COMPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS OF SMOKE CONTROL IN TALL BUILDINGS

VOLUME TWO

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COMPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS OF SMOKE CONTROL IN TALL BUILDINGS.

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INTRODUCTION

This volume contains the detailed discussion of pressure measurements, internal and external, on the 32-cell model.

Chapter 3 of this volume is an extension of chapter 3 Volume I. The results are discussed for each wind direction separately, for the two outside leakage confingurations ivestigated. The mass flow rate through each of the internal door openings on the internal pressures on floors 2 and 4, is measured and discussed separately. The results for other wind directions are related.

Chapter 4 contains the results for pressure measurements with a fire pressure in room 6 on the chosen floor (floor 2 or 4). For comparison with the results of chapter 3, measurements were taken for all wind directions up to $\alpha \triangleq 270^{o}$. Because of the limitations of space and time, chapter 4 only contains the discussion of results for $\alpha = 0^{o}$ in detail. Similar discussion for other angles can follow for other wind angles. The measured results are given in fig 4.1.1 - 4.7.6. A summary of these results appear in chapter 4 Volume I.

Appendix A contains the derivation of relationship between, internal and external pressures in terms of the leakage characteristics of a enclosure

Appendix B, contains the brief description of the computer program used for the analysis of internal pressures. The form of input data for the Darwin Building and the wind tunnel model (32-cell) is also given.

Appendix C, is a copy of the paper published in the Journal of Industrial Airodynamics entitled: "Wind Effect on Buildings with Varying Leakage characteristics - Wind Tunnel Investigation".

Appenidx D, contains a copy of the paper presented by the author of this thesis at the recent International conference on Wind Engineering held in Colorado. "Wind Induced Movement of Smoke within and Around Buildings - A wind tunnel Investigation".

CHAPTER THREE, VOL II

THE EFFECT OF VARYING SHAFT LEAKAGE AND INTERNAL DOOR OPENINGS ON INTERNAL PRESSURES.

Chapter 3

THE EFFECT OF VARYING SHAFT LEAKAGE AND INTERNAL DOOR OPENINGS ON INTERNAL PRESSURES.

3.0 Introduction

For zero wind incidence, the effect of door openings was investigated on every floor. As pressures are quite different on each floor level, the door openings on one floor may have quite substantial influence on all floors.

In tall buildings, stair shaft(s) are the major escape routes in fire situations. It is therefore necessary to keep them smoke free. Different pressure distributions on a particular floor result from the resistances offered by the doors. Pressures are highly dependent on the leakage characteristics of these doors. When a fire room door burns down, or is left open by the escapers, smoke can easily spread to neighbouring areas, such as the corridor, and threaten the shaft. From the smoke spread point of view, when the shaft door is open the situation becomes potentially dangerous.

3.1 Measurements

Three door opening configurations were investigated; apart from All Doors Closed case,

(i) All doors closed

(ii) Shaft door open ('S' open)

(iii) Room ⑥ door open ('6' open)

(iv) Shaft and Room ⑥ doors open ('S' + '6' open).

Measurements for these configurations were repeated for two different shaft leakages. They were

(a)

T	D	R
1.5	1.5	1.5

(b)

T	D	R
1.5*	1.5	1.5

as explained earlier in Volume 1 Chapter 1 .

3.2 Discussion of Results

3.2.1. The Effect of EACH Floor Door Openings:

3.2.1.1 Wind Incidence $\alpha = 0^{o}$

For this particular wind incidence, the internal pressures, when all doors are closed, are a direct reflection of external wall pressures, but as soon as any of the internal doors are opened on a floor, the pressure distribution in the immediate neighbourhood of the door changes quite considerably.

3.2.1.2 All Door Closed

For this configuration, air flows into the corridor from the shaft on each floor. Each floor is independent of the others, hence the mass rate of flow of air into and out of the corridor should be equal on all floors. This can easily be shown using the following relationship of mass flow rate and pressure difference.

$$M = \sqrt{\frac{\Delta P}{R_r}} \quad kg/s \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2.1$$

where ΔP = pressure difference across an opening (N/m)

R_r = flow resistance given by

$$\frac{1}{2\rho\ (C_d\ A_e)^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2.2$$

ρ = density of air kg/m^3

C_d = discharge coefficient (= 0.65)

A_e = area of the opening (m^2)

Since

$$\Delta P = q\ \Delta Cp \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2.3$$

where $q = \frac{1}{2}\rho V^2$, dynamic head at some reference height

$\therefore$ The mass flow rate can be written as

$$M = \sqrt{2\rho}\quad C_d A_e \sqrt{q\ \Delta Cp}$$

or

$$M = \sqrt{2\rho q\ \Delta Cp_i}\ \times\ C_d A_e \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2.4$$

Since in the present case the leakage area of all closed doors is the same and holes are of the same shape, then

$$M = k\sqrt{\Delta Cp} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2.5$$

$$\sum_{i=1}^{n} M_i = \sum_{i=1}^{n} \sqrt{\Delta Cp_i} = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2.6$$

where n is the number of doors connected to the corridor. Using the above expression, the calculated mass flow rates for each of the floors are summarised in Table 3.2.1.

Table 3.2.1

Floor	M_{in} (kg/hr)	M_{out} (kg/hr)
1	1.074	0.832
2	0.9252	0.909
3	1.050	0.969
4	1.127	0.997
5	1.086	0.986

This table shows that the figures are not exactly equal (i.e. $M_{in} \neq M_{out}$ exactly) as expected from theory. This is mainly due to the uncontrolled leakages within the model. It is very difficult to completely seal such a complicated model. The other reason for discrepancy may be due to the fact that some of the measuring tubes act as extraneous leakages which are not taken into account in the calculations. Some air may also be escaping through the floor of the model.

Considering the model as a whole, the total infiltration and exfiltration rates are as follows:

$$M_{in} = (\text{total}) = 5.264 \text{ kg/hr}$$

$$M_{out} = (\text{total}) = 4.694 \text{ kg/hr}$$

3.2.1.3 Shaft Door Open ('S' Open)

Each room and corridor pressure for all floors are summarised in Tables 3.2.2 - 3.2.6. The corridor pressures in table 3.2.6 show that except for the floor on which the shaft door is opened, the

corridor pressures on all other floors remain unaffected. This is because the shaft pressure itself does not change significantly. Except for the diagonal values (in Tables 3.2.2 - 3.2.5) the Cp_i values for a floor remain the same. The opening of the shaft door increases its leakage value, hence shaft experiences a drop in pressure -

$$Cp_i \text{ (Shaft)} = 0.06$$

Room pressures are also unaffected by the opening of the shaft door; even on the floor of opening the room pressure remains constant. This is clear from Tables 3.2.3 - 3.2.5. In room (1) for example, the pressure is the same as for the all doors closed case (compare the values in column 1). The slight variations that do occur are due to turbulence and measurement errors and the results presented are the mean values.

3.2.1.4 Room (6) Door Open:

Since this particular room has its window openings into the wake region, it is subjected to negative pressure. The opening of this room door extends its influence to the corridor making its pressure negative. As the original corridor pressure was positive then the resulting corridor pressure is higher than the original room (6) pressure before the door was opened. Table 3.2.9 shows the corridor pressures. It shows that, except for the floor on which room (6) door is opened, the corridor pressures on other floors are unaffected. The values in each of the vertical columns are the same, leaving the

diagonal out. Room pressures are shown in Tables 3.2.6 - 3.2.8. Room ⑥ and corridor pressures tend to equalise out and the measurements show that they are very nearly equal to zero. Compare marked diagonal Cp_i values of Table 3.2.9 for corridor and table 3.2.8 for room ⑥. Again, taking the mean of fluctuating values, the results are in small error but the diagonal values are so small that they can be taken as zero.

The shaft pressures remain uninfluenced, hence other floors are unaffected.

$$Cp_i \text{ (shaft)} = 0.40$$

3.2.1.5 Shaft and Room ⑥ Doors Open ('S' + '6') Open:

In this case, because of the suction through room ⑥ door open and higher push through shaft door open, the corridor experiences high pressures compared with all doors closed case, but they are slightly less than when only the shaft door is opened - see table 3.2.13. Measurements in Table 3.2.10 - 3.2.12 confirm the previous conclusions that pressures on other floors are unaffected.

$$Cp_i \text{ (shaft)} = 0.30$$

Conclusions: These measurements show that for the leakage configuration investigated, the pressure changes are confined to the floor of door openings, and because no drastic changes in shaft pressures occur, each floor is independent from the air flow point of view. Following from this, two floors (floors 2 and 4) only are chosen for subsequent pressure measurements for other wind angles.

3.3 Wind Incidence $\alpha = 0^{o}$

In this section are discussed the results for two outside leakage configurations, (a) and (b), on floors 2 and 4, with the mentioned internal leakage configurations.

3.3.1 Leakage Configuration (a): | 1.5 | 1.5 | 1.5 |

3.3.1.1 Floor 2

The shaft and corridor pressures for this configurations are shown in Fig 3.3.1. The shaft has its window openings onto the windward side and is subjected to positive pressures. The outside pressures on the windward wall increase with height and since the shaft is a single volume, the pressures at all floor levels in the shaft are the same.

(i) All doors closed: For this configuration the shaft pressure is higher than the corridor pressure with flow resulting into the corridor. As all door leakages are the same, the corridor pressure increase with height, with a maximum value on floor 4 ($cp_i = 0.32$). Even though the shaft assumes one mean value for pressure on all floor levels, the lowest pressure occurs on floor 1, so there is some tendency for air to flow downwards. Smoke tests showed this to be the case, with even small amounts of smoke escaping through the shaft leakage holes on floor 1. This means that if fire occurs in the shaft all floors are threatened, particularly the first floor where there is the highest pressure difference between the shaft and corridor. As smoke escapes through the first floor main entrance

door to the shaft, it not only threatens the occupant but also hinders the rescue operations. For this type of building then fire in the shaft is most dangerous, unless some way of increasing the corridor pressures is found.

A lobby between the shaft and the corridor is sometimes suggested as a solution and in that case the lobby pressure is maintained at a value which is higher than the shaft pressure but the pressure difference across any of the doors must not be greater than $50 N/m^2$. This means that varying flow rates are required at each floor level to maintain this pressure limit. On floor 2 the wind induced pressure difference is about $0.24\ q\ N/m^2$, which means that the lobby pressurisation fan must overcome this difference so that there is a flow from the lobby into the shaft, preventing smoke getting into the corridor.

If there is a 20 m/s wind blowing, then the wind induced pressure difference across the shaft door is about $59\ N/m^2$, helping to push air into the corridor of floor 2. This means that the fan must work so that there is a pressure difference of $59\ N/m^2$ across the shaft door. If fire in the shaft spreads further, occupants must be rescued by some other way. Lobby pressurisation can protect them from smoke and keep them confined to the floor because of the difficulty in opening corridor doors, even if some one tries to escape using the shaft.

The respective room pressures are shown in Fig 3.3.3 'All closed'

figure refers to doors closed. As all doors have the same leakage areas, the conservation of mass for the corridor gives the following relationship:-

$$(\Delta Cp_i)^{\frac{1}{2}}_{shaft} + \sum_{j=1}^{J} (\Delta Cp_i)^{\frac{1}{2}}_{j} = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ 3.3.1$$

where j = room number with door leading to the corridor

J = maximum number of rooms.

Applying the above equation to floor 2 gives

$$(0.22)^{\frac{1}{2}} + (0.46)^{\frac{1}{2}} + (0.40)^{\frac{1}{2}} + (0.21)^{\frac{1}{2}} \doteqdot (0.36)^{\frac{1}{2}} + (0.36)^{\frac{1}{2}} + (0.38)^{\frac{1}{2}}$$

$$0.469 + 0.678 + 0.632 + 0.458 \doteqdot 0.6 + 0.6 + 0.616$$

$$2.237 \doteqdot 1.816$$

These figures show that there is more inflow than outflow. Extra flow is most probably resulting through the measuring tubes.

Once again the magnitude of room pressures can be explained in terms of outside wall pressures (see Chapter 2 of Volume 1).

The above discussion is only true if all doors are kept closed. Opening any of the internal doors causes considerable pressure changes.

(ii) Shaft door open ('S' open): From Fig 3.3.1 for floor 2 openings, it is clear that the shaft pressure drops slightly from Cp_i = 0.43 (All Closed) to Cp_i = 0.39 ('S' open). This does not result in any change in internal flow pattern as air flows into the corridor on all floor levels even though the pressure difference

across the shaft doors drops slightly. Again, fire in the shaft will present similar problems to those described in the previous section.

The corridor pressure increases quite considerably as a result of opening the door -

$$\text{Corridor, } Cp_i \text{ (all closed)} = 0.21$$

$$Cp_i \text{ ('S' open)} = 0.33$$

This decreases the pressure difference across the shaft door, making it easier for flow to occur either way. Any fire in the shaft will cause smoke to spread more quickly on floor 2 than on any other floor. The occupants of rooms ④, ⑤ and ⑥ are more vulnerable to this threat as a result of prevailing negative pressures in these rooms. Any smoke getting into the corridor will be pushed out through these rooms.

Any extra pressure created by fire in the corridor may push smoke into the shaft which can quickly spread to other floors.

As seen from Fig 3.3.2 for 'S' open, the windward rooms ①, ② and ③ are quite safe even though the pressure difference across these room doors is decreased due to the increase in corridor pressure.

If fire occurs in any of rooms ④, ⑤ or ⑥, most of the smoke is drawn out through the windows, unless fire pressure overcomes the corridor pressure.

Fire in any of the windward rooms ①, ② or ③ will threaten most of the rooms on that floor as well as threatening the shaft, hence all other floors.

All room pressures remain unaffected by the change in corridor pressure, caused by the open shaft door.

(iii) Room ⑥ door open ('6' Open): The shaft pressure in this case recovers its original (i.e. all doors closed) value. Because of very low pressure in the corridor ($Cp_i \doteqdot -0.03$), the shaft pressure is slightly less than the 'All-door-closed' case, and slightly greater than 'Shaft-door-open' case (see Fig 3.3.1). No change in flow pattern occurs on any of the floors. The shaft pressure coefficients are:-

Cp_i (All Closed) = 0.43

Cp_i ('S' Open) = 0.39

Cp_i ('6' Open) = 0.40

Any fire occurring in the shaft will cause smoke to flow onto the floors and moreso on to Floor 2, the shaft door of which is subjected to very high pressure difference.

This high pressure difference results from a very low pressure in the corridor. This is the volume which connects all rooms as well as the shaft, all being at different pressures.

The pressures in the corridor are very much dependent on the pressure distribution on the leaky walls and on the internal leakage

characteristics. For inflow to equal outflow, any leakage variation of room doors causes the corridor pressure to readjust itself. If the door of a negative pressure room is opened then that room pressure becomes dominant and the corridor pressure changes to equal the room pressure. Fig 3.3.2 for '6' open, shows this quite clearly. This results in an increase in pressure difference across the shaft door (ΔCp_i = 0.43). This is much higher than any of the other floors.

In this configuration then, fire in the corridor does not pose any threat to the shaft or any other floors. In fact, the opening of one of the negative pressure room doors vents the fire and smoke flows out through the window of that room.

As in the case of shaft pressure, room pressures are slightly affected by the change in corridor pressure. With a 110 per cent drop in corridor pressure, the pressures in rooms ① to ⑤ drop by about 20 per cent at the most, but room ⑥ pressure increases by about 85 per cent. About 70 per cent of air flowing into the corridor flows out through room ⑥, while the remainder flows through rooms ④ and ⑤. This means that fire in any of the windward rooms ①, ② or ③, will only pose a threat to that floor and not to the others.

(iv) Shaft and Room ⑥ doors open ('S' + '6'Open): In this case the effects of the previous two configurations combine to give positive pressures in Shaft, Corridor and Room ⑥. Windows of room ⑥ are directly connected to the windows in the shaft,

virtually without any resistances, hence pressure in these three regions assumes a value which is different from any of the previous cases. The shaft pressures are:-

Cp_i (all doors closed) = 0.43

Cp_i ('S' open) = 0.39

Cp_i ('6' open) = 0.40

Cp_i ('S' + '6' open) = 0.30

From Fig 3.3.1 it is clear that the shaft pressures are lower than any of the other configurations but this does not have any significant affect on other floor corridor pressures,as the figure shows. On floor 2 itself, the shaft and corridor pressures are equal: this is shown clearly in Fig 3.3.2 for ('S' + '6') open.

Smoke resulting from fire in the shaft is driven out through the corridor and room ⑥ by a wind induced pressure difference which is the difference between the pressure just outside the shaft windows and that just outside the room ⑥ windows. Quite a lot of smoke will flow through this way and less will get into other floors because of the reduced pressure difference.

Fire in the corridor may threaten the shaft but again, most of the smoke will flow out through room ⑥, reducing the possibility of it getting into the shaft. The corridor pressures are as follows:-

Cp_i (All closed) = 0.21

Cp_i ('S' Open) = 0.33

Cp_i ('6' open) = -0.03

Cp_i ('S' + '6' open) = 0.31

3.3.1.2 Floor 4

Since the highest wind pressures occur on floor 4, the measurements were repeated on this floor for the same internal leakage configurations. The results are summarised in Figs 3.3.1 and 3.3.3. Comparison with floor 2 results shows that the shaft pressures remain about the same, except for ('S' + '6') open case in which floor 4 opening produced slightly higher shaft pressure.

(i) All doors closed: The shaft and corridor pressures in this case are exactly the same as those for the previous configuration. Room pressures on the other hand are much higher. As the corridor pressure on this floor is much higher than on floor 2, the amount of air flowing into floor 4 corridor is also less than that flowing into floor 2.

$$Cp_i \text{ (Corridor) Floor 4} = 0.32$$

$$Cp_i \text{ (Corridor) Floor 2} = 0.21$$

The amount of smoke flowing into floor 4 as a result of a fire in the shaft is about 30 per cent less than that flowing into floor 2, assuming of course that the fire does not cause any drastic changes in the shaft pressure. In this case the lobby pressure required to confine smoke to the shaft will be much less. In fact the fan will have to maintain a pressure difference of 27.0 N/m^2 across the shaft door compared with 59.0 N/m^2 on floor 2.

Because the outside pressure on wall R is almost uniform, the leeward room pressures do not change significantly from one floor to another.

On floor 4, since the corridor pressure is much higher, it may be that fire in the corridor may overcome the existing pressure difference across the shaft ($Cp_i = 0.11$). If that happens, some smoke will get into the shaft and it may move down the shaft and hence onto other floors. Again, suitable lobby pressure can prevent this from happening. Fire in any of the rooms will have the same consequences, as discussed in the case of Floor 2.
The respective room pressures are shown in Fig 3.3.3.

Applying equation 3.3.1 gives:-

$$(.11)^{\frac{1}{2}} + (0.65)^{\frac{1}{2}} + (0.58)^{\frac{1}{2}} + (0.33)^{\frac{1}{2}} = (0.51)^{\frac{1}{2}} + (0.51)^{\frac{1}{2}} + (0.52)^{\frac{1}{2}}$$

$$0.33 + 0.80 + 0.76 + .57 = .71 + 0.71 + 0.72$$

$$2.46 = 2.141$$

Again, the discrepancy is most probably due to the unavoidable leakage through numerous measuring tubes which may be exposed to the atmosphere. This does not in any way effect the flow patterns or invalidate any of the conclusions.

(ii) Shaft door open ('S' open): The drop in shaft pressure is the same as for floor 2.

Cp_i (shaft) All closed = 0.43

Cp_i (shaft) 'S' open = 0.39

This drop is caused by the increase in shaft leakage through which air flows out of the shaft. The corridor pressure of $Cp_i = 0.43$

in Fig 3.3.3 for 'S' open, is probably not the right measurement. The large increase in the leakage area due to the opening of the shaft door makes the shaft and corridor behave as a 'single volume' which means that pressure within that volume must be uniform.

Total inflow through rooms ①, ② and ③ is M_{in} = k (1.86) and total outflow through rooms ④, ⑤ and ⑥ is M_{out}= k (2.31). This means that the remainder of the inflow occurs through the open shaft door. If Ae is the leakage area of closed door, then the leakage area of open door must be 66.66A_e; then if ΔCp_{sh} is the pressure coefficient difference across the shaft door, the following relationship results -

$$1.86k + 66.66k\ (\Delta Cp_{sh}) = k(2.31)$$

or

$$\Delta Cp_{sh} = 0.000046$$

i.e. virtually no pressure difference.

To make inflow equal outflow, the amount of air flowing through the shaft door is 0.45k, which is about 25 per cent of the total inflow through rooms ①, ② and ③. This is much larger than the doors closed case in which the value is about 15 per cent. This means that about 10 per cent more smoke will get onto the floor if the shaft door is opened. Compared with floor 2, this value is again about 8 per cent less, which means that for floors with low corridor pressures, a lot more smoke gets into them as a result of fire in the shaft. Only very slight changes occur in the room pressures but the general flow pattern remains the same as on floor 2.

All the leeward rooms (④,⑤ and ⑥) are effected by a fire in the corridor. Since there is no pressure difference between the shaft and corridor, smoke is likely to get into the shaft, with a possibility of it spreading to either floors. A lobby maintained at a higher pressure is necessary to isolate fire floor from the corridor.

(iii) Room ⑥ door open ('6' open)

Because of constant pressure over the wall R the shaft pressure is the same as for the same configuration on floor 2. The pressure drop from the 'All door closed' case is only very slight, and the overall flow pattern remains unaltered.

Cp_i (shaft) All closed = 0.43

Cp_i (shaft) 's' open = 0.39

Cp_i (shaft) '6' open = 0.41

Because of the increased leakage, due to the opening of room 6 door, the influence of this room over the corridor pressure becomes dominant, as that corridor pressure equals the room 8 pressure (see fig 3.3.3 for '6' open). This is comparable to the same configuration on floor 2. About 75% of the total flow into the corridor flows out through room ⑥, which for a fire in corridor or any of the rooms ①, ② or ③ is very good to clear smoke. Fire in the shaft, on the other hand, threatens this floor as floor 2 is threatened for the same configuration.

One very small change occurs in room pressures due to opening of

the door. Pressures drop by only a very small percentage, much less than the drop on floor 2 room pressures.

(iv) Shaft and room ⑥ doors open ('s'+'6') open:

In this case the change in shaft pressure is similar to that on floor 2. Since there is a higher breakage on the positive pressure side (ie. wall T), the room ⑥ pressure increases slightly so that inflow into this room is equal to outflow. The shaft and corridor behave as one 'single volume' with uniform pressure (Cp_i = 0.31). There exists a very high pressure difference across room ⑥ window (Cp_i = 0.60), which means that quite a lot of the inflowing air escapes through this leakage. Fire in the shaft is directly vented and less smoke flows on the other floors. The shaft pressures are.

Cp_i (shaft) 'All closed' = 0.43

Cp_i (shaft) 's' open = 0.39

Cp_i (shaft) '6' open = 0.41

Cp_i (shaft) 's'+'6' open = 0.32

These values are very much similar to those for floor 2 openings.

Since shaft and corridor pressures are equal, a fire in the corridor may cause smoke to flow into the shaft, but since most of the smoke is sucked through room ⑥, it will not be a great threat to the people escaping using the shaft. The corridor pressures are

Cp_i (cor) 'all closed' = 0.32

Cp_i (cor) 's' open = 0.43

Cp_i (cor) '6' open =-0.03

Cp_i (cor) 's' + '6' open = 0.30

Room pressures alter only very slightly, as a result of increased corridor pressure. But the average values for the four configurations remain the same except for room ⑥.

Except for the slightly increased pressures in room ①, ② and ③, the general conclusions are the same as those for floor 2. These high pressures do not change the basic flow pattern. Compare figures 3.3.2. and .3.3.3.

3.3.2. Leakage Configuration (b)

1.5*	1.5	1.5

3.3.2.1. Floor 2

Because there is a marked change in the shaft leakage characteristics, the shaft pressures change quite considerably. This has some influence on room pressures as well. The results are summarised in figures 3.3.4. to 3.3.7 for floors 2 and 4 with four different internal leakage configurations.

(i) All doors closed (all closed)

There is a dramatic drop in shaft pressure compared to the previous configuration, which means that any corridor pressure changes can easily influence the flow pattern.

Cp_i (shaft), leakage (a) = 0.43

Cp_i (shaft), leakage (b) = 0.20

All the above figures show, it drops by about 50%. This reduces the corridor pressure by the same factor.

Cp_i (cor.), leakage (a) = 0.21

Cp_i (cor.), leakage (b) = 0.13

Figure 3.3.4. shows that, the highest corridor pressure occurs on floor 4, as for (a). Because of the reduced shaft leakage the corridor pressure is higher than the shaft pressure on the 5th floor (see fig 3.3.4.) which means that any fire on this floor will cause smoke to flow into the shaft, and onto other floors. With fire on this floor, door openings on any of the other floors will cause a further drop in the shaft pressure and hence causing more smoke to flow into the shaft.

For this leakage configuration then lobby approach is more desirable. Then the shaft pressure is low, the lobby fan on floor 2 will only have to overcome $17N/m^2$ opposing pressure compared with $59N/m^2$ for the previous leakage configuration (a), to keep floor 2 free of smoke if fire occurs in the shaft.

The room pressures are shown in fig 3.3.6. in comparison with fig. 3.3.2. show that they are considerably smaller than those for leakage (a). This results in a reduced infiltration rate. But equation 3.3.1. still applies, giving.

$$\sqrt{.07} + \sqrt{.48} + \sqrt{.41} + \sqrt{.27} \doteqdot \sqrt{.31} + \sqrt{.31} + \sqrt{.31}$$

$$.26 + .69 + .64 + .52 \doteqdot .55 + .55 + .55$$

$$2.11 \doteqdot 1.67$$

The discrepancy is again due to the uncounted leakage occuring through the measuring tubes. The amount of air flowing through this leakage is about 20% of the total inflow into corridor. This value is also confirmed by the measurements in Fig 3.3.2.

(ii) Shaft door open ('S' open):

Figure 3.3.4. shows that the drop in shaft pressure is small compared with that for configuration (a). It drops from Cp_i (All closed) = 0.20 to Cp_i('S' open) = 0.18. Shaft pressure than equalises with the corridor pressure with no flow either way. Whatever air flows into the shaft from outside flows into floor 1, as for other floors, the corridor pressures are very nearly equal to shaft pressures. This means that any extra pressure created by a fire in the shaft can create a pressure difference across the shaft door for smoke to flow on to all the floors.

Lower shaft pressure means, that to maintan a pressure difference of $50/m^2$ in the lobby, the fan will be working at a very low rate. For this configuration, it does not have to overcome any extra pressure in the shaft.

Due to opening of the shaft door the corridor pressure rises from Cp_i=0.13 (All closed) to Cp_i=0.18 ('S' open). Equal shaft and corridor pressure means that a fire in the corridor, can easily threaten the shaft with smoke. Again a higher lobby pressure can prevent this.

Small increases in room pressures occur due to the increase in corridor pressure. As there is no flow across the shaft door, air flowing into the corridor from rooms ①, ② and ③ flows directly out through rooms ④, ⑤ and ⑥. Hence application of equation 3.3.1 gives.

$$\sqrt{.45} + (.39)^{\frac{1}{2}} + (.21)^{\frac{1}{2}} \doteqdot (.36)^{\frac{1}{2}} + (.35)^{\frac{1}{2}} + (.35)^{\frac{1}{2}}$$

$$.67 + .62 + .46 \doteqdot .59 + .59 + .6$$

$$1.75 \doteqdot 1.78$$

Provided a fire in any of the windward rooms ①, ② or ③ does not cause any corridor pressure change, smoke will directly flow out through rooms ④, ⑤ and ⑥ with perhaps small amounts getting into the shaft, but not enough to unchange the floors.

But if fire occurs on the 4th Floor corridor or in rooms ①, ② or ③ and the effect of opening the shaft door on floor 2 will be to lower the shaft pressure than that of the corridor on the fire floor (ie. 4th floor), increasing smoke flow into the shaft. The worst case being when ('s' + '6') are opened on floor 2.

Smoke presents no danger anywhere in the building if fire occurs in any of the rooms ④, ⑤ or ⑥ on floor 2, as it is sucked out through the windows by prevailing negative pressure on wall R.

(iii) Room ⑥ door open ('6' open)

There is a further drop in the shaft pressure as corridor pressure becomes negative for this leakage configuration. This increases the flow rate from shaft into the corridor. The shaft pressures are:

Cp_i (all closed) = 0.20

Cp_i ('s' open) = 0.18

Cp_i ('6' open) = 0.16

The corridor pressures on other floors are shown in figure 3.3.4. It shows that for floor ④ and ⑤, they are higher than the shaft pressures. Fire on these floors, occuring either in rooms ①, ②, ③ or corridor, will make smoke flow into the shaft. Once in the shaft, it can spread to other floors. While a fire on floor 2, confines smoke onto that floor as there is a higher shaft pressure. In fact, as before, opening any of the rooms ④, ⑤ or ⑥ doors, vents the fire, and allows smoke to escape with out getting into the shaft. Fire in the shaft, on the other hand, causes more smoke to flow onto floor 2 than any other floor. In fact floors 4 and 5 are smoke free because of their high corridor pressures,

Again applying the equation 3.3.1 to corridor shows that about 72% of the air flowing into the corridor, flows out through the open door of room ⑥. The corridor pressures are:

Cp_i (all closed) = 0.13

Cp_i ('s' open) = 0.18

Cp_i ('6' open) =-0.05

In this case if smoke is to be confined to the shaft as a result of fire there, the fan in the lobby will have to overcome an already existing pressure of $39N/m^2$ (at a wind speed of 20m/s). For fire in the corridor or any of the rooms ①,②,③ the existing pressure difference ($\Delta Cp = 0.21$) is enough to stop smoke getting into shaft (it is equivalent to $51N/m^2$ at a wind of 20m/s).

(iv) Shaft and Room ⑥ door open ('s' + '6') open:

As can be seen from fig 3.3.4. there is a large drop in shaft pressure in this case.

Cp_i(all closed) = 0.20

Cp_i('s' open) = 0.18

Cp_i('6' open) = 0.16

Cp_i('s'+'6' open = 0.06

The corridor equalises with that of the shaft pressure, and positive pressure dominates due to higher leakage for these pressures. This dominance makes the room ⑥ pressure positive and nearly equal to the corridor pressure which results in a very high pressure different across room 6 window ($\Delta Cp \doteqdot 0.27$). Then if there is no air flowing from the shaft most of it flowing from rooms ①, ② and ③ is sucked out through room ⑥ windows, in fact it is about

55% of total inflow (through rooms ①, ②, and ③) escape through room ⑥. What this means in terms of a fire is one of the windward rooms or in the corridor is that most of the smoke is pushed out through room ⑥ window. Since shaft and corridor pressures are the same, it depends on the magnitude of fire pressure, how much smoke gets into the shaft.

The corridor pressures are:

Cp_i (all closed) = 0.13

Cp_i ('s' open) = 0.18

Cp_i ('6' open) =-0.05

Cp_i ('s'+'6' open) = 0.06

The rooms pressures are very much less influenced by the changes in the corridor pressures, because of the small size of this change. This change can be ignored as it does not influence any flow pattern within the model.

From these measurements for leakage configuration (b), it can be concluded that:

(i) The pressures are considerably lower compared with leakage (a), this is more pronounced in the shaft and corridor than in rooms.

(ii) As a result of this reduced leakage in the shaft, smoke can easily get into the shaft from fire on any floor, because of the reduced shaft pressures.

(iii) Lobby pressurising fan does not have to work against high wind induced pressures.

(iv) The influence of door openings on one floor is felt more on other floors in this leakage than in (a).

3.3.2.2. Floor 4

Highest room and corridor pressures occur on this floor. The results are summarised in figures 3.3.5. and 3.3.7.

(i) All doors closed (All closed):

For this case the shaft and corridor pressures are re-plotted in fig 3.3.5. for comparison. The highest corridor pressure occurs on this floor ($Cp_i \doteqdot 0.20$). Comparison with configuration (a) fig 3.3.3. shows that, this value is considerably lower.

Cp_i(a) all closed = 0.32

Cp_i(b) " " = 0.20

The other major difference is that whereas for the previous case there is a flow onto the floor from the sahft as a result of the higher shaft pressure, in this case both the shaft and the corridor are at equal pressures, indicating no net flow either way. The corridor pressure is then entirely dominated by the higher positive pressures in rooms ①, ②, and ③.

Any fire pressure (created by a fire either in the shaft or corridor) can easily upset this equiliborium and result in a smoke flow either way. If smoke gets into the shaft from the corridor it can easily spread to other floors, where there is already a flow from the shaft. In this case a lobby pressurising fan does not have to overcome any extra pressures.

Air that enters the corridor through rooms ①, ② and ③, finds its way out through rooms ④, ⑤ and ⑥, then applying equation 3.3.1.

$$(0.73)^{\frac{1}{2}} + (0.65)^{\frac{1}{2}} + (0.45)^{\frac{1}{2}} \doteqdot (0.41)^{\frac{1}{2}} + (0.41)^{\frac{1}{2}} + (0.41)^{\frac{1}{2}}$$

$$.85 + .80 + .67 \doteqdot .64 + .64 + .64$$

$$2.32 \doteqdot 1.92$$

This differnce means that there is some air escaping from the corridor, which is not accounted for. If the area through which this escape occurs is the same as one of the door leakage areas, then for inflow to equal outflow, the pressure coefficient difference is aobut 0.16. As some of the measuring tubes in the corridor may be connecting the corridor to the outside, which means pressure coefficient difference of 0.20. Therefore, it is most likely that extra outflow occurs through these tubes.

(ii) Shaft door open ('S' open):

Figure 3.3.5. shows that in this case the shaft pressure increases slightly. This probably is not true following on from the previous results. Because there is no pressure difference across the shaft door when closed, the opening of this door should not make any difference. Therefore the slight increase is perhaps an experimental error. Once again assuming that there is no flow from the corridor the corridor inflow must equal outflow. ie.

$$(.75)^{\frac{1}{2}} + (.65)^{\frac{1}{2}} + (.47)^{\frac{1}{2}} \doteqdot (.39)^{\frac{1}{2}} + (.39)^{\frac{1}{2}} + (.39)^{\frac{1}{2}}$$

$$.86 + .80 + .68 \doteqdot .62 + .62 + .62$$

$$2.34 \doteqdot 1.86$$

Once again the error is due to the reasons discussed in the earlier section.

As opening of the door does not make any difference to the pressures, the consequences of a fire are the same as the previous section.

Slight variations in room pressures are due to reading off the mean value from the chart recorder. The reading on the chart recorder can introduce an error of about $\pm$ 3% in the actual measured pressures. Since the pressure coefficients are worked out by dividing these measured values by the measured dynamic pressure (with again an error of about $\pm$3%), the resulting error in the calculated pressure coeficciants may be about $\pm$10%. The comparison of two sets of results in fig 3.3.7. (all closed 'S' open) show that the error is not greater than the above limit.

(iii) Room ⑥ door Open ('6'open):

This shaft pressure drops quite considerably (by about 25% of the 'All Doors Closed values). The corresponding drop for leakage (a) is only about 5%. This shows that, for this the leakage (b), the shaft pressures are highly dependant on the corridor pressures. The shaft pressure values are:

Cp_i (all closed) = 0.20

Cp_i ('S' open) = 0.23

Cp_i ('6' open) = 0.15

The drop in corridor pressure results in an increased flow rate into the corridor, the most of which (about 75%) escapes through room ⑥, most of the smoke generated by fire in the shaft will

flow onto this floor reducing the risk to other floors. The corridor pressures are:

Cp_i (all closed) = 0.20

Cp_i ('S' open) = 0.20

Cp_i ('6' open) =-0.06

The pressure difference across the shaft door is enough to confine smoke on to this floor resulting from fire either in rooms ①, ② or ③ or in the corridor. Fire in rooms ④, ⑤ and ⑥ does not present any problems as most of the smoke is sucked out through the windows.

The room pressures do not change significantly.

(iv) Shaft and Room ⑥ doors ('s' + '6') open.

The shaft pressure drops even further, and it equals the corridor pressure. The shaft and corridor pressures are equal to those on floor 2 (compare figures 3.3.7. and .3.3.6.). The room ⑥ pressure is dominated by the larger leakage side (T) pressure, and it assures a positive value which is slightly higher than that of the corrodor. Pressure difference across room ⑥ window is much higher than that of rooms ④ and ⑤, hence lot more air flows through room ⑥. The shaft and corridor pressures are as follows:

Shaft		Corridor
Cp_i (all closed)	= 0.20	.20
Cp_i ('S' open)	= 0.23	.20
Cp_i ('6' open)	= 0.15	-.06

Shaft	Corridor
Cp_i ('s' + '6' open) ≐ 0.06	.06

If no flow results through the shaft door, then about 60% of air flowing into the corridor leaves through room (6).

Most of the smoke from fire in the shaft or the corridor flows through this room. Room pressures, once again, change only slightly.

The result for the two leakage configuration show that for this particular wind incidence (α=0) the shaft pressures are very sensitive to the changes on floors for leakage (b) than (a).

Leakage (a) is much safer for fire occurance in any of the rooms or the corridor, where for leakage (b) the shaft is threatened as there is a tendency for air to flow into the shaft.

