to ensure that only the down-wind inlets open.

Another possibility is to arrange that the atrium only has a 'leaky facade' on the same side

Table 1. Maximum height of neutral plane above layer base ($d - \phi_n$) consistent with various atrium escape exit criteria. No wind.

Criterion	Pressure difference at inlet (Pa)	Inlet airspeed face velocity ($C_I=0.6$) (ms^{-1}/mph)	Layer Temp Excess $\bar{\theta}_a$ ($^{\circ}C$)	($D - \phi_n$) (m)
3 m s ⁻¹ inlet airspeed	15	3/6.8	50	3.1
			100	2.2
			200	1.1
5 m s ⁻¹ inlet airspeed	42	5/11.3	50	8.6
			100	4.9
			200	3.1
60Pa	60	6/13.5	50	34.5
			100	19.8
			200	12.4
100Pa	100	7.7/17.4	50	57.3
			100	32.9
			200	20.7
200Pa	200	11.0/24.6	50	115
			100	66
			200	41.6

NOTE: The indicated pressure differences would also be experienced across any closed escape door below the layer base.

as the inlets, the other sides being sealed as in 'sterile tube' designs.

A third option is to arrange that the inlets open away from the prevailing wind. Equations (34) and (22) can be used to estimate the maximum wind speed compatible with any chosen limiting exit criterion. Tables of Wind Speed and Direction (eg Ref.15) can be used to estimate the proportion of each year this limiting wind velocity is exceeded. If this proportion were sufficiently small, the design may be deemed acceptable. Clearly this approach can only be applied separately to each individual design.

It should also be noted from Table 1 that even where the condition $C_{pI} = C_{pL}$ has been achieved, the height to the neutral plane ($D - \phi_n$) must be fairly small if one expects an averagely-fit population

to be able to escape from the space below the layer. This in turn suggests that any taller atrium should be designed as a 'sterile tube' above this height.

Note also that there is a considerable rise in the height of the neutral plane as θ_a falls. This suggests the possibility of using a design trade-off between the two, using a 'Hybrid' design approach as in Section 4 above. If the height of the layer's base is chosen to give a low value of θ_a using smoke ventilation methods outlined elsewhere², it can be seen that the neutral plane within the layer will be higher than for a lower layer base (and hence a higher θ_a for any given fire. As before², θ_a should not be allowed to fall below 20°C, or stratification might be lost inside the atrium. It is interesting that deliberately raising the layer base will in this way allow a further increase in the height over which 'leaky' facades can be employed.

Alternative possibilities might include pressurising all adjacent accommodation so as to raise the height of the neutral plane measured between atrium and accommodation, without changing the pressure between the atrium floor and the exterior. Again, where the necessary air inlets are provided separately from escape doors away from the atrium, it may sometimes be appropriate to use two (or more) sets of doors in series on the escape route to ensure that high inflow velocities through the doors are prevented. This does however require that both sets of doors should not be open simultaneously. This may need careful appraisal in view of the usual means of escape requirements, and may be best used where the space between the doors is large enough to hold most or all of the expected escapers in a place of temporary safety.

Where there is no dominant inlet¹¹, the airspeed at each escape exit will be readily calculable by the flow-network algorithms discussed in Section 3 above. One can expect design solutions to be similar to those above, but calculations must be specific to each case.

5.3 Natural depressurisation-factors affecting escape criteria

Since equations (22) and (37) apply in the absence of wind, it follows that Table 1 also applies to naturally vented depressurisation systems. Since V_v increases with v_Ω (equation (14)), it follows that high winds will produce qualitatively similar problems to those discussed above for powered depressurisation systems. It also follows from equation (14) that the adverse effects can be reduced by letting $(C_{pI} - C_{pv})$ tend to zero. In this case, however, we also need to satisfy equation (17) in a critically-functioning design for all wind speeds. Where $C_{pI} = C_{pv}$ equation (17) reduces to

$$C_{pV} = C_{pL} \quad (38)$$

Hence the ideal design condition for allowing unchanged escape criteria at all windspeeds is one where $C_{pv} = C_{pI} = C_{pL}$. Clearly this will be more difficult to achieve than for powered systems. It follows, however, that similar design options to those outlined in Section 5.2 above will apply.