But if lobbies are used to confine smoke to the fire areas, then leakage (b) is much better as the pressurising fan does not have to overcome the large wind reduced pressures.

3.4 Wind Incidence $\alpha=45^{o}$

Because of a considerable change in the outside pressure distribution on two leaky walls (T and R), the internal pressure pattern also changes. The results obtained for two leakage configurations are discussed below.

3.4.1 Leakage Configuration (a)

1.5	1.5	1.5

3.4.1.1 Floor 2

As discussed earlier in chapter 2, (Vol I) the outside pressure distribution on wall T, has changed quite considerably compared

with that for the zero wind incidence case. As a result the shaft pressure has dropped quite considerably.

Cp_i(shaft) = 0.43 for $\alpha \neq 0^o$

Cp_i(shaft) = 0.15 for $\alpha = 45^o$

A reduction of about 65%. This influences the internal pressure pattern significantly, especially for different door opening configuration.

(i) <u>All doors Closed (all closed)</u>

Figures 3.4.1. and 3.4.2. summarize the shaft corridor and room pressures. When all the doors are closed, the shaft pressure is higher on all floors than the respective corridor pressure, indicating flow from the shaft.

Because of the outside pressure distribution, the 4th floor pressure is the highest, and is very nearly equal to the shaft pressure. In this floor, then, any extra pressure created by the fire in the corridor can send smoke into the shaft, hence to other floors. The situation is very similar to that of leakage (b) for $\alpha \neq 0^o$.

From figure 3.4.2. (all closed), it is clear that the corridor pressure is quite low. This low pressure causes very little air to flow through the measuring tube leakage and hence inflow is very nearly equal to the measured outflow. Considering the corridor and applying the main conservation equation.

$$\dot{k}A_e(\Delta Cp_i)^{\frac{1}{2}}\text{shaft} + \dot{k}A_e \sum_{j=1}^{J} (\Delta Cp_i)_j^{\frac{1}{2}} = 0 \qquad 3.4.1$$

where A_e is the total leakage area of door.

j = room number with door leading to the corridor

J = maximum number of rooms

$\dot{k}$ = a constant depending on fluid density

i.e. $\dot{k}A_e(0.06)^{\frac{1}{2}} + \dot{k}A_e(0.28)^{\frac{1}{2}} + \dot{k}A_e(0.43)^{\frac{1}{2}}$

$= \dot{k}A_e(0.37)^{\frac{1}{2}} + \dot{k}A_e(0.37)^{\frac{1}{2}} + \dot{k}A_e(.40)^{\frac{1}{2}}$

or $.24 + .47 + .53 + .65 = .61 + .61 + .63$

i.e $1.89 = 1.85$

Room pressures are concierably lower when compared with the zero wind incidence case.

Any fire in the shaft inevitably endangers all floors, even though the shaft pressure is quite low. If the lobby is used to confine smoke to the shaft, the pressurising fan will have overcome only very little opening shaft pressure. Again considering the 20m/s wind, the shaft pressure that will have to be overcome is about $37N/m^2$. As there is already a pressure of $22N/m^2$ in the corridor the net pressure to overcome is $15N/m^2$.

(ii) Shaft door ('S') open:

Due to the opening of this door, no change occurs in the shaft pressure, which means that the shaft is very much less influenced by the corridor pressures. The slight increase that is shown in Figure 3.4.1. is attributable to experimental error.

Cp_i(shaft) all closed = 0.15

Cp_i(shaft) 's' open = 0.16

The corridor pressure, on the other hand, increases to equal the shaft pressure.

Cp_i (corridor) all closed = 0.09

Cp_i (corridor) 's' open = = 0.16

Again applying equation 3.4.1. to the corridor shows that there is more air flowing out of rooms ④, ⑤ and ⑥ than flowing in through rooms 1, 2 and 3. This means that the extra flow must be coming from the shaft, despite the equal pressures of shaft and corridor. This is possible because of the large leakage due to open door, which means that a pressure coefficient difference of 0.002 can cause enough inflow so that total inflow is equal to outflow. The measuring instruments are not sensitive to such small differences.

Because of the small changes in the corridor pressures, room pressures remain unchanged. Any changes that are apparent from figure 3.4.2 are within the experimental error range of $\pm$ 10%.

Now, science very small differences in pressure across the open door can cause a lot of flow through that door, the fire in either the shaft or the corridor can spread smoke easily. A lobby between the shaft and corridor, maintained at higher pressure can prevent smoke spread, on to the floor or into the shaft. Since the shaft and corridor pressures are the same, the fan will have to work so as to maintain a pressure difference of $50 N/m^2$.

(iii) Room ⑥ door open ('6' open):

As the shaft pressure is dominated by the prevailing outside pressure at the shaft window positions, the dramatic drop in the corridor pressure, as a result of opening this room door, does not alter the shaft pressure very much

Cp_i (all closed) = 0.15

Cp_i ('s' open) = 0.16

Cp_i ('6' open) = 0.16

The corridor pressure, on the other hand, drops to a very low value, which is higher than rooms ④ and ⑤ pressure but much lower than the shaft, room ①, ② and ③ pressures. Thus increases the inflow from the positive pressure areas and especially from the shaft. This prevents smoke getting into the shaft resulting from a fire in either of rooms ①, ② or ③ or in the corridor. The pressure difference across the shaft door is more than enough to prevent smoke getting into the shaft, but this difference is so high that a great amount of force will be required to open this door by the escaper on floor 2. In such circumstances, then, it will be a mistake to attempt to pressurize the entire shaft, but the lobby approach will be simple. Some problems occurs for zero wind incidence.

In this case about 80% of the total inflowing air flows through room ⑥, which shows that such open door can help to clear smoke very fast.

Changes in room pressures are significant, as they do not effect the overall flow pattern.

(iv) Shaft and Room ⑥ doors open ('S' + '6') open:

When their doors are opened, the shaft pressure drops considerably, and since there are very low or virtually no resistances between shaft, corridor and room ⑥, the pressure in their areas is equal. Greater amounts of the incoming air flows out through room ⑥ window. The shaft and corridor pressures are as follows.

Doors	Shaft (Cp_i)	Corridor Cp_i
'all closed'	.15	.09
's' open	.16	.16
'6' open	.16	-.18
'S' + '6' open	.06	.06

Figure 3.4.1 shows that, for this leakage configuration the 4th floor corridor pressure is higher than the shaft pressure. This means that a fire on the 4th floor can be dangerous, as smoke will flow into the shaft. So this configuration of door opening on any floor other than the fire floor can endanger all floors, and also the shaft.

But a fire in the corridor or in rooms ①, ②, or ③ on floor 2 can also cause smoke to flow into the shaft, but most of it will be flowing through the room ⑥ window.

The change in room pressures is not big enough to cause any flow direction changes.

These measurements show that because the shaft pressures are low the fire pressure can easily upset the flow pattern to cause shaft smoke logging.

(i) As for zero wind incidence, a fire in the shaft threatens all floors, perhaps not to the same extent as the flow rates are reduced due to the reduced pressure differences. Still pressurized lobby required.

(ii) For a fire in the corridor or in any of the rooms ①, ② or ③ the shaft is vulnerable to smoke logging due to small shaft pressures. In such a situation, opening rooms ④, ⑤ or ⑥ doors can lessen the danger. But it must be noted that these door openings can increase pressure differences across some other doors, especially the shaft door rendering if difficult to open by a normal person trying to escape from the fire floor.

(iii) Fire in rooms ④, ⑤ or ⑥ does not create any danger of smoke spread, as most of it is sucked out through the windows.

3.4.1.2 Floor 4

As for the previous wind incidence ($\alpha=0^{o}$), very high room pressures occur on this floor. The results are summarized in figures 3.4.3 and 3.4.4. Each internal leakage configuration is discussed in detail below.

(i) All doors closed (all closed):

In this case, because flow is from the shaft into the floor corridor the shaft pressure remains uninfluenced by the corridor pressure. The increase in corridor pressure on this floor reduces, the

pressure difference across the shaft door, compared with that on floor 2.

Cp_i (corridor) = 0.09 Floor 2

Cp_i (corridor) = 0.14 Floor 4

This is almost equal to the shaft pressure value of Cp_i = 0.15

Application of equation 3.4.1 shows that very little air flows out through the uncontrolled leakage and inflow through rooms 1, 2 and 3 and the shaft equals the outflow through rooms ④, ⑤ and ⑥.

Pressures in room ①, ② and ③ are higher than the corresponding rooms on floor 2, but pressures in rooms ④, ⑤ and ⑥ are very much the same on the two floors (uniform pressure distribution on Side R). The reduced pressure difference across the shaft door means that smoke can easily get on to this floor from a fire in the shaft, whereas a fire in the corridor or in any of rooms ①, ② or ③ threatens the shaft as well as other floors. In such a situation lobby pressurisation is required. For a 20m/s wind a fan would not have to over come any excess pressure in the shaft, but only to maintain a pressure difference of 50N/m^2 across the closed shaft door.

Pressures in rooms ④, ⑤ and ⑥ are much lower than those for the zero wind incidence case. This is due to the lower pressures on wall R, caused by larger Eddies in the wake region.

(ii) Shaft door open ('S' open):

In the case when shaft door is closed, the shaft and corridor pressures are nearly equal. Opening this door causes, the shaft and corridor to behave as one 'single' volume, and the corridor pressure tends to equal the shaft pressure, as in previous cases. The value of corridor pressure (i.e. $Cp_i = 0.15$) shown in figures 3.4.3 and 3.4.4, confirms this conclusion. Now assuming that the corridor's pressure is $Cp_i = 0.15$, then the total inflow through rooms ①, ② and ③ is equal to the outflow through rooms ④, ⑤ and ⑥, which means that shaft to corridor flow is very little. On floor 2 a lot more air flows from the shaft (see figure 3.4.2. 's'open). Because of this, even though corridor and shaft pressures are the same for two floors, a fire in either rooms ①, ②, ③ or the corridor is made dangerous, from the smoke spread point of view than on floor 2. Higher positive room pressures on floor 4 can push smoke into the shaft. But for a fire in the shaft, less smoke will get on the floor 4 then onto floor 2.

(iii) Room ⑥ door open ('6' open):

A dramatic drop in the corridor pressure from $Cp_i = 0.14$(all closed) to $Cp_i = -0.13$ ('6' open) changes the shaft pressure slightly. The shaft pressures are:

Cp_i (all closed) = 0.15

Cp_i ('s' open) = 0.15

Cp_i ('6' open) = 0.12

As the values in figure 3.4.4 show about 75% of the inflow into the corridor, flow out room ⑥ window, which means that any smoke

generated by a fire in rooms ①, ②, ③ or the corridor, flows out through this room, leaving the shaft smoke free. Comparing this with the 'all closed' case shows that the pressure differnce increase from $\Delta Cp = 0.01$ to $\Delta Cp = 0.25$, which is enough to prevent smoke entering the shaft. In this case, then no lobby or shaft pressurisation is needed. It must be pointed out that for a wind of 20m/s, this pressure ($61N/m^2$) to higher than the recomended limit ($50N/m^2$). But as fire itself creates a pressure, causing the corridor to reduce this difference. But it is noted also that further opening of room ④ or ⑤ doors many increase this difference again. It is from this point of view that a pressurised lobby may be required. The fan setting can be worked out from the measured pressures in figure 3.4.4, and the fan characteristics.

(iv) Shaft and Room 6 doors open ('S'+'6' open):

The shaft pressure, for this configuration, given in figure 3.4.4 may not be quite correct, as it does not show any change from the previous case. As shaft and corridor pressures must be nearly equal, the shaft pressure values is more likely to be equal to 0.09 than 0.12.

Opening of these two doors connects room ⑥ with the shaft directly and therefore the room pressure is positive, which increases the flow rate through room 6 windows. The shaft corridor pressure values are:

Doors	Shaft Cp_i	Corridor Cp_i
'all closed'	.0.15	0.14
's' open	0.15	0.15
'6' open	0.12	-0.13
'5'+'6' open	0.09	0.09

Most of the smoke is sucked out through room ⑥ window, resulting from fire in rooms ①, ②, ③ or corridor. Because of the high inflow from the shaft, on to this floor, most of the smoke generated by fire in the shaft is also pulled out through this room, hence reducing the danger to other floors.

3.4.2 Leakage Configuration (b)

.1.5	1.5	1.5

The reduction in shaft window leakage increases its pressure dependence on the corridor pressures. The measured result for floors 2 and 4 are summarised in figures 3.4.5 to 3.4.8.

3.4.2.1 Floor 2

Figures 3.4.5 and 3.4.6 show the results for the shaft, corridor, and rooms on this floor for four different internal leakage configuration. All pressures are considerably reduced compared with leakage (a).

(i) All doors closed (all closed):

The shaft pressure is very nearly equal to the average corridor pressure on all floors (see fig 3.4.5). As there is very little flow into the shaft through the windows, the shaft pressure is

reduced compared with leakage (a).

Cp_i (shaft) = 0.15 Leakage (a)

Cp_i (shaft) = 0.10 Leakage (b)

Applying equation 3.4.1 to the corridor gives

$$(.02)^{\frac{1}{2}} + (.23)^{\frac{1}{2}} + (.32)^{\frac{1}{2}} + (.45)^{\frac{1}{2}} = (.31)^{\frac{1}{2}} + (.36)^{\frac{1}{2}} + (.36)^{\frac{1}{2}}$$

$$.14 + .48 + .56 + .67 = .55 + 66 + .66$$

$$\text{i.e. } 1.85 = 1.75$$

These values are within the acceptable limit of experimental error. Because of small corridor pressure, the flow occuring through uncontrolled leakage is neglegiby small.

The room pressures are unaffected by the change in shaft leakage. Compare figures 3.4.2 and 3.4.6. Because of the much reduced pressure difference across the shaft door, on floor 2 as well as on other floors it can not prevent smoke entering the shaft and spreading to other floors. From this point of view, niether of these leakage configurations (a) or (b) are effective for this wind incidence (α=45). Pressurized lobby approach is necessary to confine smoke to the seat of the fire. This assumes, of course that location of the fire is known exactly. If this is not known then shaft prenounsation must be employed. As shaft door difference on all floors(except floor1) is the same, a uniform high shaft pressure will ensure a pressure difference of 50N/m^2across the shaft door. This can not be said for the

zero wind incidence case, where the corridor pressures vary considerably from floor to floor. Shaft pronounsation in that case can result in over pressure or under-pressure across some of the doors. From a fire in rooms ④, ⑤ or ⑥, smoke is taken out of the window of the room.

(ii) Shaft door open ('S' open):

Opening this door does not alter pressures to any significant extent. There is about the same amount of air flowing into the corridor as before (ie. as for the 'all closed' case). Because the leakage area has increased by about 98%, the pressure difference causing that flow is undetectable, being so small, The shaft pressure remains unchanged, but the corridor pressures has risen very slightly.

Cp_i = 0.05 'all closed'

Cp_i = 0.10 's' open

As for earlier cases, the risk of smoke spread to other floors has increased, because very small pressure changes can cause a lot of flow either way. Because of the high pressure difference across room ④, ⑤ and ⑥ doors, these across room ①, ② and ③ doors evidently more air flows out than that flows into the corridor. The rest comes in through the open shaft door, and it is about 10% of the total inflow through rooms ①, ② and ③. The shaft door opening does not have any effect on the corridor pressures of other floors, this is because the shaft pressure remains unaltered (see fig 3.4.5). This figure also shows that on all floors, except for floor 1, the pressure difference across the shaft doors

is very small. Fire occuring in the shaft, can endanger all floors, and particularly the one where the shaft door is open, because of the very high flow rate from the shaft through this door compared with the closed doors.

Smoke can also flow very easily into the shaft due to a fire in rooms ①, ②, ③ or the corridor of floor 2, as very small pressure differnces are required to reverse the flow through the shaft door. Once it gets into the shaft, it can spread to other floors.

On floor 1, the shaft pressure is very much higher than the corridor pressure, preventing any flow from corridor into the shaft.

For this case, the shaft pressurisation does not cause any over pressures across shaft doors on any floor, with the exception of floor 1. But if an efficient method of fire detection is available, then lobby approach is the best. In the case of a fire in the shaft, all lobbies will have to be pressurised, with the same fan setting.

Room ⑥ door open ('6' open):

Figures 3.4.5 shows that there is a considerable drop in shaft pressure on all floors.

Cp_i (all closed) = 0.10

Cp_i ('s' open) = 0.10

Cp_i ('6' open) = 0.06

This is caused by the increased flow rate through the door as a result of a big drop in corridor pressure.

Cp_i (all closed) = 0.08

Cp_i ('s' open) = 0.10

Cp_i ('6' open) =-0.16

As figure 3.4.5. shows, the corridor pressures on other floors are unaffected.

On floor 2 itself, the corridor pressure is dominated by the negative pressures in rooms ④, ⑤ and ⑥ because of the increased leakage due to room ⑥ door opening. The result is that more than three times more air flows through the shaft door than the case when all doors are closed. On the other hand about 77% of the total inflow into the corridor escapes through room 6.

The room pressures remain unaffected, very small pressure changes that occur, do not make any difference to the overall flow pattern.

The consequence of a fire occuring in room ①, ②, ③ or the corridor is that almost all the smoke flows out through rooms ④, ⑤ and ⑥, now getting into the shaft, because of a very high pressure difference across the shaft door. If may be that fire increases the corridor pressure, which may result in a decrease in the pressure difference across the shaft door. But in the initial stages of the fire the change is not going to be very big.

If the pressures remain unchanged, no lobby pressurisation is required, and the wind induced pressure difference is enough to prevent smoke spreading to other floors.

A fire in rooms ④, ⑤ or ⑥ does not present any serious danger, smoke flows out directly through the windows.

Fire in the shaft threatens this floor more than any other, because of the increased flow rate.

(iv) Shaft and Room ⑥ door open ('S' + '6' open):

Figure 3.4.5 shows that the drop in shaft pressure on all floors, is more than in any of the previous configurations. In fact the shaft pressure becomes negative, reversing the flow pattern across the shaft doors on all other floors. In comparison with leakage (a), although the pressure drops, but it still remains positive.

Cp_i (shaft) = 0.06 Leakage (a)

Cp_i (shaft) =-0.06 Leakage (b)

The corridor pressure measurements shown in figure 3.4.5. show that except for floors 1 and 2, the pressures are positive, and that the changes are quite significant compared with other door opening configuration. The corridor pressures are.

Cp_i ('all closed) = 0.08

Cp_i ('s' open) = 0.10

Cp_i ('6' open) =-0.16

Cp_i ('s' +'6' open) =-0.06

The shaft, corridor and room ⑥ behave as one single volume, and the pressure there is very nearly uniform (see figure 3.4.6). This connects the wall R and T directly without any large resistance, and therefore, the flow through doors 's' and '6' is governed by the outside pressure difference at wall T and R at the appropriate openings. But also most of the air flowing through rooms ①, ② and ③ flows but through room ⑥. Fire in these rooms or the corridor does not threaten other floors, as most of the surface escapes through room ⑥. Smoke resulting from fire in the shaft is also taken out through room ⑥, decreasing the danger to other floors.

From the above discussion for leakage (b) on floor 2 it follows that:

(i) For a fire in the shaft the risks are not any different from that for leakage (a). The magnitude of pressures in the shaft does not change considerably, except for ('s' + '6') open case.

(ii) Some conclusions held for fire in rooms ①, ②, ③ or the corridor.

(ii) Because there is no change in room pressures, fire in rooms ④, ⑤ or ⑥ does not present any problems for the shaft.

3.4.2.2 Floor 4:

The pressure measurements for this floor are shown in figures 3.4.7 and 3.4.8. The shaft pressures do not differ significantly

from those on floor 2, but are considerably lower than in the case of (a). The comparison of figures 3.4.3 and 3,4,7 shows that the drop in shaft pressure for various door openings is more in leakage (b) than in (a),

(i) All doors closed ('all closed):

The shaft pressure measurements for this floor must be equal to those for floor 2. Comparison of figures 3.4.6 and 3.4.5. shows that there is a slight difference of about $0.02N/m^2$. This is well within the experimental error limit.

The corridor pressure on floor 2 is very much the same as on this floor. In fact from figure 3.4.7, it is clear that the corridor pressures on all floors except floor 1, are the same. The average value being about $Cp_i=0.075$. This is due to the fact that the influence of shaft is decreased (very small shaft window leakage) and also that outside pressure contains on wall T are almost vertical, at least in the control part of that wall (see fig 3.4).

There is very small or no pressure difference across the shaft door, indicating no flow either way. Application of equation 3.4.1 to the corridor, confirms that inflow through rooms ①, ②, ③ is equal to the outflow through rooms ④, ⑤ and ⑥, with very small percentage flowing in through the shaft door. Because of the very small, corridor pressures, the flow through uncontrolled leakage is very small.

The room ①, ② and ③ pressures are higher than those on floor 2, resulting in increased flow rate. Room ④, ⑤ and ⑥ pressures are less than those on floor 2, and the pressure difference across these room doors is such that the increased inflow results in increased outflow, keeping the corridor pressure the same as on floor 2.

A fire on this floor presents the same problems as discussed for floor 2.

(ii) Shaft door open ('S' open):

The shaft and corridor pressures on this floor as well as on other floors remain unchanged (see fig 3.4.7). Slight drop in the shaft pressure is probably due to the experimental error. The pressures are

	Shaft	Corridor
All closed	0.08	0.08
's' open	0.07	0.07

The condition of flow through the shaft door is unaltered, and most of the inflow and outflow occurs through rooms ①, ②, ③, and ④, ⑤, ⑥ respectively. Because there is a slightly more inflow than outflow it is likely that some air flows into the shaft. The room pressures, as expected, remain unchanged. Compard with some configuration on floor 2, the flow direction across the shaft door is increased, because of the increased inflow through rooms ①, ②, ③. This reversal does not have a great significance

as many small amounts of air flow is involved. Any additional fire pressure can easily overcome this difference.

Apart from that, the consequences of having a fire on this floor are the same as on floor 2.

(iii) Room ⑥ door open ('6' open):

The change in shaft pressure due to this door opening is of the same order of magnitude as for floor 2, because of the similar pressures in rooms on both floors.

Cp_i(shaft) = 0.06 Floor 2 opening

Cp_i(shaft) = 0.04 Floor 4 opening

The change compared with other door openings is not very great.

Cp_i (shaft)= 0.08 all closed

Cp_i (shaft)= 0.07 's' open

Cp_i (shaft)= 0.04 '6' open.

As on floor 2 the reduction in corridor pressure is significant, which results in an increased flow rate from the shaft. The shaft pressure difference for openings on floors 2 and 4 is the same (Compare figs 3.4.6 and 3.4.8). Despite the increased flow rate through rooms ①, ② and ③ still about 75% of the total air inflow, flows out through room ⑥ window.

The changes in room pressures are insignificant.

Because there are no changes in the overall pressure pattern due to the increased pressures in rooms ①, ② and ③, the consequences of a fire are the same as discussed earlier for floor 2

(iv) Shaft and Room ⑥ doors open ('s' + '6') open:

The drop in shaft pressure is the same as for floor 2 openings. The corridor pressure on all floors are negative. The shaft, corridor and room ⑥ pressures, are the same as before. There is no change in the overall flow pattern, most of the flow still occurs through room ⑥ window. The shaft and corridor pressures are:

	Shaft	Corridor
All closed	.08	.08
's' open	.07	.07
'6' open	.04	-.17
's' + '6' open	-.09	-.08

The consequences of a fire are the same as for floor 2.

These measurements, compared with those for $\alpha=0^{o}$ show that the wind induced pressure difference across the shaft doors on each floor level, is more uniform and small in magnitude, at least when all doors are kept closed. This makes the shaft pressurisation a feasible possibility. The reduction in shaft window leakage, does not present any serious problems. It is recommended, in both cases, that ('s'+'6') open type of configuration is to be avoided

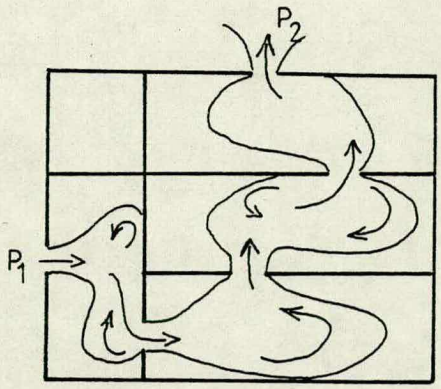
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3.5 Wind Incidence, $\alpha=90^{o}$

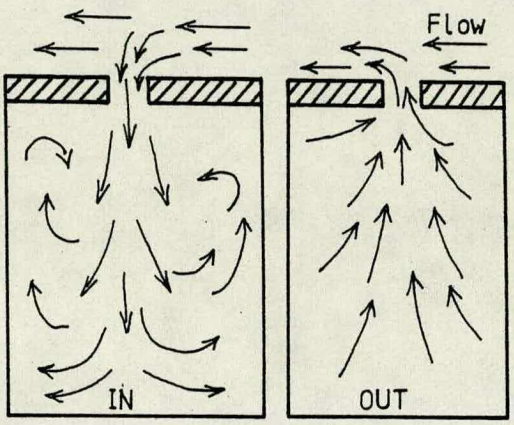
The outside pressure distribution on two leaky walls (T and R) is shown in fig 3.5. As compared with any of the precious two wind directions investigated, both the walls are subjected to very high negative pressures. Under such outside wind flow conditions, three types of internal flows are possible. The air change by the flow through a (i), occures when openings are located in areas of different pressure. The phenomena is very similar to forced ventilation, the only difference being that the flow is not steady and depends on the External conditions.

Pulsating flow takes place when all the holes are located in an area of the same external pressure, or when the pressure difference is very small, but variation of the pressure in time predominates ii(A). Another type of pulsation flow exists when the external pressure changes between two or more holes are in such a way that the flow periodically changes direction, ii(B) The difference between unsteady continous flow and pulsating flow is distinguished as follows: Continous flow is, when inflow and outflow of mixture is through different openings, and pulsation, when inflow and outflow is through the same, one or more openings, or by reversed flow direction.

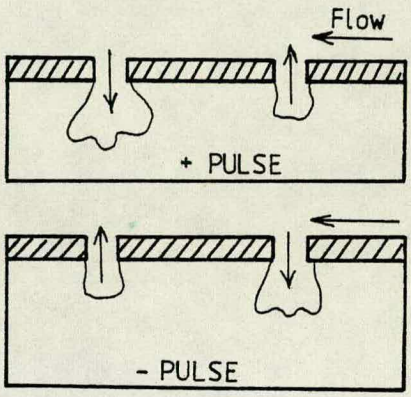
If the external flow is turbulane, or potenetial turbulence is created in the vicinity of the hole then eddies, by penetration into the building are carrier vehicles for the conveyance of external air into the building nd for the removal of the internal mixture of air to the outside (iii).



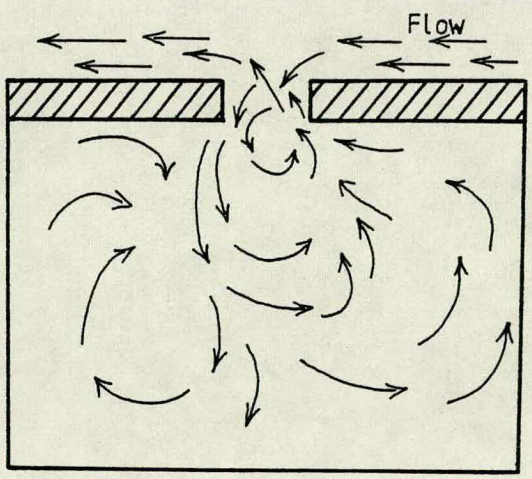
(i) Through flow $P_1 > P_2$



(ii)A Pulsation : one hole



(ii)B Pulsation : two holes



(iii) penetration of eddies

The internal pressure measurements are shown in figures 3.5.1 to 3.5.6. The results are discussed below.

3.5.1 Leakage Configuration (a)

1.5	1.5	1.5

3.5.1.1 Floor 2

The shaft and corridor pressure measurements are summarised in figure 3.5.1. It shows that on all levels, the pressures are negative (i.e. below atmospheric pressure) and that the shaft pressures are higher than the corridor pressure. Once again the shaft pressures are the same on all floors. The changes in pressures caused by the change in internal leakage are discussed below.

(i) All doors closed (all closed):

On all floors the shaft pressure is higher than the corridor pressure, showing flow into corridor from the shaft. Also as figure 3.5.1 shows that the corridor pressures become more negative towards upper floors. This follows from the outside pressure distribution shown in fig 3.5.

Figure 3.5.2 shows the room pressures in relation to corridor and shaft pressures for four different configurations, on floor 2. For the All Doors Closed case, it can be seen tha the room pressures in opposing rooms are nearly the same. For the rooms with opening is to one wall, pressures increase down wind, with lowest presures in rooms ③ and ④ and highest in the shaft. The relative magnitude of these pressures show that there is a tendency for air to flow from corridor into each of the rooms. But since shaft

pressure is higher than the corridor pressure, a flow into the corridor results.

It must be stressed here that there are the mean pressure values, and that the pressures fluctuate a great deal. The flow directions indicated on the diagrams resulting from the measured mean values do not describe the flow pattern fully, since inflow must equal outflow, in the corridor, there must be some more infow into the floor corridor besides that one from the shaft. To ascertain the actual flow pattern, smoke tests were carried out.

The smoke introduced into the shaft showed that after filling up the shaft it quickly got into corridors on all floors, almost an equal amount at each level. From the corridor, it first got into rooms ③ and ④ where concentration was the most. Rooms ② and ⑤ were the next to fill up with reduced concentration. In rooms 1 and 6 very small traces of smoke were visible, almost free of smoke. Once smoke got into rooms, it escaped through the windows. Not all of the smoke in the shaft flowed on to the floors, as quite a lot of it escaped through the shaft windows at all levels. At lower levels (i.e 1 and 2) very complicated mixing of smoke with air near the window holes of the shaft was observed. It showed that sometimes air flowed into the shaft through a hole and other smoke flowed out through the same hole. Hence a fire in the shaft threatens all floors.

Then smoke was introduced into each of the rooms, and the corridor and following observations were made. Room ① and ⑥: Most of the smoke introduced into either of these rooms flowed out through the windows. some of it did flow into the corridor through door leakage, but this happened in a periodic fashion. The same periodicity of inflow and outflow was observed at the window holes, showing the pulsating nature of flow. Air was flowing into the rooms through some of the window holes whereas outflowing through others, accompanied by the small amount that flows in through the door. Smoke getting into the corridor was flowing out through rooms ③ and ④ and some through rooms ② and ⑤. Room ② and ⑤: A similar flow pattern was observed as before, but this time very much less smoke flowed into the oorridor. Whatever did manage to get into the corridor flowed out through rooms ③ and ④. No smoke got into the shaft. A very complicated inflow and outflow system was observed at the window holes. Room ③ and ④: In this case no smoke flowed into the corridors. Inflow and outflow resulted through this window hole, where very complicated flow pattern was observer.

What these smoke tests showed that, there is a very complicated internal flow pattern, and that the measured mean pressures do not fully describe this flow. The values shown in figs 3.5.1 and 3.5.2 do not give a complete picture, but they point to the course that air will take, if supplied from the outside. Fire can be such a source, which accompanies mans production, in that case the smoke will follow the directions indicated on the diagrams.

(ii) Shaft door open ('s' open)

The shaft pressure remains unaltered, whereas the corridor pressure is raised to equal shaft pressure. The room pressures remain unchanged. Because of the increased leakage very little pressure difference is required to cause a large amount of flow rate through the open door.

Smoke tests showed that, almost all the smoke from the shaft flowed through the open shaft door on to floor 2 quickly filling up rooms ③, ④ and ⑤. Since the pressure difference across room 1 and 6 doors has increased more smoke gets into these rooms than in the previous case. All smoke escapes through the room windows, where the complicated flow pattern still persistes. Other floors contain no smoke.

Some introduced into the corridor showed no traces of it in the shaft and all escapes through rooms, where the smoke density is proportional to their respective pressure differences. Introduction of smoke in rooms produced the same results as before since the doors are closed.

(iii) Room 6 door open ('6' open)

The shaft pressure for this case remains unchanged, while the corridor pressure is reduced to Cp=-.31(see fig 3.5.2). Most of the smoke in the corridor will flow through room 6 while the rest flowing through other rooms in proportion to their pressure differences. The room pressures are unchanged except for room ⑥.

(iv) Shaft and Room ⑥ door open ('s'+'6' open)

Shaft and corridor pressures tend to equalise but the room 6 pressure is lower than this value.

Floor 2 with these two doors open is not different from these doors being closed. Smoke also gets into other floors as well. Room ⑥ with door open is relatively free from smoke compared with room 2, ③, ④ and ⑤, add much less getting into room 1.

No smoke flows into shaft, when it is introduced into the corridor. Even through room 6 door is open, it is relatively free of smoke, whereas most of it gets into rooms ②, ③, ④ and ⑤.

These measurements and smoke tests show that for all door opening configuration the flow is always from the shaft into the corridor. Fire in the shaft threatens all floors, but if shaft door is opened on one of the floors, the danger to other floors is much reduced and almost all the smoke flows out through the open door. Rooms ②, ③, ④, and ⑤ experience high concentration of smoke, if fire occurs in the corridor, or shaft. But if fire occurs in any of these rooms, most of the smoke flows out through their window. This is not the case for rooms ① and ⑥, other door openings do not make much difference.

3.5.1.2 Floor 4

The room, corridor and shaft pressure measurements on this floor are shown in figs 3.5.1 and 3.5.3. Figure 3.5.1 shows that the shaft pressures do not change much due to the opening of doors

on this floor compared with the openings on floor 2. The shaft pressure being higher than the corridor pressure, flow direction across the shaft door remain unchanged an all floors. Comparison of figs 3.5.2 and 3.5.3 show no drastic changes in pressure, Hence discussion is the same as for floor 2.

Smoke tests on this floor, showed a similar kind of complicated flow pattern across the door and window holes. For this particular wind direction a fire in any of the rooms will not present any problems, provided the window leakage area of the fire room was large enough to allow the smoke to be drawn out by the prevailing high outside negative pressures. Small window leakage can result in the smoke being sucked into the corridor. In the present case no shaft pressurisation is required for smoke control purposes.

3.5.2 Leakage Configuration (b)

1.5*	1.5	1.5

The reduction in shaft leakage reduces its influence on the corridor pressures, and as a result the corridor pressures decrease (i.e. becomes more negative). Due to the reduced influence of the outside pressures on the shaft, it s pressure drops so as to equal the corridor pressure on each floor level. For this leakage then, the pressure difference across the shaft door is considerably reduced. Compare fig 3.5.1 and 3.5.4. It is because of this reason that the influence of door openings is small, and can be seen from the following discussion.

Floor 2

The measurements of room, corridor and shaft pressures are shown in fig 3.5.5. A comparison with room pressures given in fig 3.5.2 show that the change in shaft leakage does not have any effect on the room pressures. Even corridor pressure is changed only negligibly.

Cp_i (corridor) = 0.37 Leakage (a)

Cp_i (corridor) =-0.41 Leakage (b)

The shaft pressure goes through the biggest change

Cp_i (shaft) =-0.18 Leakage (a)

Cp_j (shaft) =-0.33 Leakage (b)

The consequent reduction in the pressure difference across shaft door has very important implications from the smoke control point of view. If a fire occuring in any of the rooms, causes the corridor pressure to increase, so that it over comes the shaft pressure, the smoke can then easily flow into the shaft. since on other floors, the flow is from the shaft, such a situation can endanger all floors, and shaft smoke logging can make escape difficult. So, for this particular wind direction, if there is no shaft pressurisation system employed, leakage (a) can prevent smoke entering the shaft.

As before, a very complicated flow pattern exists across the room windows as well as across doors. Further measurements and flow visualisation tests are required to assess the exact flow pattern.

As the shaft and corridor pressures are very nearly equal, the opening of shaft door ('s' open) does not cause any big pressure changes (see fig 3.5.5). The flow pattern remain unaltered Similarly no big changes for other door opening configurations as shown in fig 3.5.5.

Floor 4

The pressure measurements on this floor are shown in fig 3.5.6. It shows that no drastic changes occur in the flow pattern, as a consequence of the decreased outside pressure. The above discussion holds for this floor as well.

3.5.3. Conclusions:

For the wind incidence of $\alpha=90^{o}$, the following conclusions can be drawn from the pressure measurements and smoke tests.

(i) The measurement of mean pressures in the shaft, corridor and room areas, do not describe the flow pattern fully.

(ii) Pulsating flow occurs across the door and window leakage holes.

(iii) For smoke control purposes, Leakage(b) is suitable for shaft pressurisation and Leakage(a) if there is no shaft pressurisation present.

3.6 Wind Incidence, $\alpha=135^{o}$

At this particular wind direction the room ④, ⑤ and ⑥ pressures become positive, and those of rooms ①, ② and ③ negative.