The dependence of v_I on A_I in naturally ventilated depressurisation systems does however allow further alternatives for alleviating problems caused by winds.

Referring to Fig.1 and Section 2 above, we can show that the inlet mass flow is

$$M_I = \frac{A_I C_I \rho_1}{T_a} \left[v_\Omega^2 T_a^2 (C_{pI} - C_{pL}) + 2g\Theta_a T_a (D - \phi_L) \right]^{1/2} \quad (39)$$

and the outlet mass flow is

$$M_e = \frac{A_V C_V \rho_1}{T_a} \left[v_\Omega^2 T_1 T_a (C_{pL} - C_{pV}) + 2g\Theta_a T_1 \phi_L \right]^{1/2} \quad (40)$$

Setting $M_I = M_e$ we get:

$$\frac{A_V C_V}{A_I C_I} = \left[\frac{v_\Omega^2 T_a^2 (C_{pI} - C_{pL}) + 2g\Theta_a T_a (D - \phi_L)}{v_\Omega^2 T_1 T_a (C_{pL} - C_{pV}) + 2g\Theta_a T_1 \phi_L} \right]^{1/2} \quad (41)$$

If the design of the system creates satisfactory values of inlet velocity at $v_\Omega = 0$ (this in effect fixes a value of ξ), and if from equation (17) the system is able to work at the desired maximum v_Ω , then

combining equations (41) and (2), algebraic manipulation yields

$$\phi_L = \frac{T_a}{2g\Theta_a \xi} (C_{pI} - \xi C_{pL} + (\xi - 1) C_{pV}) v_\Omega^2 + \frac{D}{\xi} \quad (42)$$

For all conditions where equation 18 is satisfied, $(C_{pI} - \xi C_{pL} + (\xi - 1) C_{pV}) \leq 0$.

Hence any increase in v_Ω above 0 will cause the neutral plane to rise. This in turn will increase the mass flow passing through the atrium and in turn the inlet velocity. The effect of the additional wind-induced suction across the roof vents may be alleviated by either:

- reducing the area of the exhaust ventilation $A_V C_V$ with increasing wind velocity and hence maintaining the value of mass flow calculated at $v_\Omega = 0$, or
- increasing the area of inlet ventilation $A_I C_I$ with increasing values of v_Ω and hence maintaining the inlet velocity calculated at $v_\Omega = 0$ as that compatible with safe means of escape.

Option a) can be simply achieved by using equation (41) and inserting the value of $A_I C_I$ used at $v_\Omega = 0$ to determine the value of $A_V C_V$ required at differing wind velocities.

This is shown in Fig.6 for the example given

Figure 6. An example of reducing A_V to maintain M_e or increasing A_I to maintain V_I at increasing wind velocities.

Taken from the example of Figure 3, but with $C_{pv} = -0.7$

in Fig.3 but with $C_{pv} = -0.7$. As can be seen, the value of $A_v C_v$ decreases with increasing values of v_Q to maintain the neutral pressure plane at the desired position and hence maintain the pressure drop across the inlet at that for $v_Q = 0$. Option b) involves a slightly more complicated approach, as the mass flow will increase as a result of increasing $A_I C_I$. Referring to equation (39) at $v_Q = 0$ this reduces to:

$$M_I = A_I C_I \phi_1 \left(\frac{2g\Theta_a(D - \phi_L)}{T_a} \right)^{1/2} \quad (43)$$

with conservation of mass, and neglecting heat losses

$$M_I = M_e = \frac{Q_f}{C_p \Theta_a} \quad (44)$$

combining equations (41), (43) and (44) we have

$$\begin{aligned} & \frac{Q_f}{\rho_1} \left[\frac{T_a}{2g(D - \phi_L)\Theta_a^3} \right]^{1/2} \\ &= A_I C_I \left[\frac{v_Q^2 T_a (C_{pL} - C_{pV}) + 2g\Theta_a \phi_L}{v_Q^2 T_1 (C_{pI} - C_{pL}) + 2g\Theta_a (D - \phi_L)} \right]^{1/2} \quad (45) \end{aligned}$$

This equation can be solved by iteration to find $\theta_a T_a$ for a value of v_Q and thence using equation (41) to find the new value of $A_I C_I$ required to maintain the inlet velocity at the value set at $v_Q = 0$. Figure 6 also shows the application of this procedure in determining the change in A_I for the example of Fig.3, with $C_{pv} = -0.7$.