From the model geometry it is clear that the outside pressures on side R for $\alpha=135^{o}$, should be the same as those for side T, $\alpha=45^{o}$. A comparison of Fig 3.4 and 3.6 shows that there are slight variations, which are most likely caused by the misalignment of model to the wind. In other words, the model when turned for $\alpha=135^{o}$, is not quite at that angle to the flow. The contours shown in fig 3.6 for side R, show that the actual wind is at an angle less than 135^{o} causing small Cp_o values at the leading edge of R, even resulting in negative pressures in some regions near the trailing edge. But the overall trend is the same as for $\alpha=45^{o}$.

The side T is in the wake region and because of the two sharp edges facing the flow, the size of vortices shed from them is larger than for $\alpha=0$ case, hence higher negative pressures on wall T. The values shown in fig 3.6(T) indicates that, the pressure over side T is quite constant ($Cp_o=0.33$). As discussed in chapter 2, (Vol I) the internal pressures are a reflection of external pressures, if all doors have the same leakage. Some of the rooms having the same pressure on floors 2 and 4 can be identified from fig 3.6. The pressures in rooms ①, ② and ③ are more uniform than in ④, ⑤ and ⑥.

The internal pressures for different outside and inside leakage configuration are discussed below.

3.6.1 Leakage Configuration (a)

1.5	1.5	1.5

3.6.1.1 Floor 2

The pressure measurements in the shaft, corridor and rooms, are shown in figures 3.6.1 and 3.6.2. The, shaft being in the wake region, is subjected to negative pressures of the same order of magnitude as for the previous wind incidence ($\alpha=90^{o}$). This is because the outside pressures in the shaft region do not change a great deal. On the other hand, corridor pressures on all floors, change dramatically, though still negative, but are higher than the shaft pressures. On all floors then the flow is from corridor into the shaft (opposite to the case for $\alpha=45^{o}$). The results for different internal leakage configurations are discussed below.

(i) All doors closed (all closed):

For this configuration as shown in fig 3.6.1 (floor 2 openings) the highest corridor pressures occur on floor 4 ($Cp_i=0$, it being negative on all other floors), Floor 2 corridor experiences the lowest pressure ($Cp_i=-0.10$). The room pressures are shown in fig 3.6.2 (all closed) in relation to the shaft and corridor pressures. From these measurements it is clear that the inflow into the corridor is through rooms ④, ⑤ and ⑥ doors, and outflow takes place through rooms ①, ② and ③ as well as the shaft door. Because the room pressures are determined by the prevailing wind pressures

on sides T and R (window leakage being higher than the door leakage), the corridor pressure adjusts itself accordingly to make inflow equal to outflow. The door leakage (4 doors) to the negative pressure regions is higher than to the positive pressure regions (3 door). Hence the influence of the negative pressures on the corridor is dominant, and the corridor pressure becomes negative (Cp_i=-0.10). Since the shape and the area of door leakage holes is the same, therefore for inflow to equal outflow, the following must be true.

$$\sum_{j=1}^{J} (\Delta Cp_i)_j^{\frac{1}{2}} + (\Delta Cp_i)_{sh}^{\frac{1}{2}} = 0 \qquad \ldots.3.6.1$$

where j= room No.

J= total number of rooms with doors to the corridor.

and $(\Delta Cp_i)_j = (Cp_i)_j - (Cp_i)_{corridor}$

$(\Delta Cp_i)_{sh} = (Cp_i)_{shaft} - (Cp_i)_{corridor}$

Applying equation 3.6.1 to fig 3.6.2 (all closed) gives:

$$(.49)^{\frac{1}{2}} + (.46)^{\frac{1}{2}} + (.32)^{\frac{1}{2}} = (.2)^{\frac{1}{2}} + (.27)^{\frac{1}{2}} + (.24)^{\frac{1}{2}} + (.15)^{\frac{1}{2}}$$

$$.7 + .68 + .56 = .45 + .52 + .49 + .39$$

$$1.94 = 1.85$$

The results show that the two sides of equation are not exactly equal, but since it was impossible to absolutly seal the model, some air must have leaked through unknown leakages (such as

measuring tubes being exposed to atmosphere). The experimental error is well within the acceptable limit.

About 23% of the total inflow into the corridor, flows out through the shaft door. If fire occurs in any of the rooms ④, ⑤, ⑥ or the corridor, considerable amounts of smoke can get into the shaft, threatening people trying to escape in a fire situation. Fire in rooms ①, ②, ③ does not cause smoke to flow into corridor or the shaft, as most of it escapes through the window.

(ii) Shaft door open ('s' open):

Opening this door joins the shaft and corridor without any resistances increasing the shaft volume. As a result the original shaft pressure changes very slightly while the corridor pressure drops to assume this value (Cp_i=-0.29). As in the case of previous wind directions, the room pressures do not undergo any marked change in value. This reduced corridor pressure increases the flow rate through rooms ④, ⑤ and ⑥ doors, while decreasing outflow from rooms ①, ② and ③. In fact, the room ③ and corridor pressures are such that there is a small amount of inflow through room ③ door. For inflow to equal outflow, the rest of the air must flow through the open shaft door. Since the leakage area (area of the door) has increased quite considerably, only very small pressure differences are required to increase the flow rate. The measurements in figure 3.6.2 ('s' open) show that about 80% of the total inflow into the corridor, flows out through the open shaft door.

This has a very serious implication from the smoke spread point of view. There is no doubt that a fire in rooms ④, ⑤ and ⑥ will cause shaft to be smoke logged very quickly. But whereas for the previous case there was no danger of smoke flowing from fire in rooms ①, ② and ③, in this case, it is likely to flow into the corridor from these rooms. In fact room ③ pressure is close to the corridor pressure that the flow is resulting into the corridor.

Because the shaft pressure change is insignificant, the corridor and room pressures on other floors are unaffected.

(iii) Room ⑥ door open ('6' open):

The corridor pressure becomes positive as a result of opening this door. As the shaft and room pressures, except for room ⑥, remain unchanged the increased inflow results in an increased outflow through rooms ①, ②, ③ and the shaft doors. Higher corridor pressure decreases the flow rate through room ④ and ⑤ doors, as a result about 63% of the total inflow occurs through open room ⑥ door. About 24% of the total inflow leaves the corridor through shaft door.

From this it follows that as long as the shaft door is kept closed, no more smoke will flow into the corridor than in the All Doors Closed case, due to a fire in rooms ④, ⑤, ⑥ or in the corridor.

(iv) Shaft and Room 6 doors open ('s' + '6' open):

In this case the shaft window leakages are connected directly to the room ⑥ windows through the corridor. Since leakage on the negative pressure side is greater than that on the positive pressure side, the pressure in "single" volume (shaft + corridor + Room ⑥) is negative and uniform (Cp_i=-0.22). Most of the air flows in through room ⑥ and out through the shaft. The drop in corridor pressure causes increased flow rate through rooms ④ and ⑤, while decreases that through ①, ② and ③. Room ③ pressure is, in fact, very nearly equal to the corridor pressure.

This configuration seems to be the worst one, from the smoke spread point of view. All most all the smoke generated by a fire in room ⑥ gets into the shaft. The same is true for a fire in rooms ④ and ⑤, only very small amounts flow out through rooms ① and ②. Room ③[as in the case of 's' open] fire can also send smoke into the corridor and shaft.

For all these configurations on floor 2 the shaft pressures do not change very much in relation to the corridor pressures. It is concluded, therefore, that the door openings on a floor do not have any significant effect on the corridor and room pressures on other floors. Other floors are not threatened by the smoke. But in the event of fire spreading to other floors, shaft smoke logging prevent occupants from escaping. It is for this reason that, the escape route such as the shaft must be kept free of smoke. This is done either by pressurising the

shaft or a lobby which separates shaft from the corridor on each floor. For the shaft door pressure difference not to exceed the recommended limit ($50N/m^2$), a knowledge of the wind induced pressures is essental to avoid any under-pressure or over-pressure across the doors.

3.6.1.2. Floor 4

The room and consequently the corridor and shaft pressures are much higher on this floor, especially those in rooms ④, ⑤ and ⑥ as shown in fig 3.6.1 (all closed). This is, as discussed, earlier, due to the higher outside wind pressures on wall R [fig 3.6] . Measurements on this floor were also made for the same internal leakage configuration. The results are shown in figs 3.6.1 [Floor 4 openings] and fig 3.6.3.

(i) All doors closed (all closed)

Comparing with the same configuration on floor 2 (fig 3.6.2) the corridor pressure is much higher.

Cp_i (corridor) = -0.10 Floor 2

Cp_i (corridor) = 0.0 Floor 4

Air still flows into corridor through rooms ④, ⑤ and ⑥ doors, and leaves through rooms ①, ②, ③ and shaft doors. The infiltration rate has increased due to the increased pressures. About 25% of the total inflow rate flows out through the shaft door, which is equal to that on floor 2. Allowing for the experimental error, measured figures (Apply eq. 3.6.1) show inflow equal to outflow.

The consequences of a fire in any of the rooms or the corridor are the same as for floor 2.

(ii) Shaft door open ('s' open)

The major difference in this case is that the flow is now reversed for the room ③ door (see fig 3.6.2) But the pressure difference is still small which can easily be altered by the fire pressure. This out-flow through room ⑥ door results in a decrease in outflow through the open door (64% of the inflow compared with 80% floor 2). This means that less smoke gets into the shaft due to a fire on this floor. A fire in room ③ still cause the same problems as on floor 2.

(iii) Room ⑥ door open ('6' open):

No change in any flow direction occurs, still about the same percentage of inflow occurs through room ⑥ door (59%) as on floor 2. Implications of a fire are the same as these for floor 2.

(iv) Shaft and Room ⑥ door open ('s' + '6' open):

Comparison of figures 3.6.2. and 3.6.3 for the same configuration show that the flow pattern remains the same on two floors. Still most of the inflow occurs through room ⑥. Implications of fire are the same as for floor 2.

3.6.2 Leakage Configuration (b)

1.5*	1.5	1.5

3.6.2.1 Floor 2

Due to the reduction in shaft leakage, the influence of shaft on corridor is much reduced, which results in higher corridor and shaft pressures. Figures 3.6.4 (Floor 2 openings) shows that the shaft and corridor pressures on all floors are very nearly equal or in other words, the pressure differences across shaft doors are very small, compared with those for leakage (a). Comparison of figures 3.4.5 (for $\alpha=45^{o}$) and 3.6.4 shows that the flow through the shaft door is reversed. Because the shaft pressures in this case are more dependent on the corridor pressures than in the case of Leakage (a) any changes in shaft pressures due to door openings on a floor also influence the corridor pressures on other floors. The results for different configurations are discussed below.

(i) All doors Closed (all closed):

Because the shaft is not directly exposed to the negative pressures on wall T, its pressure increases due to the increase in influence of rooms ④, ⑤ and ⑥.

Cp_i (shaft) = -0.30 Leakage (a)

Cp_i (shaft) = -0.07 Leakage (b)

An increase in corridor pressure occurs the same way. As a result there is much less air flows into the shaft. Only about 12% of the total inflow rate, gets into the shaft, which is about half the amount for leakage (a) (23%).

Because the out flow occurs through more doors which are exposed to the negative pressures, the corridor pressure is still dominated by these pressures, and hence is negative. Application of Equation 3.6.1 to figure 3.6.5 (all closed) shows that, within the limits of experimental error, the inflow is very nearly equal to outflow.

The consequence of a fire occuring in rooms ④, ⑤, ⑥ or in the corridor is that about 90% of the smoke escapes through the rooms ①, ② and ③, reducing the danger of shaft smoke logging. But on the other hand if smoke does get into the shaft due to the intensity of fire, it can quickly spread to other floors because of the much reduced pressure difference across shaft doors. For the shaft pressurisation, there are much less negative pressures to overcome before maintaining $50N/m^2$ across the shaft door, than in Leakage (a).

(ii) Shaft door open ('s' open):

Opening this door causes a small increase in shaft pressure, which compensated by the decrease in corridor pressure. The corridor pressures on other floors are changed slightly (see fig 3.6.4), but without any change in flow directions.

Most of the inflowing air still flows out through rooms ①, ② and ③, but flow into the shaft has increased slightly from 12% (door closed) to 17% (door open), this is still much less than the same case for leakage (a), in which this amounts to about 80%.

This means that the reduced shaft leakage, reduces the smoke flow into shaft, due to a fire in rooms ④, ⑤, ⑥ or the corridor.

(iii) Room ⑥ door open ('6' open):

As room 6 is at positive pressure, the corridor pressure rises to equal this pressure, due to the opening of room 6 door. Fig 3.6.5 ('6' open) shows in fact that the room and corridor pressures are equal (Cp_i=0.15). Due to the increase from into the shaft from this floor, the shaft pressure increases slightly which cause small changes in the corridor pressures on other floors (see fig 3.6.4).

The measurements shown in fig 3.6.5 show that about 60% of the total inflow occurs through room ⑥, and while only 17% of it flows out through the shaft door.

(iv) Shaft and Room ⑥ door open ('s'+'6' open):

Figure 3.6.4 shows that the shaft pressure in this case increases quite considerably, and becomes positive (Cp_i=0.06) to equal the corridor and room ⑥ pressure. Most of the flow occurs through these open doors, which means that a fire in rooms ④, ⑤ and ⑥ can completely fill the shaft with smoke, since there is very small shaft window leakage area available for it to escape. The shaft and corridor pressures on other floors are very nearly equal (see fig 3.6.4) which can easily result in a flow into the corridors, threatening all floors. From this point of view then this configuration is

the most dangerous for leakage (b) than for (a), because in that case there is enough shaft leakage available for smoke to escape without spreading to other floors. In fact large flow rates from corridor into shaft for (a) prevent this from happening. But it must be noted that for other door opening configuration shaft is reatively safer in the case of (b) than in (a).

3.6.2.2 Floor 4

The results for this floor are summarised in figures 3.6.4 and 3.6.6. These do not show any drastic variations, except for the fact that the room pressures are higher than those on floor 2.

(i) All doors closed (all closed):

The inflow and outflow directions remain unchanged. The corridor pressure differ slightly from that on floor 2.

Cp_i (corridor) = -0.02 Floor 2

Cp_i (corridor) = -0.01 Floor 4

The flow rate into the shaft is also the same. The application of Eqn. 3.6.1 shows that inflow is very nearly equal to outflow. The consequences of a fire in rooms or the corridor are the same as for floor 2.

(ii) Shaft door open ('s' open):

Flow pattern is the same as on floor 2 but only the total infiltration rate is increased due to the increased room pressures. Flow into

the shaft is about 21% of the total inflow, which is a little higher than on floor 2 (17%). This means slightly more smoke getting into the shaft. Smoke spread follows the same pattern as for floor 2.

(iii) Room ⑥ door open ('6' open):

As the figure 3.6.6 ('6' open) shows, the flow into the shaft has increased compared with all doors closed case. This results from the increased flow through room ⑥ door. The flow pattern is the same as for floor 2.

(iv) Shaft and Room ⑥ doors open ('s'+'6' open):

The change in the shaft, corridor and room ⑥ pressures is of the same order of magnitude as on floor 2. In this case the shaft pressures on all floors are higher than the corridor pressures (see fig 3.6.4). Since, in the case of a fire in rooms ④, ⑤, ⑥ or the corridor, smoke does flow into the shaft, it can very easily flow on to other floors due to the existing favourable pressure differences. As for floor 2, this configuration is even more dangerous on this floor.

3.6.3 Conclusions:

The measurements for wind incidence $\alpha=135^{o}$ show that:

(i) The shaft being in the wake region is subjected to negative pressures, which help to pull the smoke from the fire floor corridor.

(ii) Fire in rooms ④, ⑤ and ⑥ is most dangerous as smoke is pushed into the corridor and shaft by the outside wind. A fire in any of the rooms ①, ② or ③ does not present any serious problems. As most of the smoke is pulled out of the windows.

(iii) With a fire in rooms ④, ⑤ or ⑥, opening of the shaft door spreads smoke to the shaft very quickly. Other door openings have similar consequences. All doors, therefore, must be kept closed.

(iv) For leakage (a) shaft pressurisation is required to prevent smoke getting into the shaft.

(v) If shaft pressurisation is to be employed, Leakage (b) must be used for better efficiency, as in this case the wind induced pressure defferences across shaft doors are small.

3.7 Wind Incidence, $\alpha=180^{o}$

From the model geometry it follows that outside pressures on wall R are the same as outside pressures on wall T for wind incidence $\alpha=0$. Compare figures 3.3 and 3.7. These figures also show that the wall exposed to the wake has a uniform negative pressure (wall R for $\alpha=0$ and wall T for $\alpha=180^{o}$). Except for some of the minor variations the contours on sides T($\alpha=0^{o}$), and R($\alpha=180^{o}$) showed a marked similarity. The stagnation point occurs at about 4/5th height of the model.

The measurements on side T show that the pressure over this surface is constant ($Cp_{o}=-0.20$).

As for other cases, the internal pressures are a reflection of the external pressures. From figure 3.7 follows that, no rooms will have equal pressures on different floors (As was the case for $\alpha=45^{o}$ and 135^{o}).

The internal pressures for different outside and inside leakage configuration are discussed below.

3.7.1 Leakage Configuration (a)

1.5	1.5	1.5

3.7.1.1 Floor 2

On this floor, as can be seen from figure 3.7., highest outside pressures occur, outside room (5), and decreasing towards the side walls. The internal pressure also vary accordingly. Figures 3.7.1

(floor 2 openings) and fig 3.7.2 show the measurements for shaft, corridor and room pressures. Since shaft window leakage is still exposed to the negative wake pressures, pressure these is also negative.

(i) <u>All doors closed (all closed)</u>:

The pressures for this configuration together with others are shown in figures 3.7.7 and 3.7.2. Here the main difference from that of $\alpha=0^{o}$ is that, the shaft pressure is negative, and is less than the corridor pressures on all floors. This results in a flow into the shaft from corridor.

$$Cp_i(\text{shaft}) = 0.43 \quad \alpha = 0^{o}$$

$$Cp_i(\text{shaft}) = -14 \quad \alpha = 180^{o}$$

The corridor pressure becomes positive compared with the previous wind incidence case ($\alpha=135^{o}$). This is due to the high positive pressures in rooms ④, ⑤ and ⑥, which results in an increased flow rate into corridor. If inflow is to equal outflow, for the corridor, and since leakages of all doors are the same, therefore.

$$\sum_{j=1}^{J} (\Delta Cp_i)_j^{\frac{1}{2}} + (\Delta Cp_i)_{shaft}^{\frac{1}{2}} = 0 \qquad \ldots.3.7.1$$

Applying this equation to floor 2 all closed case gives:

$$(.55)^{\frac{1}{2}} + (.56)^{\frac{1}{2}} + (.41)^{\frac{1}{2}} = (.18)^{\frac{1}{2}} + (.22)^{\frac{1}{2}} + (.20)^{\frac{1}{2}} + (.22)^{\frac{1}{2}}$$

$$.74 + .75 + .64 = .42 + .47 + .45 + .47$$

$$2.13 = 1.81$$

This shows that there is more inflow than outflow, which means that some air is flowing out through uncontrolled leakage, as it is difficult to completely seal the model. But this leakage is quite small to have any significant effect on the measured values.

(iii) Shaft door open ('s' open):

Because of the increased influence of negative pressures on the corridor, due to opening of this door, the corridor pressure drops significantly. As a result the flow through room ①, ② and ③ doors also decreases. Most of the inflow, then, flows into the shaft. In fact the measurement on figure 3.7.2('s'open) show that about 75% of the total inflow through rooms ④, ⑤ and ⑥, flows out into the shaft through the open shaft door. Pressure difference causes this flow to be very small because of the higher leakage area. In fact it is so small that it is not even registered by the measuring instruments. The shaft and corridor pressures shown in the figure are the same. Figure 3.7.1 shows that the corridor pressures on other floors are unaffected.

The change in room pressures on the floor is very small and can be ignored.

From the smoke spread point of view, a fire in any of the rooms ④, ⑤ or ⑥ or the corridor can fill the shaft with smoke, threatening people trying to escape from other floors using the shaft. Fire in rooms ①, ② and ③ can also be critical, as much reduced pressure

differences across these room doors, are not enough to stop smoke getting into the corridor and shaft. Open shaft,door, therefore, can be very dangerous. No smoke flows on to other floors, because of the higher corridor pressures there.

(iii) Room ⑥ door open ('6' open):

The shaft pressure, remains unchanged whereas, the corridor pressures becomes very highly positive (Cp_i=0.27). This causes an increased flow rate through the shaft as well as through the doors of room ①, ② and ③.

About 60% of the total inflow into the corridor occurs through the open door of room ⑥. Any fire in this room or in rooms ④ or ⑤ will again seriously threaten the shaft with smoke as flow rate through the shaft has greatly increased. The increased corridor pressure causes about 80% of smoke to flow through room ①, ② and ③.

The increased corridor pressure does not cause any significant change in the room pressures.

(iv) Shaft and Room ⑥ door open ('s'+'6' open)

Now, if room ⑥ door is opened together with the shaft door, this results in lowering the corridor pressure and consiquently decreasing the flow rate through rooms ①, ② and ③ doors. Most of the air flows into the shaft.

A fire in any of the rooms④,⑤,⑥, or the corridor fills the shaft with smoke. Since pressure differences across room①,② and③ rooms are reduced, fire in these rooms can have very serious consequences, causing smoke to flow into the corridor as in the case of 's'open.

These measurements, then show that no matter what the configuration, smoke always gets into the shaft due to a fire in rooms④,⑤,⑥ or the corridor. Any door openings only make the bad situation worse. It is necessary, therefore, to empty some smoke controlled devices, such as the shaft or lobby pressurisation. In doing so a knowledge of the wind induced premises is essential so as not to exceed the 50N/m^2 limit pressure difference across the doors, In the present case, any fan system employed to pressurise the shaft must first overcome the wind induced negative pressure, (which depends on the door opening configuration) to maintain 50N/m^2 pressure difference.

As higher pressures exist on floor 4, the effect of door openings on this floor was also investigated.

3.7.1.2 Floor 4:

The results for this floor are shown in figures 3.7.1 and 3.7.3. Once again from fig 3.7.1 (floor 4 openings) it is clear that other floor corridor pressures are independent of these openings.

(i) All doors closed (all closed)

The shaft pressure is the same as before, but there is a much higher corridor pressure.

Cp_i (corridor) = 0.04 Floor 2

Cp_i (corridor) = 0.12 Floor 4

This increases the flow rate into the shaft. Application of equation 3.7.1 shows that inflow does equal outflow. Higher room pressures do not cause any change in the flow pattern, and hence the consequences of a fire in this floor are the sam as on floor 2.

(ii) Shaft door open ('s' open)

The corridor pressure drops to the same value as on floor 2 for the same configuration. Higher pressures in rooms ④, ⑤ and ⑥ means increased flow rate into the corridor. Any fire in these rooms or in the corridor will cause more smoke flow rate into the shaft than on floor 2, filling up the shaft more quickly. Except for that, there is no change in the overall flow pattern

(iii) Room ⑥ door open ('6' open):

Except for the increased flow rate through all doors, the flow pattern is similar to that on floor 2. Smoke hazards are the same. Compare figures 3.7.2 and 3.7.3.

(iv) Shaft and Room 6 door open ('s'+'6' open).

Similar flow pattern to that on floor 2, but the flow rates are much higher.

The comparison of pressure differences across the shaft doors on these floors show that for different door opening configuration, they vary quite considerably. Any pressurising fan must take them into account. They are very critical in some of the other wind directions.

3.7.2 Leakage Configuration (b)

1.5*	1.5	1.5

3.7.2.1 Floor 2

Because of the greatly decreased external leakage of the shaft, the pressures there are much influenced by the corridor pressures. Hence shaft pressures increase and are infact positive. Compare fig 3.7.1 and 3.7.4.

(i) All doors closed (all closed):

Figures 3.7.4 (floor 2 openings) shows the shaft and corridor pressures on all floor levels. For when all doors are closed, the shaft pressures are higher than the corridor pressures, with smallest pressure difference across shaft door on floor 2 and largest on floor 4. At all floor levels air flows into the shaft at different rates, which are easily calculated from the pressure measurements.

The room pressure in realation to the corridor and shaft pressures are shown on fig 3.7.5 (all closed). They show that very much less air flows into the shaft, compared with that in case of leakage (a). In fact it is only about 10% of the total inflow compared with 20% for leakage (a). Therefore, most of the inflowing air leaves the corridor through rooms ①, ② and ③.

This means then that the reduction in shaft leakage reduces the rate of smoke flow into the shaft by about half, assuming, of course, that fire does not alter any of the flow rates through rooms.

The reduction in the pressure difference across shaft door also means that, the pressurising fan has to overcome less opposing pressure. The overall flow pattern remains unchanged.

Application of equation 3.7.1 shows that inflow is equal to outflow, within the acceptable limit of experimental error.

(ii) Shaft door open ('s' open):

The shaft and corridor pressures change by negligible amounts, as is apparent from figure 3.7.4. As a result no change in flow pattern occurs on any floor.

The room pressures remain unchanged as shown on figure 3.7.5 ('s' open). Because of the positive corridor pressure, the flow rate through rooms ④, ⑤ and ⑥ is less than in (a), and is more through rooms ①, ② and ③ than in (a). This means that most of the inflow is sucked out through rooms ①, ② and ③, while small amounts flowing through the open shaft door. The opposite is true for leakage (a). Compare fig 3.7.2 and 3.7.5 ('s' open.) About 22% of the total inflow passes through shaft door, and the rest leaving through room ①, ② and ③. But for leakage (b) this figure is about 75%.

Clearly much less smoke gets into the shaft in the present case due to a fire in rooms ④, ⑤, ⑥ or the corridor. Since the overall flow pattern is the same, some pressurisation system is still required, although it has to overcome small opposing pressures.

(iii) Room ⑥ door open ('6' open):

In this case, corridor pressure is the highest, causing more flow into the shaft, and consequently increasing its pressure. See fig 3.7.4. The corridor pressures on other floors also increase slightly. These changes do not cause any changes in the flow pattern on all floors.

Flow into the shaft is less than in the case of leakage (a), and the flow pattern remains unchanged. Pressurisation systems have to overcome very small opposing pressures. Compare fig 3.7.2 and 3.7.7 ('6' open).

(iv) Shaft and Room ⑥ doors open ('s'+'6' open):

Again flow rate into the shaft is greatly reduced compared to that for (a), due to the positive pressures in the shaft, corridor and room⑥. The flow pattern remains unchanged. The shaft or lobby pressurisation still required but to overcome small opposing pressures.

Figures 3.7.4 shows that the shaft pressures increases quite considerably.

Cp_i (shaft) = 0.08 All closed

Cp_i (shaft) = 0.24 's'+'6' open.

This figure also shows that the corridor and shaft pressures on other floors are very nearly equal, which means that the smoke can very easily flow on to other floors as well as from the shaft. This configuration then threatens all floors. From this point fo view leakage (a) is safe, as no smoke flows on to other floors.

Apart from this if the building is to employ a pressurising system, the reduced shaft leakage is not advantageous.

On the whole, the effect of shaft window leakage reduction is marked. The positive shaft pressures oppose the smoke flowing into the shaft, whereas in leakage (a) the negative shaft pressures suck it from the corridor.

3.7.2.2. Floor 4

Because of the high room pressures, measurements were also made on this floor to confirm or deny the conclusion of floor 2.

The results in figure 3.7.4 (floor 4 openings) show that as the shaft door is opened, the corridor pressure drops considerably, and that if the shaft rises, to assume average value (Cp_i=0.14) in these two spaces. This drop increases the flow rate from rooms ④, ⑤ and ⑥ and about 32% of the total inflow finds its way into the shaft, through open shaft doors. This is higher than the corresponding value (22%) on the 2nd floor. Pressures on other floors are unchanged, and flow from corridor into shaft persists.

The corridor pressure on floor 4 increases to a very high value (Cp_i=0.60) as a result of opening the room ⑥ door. This decreases the inflow through rooms ④ and ⑤ which is compensated by the increased flow through the open door of room ⑥. The outflow through shaft door as well as through rooms ①, ② and ③ doors is increased, and the shaft pressure drops slightly from the previous configuration value, but is higher than the 'all closed' value because of the increased flow rate. No change in the flow pattern occurs, except that the flow rates are increased. The room pressures only change very significantly. The corridor pressures on the other floors, do not change to cause any change in the flow pattern.

The biggest changes in shaft and corridor pressures on all floors occur when shaft and room ⑥ doors are opened together, as shown in fig 3.7.4. The shaft pressure rises to a very high value (Cp_i=0.32) so that it is now higher than the corridor pressure on all the other floors. If the inflow from rooms ④, ⑤ and ⑥ carries smoke with it, this smoke fills up the shaft and is driven on to other floors by the high shaft pressures, endangering all floors.

This configuration can also prevent smoke entering the shaft, due to a fire on any other floors, except the 4th floor. E.g. if fire occurs on the 2nd floor, and the shaft and room ⑥ doors are opened on the 4th floor, these pressurises the shaft (i.e. raising its pressure) and confines them to the fire floor. This combination of door openings together with the 4th floor openings can provide enough pressure in the shaft, to keep it absolutely smoke free. But this will only work if all doors are closed on the fire floor.

These measurements show that some door openings configurations can be critical. The higher room pressures on floor 4 can perform useful tasks in certain cases.

3.7.3 Conclusions:

For the wind incidence of $\alpha=180^{o}$, the following conclusions can be made.

(i) The shaft being in the wake region (i.e subjected to negative pressures) helps to draw smoke from the fire floor. Hence shaft pressurisation is required.

(ii) Opening of any of the door combinations investigated must be avoided, as it results in an increased flow rate into the shaft.

(iii) Shaft pressurisation is more effective with leakage (b).

3.8 Wind Incidence, $\alpha=225^{o}$

In order to correlate the internal pressures, with the external pressures on two of the leaky walls, the measurements of outside pressures were also made. The results are shown in figure 3.8. The wall T is in the wake region which contains larger size eddies compared to the wake of $\alpha=180^{o}$, because of the two sharp edges (one of shaft and the other of room ④) Consequently the pressures on side T much lower (high negative values) that those for $\alpha=180^{o}$. In fact the comparison of figures 3.6 and 3.8 (for side T) shows that the average pressures are the same, remember that in the case of $\alpha=135^{o}$ room ③ corner is the same as shaft corner in the present case. From the symmetry of the model it follows that the pressure distribution on side R for $\alpha=45^{o}$ should be the same as side T distribution for $\alpha=135^{o}$ and $\alpha=225^{o}$. The differences which are apparent from figs 3.4, 3.6 and 3.8 are due to model misalignment, which is discussed below.

Comparison of figs 3.6 and 3.8 show that for side R the overall pressure distribution is the same remembering that the leading edge in one case becomes trailing edge in the other. The appearence of negative pressures towards the trailing edge (i.e. in the duct region for $\alpha=135^{o}$ and room ④ region for $\alpha=225^{o}$) shows that the model is not exactly aligned to the flow at the nominal angles. The comparison with fig 3.4 confirms this conclusion. From fig 3.8, it can be said that the wind incidence is higher than 225^{o} and in the case of figure 3.6, it is less than 135^{o}.

In the case of figure 3.4, since side R pressures are very close to those for $\alpha=0^{o}$, it is obvious that wind angle is much less than 45^{o}.

The internal measurement for different leakage configurations are discussed below.

3.8.1 Leakage Configuration (a)

1.5	1.5	1.5

3.8.1.1 Floor 2:

The rate of corridor inflow and outflow depends on the relative wind induced pressures in room and the shaft. The highest outside pressures occur in the region of duct, and lowest in the region outside room④. As a result the total effect of room④, ⑤ and ⑥ pressures on the corridor is reduced. But from the pressure distribution of side T, it is clear that the suction pressure outside rooms①, ② and is increased whereas outside shaft it decreased. As a result the corridor pressure in both cases ($\alpha=135^{o}$, and $\alpha=225^{o}$) remains very nearly the same (see figures 3.6.2 and 3.8.2)

Cp_i (corridor) = -0.10 $\alpha = 135^{o}$

Cp_i (corridor) = -0.12 $\alpha = 225^{o}$

The result for different internal leakage configurations are discussed below.

(i) All doors closed (all closed):

The results for this case together with others are shown in fig 3.8.1 and 3.8.2. The highest pressures occur on floor, and the lowest on floor 2. On all floors the flow is from corridor into the shaft. The room pressures together with shaft and corridor pressures are shown in fig 3.8.2. The results show that inflow is very nearly equal to outflow and the measurement errors are within the acceptable limits. Since the carrier pressure is negative, and uncontrolled leakages in the corridor are exposed to the atmosphere through the measuring tubes, the excess outflow shown by these figures is through these tubes. Only about 18% of the total inflow gets into the corridor, while for $\alpha=135^{o}$, the figure is about 23%. If this is smokey air caused by a fire in rooms ④, ⑤, ⑥ or the corridor, it can cause a considerable danger to escaping people. Since other floor corridors are at a higher pressure than the shaft, no smoke can get onto these floors. Most of it escapes through the shaft windows.

Almost all the smoke generated by a fire in rooms ①, ② or ③ flow out through the windows, unless the fire is capable of overcoming the large pressure difference across these room doors.

(ii) Shaft door open ('s' open)

The effect of opening this door is to equalise the shaft and corridor pressures, with air still flowing into the shaft. To do this only very small pressure differences are required across this

greatly increased leakage area. The decreased corridor pressure increases the inflow through room ④, ⑤ and ⑥ doors, while decreasing outflow through room ①, ② and ③ doors, with the result that about 28% of the total inflow leaves the corridor through the open shaft door. This increased flow does not prevent any serious problems, as the corridor pressures on other floors are uninfluenced by the small changes in the shaft pressures. The flow pattern remains the same as before.

Smoke resulting from a fire in rooms ①, ② or ③ escapes through the windows.

To keep the shaft clear of smoke, the shaft pressurisation is essential. In this case the fan will have to work against the opposing pressures as well as maintaining enough pressure to stop inflow ($\Delta P=50N/m^2$).

(iii) Room ⑥ door open ('6'open):

The decrease in shaft pressure shown in fig 3.8.1 (floor 2 openings) is most probably due to a measurement error. There is no reason why it should drop to such low value (Cp =-0.33) which is lower than the all closed case. If anything, it should increase or be the same as allclosed case, because the higher corridor pressure increases the flow rate through the shaft door. Even if this error is accepted, the flow pattern on other floors remain unchanged.

Increased corridor pressure, causes decrease in pressure differences across room ④ and ⑤ doors. See fig 3.8.2 '6' open). If fire occurs in room ④ it is likely that most of the smoke will flow out through the window. Such an example is not found for any other wind incidence. For a fire in rooms ⑤, ⑥ or the corridor, shaft pressurisation is needed.

(iv) Shaft and Room ⑥ door open ('s'+'6' open):

The shaft pressure increases slightly due to the influence of positive corridor pressure. The corridor pressure again drops, increasing the flow rate through rooms ④ and ⑤. Most of the inflow occurs through room ⑥, and directly into the shaft.

The flow pattern on other floors remain unchanged, confining smoke flowing from floor 2 to the shaft. Increased flow rate into the shaft means that the presurising fan will have to work at a higher rate to confine smoke to the fire floor.

The changes in shaft pressures caused by the door openings on floor 2 do not have any significant effect on the flow patterns on other floors. The particularly interesting configuration is that of room ⑥ door open, which has the effect of pressurising the corridor to prevent smoke flow from a fire in room ④. Shaft or lobby pressurisation could be essential.

3.8.1.2 Floor 4

Higher room and corridor pressures on this floor, mean that the flow rate into the shaft is also high. The room, shaft and corridor pressure measurements are shown in fig 3.8.1 and 3.8.3. From fig 3.8.1 it is clear that door openings on this floor does not cause any significant corridor pressure changes on other floors. The changes in shaft pressures do not alter the flow pattern. The highest pressure difference occurs across the shaft door when room ⑥ door is opened. If the wind is blowing strongly, it may be very difficult to open the shaft door under these conditions. For example for 20m/s wind, the wind induced pressure difference across the door is about 128N/m^2. If the door size is about 1.7m x 3m, then the force required to the door will be about 575N. The force that an average person can exert is about 100N, and under such wind conditions, opening the door will be an impossible task.

Apart from the increase mass flow rates, no changes in flow directions occur. The consequences of a fire on the 4th floor has the same as on floor 2, discussed earlier. But in view of the higher pressures, the shaft pressurising fan must work at higher rates to maintain the required pressure difference.

3.8.2 Leakage Configuration (b)

1.5*	1.5	1.5

3.8.2.1 Floor 2

The effect of reduced shaft leakage is the largest on the shaft pressures. The shaft pressures increase due to the reduced effect of outside suction pressures. The corridor pressure also increase.

The comparison of fig 3.6.4 (for $\alpha=135^{o}$) and 3.84 show that the increase is smaller in this case, but the pressure differences across the shaft door are of the same order of magnitude. The result for each door opening configuration are discussed below.

(i) All doors closed (all closed):

Figure 3.8.4 shows that the shaft and corridor pressures on all floors move very close to each other. The highest corridor and pressure still occurs on floor 4. The shaft, corridor and the room pressures are shown in fig 3.8.5 (all closed). In comparison with the previous leakage (a), the flow rate into the corridor has been reduced. Since the increase in corridor pressure.

Cp_i (corridor) = -0.12 Leakage (a)

Cp_i (corridor) = -0.06 Leakage (b)

Causes increased pressure difference across room ①, ② and ③ doors, most of the outflow result through these rooms, decrease the flow through the shaft door, which carries smoke into the shaft, in case of a fire in rooms ④, ⑤ or ⑥. The figures show that the inflow into the corridor is equal to outflow, and that only about 8% of the total inflow gets into the shaft. This is much less than the flow in the case of leakage (a), 18%. The comparison of room pressures in figures 3.8.2 and 3.8.5 show that they remain unchanged due to the change in outside leakage.

Due to the decreased pressure differnces across shaft doors, it is much easier to pressure the shaft, and no great amount of pressurising is lost through the shaft windows. The fan only has to over come a pressure difference of $\Delta Cp \fallingdotseq 0.02$ in the case compared with $\Delta Cp = 0.11$ for leakage (a).

(ii) Shaft door open ('s' open):

Opening of this door equalises the shaft and corridor pressures, and the shaft pressure changes very negligibly as shown in fig 3.8.4.

Cp_i (shaft) =-0.08 All closed

Cp_i (shaft) =-0.07 's' open

The corridor pressures on other floors are unaffected and therefore the flow is still from the corridor into the shaft.

The room pressures together with the shaft and corridor pressures are shown in fig 3.8.5 ('s' open). The flow rate into the corridor remains unaltered. Because most of the airflow escapes through rooms ①, ② and ③, very little flows into the shaft (only about 4%). This is very small flow rate into the shaft cannot cause smoke logging, assuming of course, that the flow rate remains the same when fire occurs. But anycase, any shaft pressurisation system does not have to fight any larger opposing pressures even when the shaft door is open.

(iii) Room ⑥ door open ('6' open):

The change in shaft pressure is negligible as can be seen from fig 3.8.4. The corridor pressure, except for that on floor 2, also varies unsignificantly - No changes in flow pattern occurs on other floors.

The room pressure measurements shown in fig 3.8.5 ('6' open) show that the corridor pressure rises to a value higher than the room ④ pressure. From this it follows that almost all the smoke generated by fire in room ④ escapes through the windows, and any flow that result into the corridor flows out through room ①, ② and ③ before reaching the shaft door. But if fire occurs in rooms ⑤ or ⑥ more smoke gets into the shaft compared with previous configuration, as a result of the increased pressure difference (ΔCp shaft door = 0.23). In this case large amounts of smoke getting into the shaft can flow onto other floors, because of the small pressure differnce across shaft doors. In this case the pressurising fan will have to work at a high rate.

(iv) Shaft and room ⑥ door open ('s'+'6' open)

In the case of leakage (a) the corridor pressures remain higher than the shaft pressures for all door opening configuration. But in this case as seen from fig 3.8.4, the shaft pressure increases to become higher than the corridor pressures on all floors except floor 2. This causes the flow pattern to reverse. Smoke getting into the shaft from a fire on floor 2 will quickly

spread to other floors due to the favourable wind induced pressures already existing.

These measurements show that although reduced shaft leakage makes it easier to pressurise the shaft, but if pressurising system does not exist in a building, smoke not only gets into the shaft, it also seriously threatens other floors.

3.8.2.2. Floor 4

The higher room pressures on this floor results in increased flow rates into the shaft. The measured resuls are shown in figures 3.8.4 and 3.8.6. The door openings do not change the flow pattern from those existing on floor 2. Therefore, the same conclusion for this floor as well.

3.8.3. Conclusions:

From the pressure measurements for wind incidence $=225^{o}$, the following conclusions can be made.

(i) The negative shaft pressure helps to draw smoke into the shaft from the fire floor corridor. Hence a need for shaft pressurisation.

(ii) Two openings on the fire floor must be avoided.

(iii) For efficient working of the shaft pressurisation system, leakage (b) must be used.

(iv) Even if no shaft pressurisation is present, leakage (b) cause less smoke to flow into the shaft then leakage (a).

3.9 Wind Incidence, $\alpha=270^{o}$

The outside pressure distribution for both the leaky walls (T and R) is similar to that for $\alpha=90^{o}$. Compare fig 3.9 and 3.5. The difference is that whereas for $\alpha=90^{o}$, rooms 3 and 4 were subjected to highest negative pressures, in this case it is the shaft and the duct regions. Since the duct (D) is completely isolated internally from the rest of the building, it has no effect on the internal pressures. The outside pressures vary considerably from point to point on the wall surfaces. Accordingly, the internal pressures are expected to vary from floor to floor.

The flow pattern for this wind angle is expected to be similar to the $\alpha=90^{o}$ case, because of the high negative pressures on the leaky walls. No smoke tests were possible in the present case, due to shortage of time and the availability of wind tunnel. Limited amounts of measurements made are discussed below.

3.9.1 Leakage Configuration (a)

1.5	1.5	1.5

The room, corridor and shaft pressure measurements are shown in fig 3.9.2 and 3.9.3 for floors 2 and 4 respectively. Because of the shortage of time, no measurements were possible for internal door opening configurations.

The results shown in these figures are for the 'All doors Closed' case, and indicate the basic internal flow pattern.

3.9.1.1 Floor 2

From the pressure measurements on this floor it is clear that, in accordance with the outside pressure distribution, the shaft is subjected to highest negative pressure (Cp_i (shaft) $\doteq$-0.72). The corridor pressure is influenced by the room as well as the shaft pressures. The measured mean value of the corridor pressure is

Cp_i (corridor) = -0.43

Since the corridor pressure is higher than the shaft pressure, air flows into the shaft through the leakage holes in the shaft door. So the the flow is reversed in comparison with the $\alpha=90^o$ case.

The pressures in rooms ③ and ④ are higher than the corridor pressure, and as a result air flows into the corridor from these rooms Smoke from a fire in any of these two rooms can easily flow into the shaft. As fig 3.9.1 shows, similar flow pattern exists on other floors. So once smoke gets into the shaft, there is no danger of it spreading to other floors, but because shaft is the major escape route in a fire situation, it can make escape difficult. Shaft pressurisation in this case is essential.

For rooms ② and ⑤, the mean pressure measurements indicate a flow into these rooms. The pressure differences across these room doors are so small that a periodic flow into the corridor must also be occuring. The nature of the pulsating flow is the same as for $\alpha=90^o$. It is because of this that the calculated inflow and outflow for the corridor is not equal as for other wind directions.

This shows that the mean pressure measurements are not enough to describe the flow fully.

Fire in rooms ② or ⑤ can easily overcome the wind induced pressure difference across these room doors to cause smoke to flow into the corridor and from there into the shaft.

Fire in rooms ① or ⑥ does not present any great danger as most of the smoke is sucked out through the windows by the large prevailing negative pressures. The wind induced pressure difference across these room doors is enough to confine smoke to these rooms.

The shaft and corridor pressure measurements for door opening configuration are shown in fig 3.9.1. It shows that for all these configurations the shaft pressure remain lower than the corridor pressures, indicating no change in flow direction across the shaft door.

3.9.1.2 Floor 4

The pressure measurements on this floor are shown in fig 3.9.3. Comparison with the floor 2 measurements (fig 3.9.2) shows that the room pressures differ only insignificantly and the shaft and corridor pressures are the same. Some discussion, therefore, holds for this floor.

The corridor and shaft pressure measurements for other door opening configurations are shown in fig 3.9.1. It shows that the flow is always into the shaft. Shaft pressurisation is required to confine smoke to the fire floor.

3.9.2 Leakage Configuration (b)

1.5*	1.5	1.5

The relative shaft and corridor pressures are shown in fig 3.9.4. The results indicate that, the shaft and corridor pressures are very close to each other. A comparison with the Leakage (a) results (fig 3.9.1) show that the shaft pressure increases considerably.

Cp_i (shaft) =-0.72 Leakage (a)

Cp_i (shaft) =-0.44 Leakage (b)

The reduction in pressure difference across the shaft door reduces the rate of air flow into the shaft. This indicates that very much less smoke gets into the shaft, due to a fire on any floor, for leakage (b) than for (a). Small shaft door pressure differences also make it easier to pressurise the shaft.

3.9.2.1 Floor 2

For this configuration, pressure measurements were made for all door opening configurations and are shown in fig 3.9.5.

(i) All doors closed ('all closed')

Figure 3.9.5 shows that the flow pattern based on the mean pressure measurements is very much similar to that for leakage (a). Only difference is that the flow rates have changed across the internal doors due to the change in shaft and corridor pressures. A comparison with fig 3.9.2 shows that the change in room pressures is negligible. It is only due to the change in corridor pressures that the pressure difference across room doors changes.

Cp_i (corridor) =-0.43 Leakage (a)

Cp_i (corridor) =-0.36 Leakage (b)

This increased corridor pressure, reduces the pressure difference across room ③ and ④ doors. This means that comparatively less smoke flows into the corridor due to a fire in either of these two rooms. Most of the smoke that finds its way into the corridor is sucked out through room ①, ②, ⑤ and ⑥ because of the very high pressure differences across these room doors.

For a shaft pressurisation, the shaft door pressure difference is very critical. Due to the reduction in shaft leakage, this pressure difference is also reduced considerably.

ΔCp_i(shaft) = 0.29 Leakage (a)

ΔCp_i(shaft) = 0.08 Leakage (b)

This not only reduces the rate of flow of smoke into the corridor, but also makes the shaft pressurisation easier.

For this particular wind direction (α=270^{o}) then Leakage (a) must be avoided, and shaft pressureisation is essential. In comparison no shaft pressurisation is required for α=90^{o}

(ii) Shaft door open ('s' open):

Opening this door increases the shaft pressure slightly. The flow pattern remains the same.

(iii) Room ⑥ door open ('6' open):

The effect of opening this door is to decrease the corridor pressure. The flow rate through the open door is increased dramatically taking most of the smoke out the corridor. The shaft and corridor pressures are very nearly equal, indicating no flow either way (see fig 3.9.5). If no shaft pressurisation is present, opening of the room doors can be an effective way of keeping the shaft free of smoke.

(iv) Room ⑥ and shaft door open ('s'+'6' open)

As the shaft and corridor pressures were nearly the same in (iii), the shaft door opening does not make any difference to the flow pattern.

3.9.2.2. Floor 4

No room measurements are possible on this floor due to the shortage of time. The shaft and corridor pressure measurements are shown in fig 3.9.4. It shows large variations in shaft pressures due to opening the doors. This is probably due to the higher negative pressures on floor 4. But further measurements are

necessary to confirm this.

3.9.3 Conclusions:

From the small number of measurements for $\alpha=270^{o}$, the following conclusions can be made.

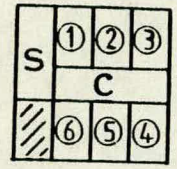
(i) Shaft pressurisation is necessary to keep the shaft free of smoke.

(ii) Outside shaft leakage must be kept to a minimum i.e. Leakage (b).

(iii) Since all the rooms are subjected to negative pressures, opening room doors other than the fire room can help to prevent smoke entering the shaft.

Table 3.2.2 Pressure variation in rooms (Cp_i), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



Cp_i in Room ①

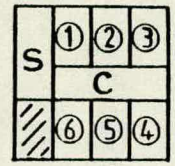
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.61	0.60	0.74	0.81	0.74
1st 'S' Open	0.63	0.61	0.71	0.90	0.74
2nd 'S' Open	0.64	0.64	0.64	0.87	0.77
3rd 'S' Open	0.61	0.58	0.74	0.89	0.76
4th 'S' Open	0.62	0.60	0.76	0.90	0.76
5th 'S' Open	0.59	0.61	0.76	0.85	0.79

Cp_i in Room ②

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.56	0.52	0.68	0.77	0.68
1st 'S' Open	0.63	0.53	0.71	0.81	0.69
2nd 'S' Open	0.60	0.56	0.69	0.79	0.68
3rd 'S' Open	0.60	0.58	0.71	0.81	0.69
4th 'S' Open	0.60	0.52	0.70	0.82	0.70
5th 'S' Open	0.57	0.53	0.68	0.76	0.71

Table 3.2.3 Pressure variation in rooms (Cp_i), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



Cp_i in Room ③

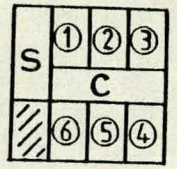
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.39	0.37	0.50	0.61	0.61
1st 'S' Open	0.40	0.39	0.53	0.58	0.60
2nd 'S' Open	0.37	0.43	0.48	0.63	0.60
3rd 'S' Open	0.37	0.37	0.53	0.64	0.60
4th 'S' Open	0.38	0.41	0.51	0.63	0.62
5th 'S' Open	0.36	0.39	0.51	0.61	0.61

Cp_i in Room ④

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.16	-0.14	-0.16	-0.16	-0.14
1st 'S' Open	-0.13	-0.14	-0.16	-0.14	-0.14
2nd 'S' Open	-0.14	-0.14	-0.13	-0.16	-0.14
3rd 'S' Open	-0.14	-0.14	-0.14	-0.16	-0.16
4th 'S' Open	-0.14	-0.14	-0.16	-0.16	-0.16
5th 'S' Open	;0.15	-0.14	-0.15	-0.15	-0.15

Table Pressure variation in rooms (Cp_i), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



Cp_i in Room

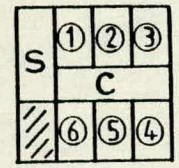
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.13	-0.13	-0.14	-0.14	-0.16
1st 'S' Open	-0.11	-0.13	-0.14	-0.14	-0.14
2nd 'S' Open	-0,14	-0.10	-0.13	-0.13	-0.14
3rd 'S' Open	-0.11	-0.13	-0.14	-0.14	-0.14
4th 'S' Open	-0.11	-0.16	-0.14	-0.14	-0.08
5th 'S' Open	-0.11	-0.14	-0.14	-0.15	+0.15

Cp_i in Room

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.10	-0.13	-0.14	-0.16	-0.16
1st 'S' Open	-0.06	-0.11	-0.14	-0.16	-0.16
2nd 'S' Open	-0.08	-0.10	-0.13	-0.13	-0.16
3rd 'S' Open	-0.08	-0.11	-0.11	-0.14	-0.16
4th 'S' Open	-0.13	-0.13	-0.13	-0.13	+0.16
5th 'S' Open	-0.07	-0.12	-0.14	-0.14	-0.14

Table 3.2.5 Pressure variation in rooms (Cp_i), $\alpha = 0^\circ$

T	D	R
1.5	1.5	1.5



Cp_i in Room CORRIDOR

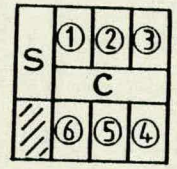
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.21	0.26	0.29	0.32	0.31
1st 'S' Open	0.47	0.24	0.26	0.32	0.29
2nd 'S' Open	0.22	0.45	0.29	0.32	0.29
3rd 'S' Open	0.19	0.26	0.48	0.34	0.29
4th 'S' Open	0.19	0.25	0.28	0.49	0.32
5th 'S' Open	9.20	0.24	0.27	0.32	0.45

Cp_i in Room

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed					
1st 'S' Open					
2nd 'S' Open					
3rd 'S' Open					
4th 'S' Open					
5th 'S' Open					

Table Pressure variation in rooms (Cp_i), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



Cp_i in Room ①

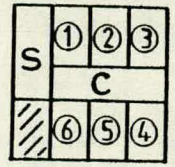
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.61	0.60	0.74	0.81	0.74
1st 'G' Open	0.56	0.60	0.71	0.85	0.76
2nd 'G' Open	0.61	0.59	0.74	0.87	0.75
3rd 'G' Open	0.56	0.60	0.69	0.87	0.76
4th 'G' Open	0.60	0.62	0.75	0.85	0.75
5th 'G' Open	0.60	0.57	0.75	0.86	0.72

Cp_i in Room ②

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.56	0.52	0.68	0.77	0.68
1st 'G' Open	0.55	0.52	0.67	0.78	0.67
2nd 'G' Open	0.56	0.50	0.70	0.81	0.70
3rd 'G' Open	0.56	0.54	0.65	0.81	0.70
4th 'G' Open	0.56	0.55	0.70	0.76	0.69
5th 'G' Open	0.57	0.52	0.67	0.75	0.62

Table 3.2.7 Pressure variation in rooms (Cp_i), $\alpha = 0^\circ$

T	D	R
1.5	1.5	1.5



Cp_i in Room ③

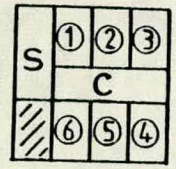
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.39	0.37	0.50	0.61	0.61
1st '6' Open	0.34	0.36	0.46	0.61	0.57
2nd '6' Open	0.37	0.32	0.50	0.62	0.56
3rd '6' Open	0.35	0.37	0.47	0.60	0.60
4th '6' Open	0.37	0.37	0.47	0.57	0.57
5th '6' Open	0.35	0.37	0.50	0.60	0.56

Cp_i in Room ④

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.16	-0.14	-0.16	-0.16	-0.14
1st '6' Open	-0.15	-0.12	-0.16	-0.15	-0.15
2nd '6' Open	-0.12	-0.14	-0.14	-0.15	-0.15
3rd '6' Open	-0.16	-0.12	-0.15	-0.15	-0.15
4th '6' Open	-0.15	-0.14	-0.14	-0.17	-0.15
5th '6' Open	-0.14	-0.12	-0.15	-0.15	-0.15

Table 3.2.8 Pressure variation in rooms (Cp_i), $\alpha = 0^\circ$

T	D	R
1.5	1.5	1.5



Cp_i in Room ⑤

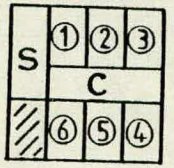
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.13	-0.13	-0.14	-0.14	-0.16
1st 'G' Open	-0.13	-0.12	-0.12	-0.15	-0.16
2nd 'G' Open	-0.12	-0.14	-0.12	-0.15	-0.14
3rd 'G' Open	-0.12	-0.11	-0.14	-0.12	-0.15
4th 'G' Open	-0.12	-0.11	-0.12	-0.15	-0.15
5th 'G' Open	-0.12	-0.11	-0.14	-0.15	-0.15

Cp_i in Room ⑥

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.10	-0.13	-0.14	-0.16	-0.16
1st 'G' Open	-0.02	-0.12	-0.12	-0.15	-0.15
2nd 'G' Open	-0.06	+0.01	-0.12	-0.14	-0.15
3rd 'G' Open	-0.06	-0.12	-0.0	+0.14	-0.15
4th 'G' Open	-0.05	-0.10	10.12	+0.01	-0.15
5th 'G' Open	-0.07	-0.12	-0.14	-0.14	-0.0

Table 3.2.9 Pressure variation in rooms (Cp_i), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



Cp_i in Room CORRIDOR

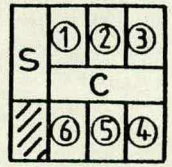
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.21	0,26	0.29	0.32	0,31
1st 'S' Open	-0.01	0.24	0,27	0,32	0.29
2nd 'S' Open	0,16	-0.01	0,26	0,34	0.30
3rd 'S' Open	0,15	0,25	-0.04	0,32	0.30
4th 'S' Open	0.15	0,26	0.29	-0,0-	0.30
5th 'S' Open	0.15	0,25	0.29	0.23	-0.01

Cp_i in Room

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed					
1st 'S' Open					
2nd 'S' Open					
3rd 'S' Open					
4th 'S' Open					
5th 'S' Open					

Table 3.2.10 Pressure variation in rooms (C_{p_i}), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



C_{p_i} in Room ①

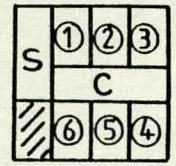
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.61	0.60	0.74	0.81	0.74
1st ('S'+'6') Open	0.61	0.58	0.71	0.84	0.74
2nd ('S'+'6') Open	0.58	0.61	0.74	0.84	0.74
3rd ('S'+'6') Open	0.61	0.61	0.74	0.84	0.74
4th ('S'+'6') Open	0.61	0.58	0.75	0.87	0.75
5th ('S'+'6') Open	0.62	0.61	0.76	0.91	0.78

C_{p_i} in Room ②

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.56	0.52	0.68	0.77	0.68
1st ('S'+'6') Open	0.60	0.52	0.68	0.79	0.61
2nd ('S'+'6') Open	0.58	0.48	0.71	0.81	0.68
3rd ('S'+'6') Open	0.58	0.48	0.71	0.81	0.68
4th ('S'+'6') Open	0.56	0.53	0.66	0.81	0.70
5th ('S'+'6') Open	0.56	0.53	0.70	0.83	0.73

Table 3.2.11 Pressure variation in rooms (C_{p_i}), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



C_{p_i} in Room ③

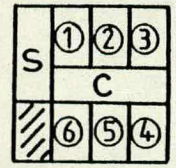
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.39	0.37	0.50	0.61	0.61
1st ('S'+'6') Open	0.42	0.39	0.48	0.58	0.58
2nd ('S'+'6') Open	0.34	0.42	0.48	0.60	0.53
3rd ('S'+'6') Open	0.37	0.35	0.51	0.61	0.58
4th ('S'+'6') Open	0.34	0.37	0.48	0.62	0.56
5th ('S'+'6') Open	0.36	0.39	0.50	0.63	0.62

C_{p_i} in Room ④

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.16	-0.14	-0.16	-0.16	-0.14
1st ('S'+'6') Open	-0.13	-0.14	-0.16	-0.16	-0.14
2nd ('S'+'6') Open	-0.14	-0.13	-0.16	-0.16	-0.14
3rd ('S'+'6') Open	-0.16	-0.13	-0.16	-0.16	-0.16
4th ('S'+'6') Open	-0.14	-0.12	-0.14	-0.16	-0.16
5th ('S'+'6') Open	-0.16	-0.16	-0.16	-0.17	-0.16

Table 3.2.12 Pressure variation in rooms (C_{p_i}), $\alpha = 0°$

T	D	R
1.5	1.5	1.5



C_{p_i} in Room ⑤

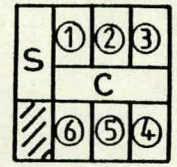
Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.13	-0.13	-0.14	-0.14	-0.16
1st ('S'+'6') Open	-0.11	-0.13	-0.13	-0.14	-0.14
2nd ('S'+'6') Open	-0.13	-0.13	-0.14	-0.14	-0.16
3rd ('S'+'6') Open	-0.13	-0.13	-0.14	-0.16	-0.16
4th ('S'+'6') Open	-0.11	-0.12	-0.14	-0.14	-0.16
5th ('S'+'6') Open	-0.14	-0.12	-0.16	-0.16	-0.16

C_{p_i} in Room ⑥

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	-0.10	-0.13	-0.14	-0.16	-0.16
1st ('S'+'6') Open	+0.37	-0.14	-0.13	-0.16	-0.16
2nd ('S'+'6') Open	-0.08	0.39	-0.13	-0.14	-0.16
3rd ('S'+'6') Open	-0-09	-0.13	0.39	-0.16	-0.16
4th ('S'+'6') Open	-0.08	-0.12	-0.14	0.41	-0.16
5th ('S'+'6') Open	-0.08	-0.12	-0.12	-0.16	0.41

Table 3.2.13 Pressure variation in rooms (Cp_i), $\alpha = 0^\circ$

T	D	R
1.5	1.5	1.5



Cp_i in Room — CORRIDOR

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed	0.21	0.26	0.29	0.32	0.31
1st ('S'+'6') Open	0.37	0.24	0.27	0.31	0.29
2nd ('S'+'6') Open	0.14	0.35	0.27	0.31	0.27
3rd ('S'+'6') Open	0.14	0.24	0.37	0.31	0.29
4th ('S'+'6') Open	0.14	0.23	0.25	0.37	0.28
5th ('S'+'6') Open	0.17	0.23	0.26	0.37	0.39

Cp_i in Room

Floor / Doors	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
All Closed					
1st ('S'+'6') Open					
2nd ('S'+'6') Open					
3rd ('S'+'6') Open					
4th ('S'+'6') Open					
5th ('S'+'6') Open					

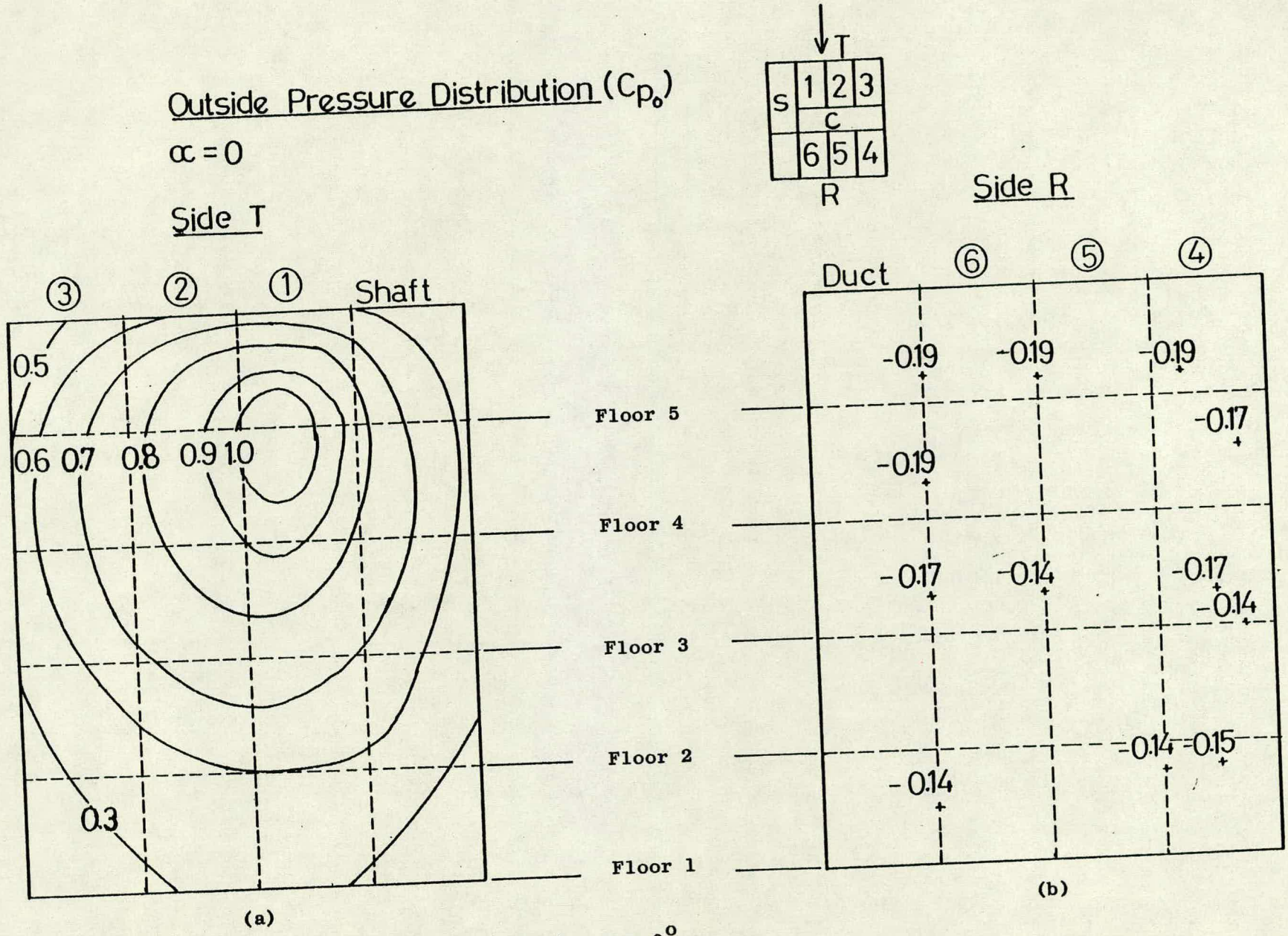


Fig 3.3: Outside Pressure Distribution (C_{p_o}), $\alpha = 0^o$

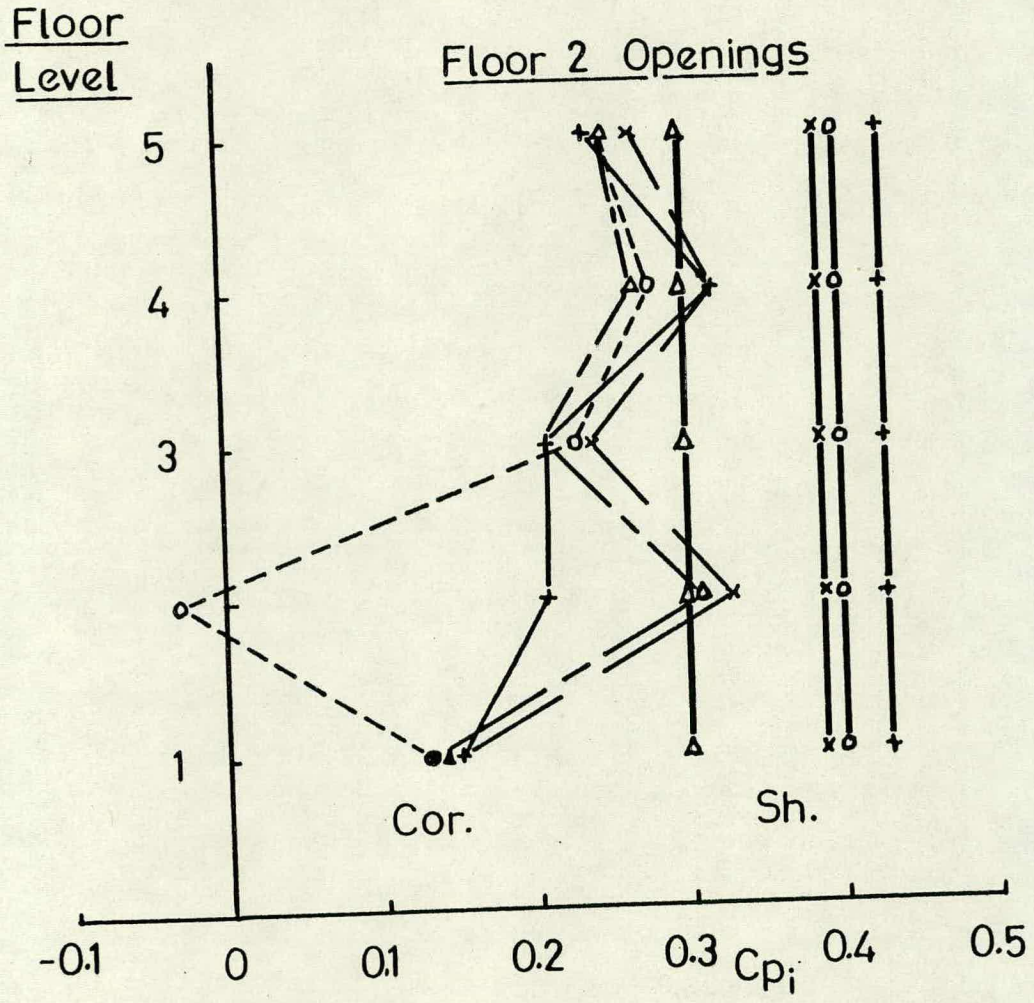
Shaft and Corridor Pressure Distribution

T	D	R
1.5	1.5	1.5

S	C		

$\alpha = 0$ + Closed × 'S' Open

o '6' Open Δ ('S'+'6') Open



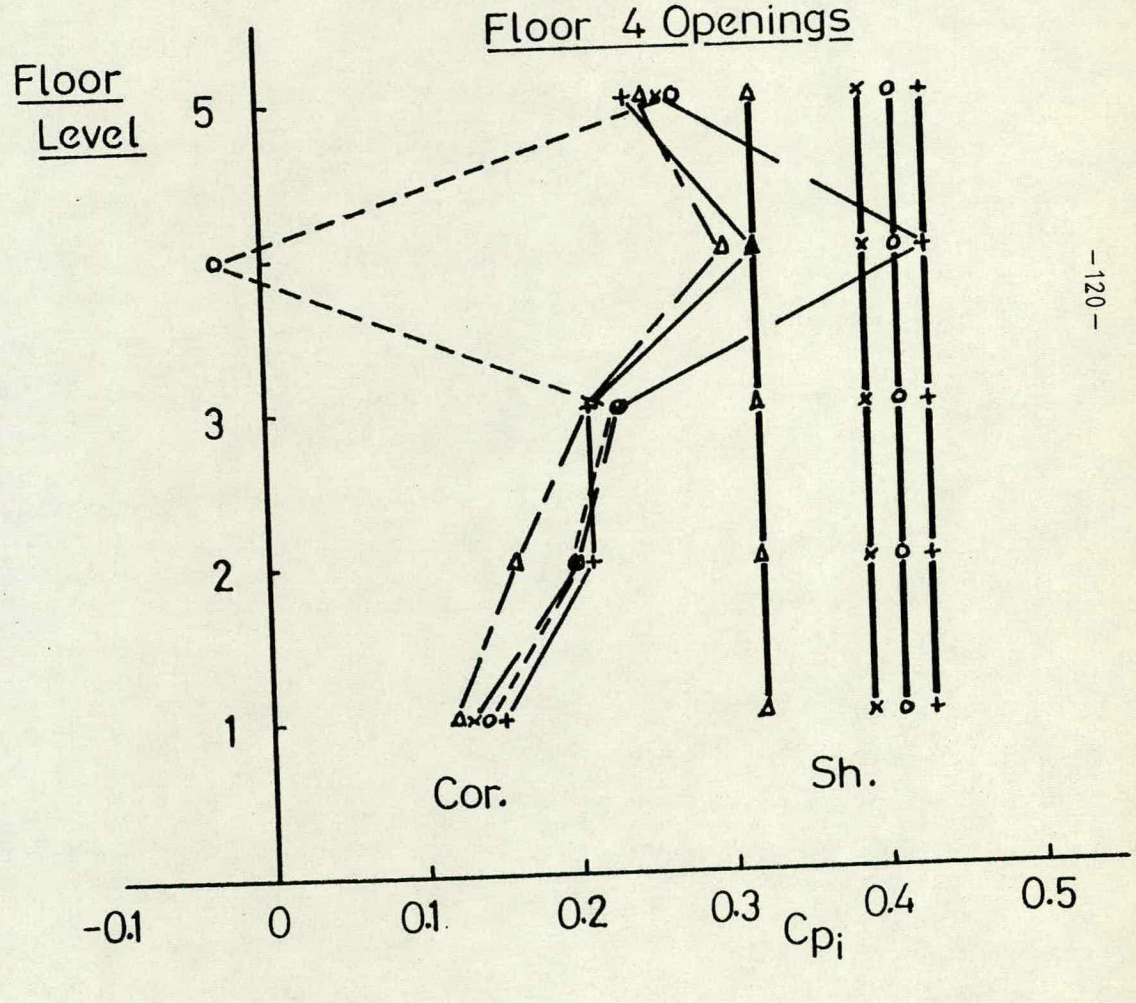


Fig 3.3.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 0$, Leakage (a).