Either of these options may be utilised by the addition of a wind-speed sensing device controlling the quantity of ventilation or inlet area open. Since in practice the various values of wind pressure coefficients also depend on the wind direction, there is a possibility of using a wind direction sensor as well to actively control the system for a given building. This could readily be done using a pre-calculated program for simplicity.

5.4 Criteria where no escape routes are open to the atrium

Equations (33) to (37) will also apply in this case. Where there is no requirement, however, for people to be able to open atrium doors, or to escape from the atrium after the layer has become established different pressure difference criteria

(ie suction) can apply. Ultimately the acceptable limit to the suction will be set by the possibility of damage to the structure or its facade. These are perhaps best left to structural engineers to calculate. There are no recorded instances of these 'structural' criteria having been exceeded in atrium fires to date and so they must remain a hypothetical limit for extremely tall atria.

Another factor favouring depressurisation of 'leaky' atria having no means of escape requiring protection, is that it would not matter in principle if θ_a is small enough to allow downward mixing from the atrium layer. If the atrium itself is uninhabited, it would not matter if it totally fills with smoke. This suggests that for this circumstance it should be acceptable for θ_a to become much less than 20°C , even though care should be taken to prevent the ordinary ventilation system picking up cool smoke and circulating it to other parts of the building.

If, however, the inlet pressure differential in the absence of wind is acceptable, but the additional wind-induced differential exceeds the desired level, then when using a natural depressurisation system the procedure described by equations (41-45) can be employed to reduce the effects of wind pressures to the no-wind condition.

REFERENCES

1. R Saxon. Atrium buildings. Development and design. The Architectural Press, London, 1983.
2. H P Morgan and G O Hansell. Atrium buildings: Calculating smoke flows in atria for smoke control design. Fire Safety Journal 12 (1) 1987, 9-35.
3. M Law. Comments on 'Atrium Buildings: Calculating smoke flows in atria for smoke-control design'. Fire Safety Journal 13 (1988), 219.
4. H P Morgan and G O Hansell. Atrium building smoke flows. Fire Safety Journal. 13 (1988) 221-224.
5. H E Nelson et al. Fire Safety Evacuation

- System for National Park Service Overnight Accommodation. NBSIR84-2896 National Bureau of Standards, Washington, (1984)
6. GLC fire safety for the atrium. Technical Information Note, London, July 1985.
 7. Fire tests with a model theatre. The Builder's Journal and Architectural Record, 20 December 1905.
 8. Safety in theatres. Striking experiments with fire in Vienna. Daily Chronicle, 23 November 1905.
 9. A J M Heselden. Private Communication. UK Fire Research Station 1978.
 10. K Kawagoe. Fire behaviour in rooms. Japanese Ministry of Construction Building Research Institute. Report No 27, Tokyo, Sept 1958.
 11. The assessment of wind loads. Part 8: Internal Pressures. Building Research Establishment Digest 346 (1990).
 12. W Douglas Baines. Effects of velocity distribution on wind loads and flow patterns on buildings. Proceedings of Symposium No.16 'Wind effects on buildings and structures', at the National Physical Laboratory 1963, HMSO, 1965.
 13. British Standards Institution. Code of basic data for the design of buildings. CP3 Chapter V (loading) Part 2 (wind loads). BSI, London, 1972.
 14. P H Thomas et al. Investigation into the flow of hot gases in roof venting. Fire Research Technical Paper No.7. London, HMSO, 1963.
 15. Tables of surface wind speed and direction over the UK. Meteorological Office, (0.79) London, HMSO, 1968.
 16. J K Lathrop. Atrium fire proves difficult to ventilate. Fire Journal 1979, 73 (1) 30-31.
 17. R E H Read and M P Shipp. An investigation of fire door closer forces. Building Research Establishment Report. HMSO, London, 1979.
 18. Institute for Consumer Ergonomics, Loughborough. Ergonomic data for evaluation and specification of operating devices on components. Contract Reports to Princes Risborough Laboratory, Building Research Establishment 1975 and 1976 (unpublished).
 19. British Standards Institution. Code of Practice for fire precautions in the design of buildings. Smoke control in protected escape routes using pressurisation. British Standard BS 5588: Part 4: 1978. BSI, London, 1978.
 20. H P Morgan. Smoke control methods in enclosed shopping complexes of one or more storeys: A design summary. Building Research Establishment Report. HMSO, London, 1979.
 21. A D Penwarden. Acceptable wind speeds in towns. Building Research Establishment Current Paper CP 1/74, Garston, 1974.