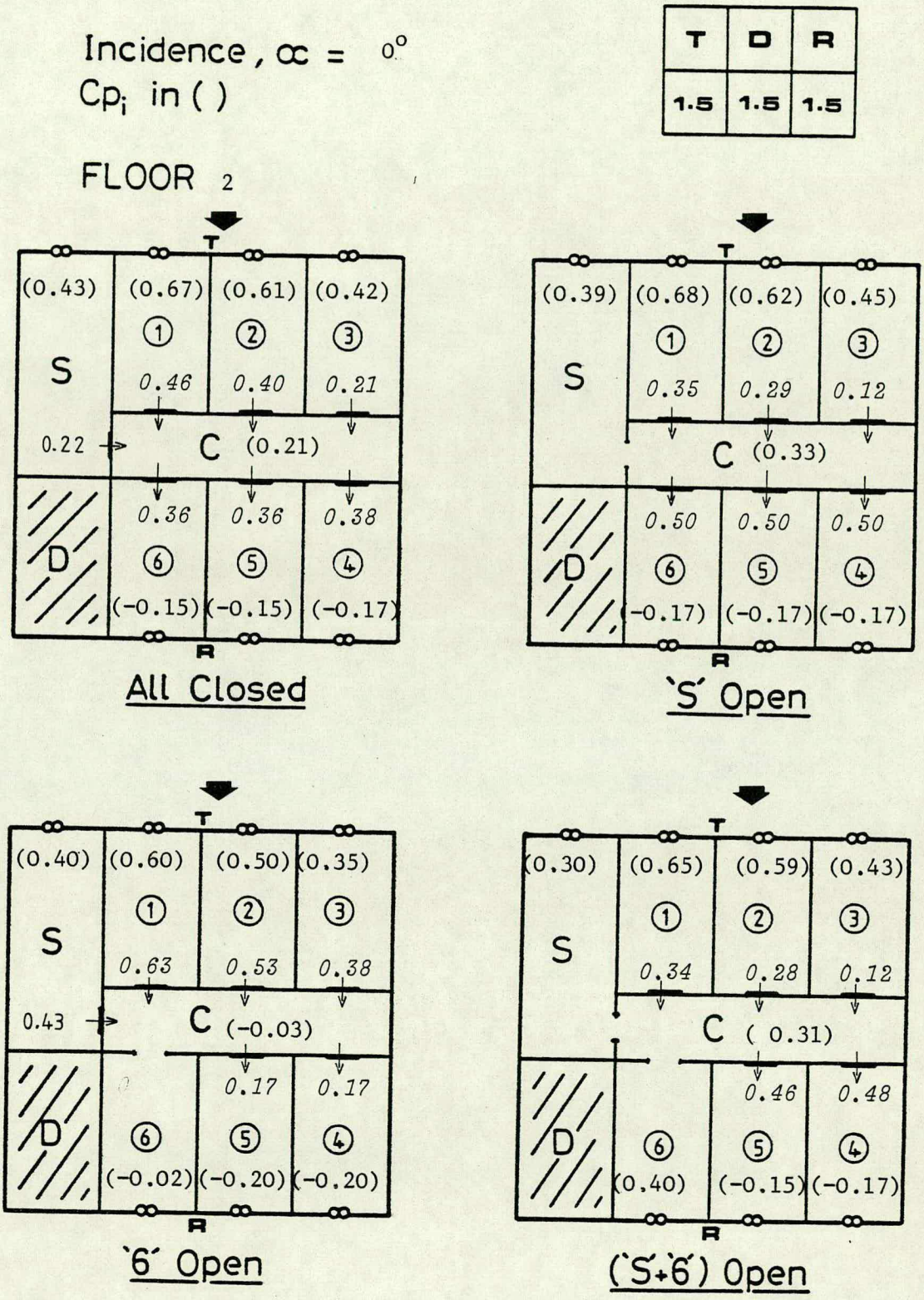


Fig 3.3.2: Wind Induced Pressure Distribution, α = 0°

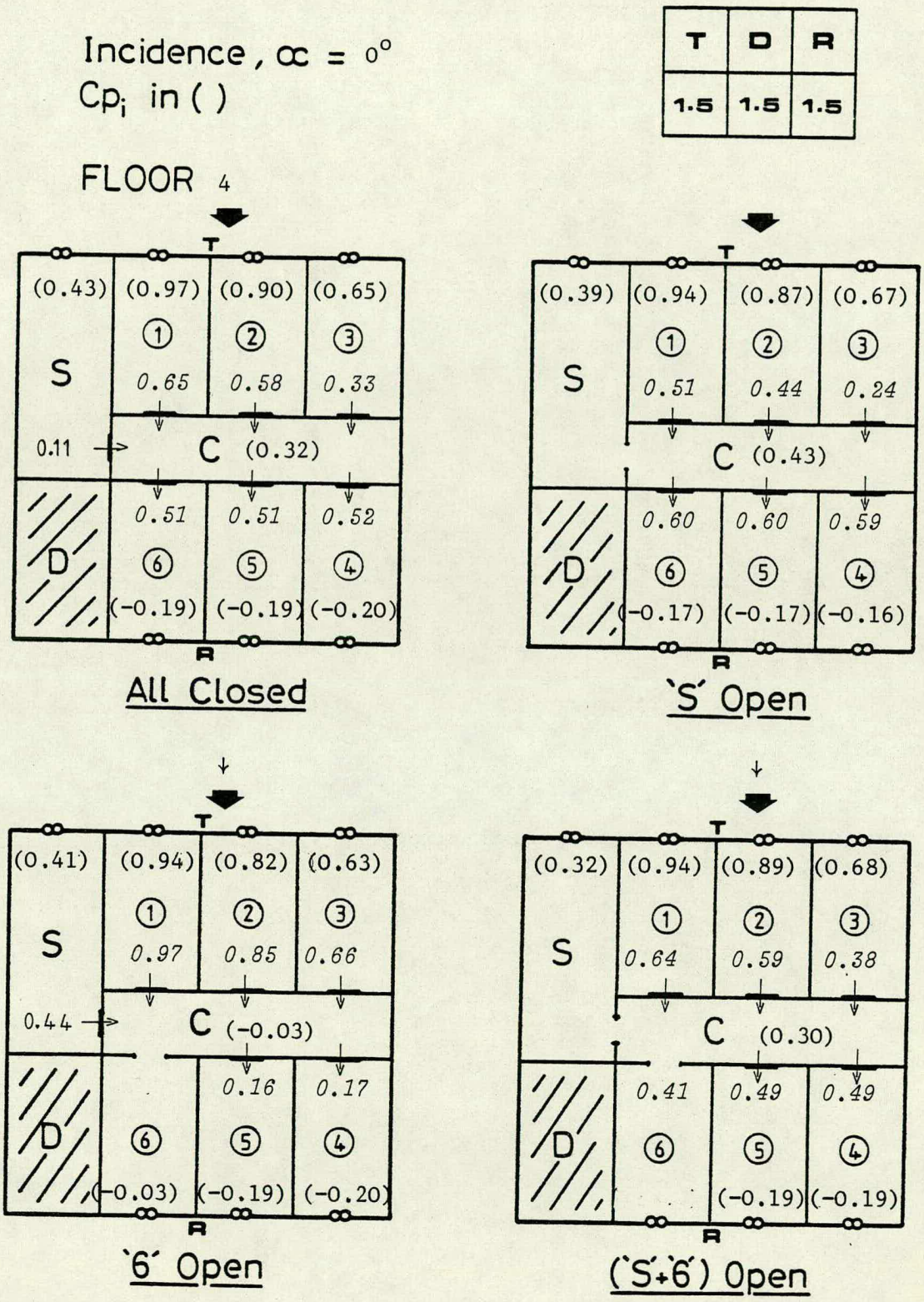


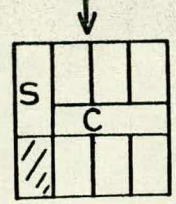
Fig 3.3.3: Wind Induced Pressure Distribution, α = 0°

Shaft and Corridor Pressure Distribution

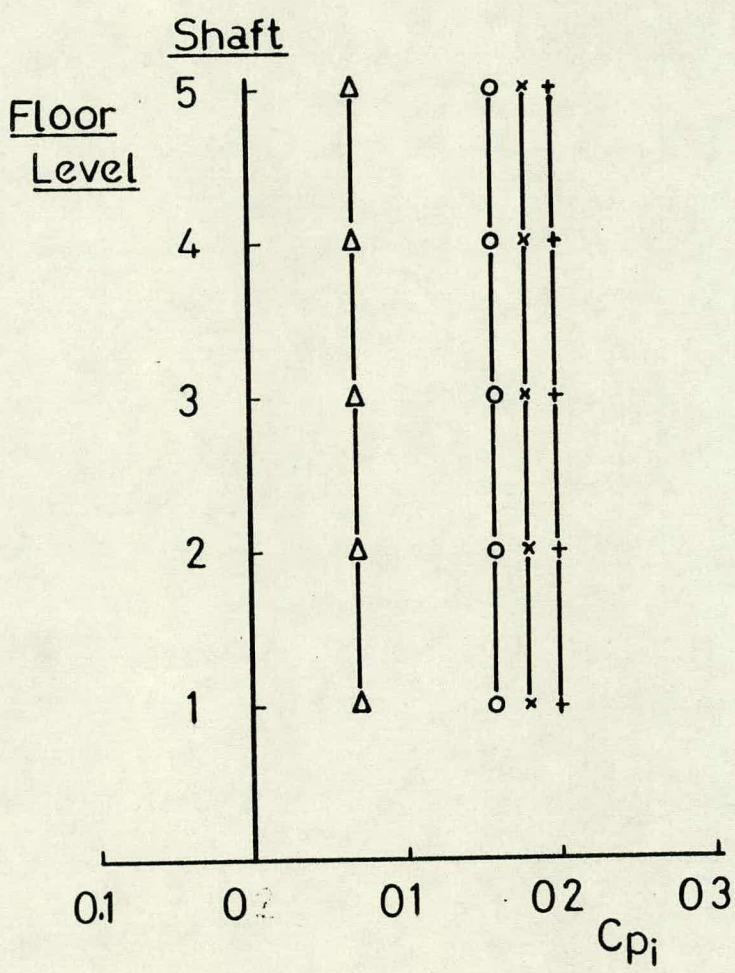
$\alpha = 0$

+ Closed
× 'S' Open
o '6' Open
Δ ('S'+'6') Open

T	D	R
1.5*	1.5	1.5



Floor 2 Openings



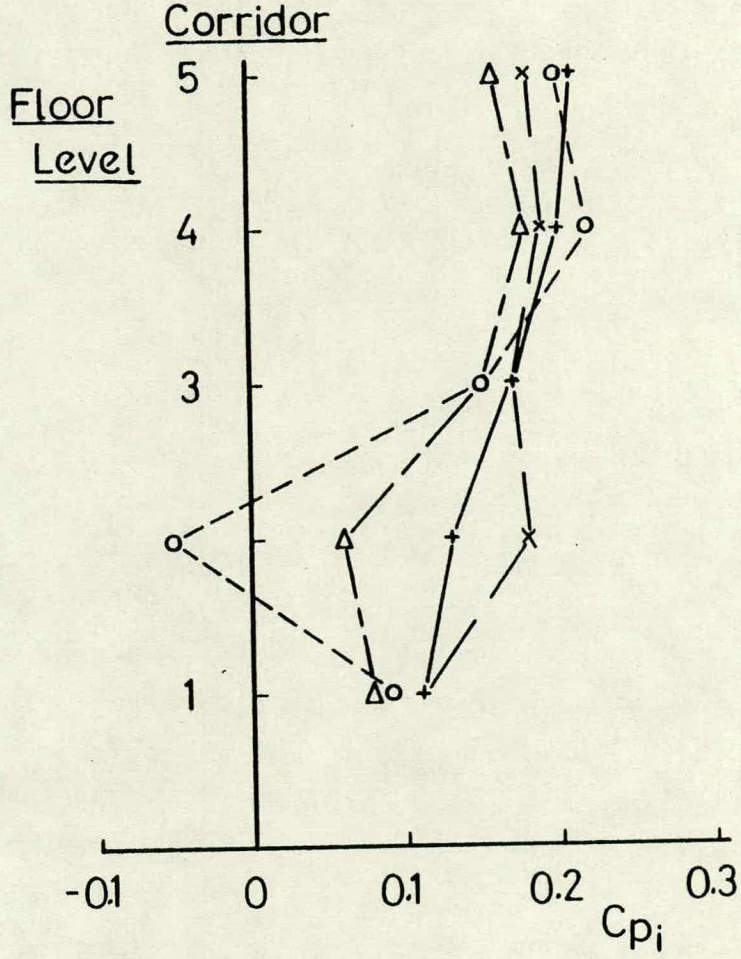


Fig 3.3.4: Shaft and Corridor Wind Induced Pressures, α = 0, leakage (b).

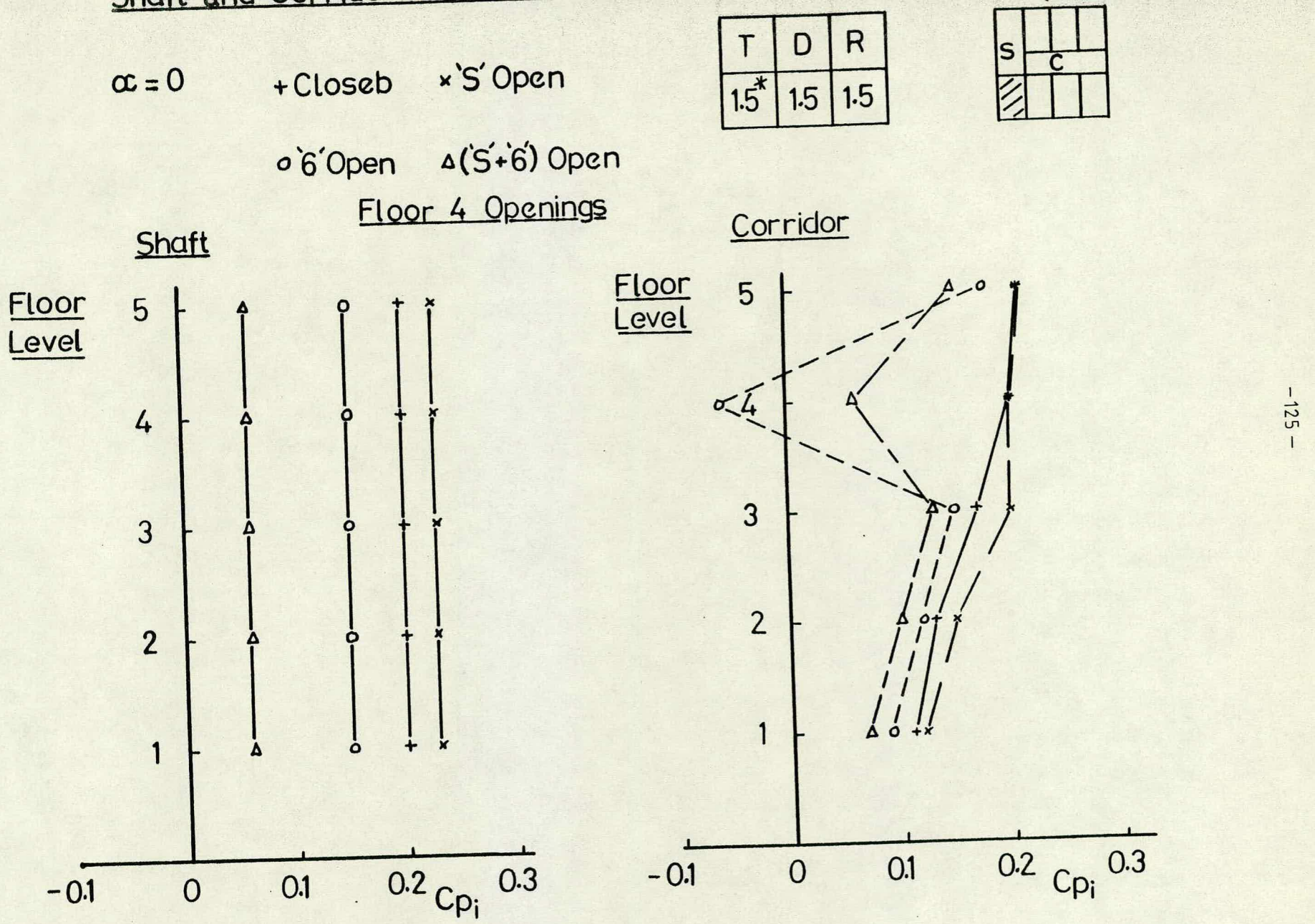
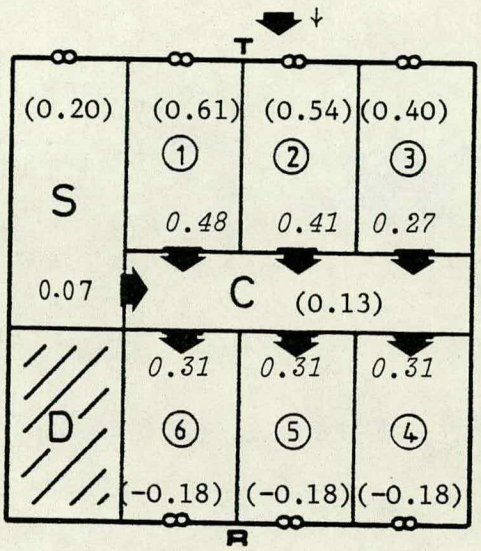


Fig 3.3.5: Shaft and Corridor Wind Induced Pressures, α = 0, leakage (b).

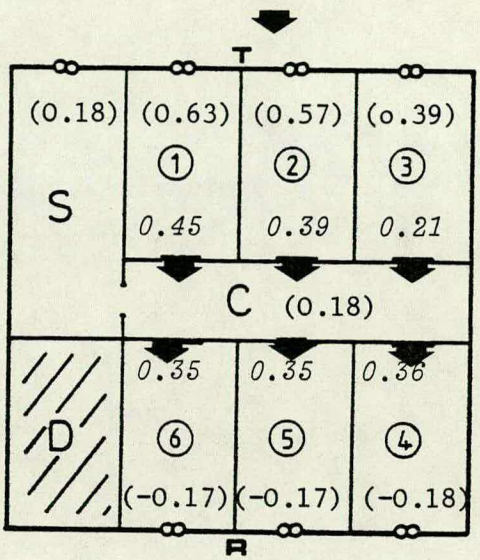
Incidence, α = 0°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

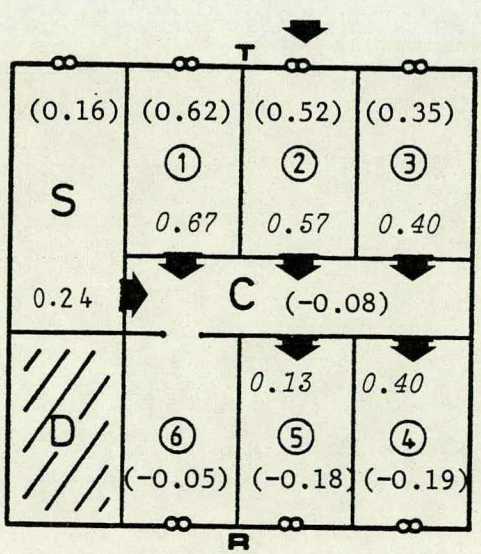
FLOOR 2



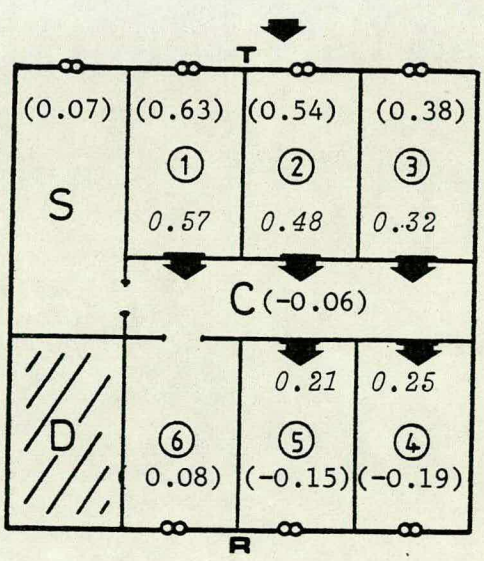
All Closed



'S' Open



'6' Open



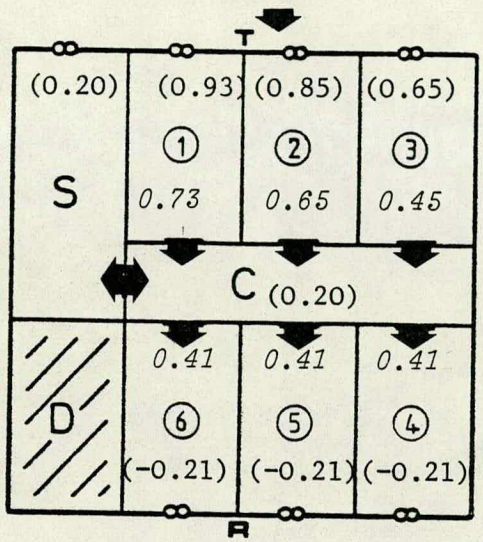
('S'+'6') Open

Fig 3.3.6 : Wind Induced Pressure Distribution, α = 0°

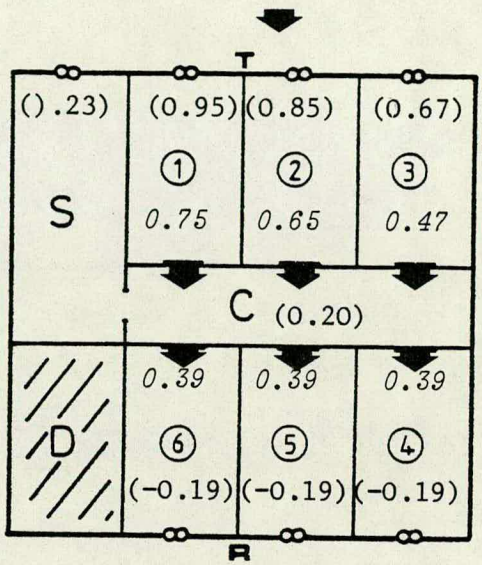
Incidence, α = 0°
Cp_i in ( )

T	D	R
1.5*	1.5	1.5

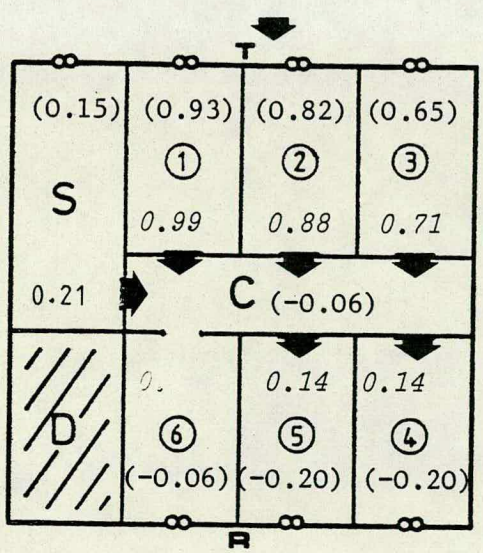
FLOOR 4



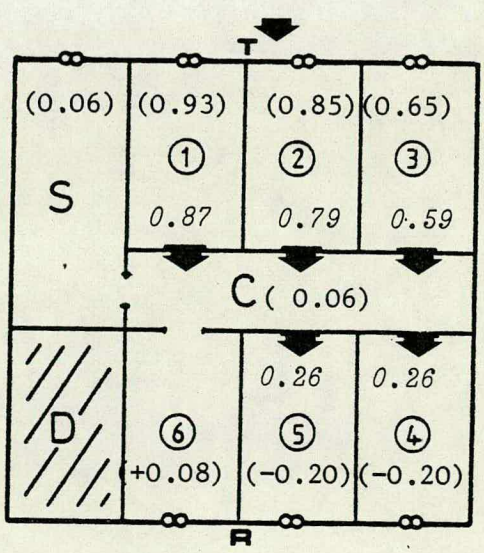
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.3.7: Wind Induced Pressure Distribution, α = 0°

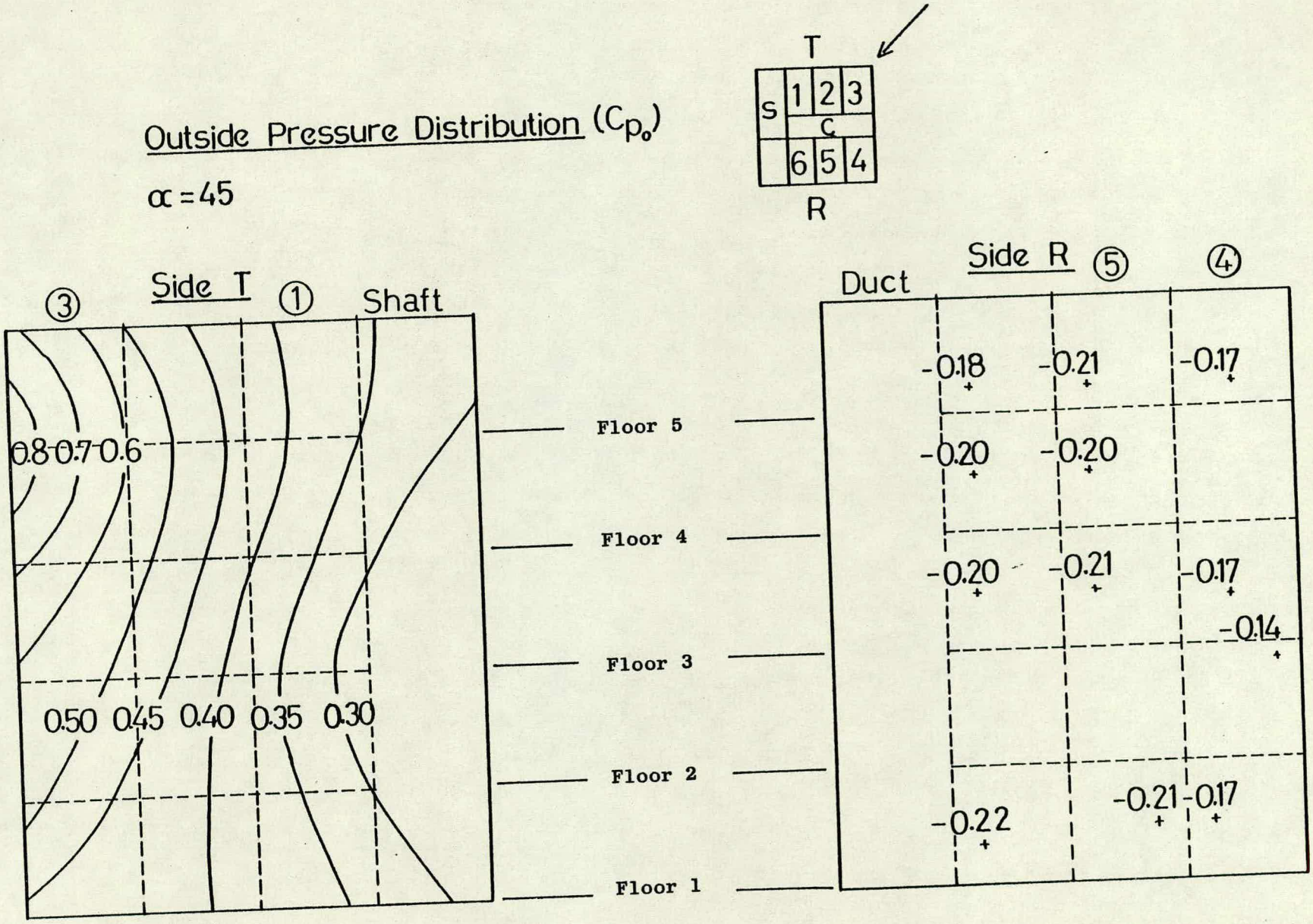


Fig 3.4 : Outside Pressure Distribution (Cp_o), $\alpha = 45^o$.

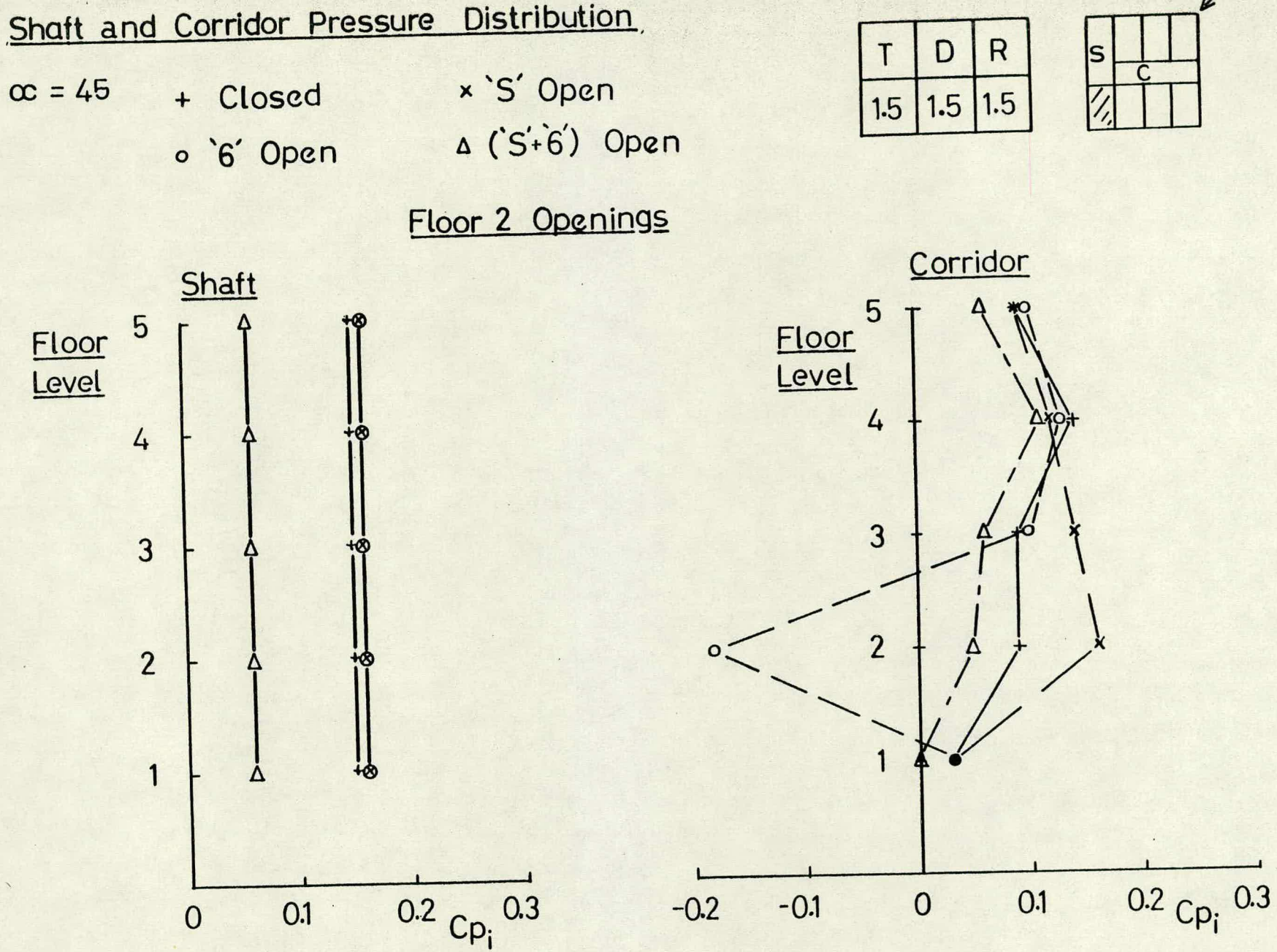


Fig 3.4.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (a)

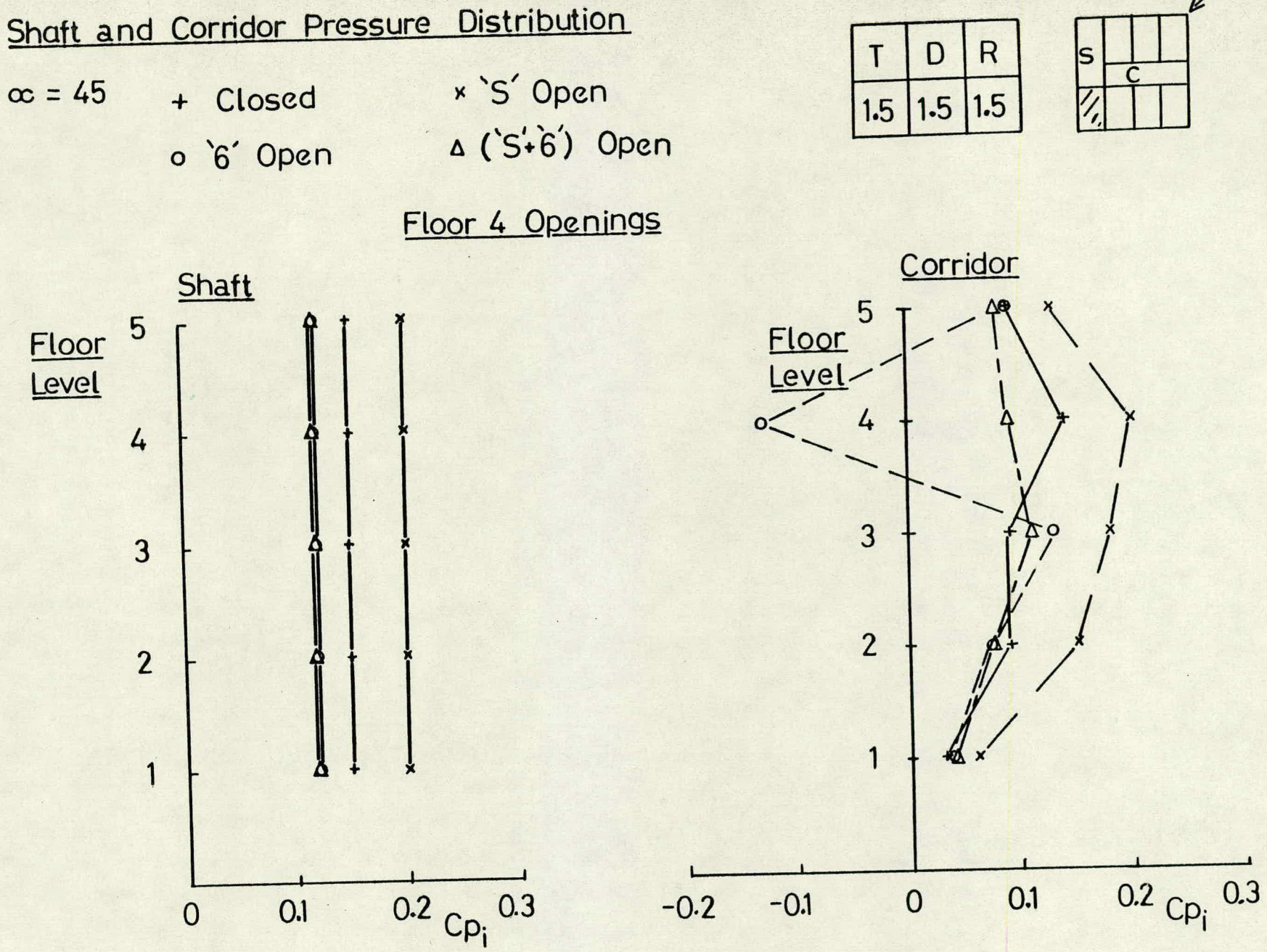
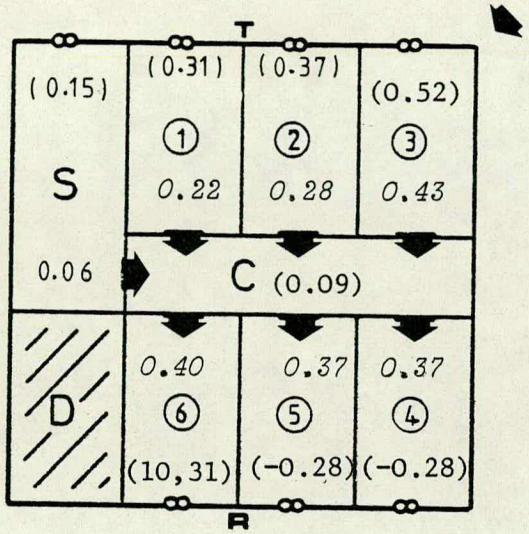


Fig 3.4.3: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (a).

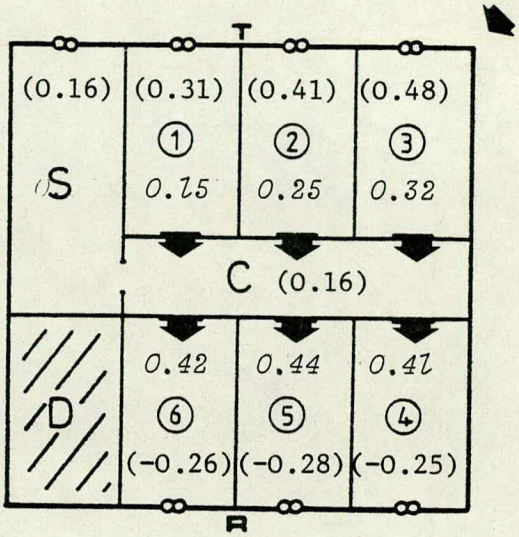
Incidence, α = 45°
Cp_i in ( )

FLOOR 2

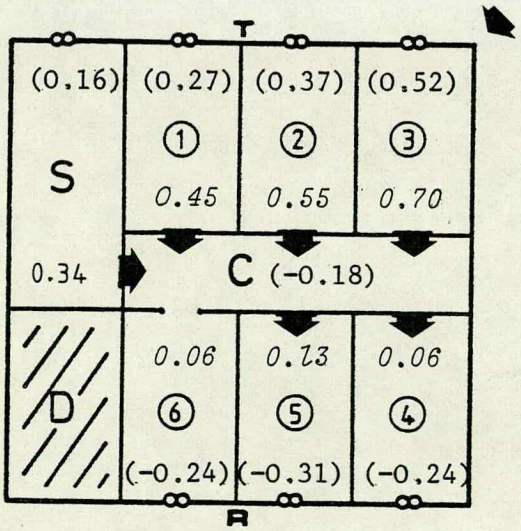
T	D	R
1.5	1.5	1.5



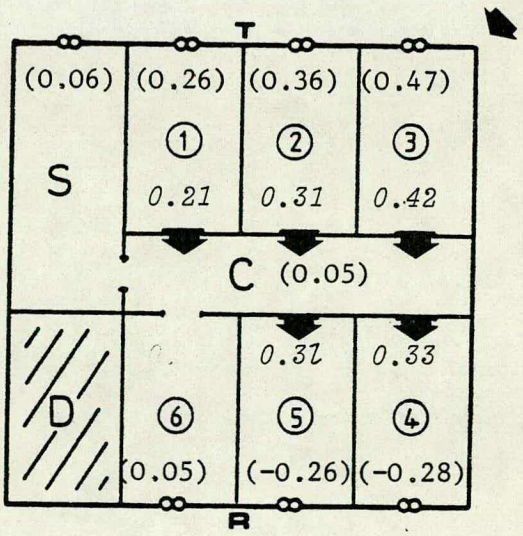
All Closed



'S' Open



'6' Open



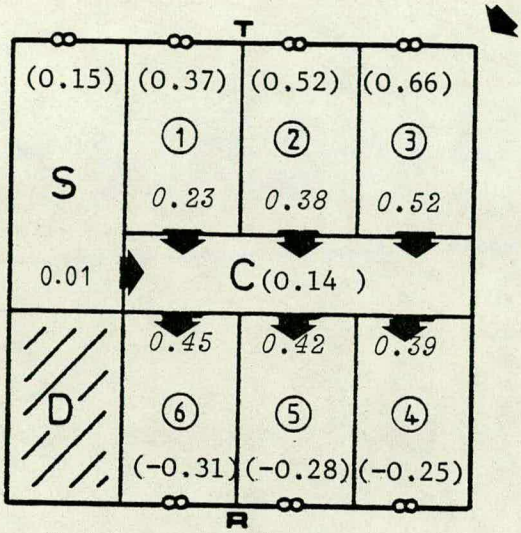
('S'+'6') Open

Fig 3.4.2: Wind Induced Pressure Distribution, α = 45°.

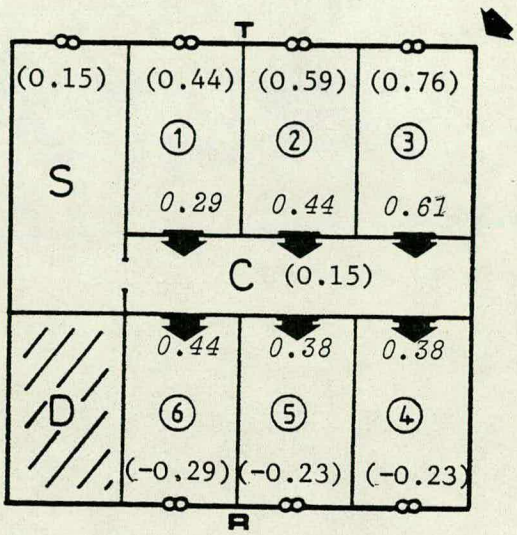
Incidence, α = 45°
C_{p_i} in ( )

FLOOR 4

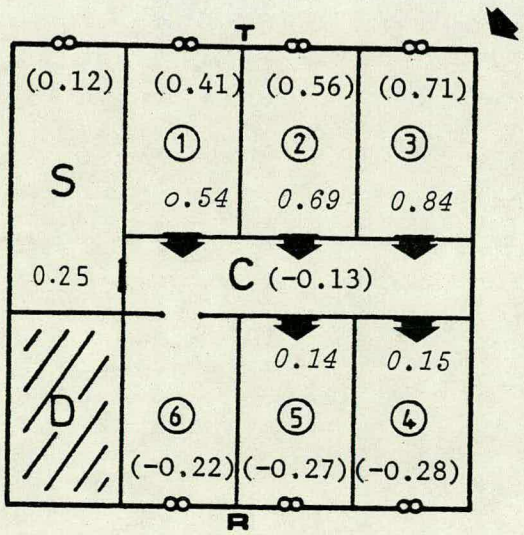
T	D	R
1.5	1.5	1.5



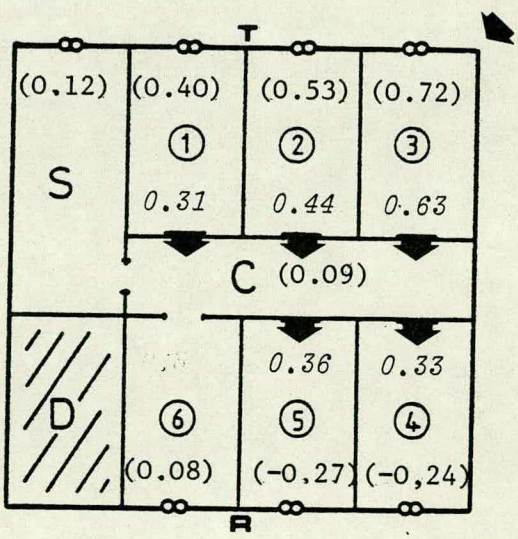
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.4.4: Wind Induced Pressure Distribution, α = 45°

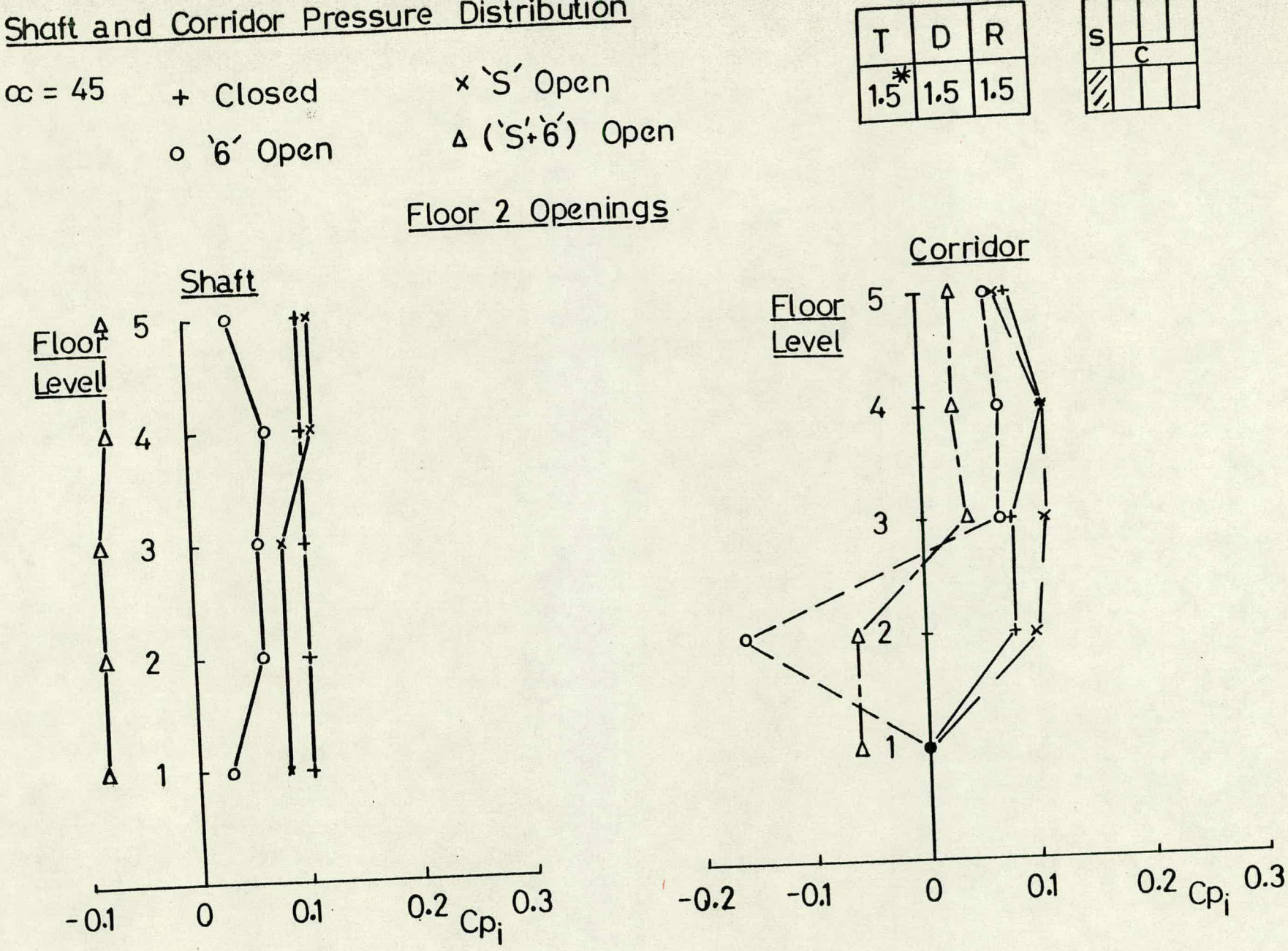


Fig 3.4.5: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (b).

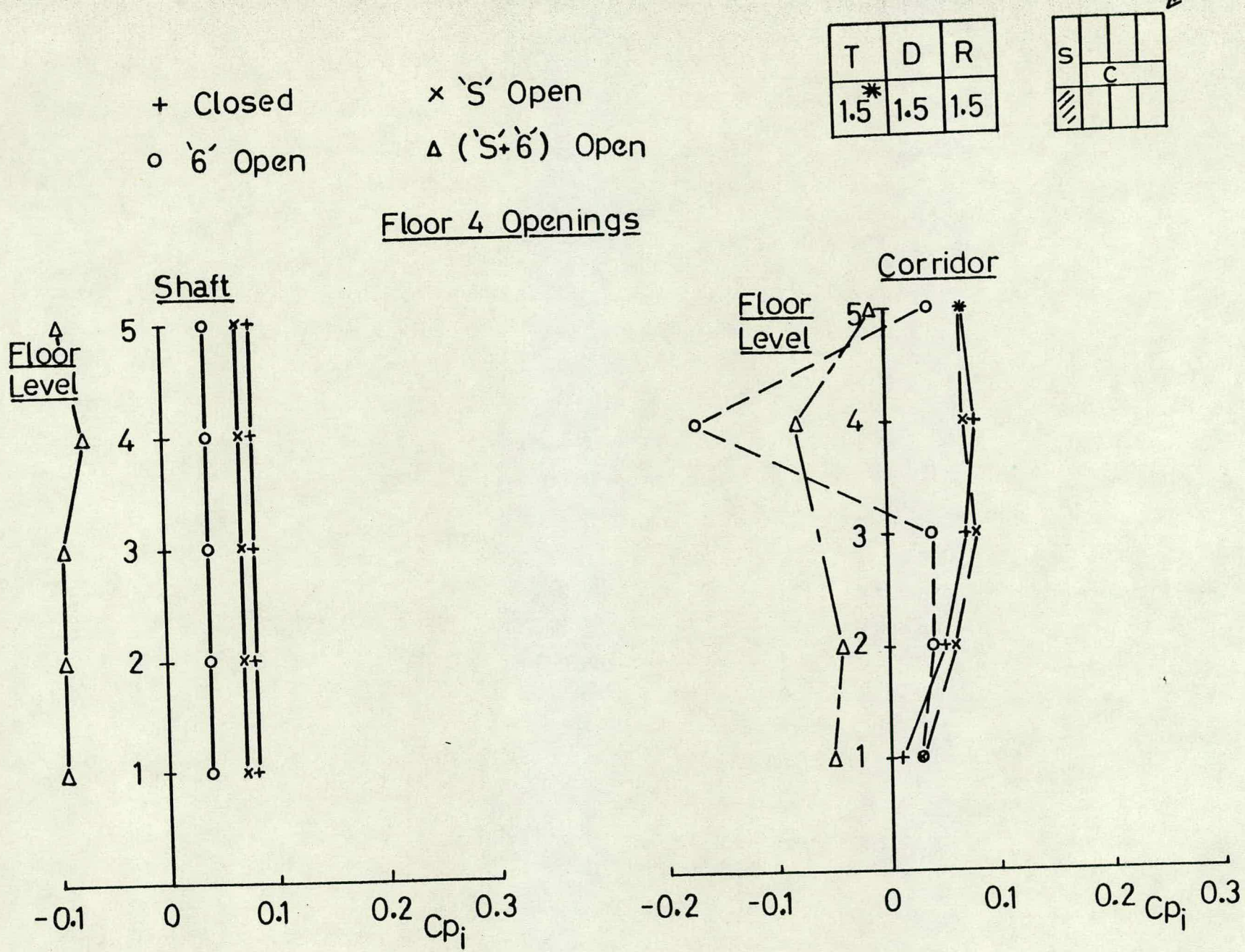
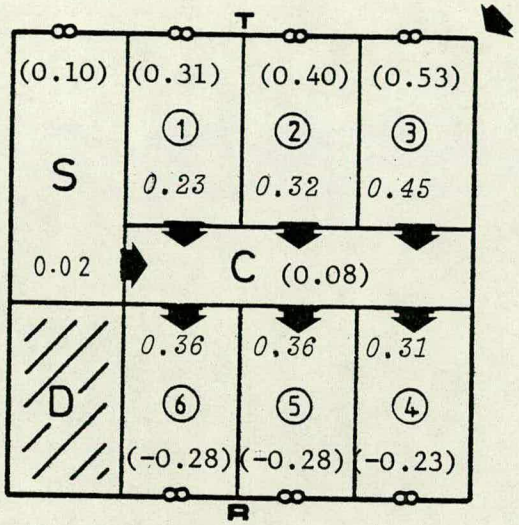


Fig 3.4.7: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (b).

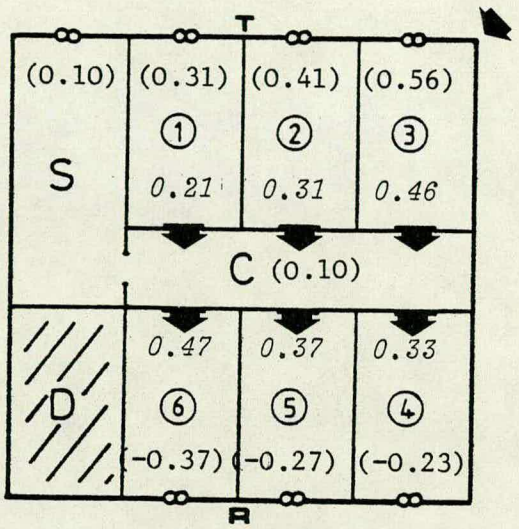
Incidence, α = 45°
C_{p_i} in ( )

FLOOR 2

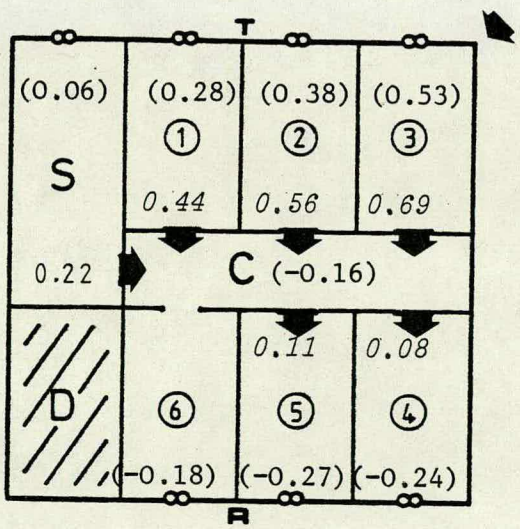
T	D	R
1.5*	1.5	1.5



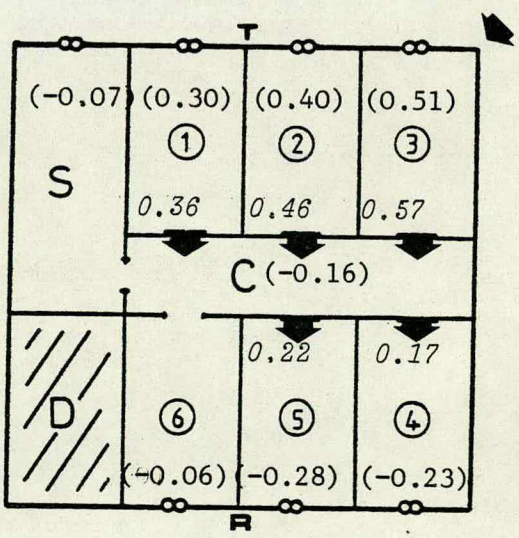
All Closed



'S' Open



'6' Open



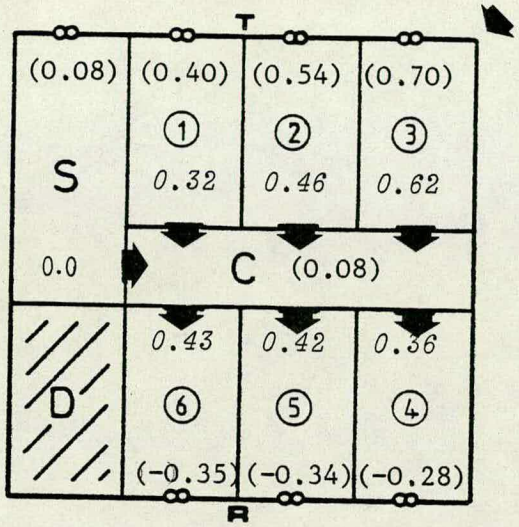
('S'+'6') Open

Fig 3.4.6: Wind Induced Pressure Distribution, α = 45°

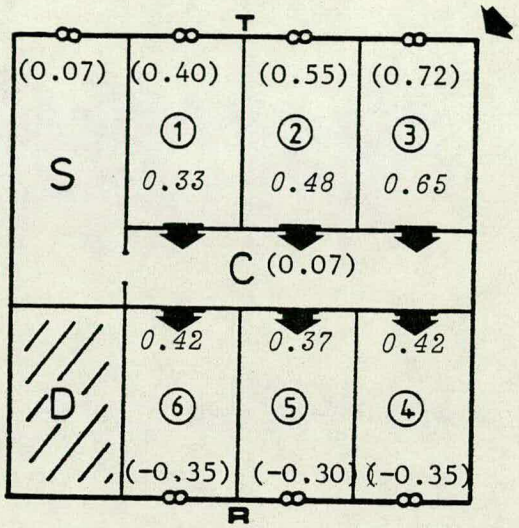
Incidence, α = 45°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

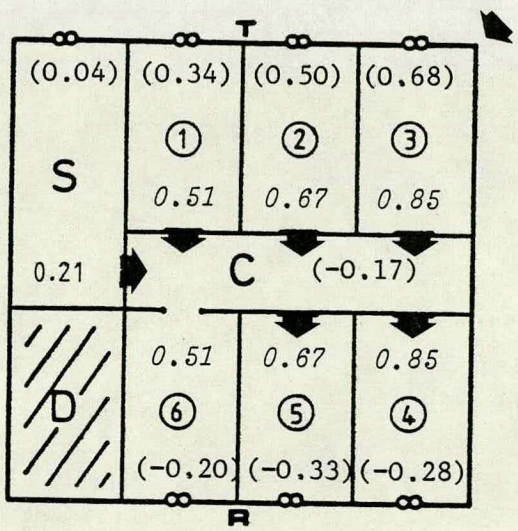
FLOOR 4



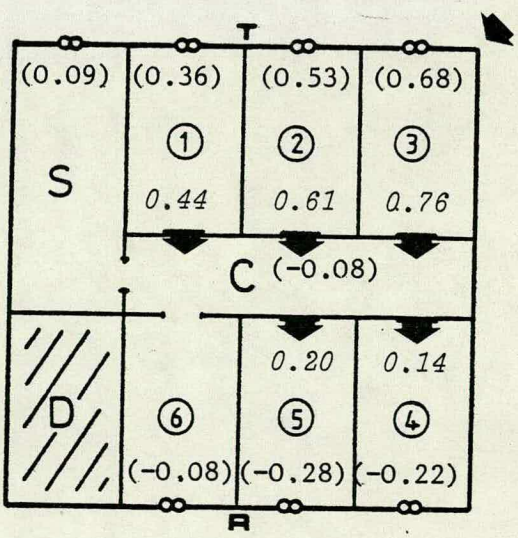
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.4.8: Wind Induced Pressure Distribution, α = 45°

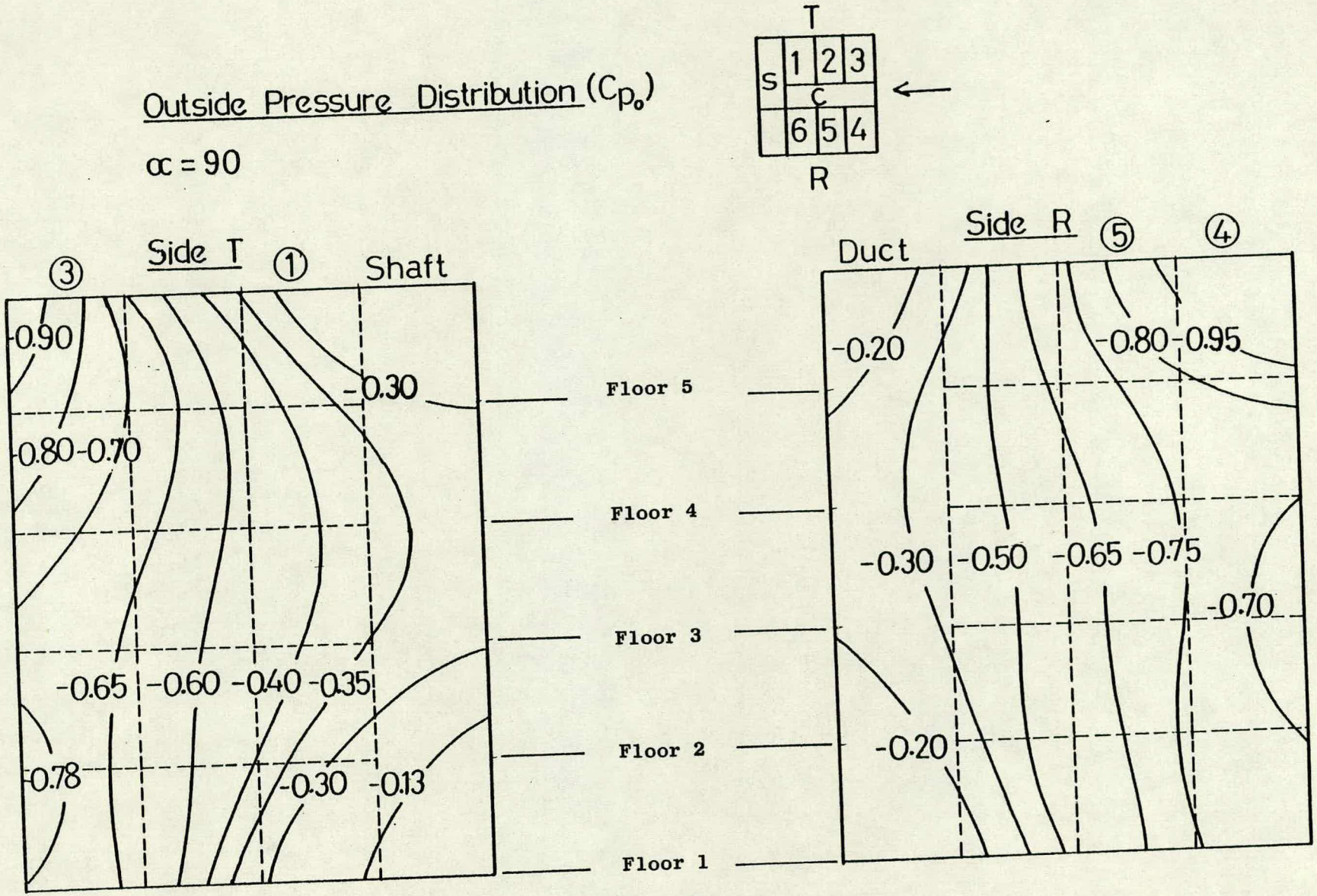


Fig 3.5 : Outside Pressure Distribution, C_{p_o}, $\alpha = 90^o$.

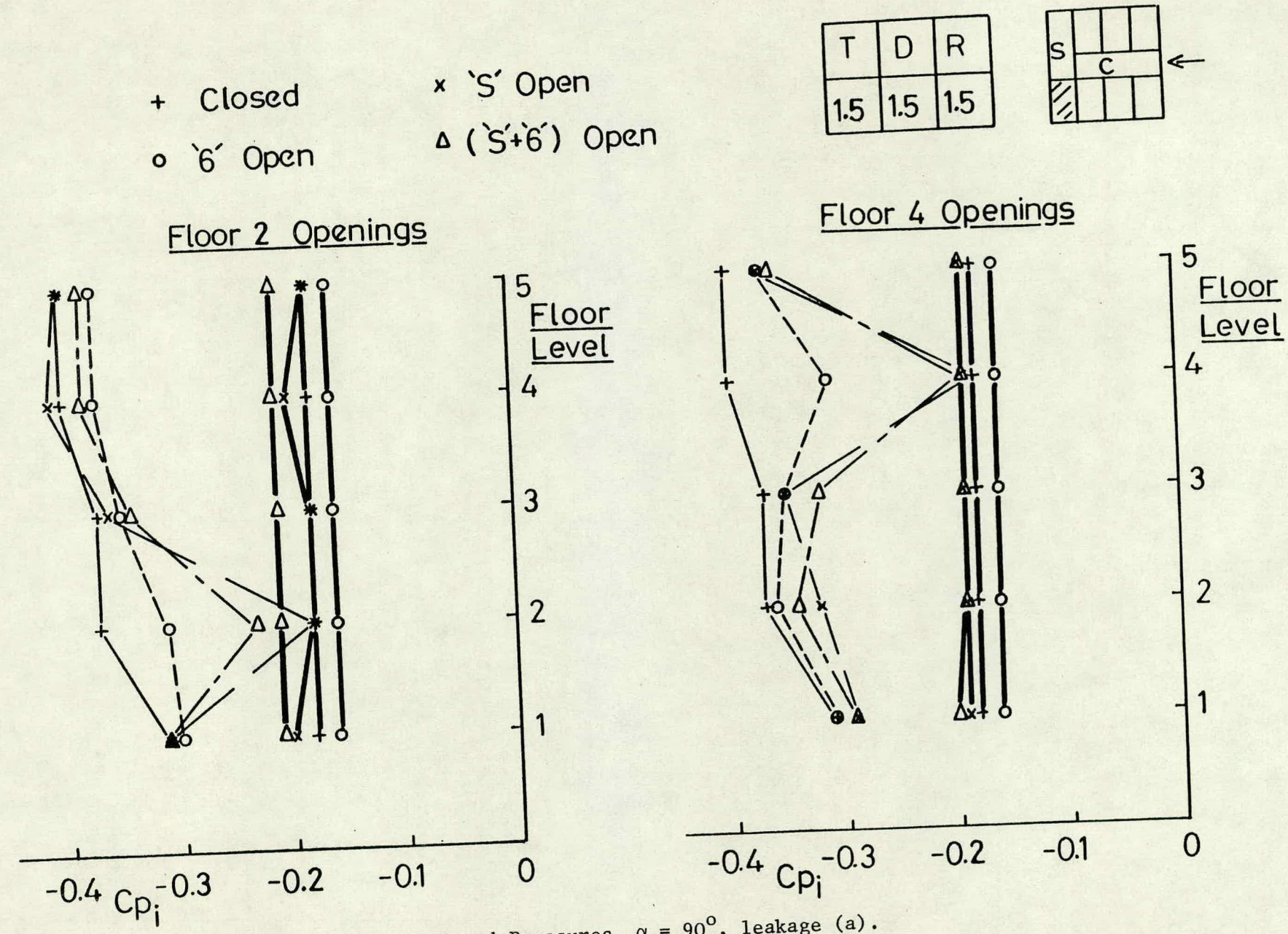


Fig 3.5.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 90^{o}$, leakage (a).

Incidence, α = 90°
Cp_i in ( )

FLOOR 2

T	D	R
1.5	1.5	1.5

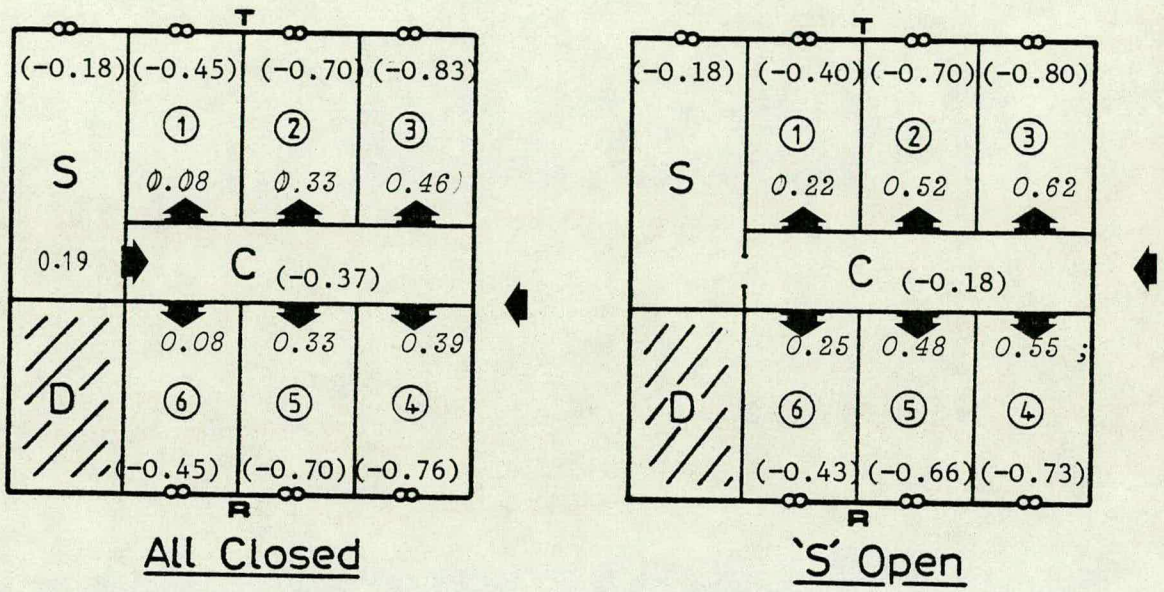
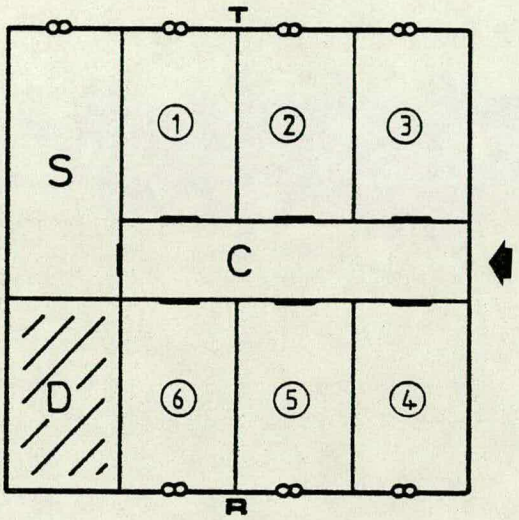


Fig 3.5.2: Wind Induced Pressure Distribution, α = 90°

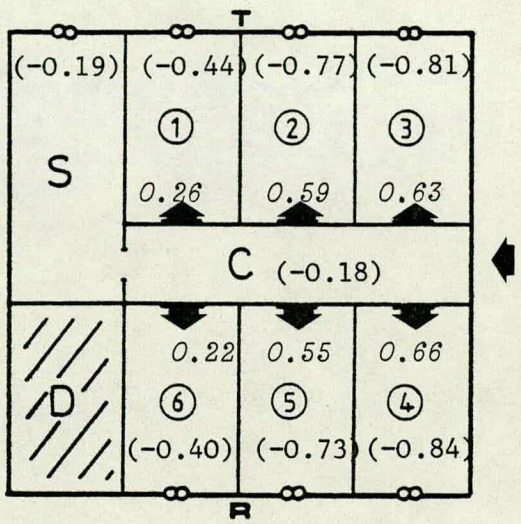
Incidence, α = 90°
Cp_i in ( )

T	D	R
1.5	1.5	1.5

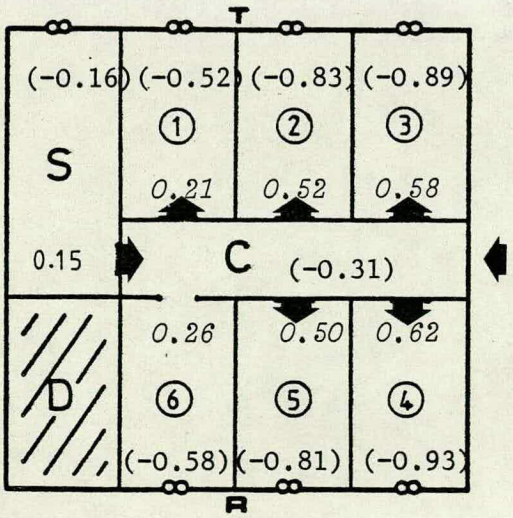
FLOOR 4



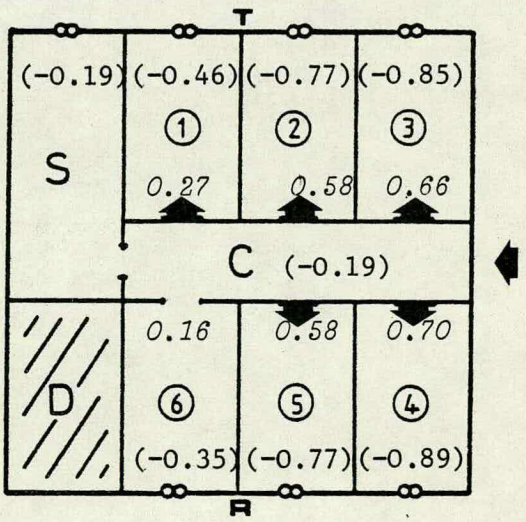
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.5.3: Wind Induced Pressure Distribution, α = 90°

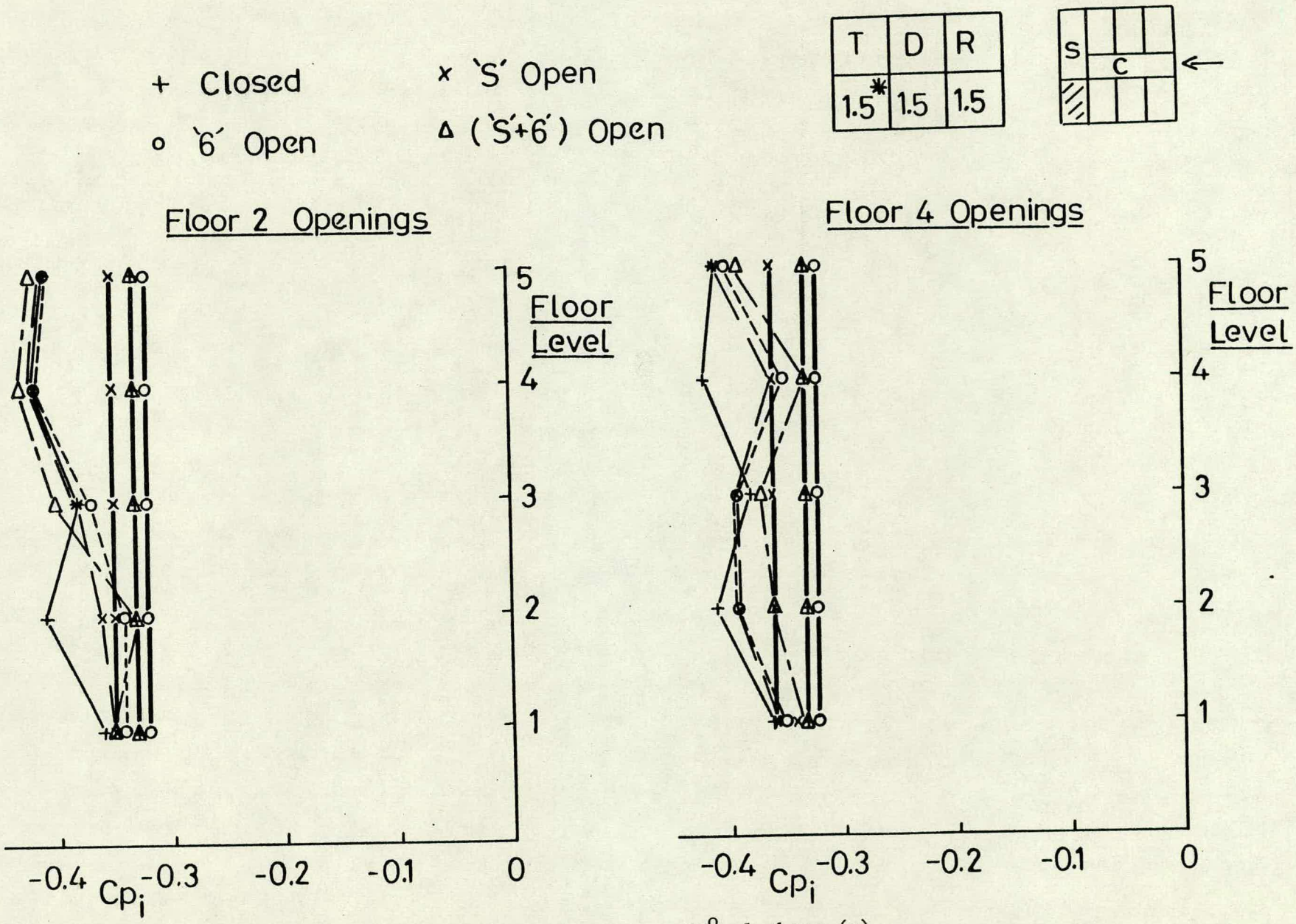
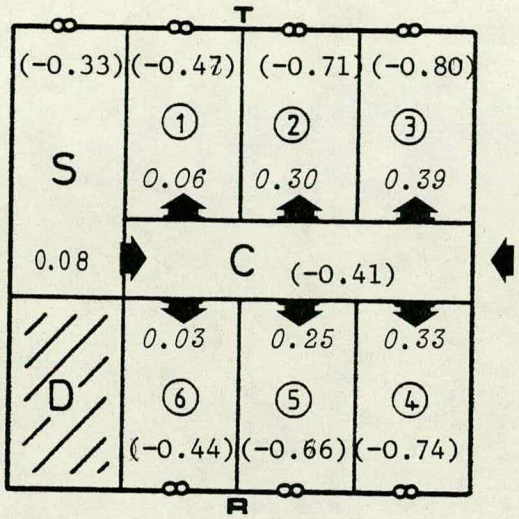


Fig 3.5.4: Shaft and Corridor Wind Induced Pressures, $\alpha = 90^{o}$, leakage (a).