ACKNOWLEDGEMENT

This paper forms part of the work of the Fire Research Station, Building Research Establishment, Department of the Environment. It is contributed on behalf of the Controller, HMSO by permission of the BRE Chief Executive Agency.

NOMENCLATURE

A	Cross-sectional area	(m ²)
c _p	Specific heat (at constant pressure) of air	(kW kg ⁻¹ °C ⁻¹)
C	Entry or discharge coefficient	
C _c	Convective heat transfer coefficient	
C _p	Wind pressure coefficient	
D	Depth of smoke layer in atrium below vent or exhaust fan intake	(m)
g	Acceleration due to gravity	(ms ⁻²)
h	Height of atrium	(m)
k	Thermal conductivity of a material (eg atrium glazing)	(Wm ⁻¹ K ⁻¹)
l	Thickness of conducting material (eg atrium glazing)	(m)
m	Arbitrary integer limiting the accuracy of iterative calculation	

M	Mass flow rate of gases	(kgs ⁻¹)
N	Total number of storeys	
Q	Convective heat flux	(kW)
q	Heat transmission per unit of surface area	(kWm ⁻²)
S	Area of part of surface of smoke layer in atrium, identified by subscripts. NB $S_{Ath} = S_A + S_t + S_b$	(m ²)
t	Gas temperature	(°C)
T	Absolute temperature	(K)
v	Speed of air or smoky gases	(m s ⁻¹)
V	Volume flow rate	(m ³ s ⁻¹)
V'	Volume flow rate transformed to atrium layer temperature	(m ³ s ⁻¹)
V_V^*	Defined by equation (35)	(m ³ s ⁻¹)
Z	Flow resistance of an opening	(kgm ⁻⁷)
Δp	Difference in pressure	(Pa)
Δp_α	Difference in pressure at a point on the building's exterior between no-wind and windy conditions	(Pa)
Δp_ϕ	Difference in pressure between a depth ϕ in the atrium and a point at the same height outside the atrium in the absence of wind. Δp_ϕ is determined along a line through an opening indicated by a further subscript	(Pa)
ζ	Height above atrium floor	(m)
ξ	Parameter defined by equation (2)	
ϵ	Emissivity of a surface	
ϕ	Depth below vent	(m)
σ	Stefan-Boltzman's constant	(kWm ⁻² s ⁻¹ K ⁻⁴)
ρ	Gas (or air) density	(kgm ⁻³)
$\Delta\rho$	Difference in gas (air) density from ambient	(kgm ⁻³)
Θ	Excess temperature above external ambient	(°C)

SUBSCRIPTS

a	A property of the atrium layer
A	Evaluated at the atrium facade surface
b	Evaluated at the layers base in the atrium
D	Evaluated on the leeward side of the atrium
e	Evaluated at the smoke exhaust point (powered or natural)
E	Evaluated at the external facade
f	A property of the fire and/or of the complete combustion of fuels
g	Evaluated at the internal (accommodation) surface of the atrium wall glazing
i	A property of the building's interior
I	A property of the air inlet
L	Evaluated at the highest leeward leakage path
n	Evaluated at the nth storey
r	A property of a flow resistance between the external and atrium facades of the building
S	A property of a surface
t	Evaluated at the atrium roof
U	Evaluated at the windward side of the building
v	Evaluated at the smoke vent
1	An external ambient property
λ	A property of radiant energy
π	Evaluated at the neutral plane in the atrium
ϕ	Evaluated at a depth ϕ within the atrium
Ω	A property of the wind