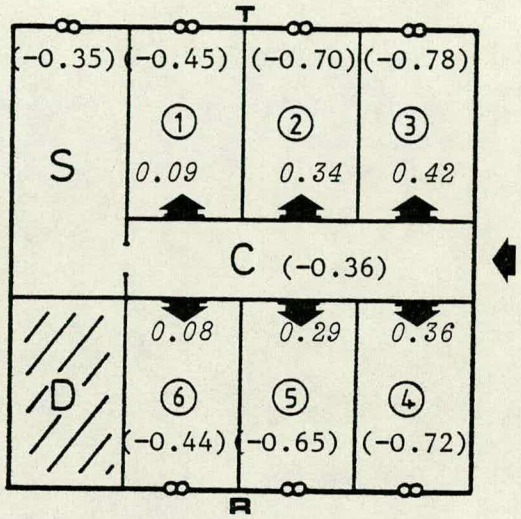
Incidence , α = 90°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

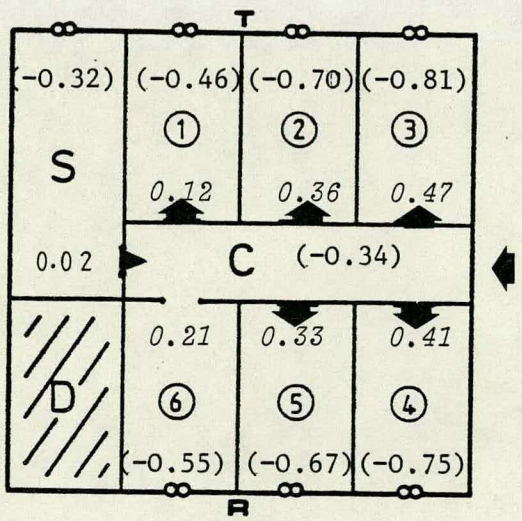
FLOOR 2



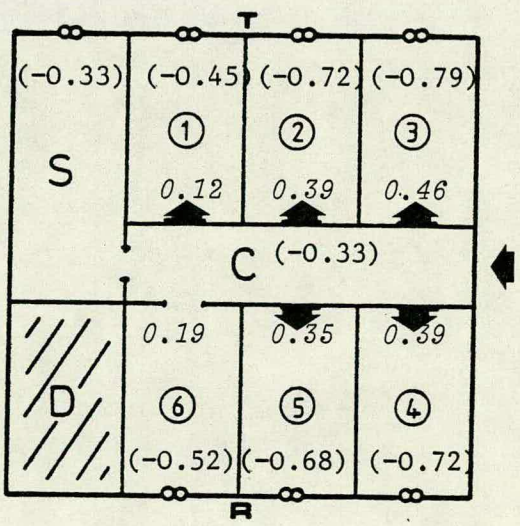
All Closed



'S' Open



'6' Open



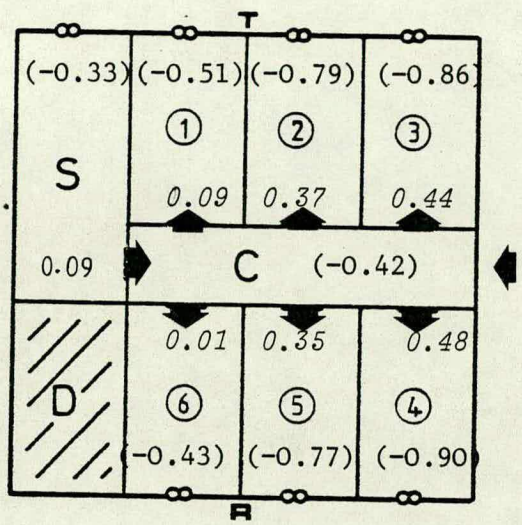
('S'+'6') Open

Fig 3.5.5: Wind Induced Pressure Distribution, α = 90°

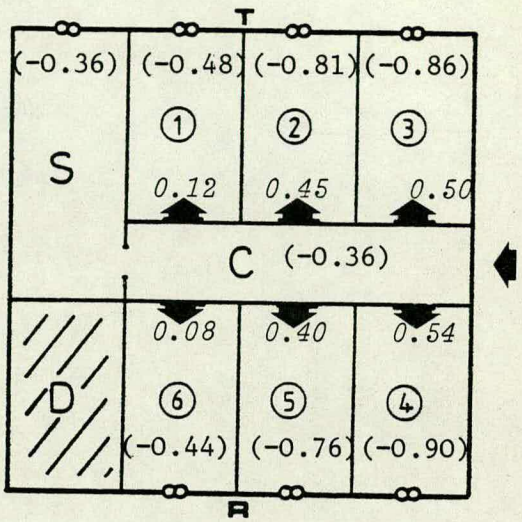
Incidence, α = 90°
C_{p_i} in ( )

FLOOR 4

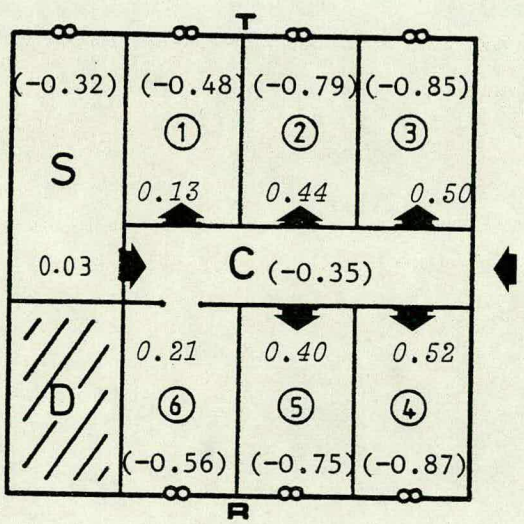
T	D	R
*1.5	1.5	1.5



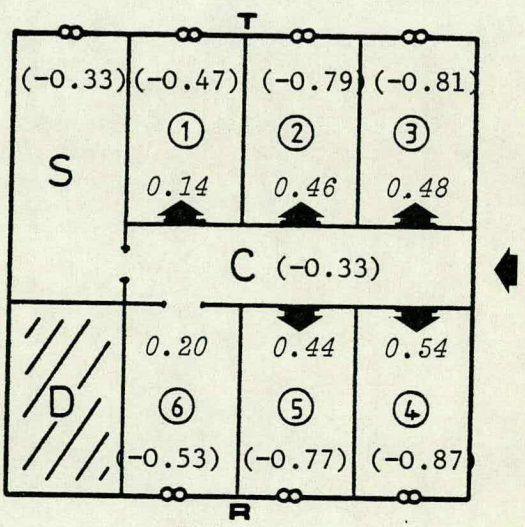
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.5.6: Wind Induced Pressure Distribution, α = 90°

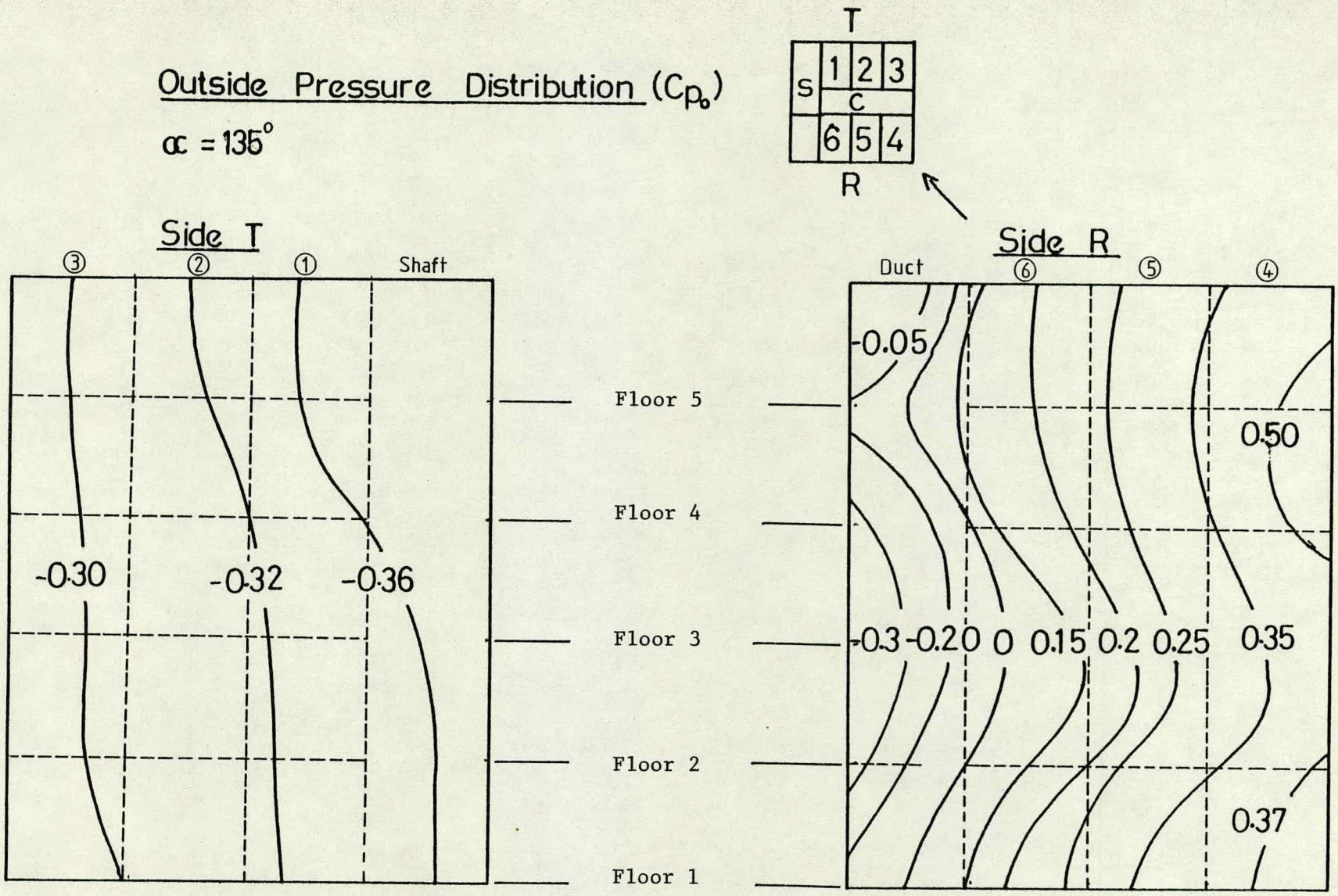


Fig 3.6: Outside Pressure Distribution (Cp_o), $\alpha = 135^\circ$

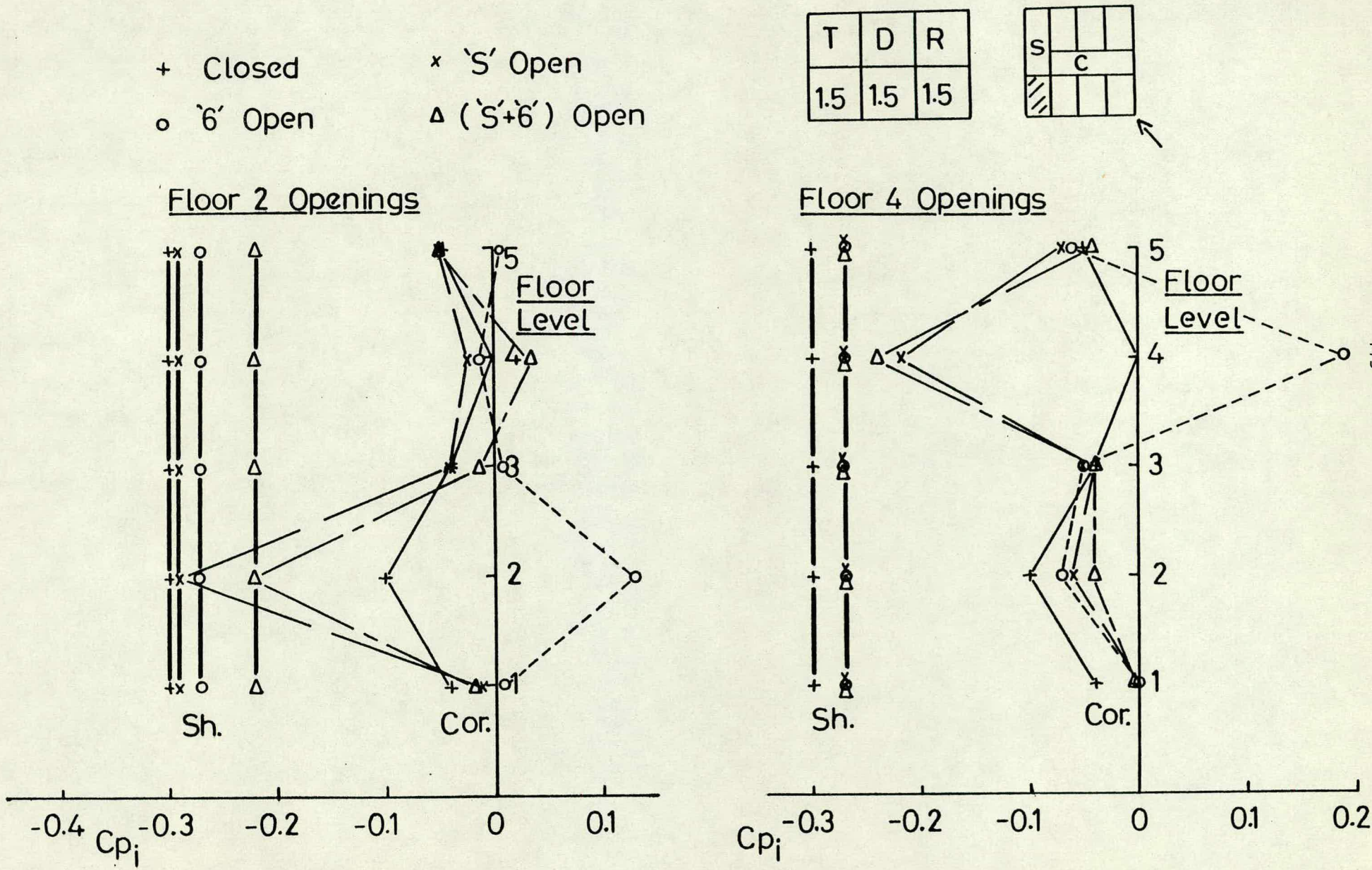
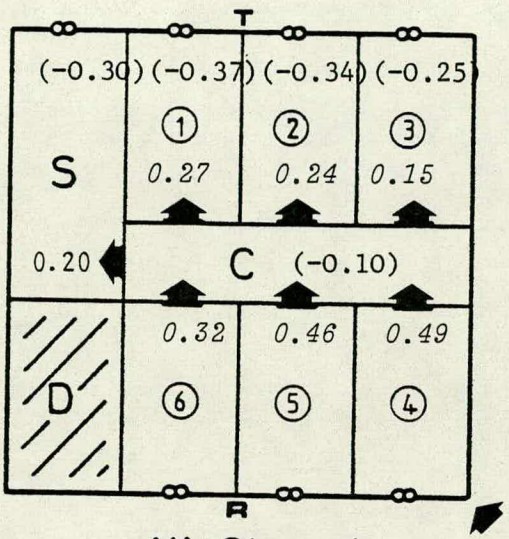


Fig 3.6.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 135^{o}$, leakage (a)

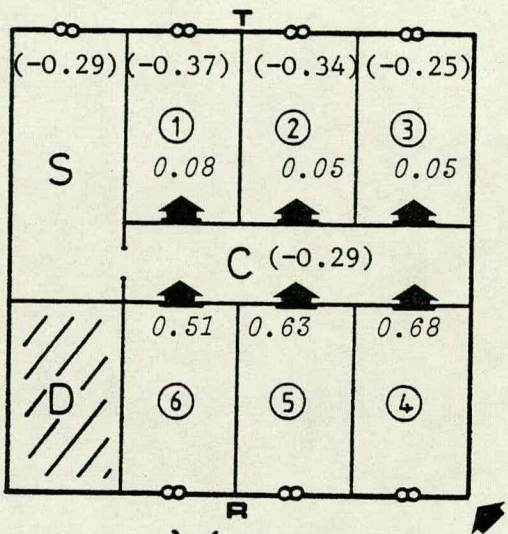
Incidence, α = 135°
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

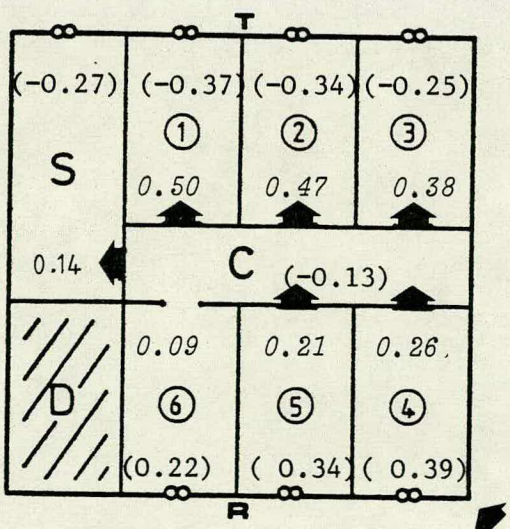
FLOOR 2



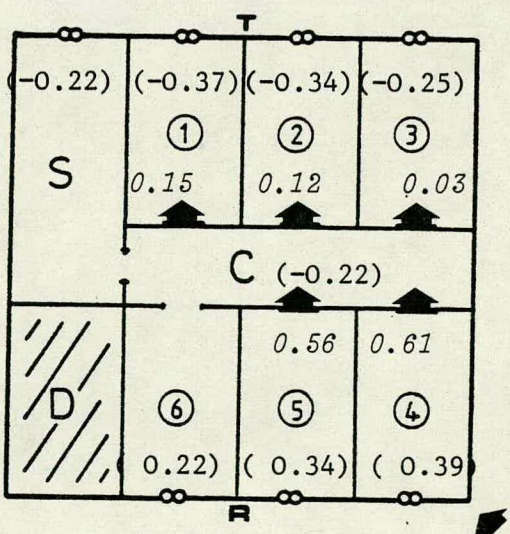
All Closed



'S' Open



'6' Open



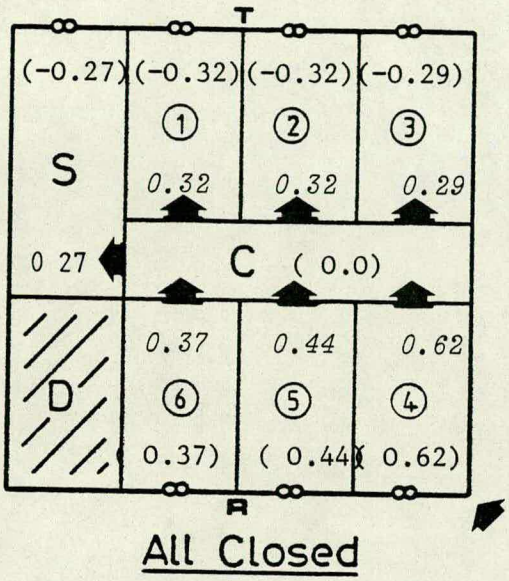
('S'+'6') Open

Fig 3.6.2: Wind Induced Pressure Distribution, α = 135°

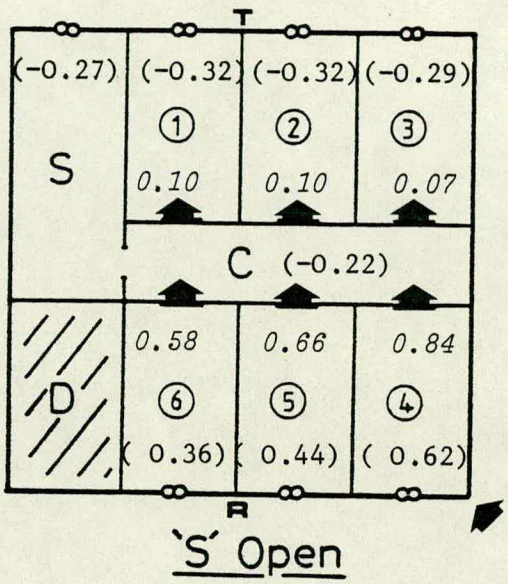
Incidence, α = 135°
C_{p_i} in ( )

FLOOR 4

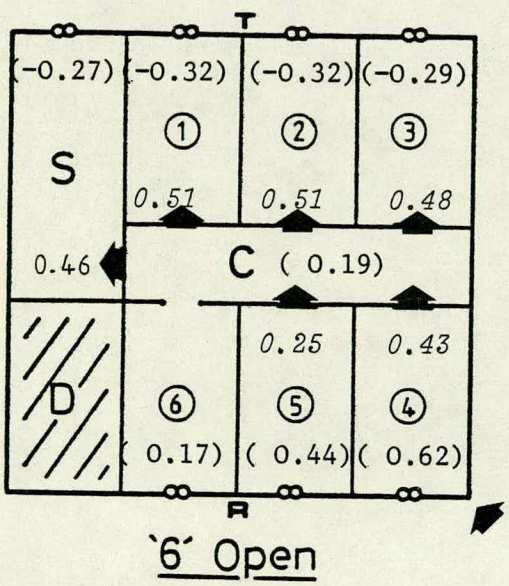
T	D	R
1.5	1.5	1.5



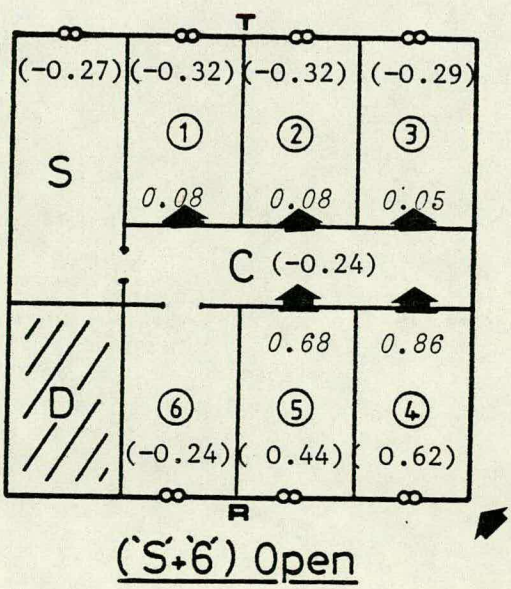
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.6.3: Wind Induced Pressure Distribution, α = 135°

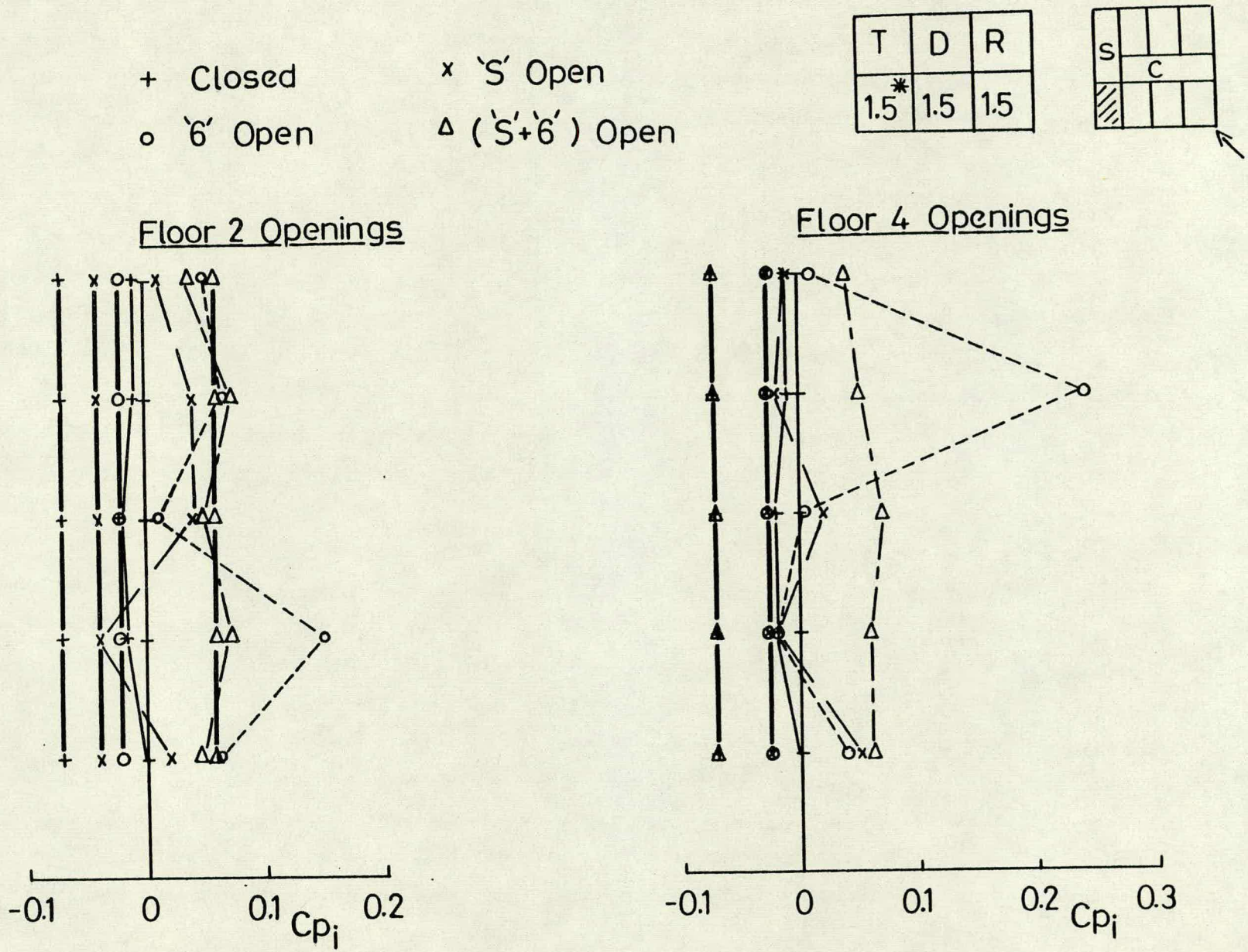


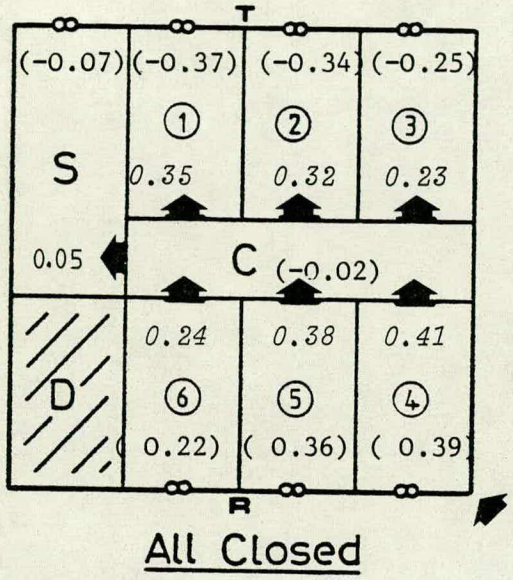
Fig 3.6.4: Shaft and Corridor Wind Induced Pressures, $\alpha = =35^{o}$. Leakage (b)

Incidence, α = 135^{o}

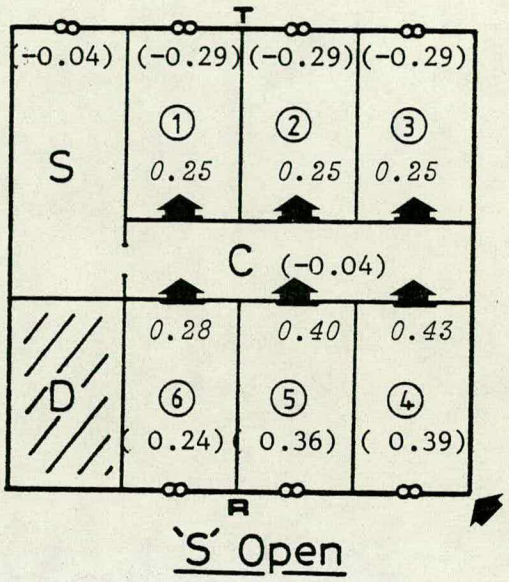
Cp_i in ( )

FLOOR 2

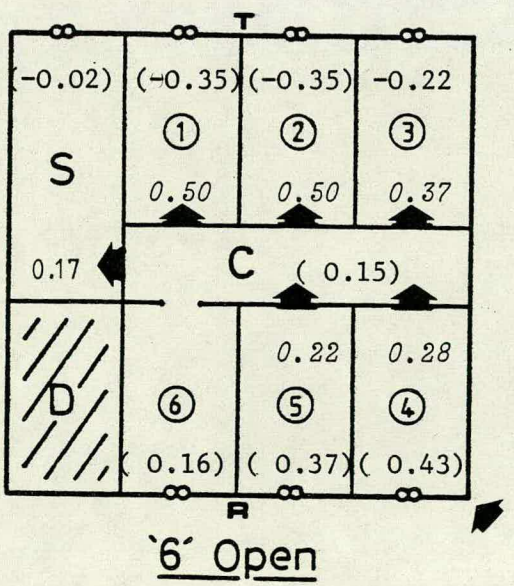
T	D	R
1.5*	1.5	1.5



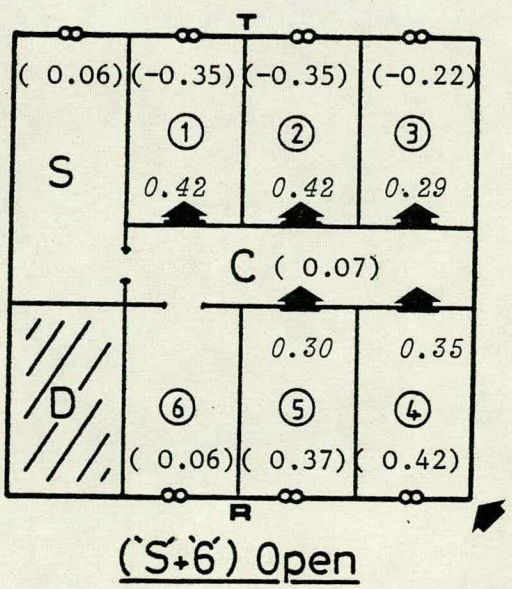
All Closed



'S' Open



'6' Open



('S'+'6') Open

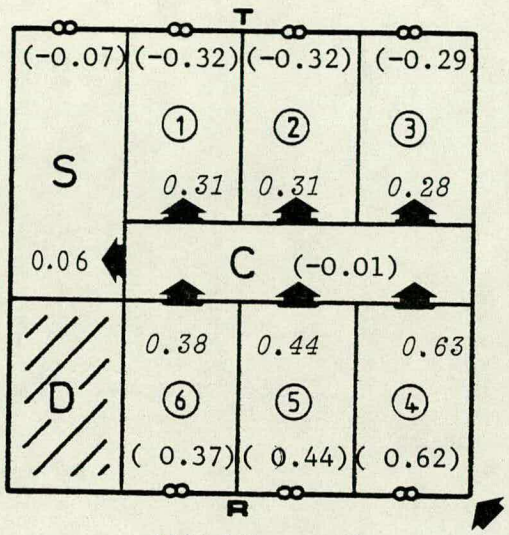
Fig 3.6.5: Wind Induced Pressure Distribution, α = 135^{o}

Incidence, α = 135°

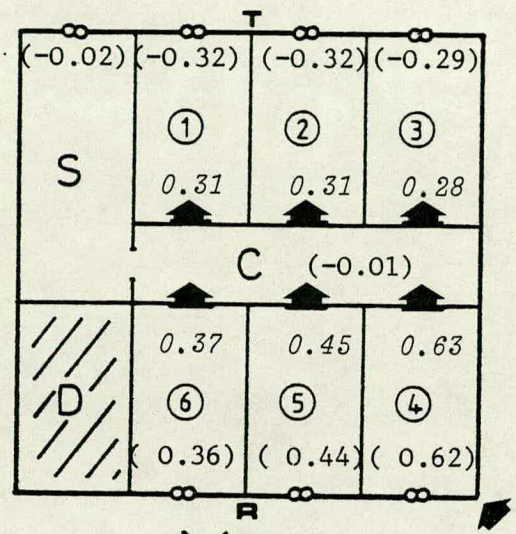
C_{p_i} in ( )

FLOOR 4

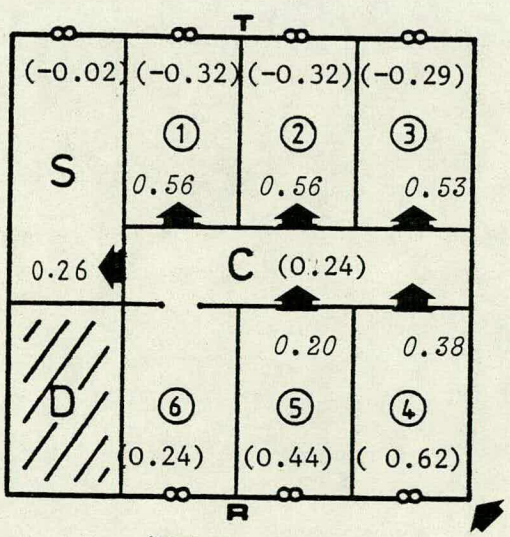
T	D	R
1.5*	1.5	1.5



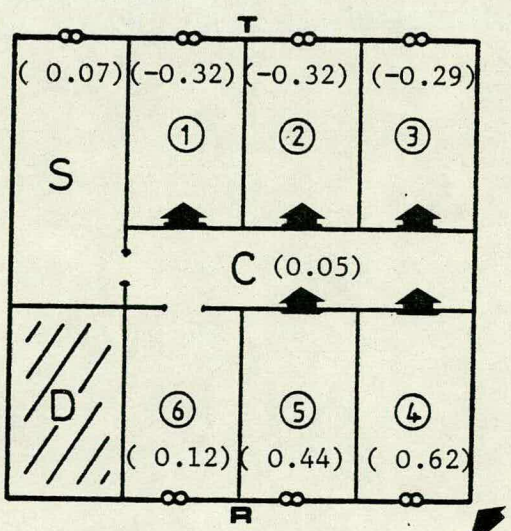
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.6.6: Wind Induced Pressure Distribution, α = 135°

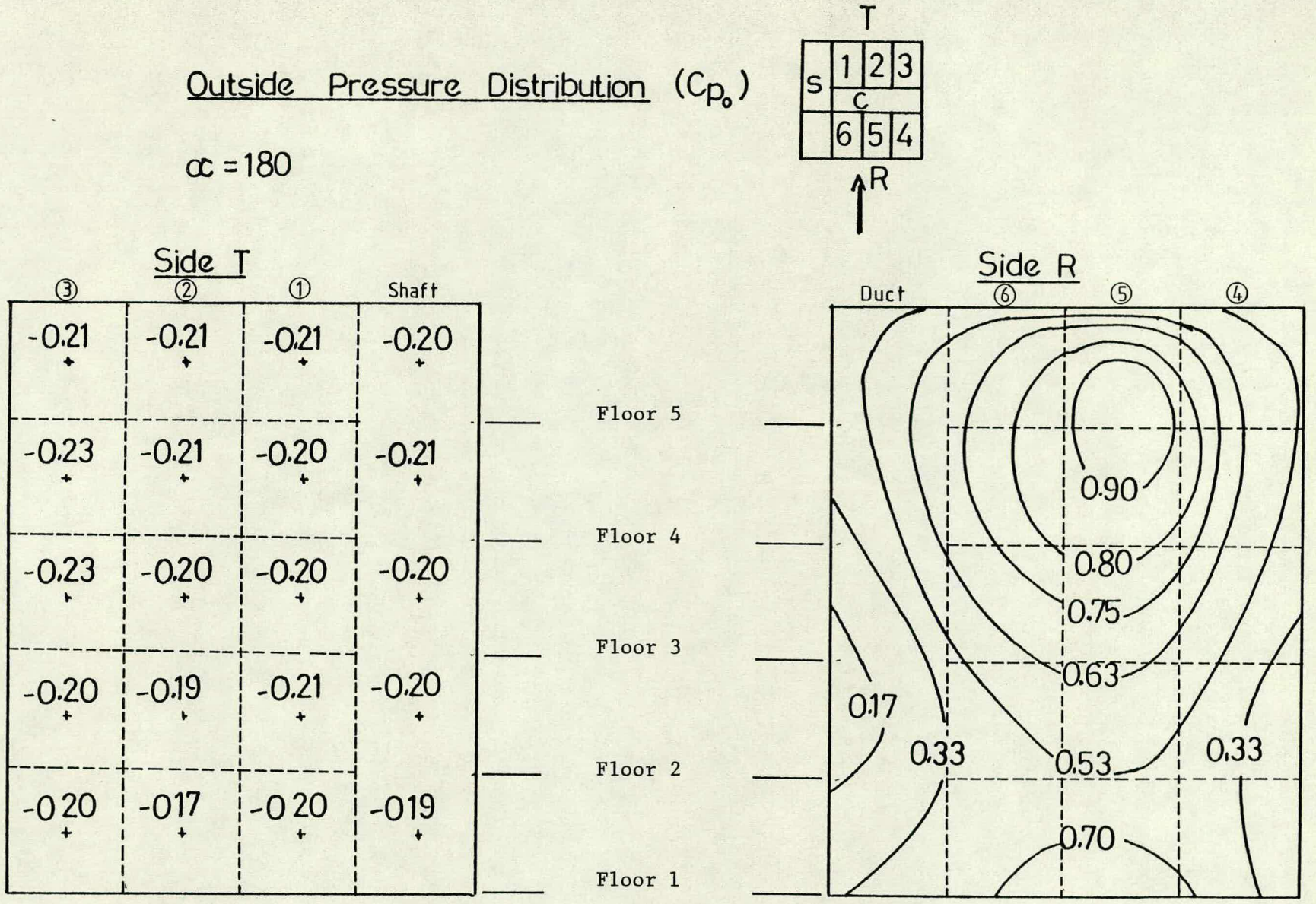


Fig 3.7: Outside pressure distribution (Cp_o), $\alpha = 180^o$, Leakage (a).

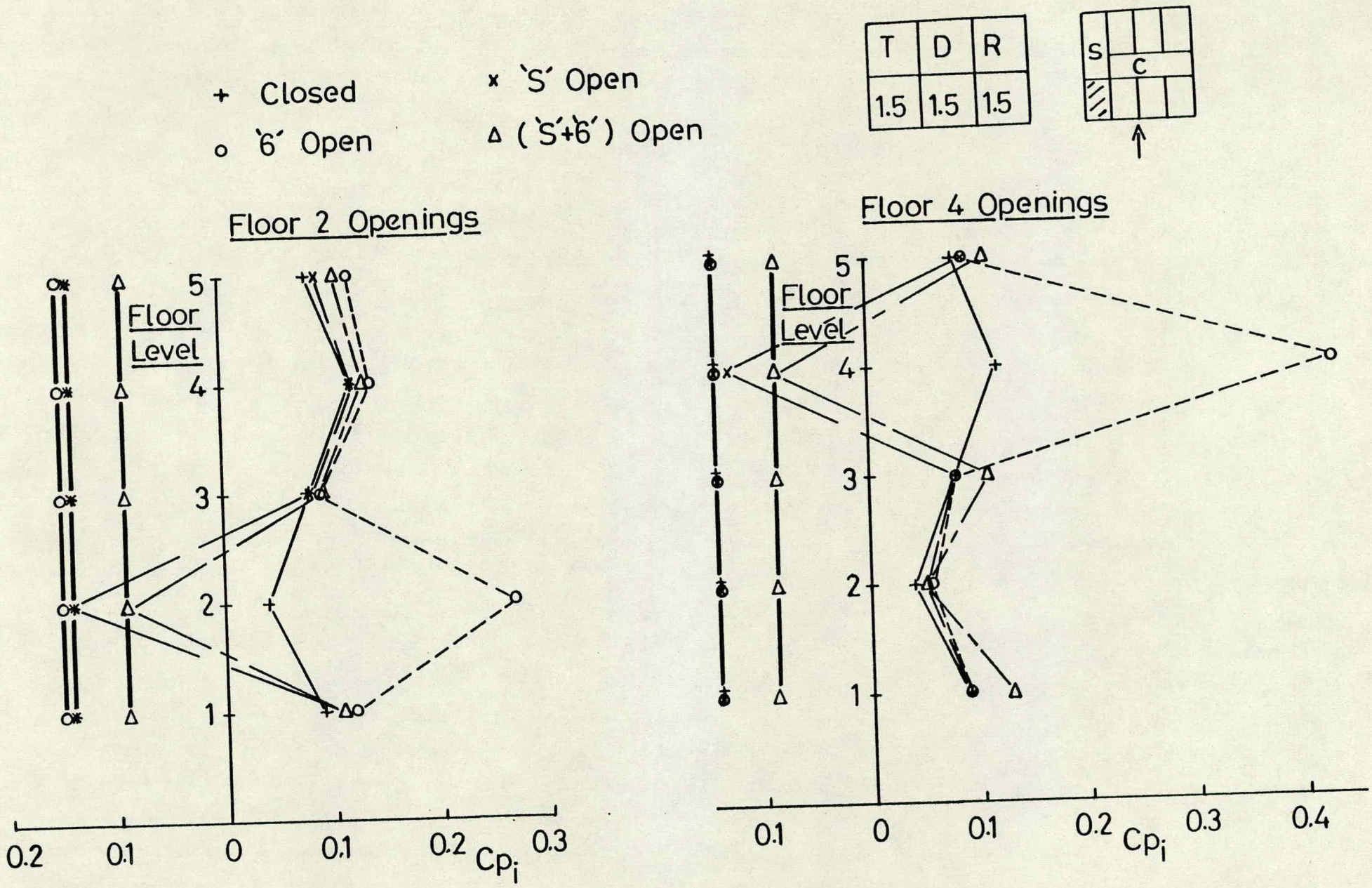
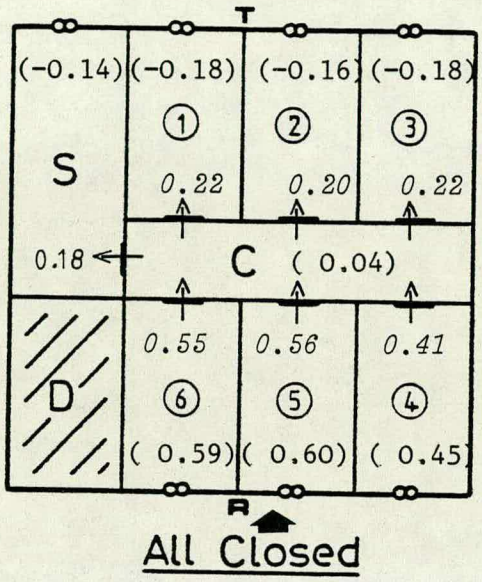


Fig 3.7.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 180^{o}$, Leakage (a).

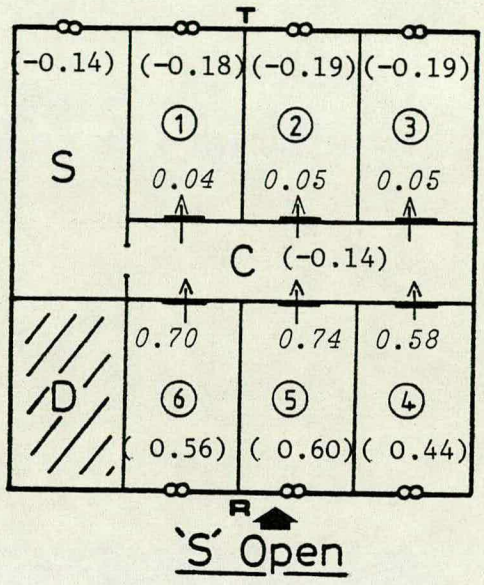
Incidence, α = 180°
Cp_i in ( )

FLOOR 2

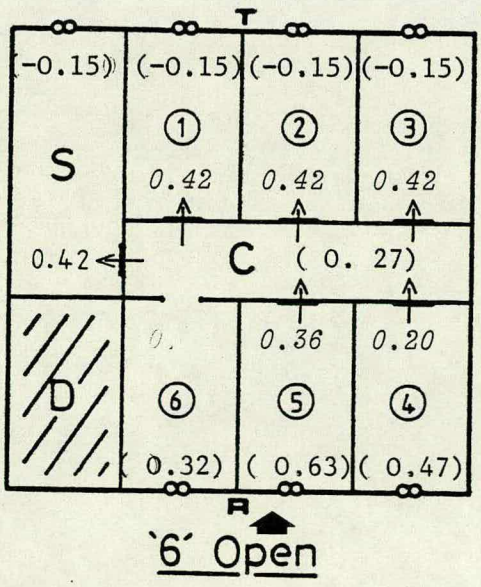
T	D	R
1.5	1.5	1.5



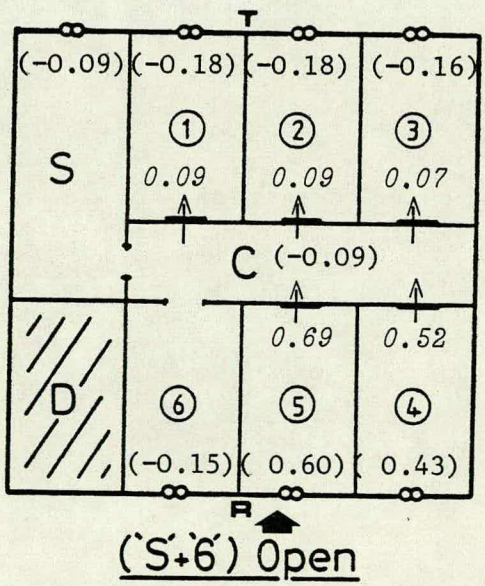
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.7.2: Wind Induced Pressure Distribution, α = 180°

Incidence, α = 180°
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

FLOOR 4

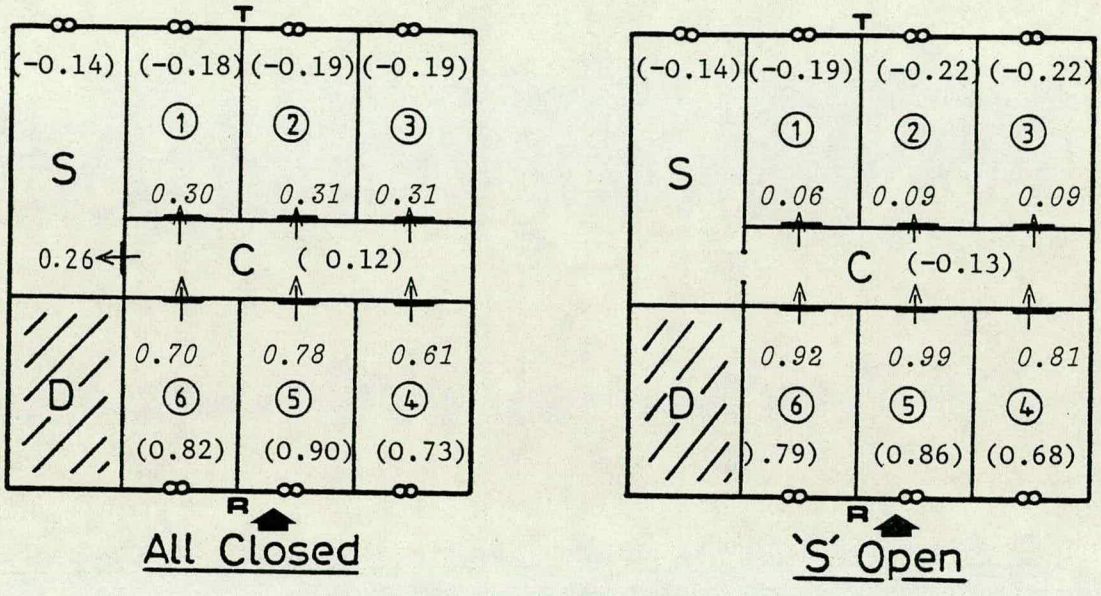


Fig 3.7.3: Wind Induced Pressure Distribution, α = 180°

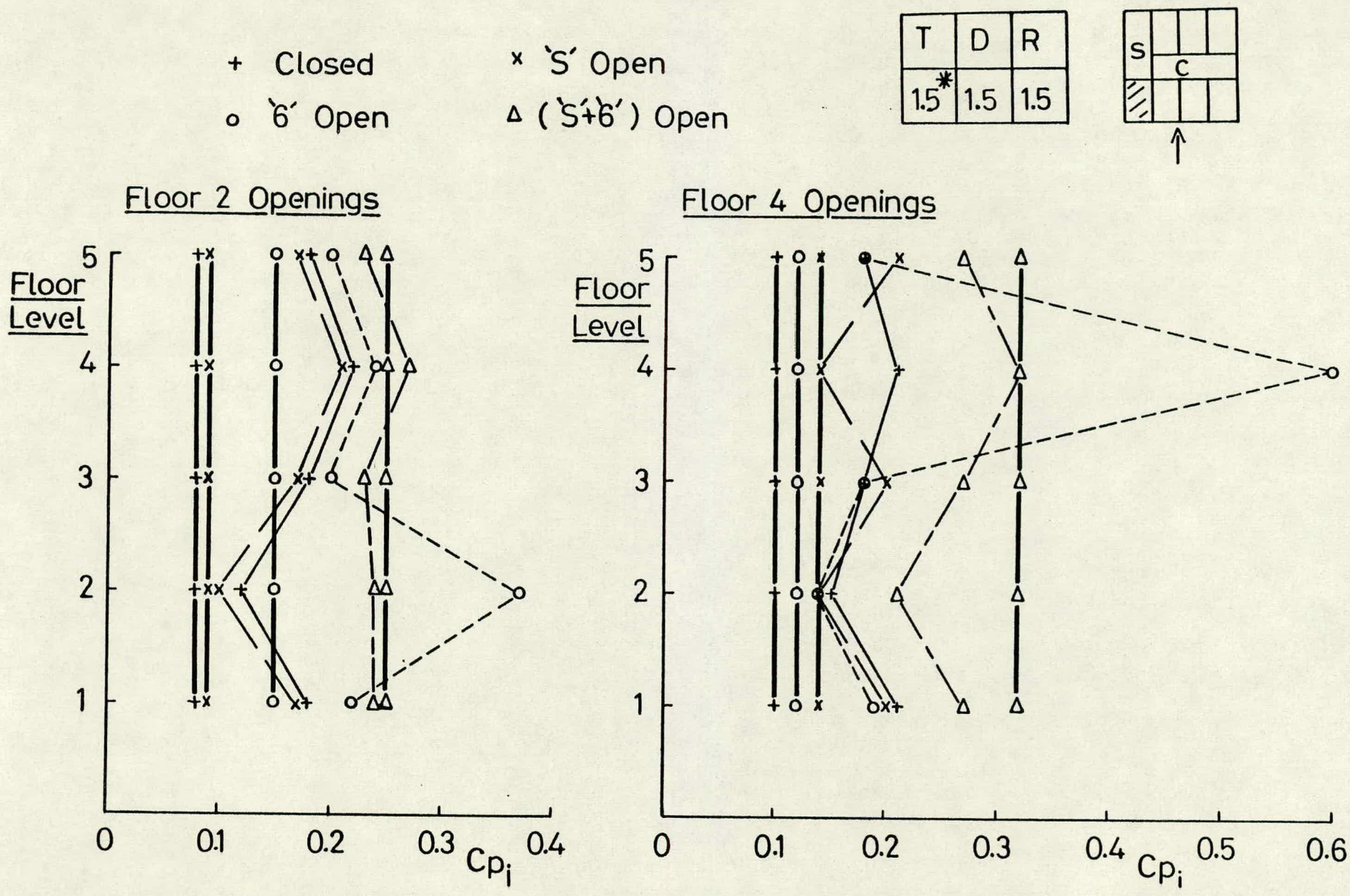
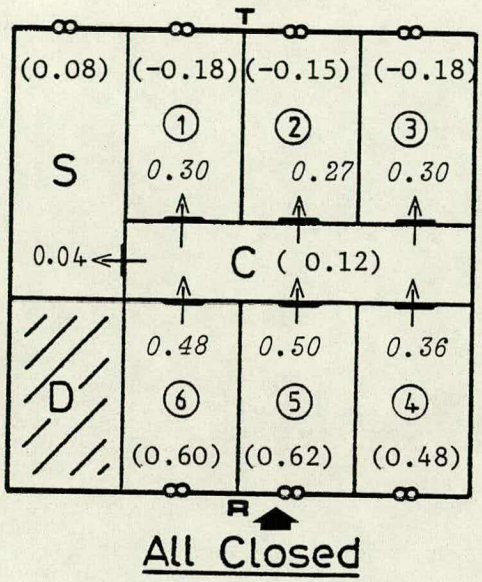


Fig 3.7.4: Shaft and Corridor Wind Induced Pressures (Cp_i) $\alpha = 180^{o}$, Leakage (b).

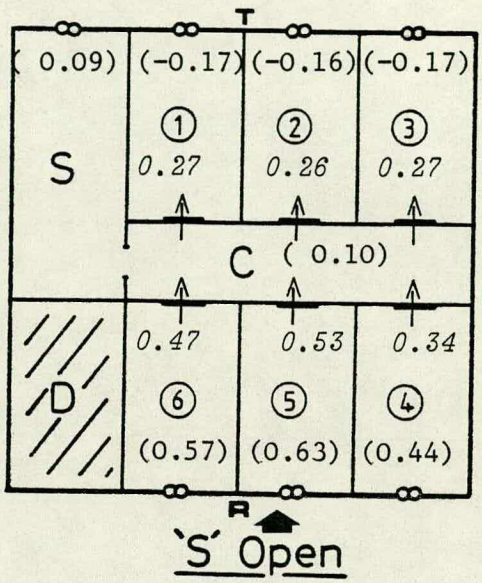
Incidence , α = 180°
Cp_i in ( )

FLOOR 2

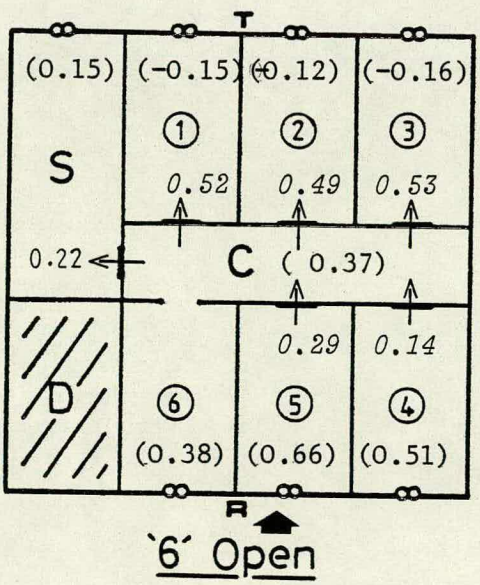
T	D	R
1.5*	1.5	1.5



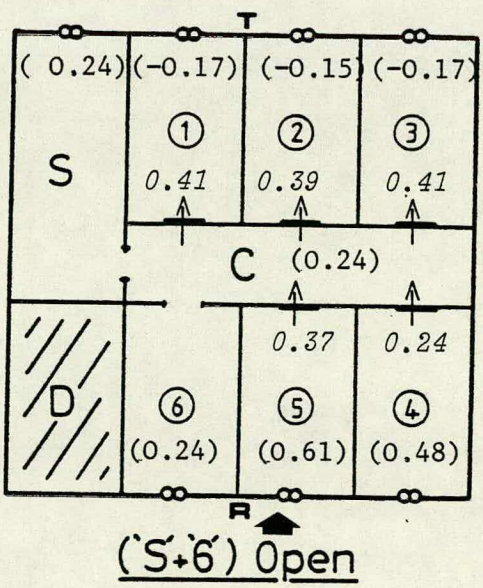
All Closed



'S' Open



'6' Open



('S'+'6') Open

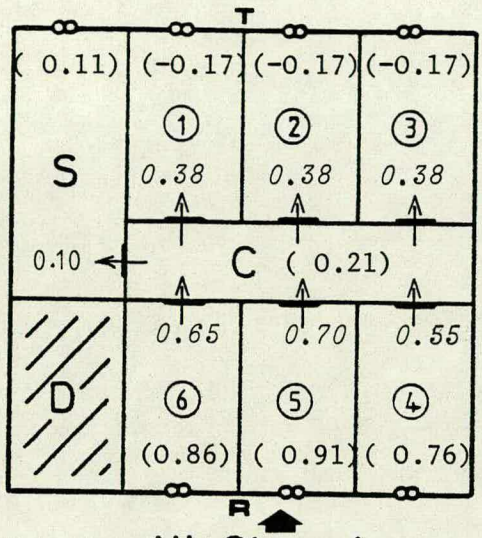
Fig 3.7.5: Wind Induced Pressure Distribution, α = 180°

Incidence , α = 180°

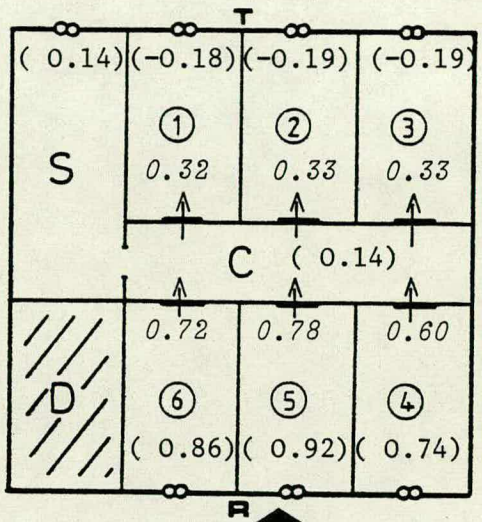
Cp_i in ( )

T	D	R
1.5*	1.5	1.5

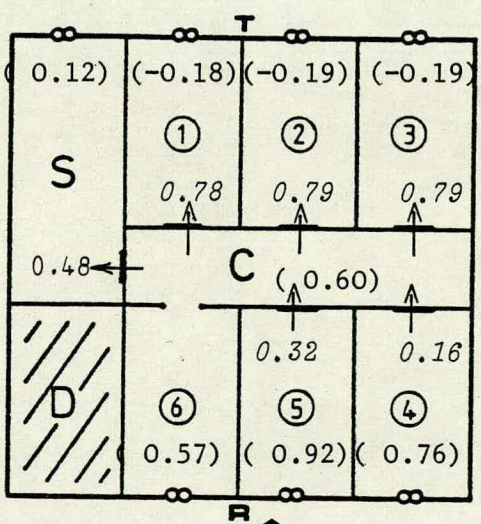
FLOOR 4



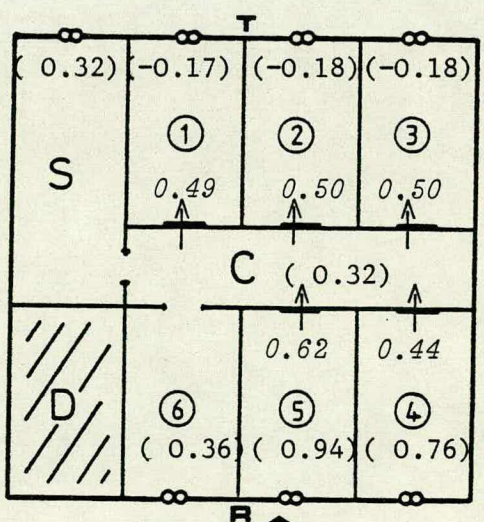
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.7.6: Wind Induced Pressure Distribution, α = 180°

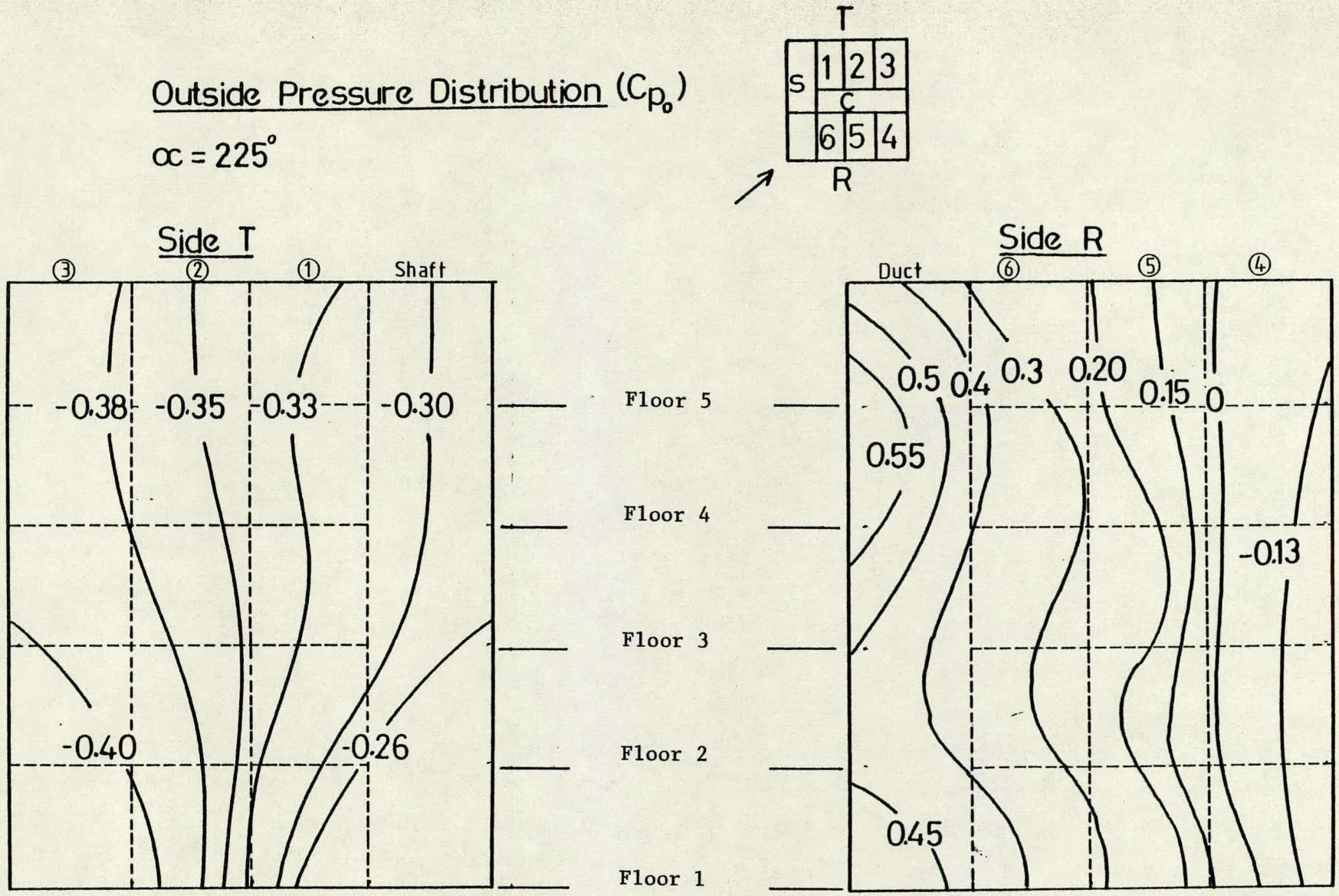


Fig 3.8: Outside pressure distribution (Cp_o), $\alpha = 225^o$.

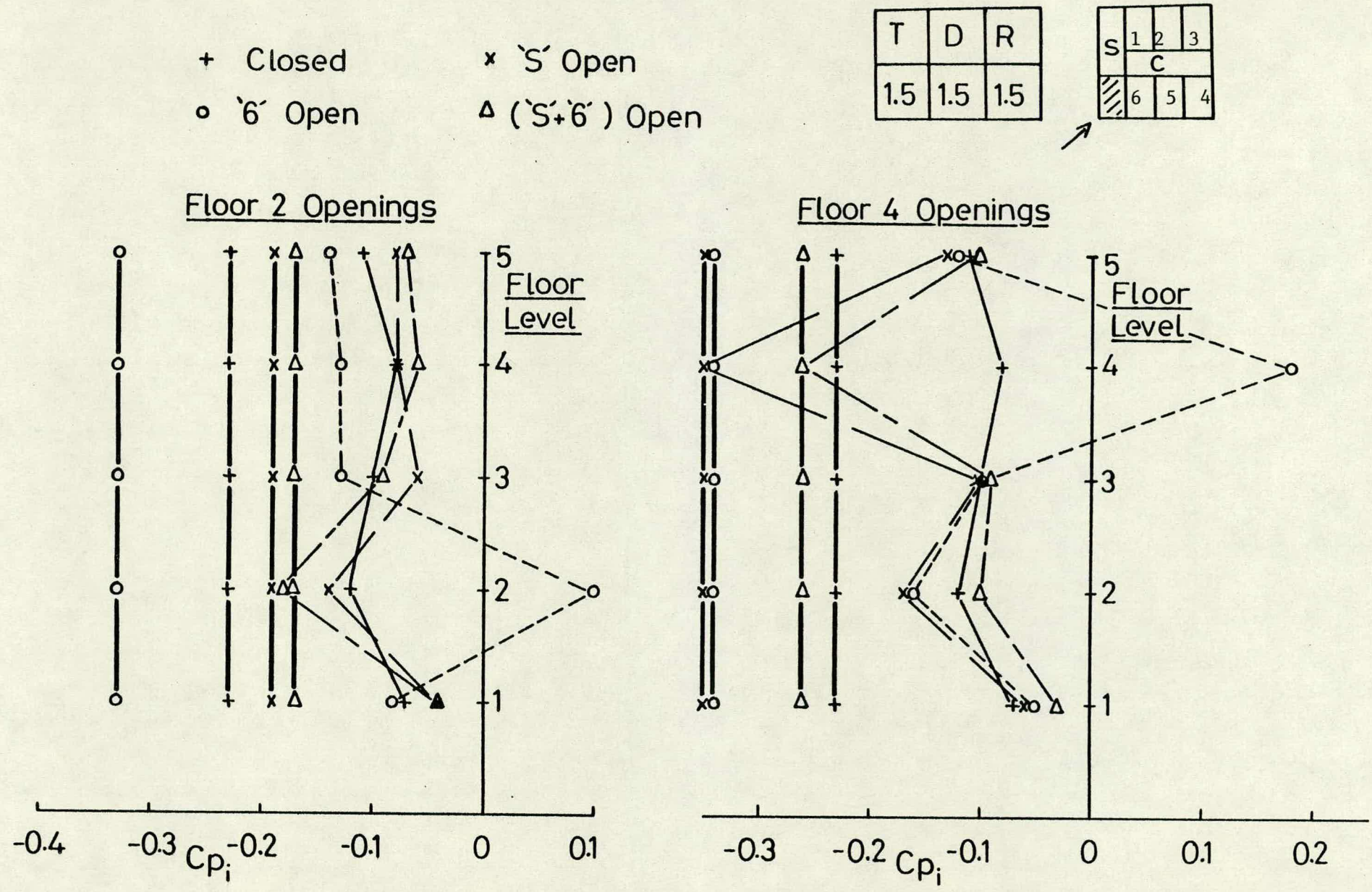


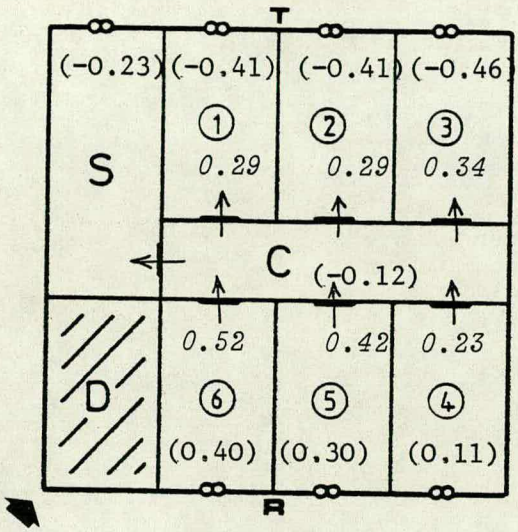
Fig 3.8.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 225^{o}$, Leakage (a).

Incidence, α = 225°

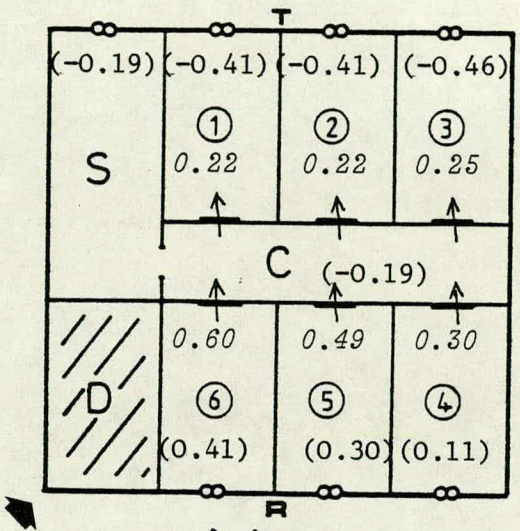
Cp_i in ( )

T	D	R
1.5	1.5	1.5

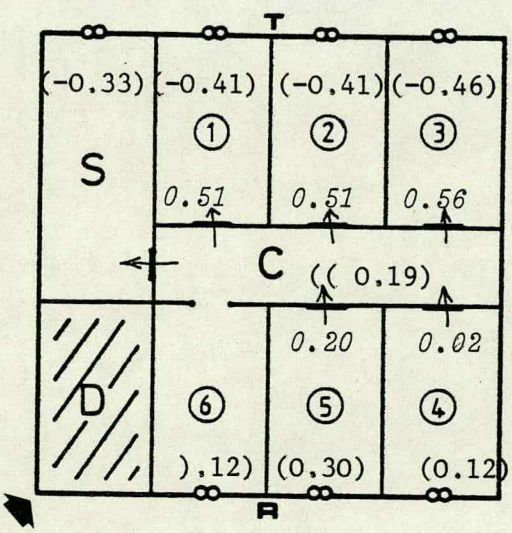
FLOOR 2



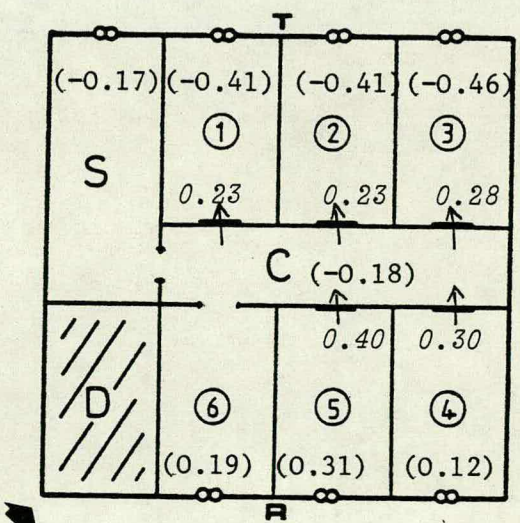
All Closed



'S' Open



'6' Open



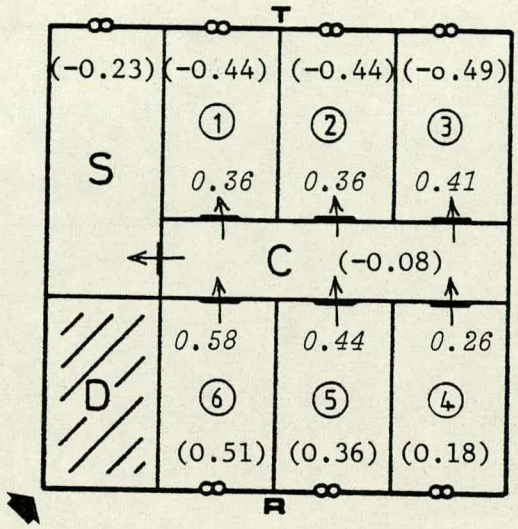
('S'+'6') Open

Fig 3.8.2: Wind Induced Pressure Distribution, α = 225°

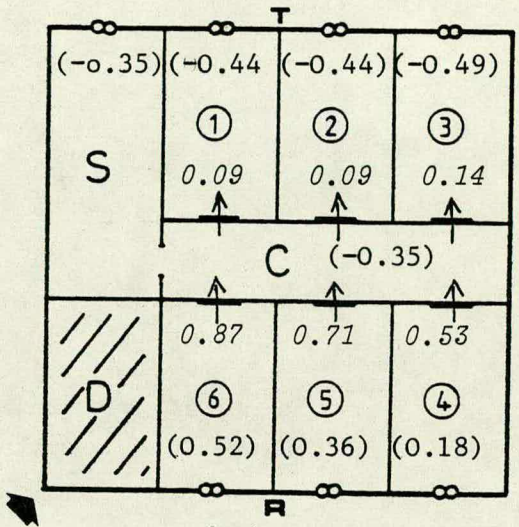
Incidence, α = 225°
Cp_i in ( )

FLOOR 4

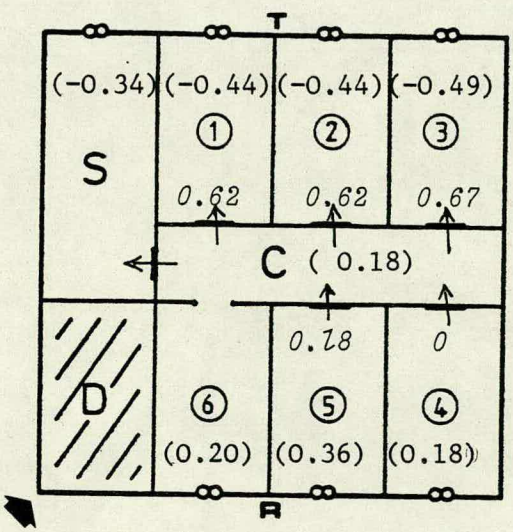
T	D	R
1.5	1.5	1.5



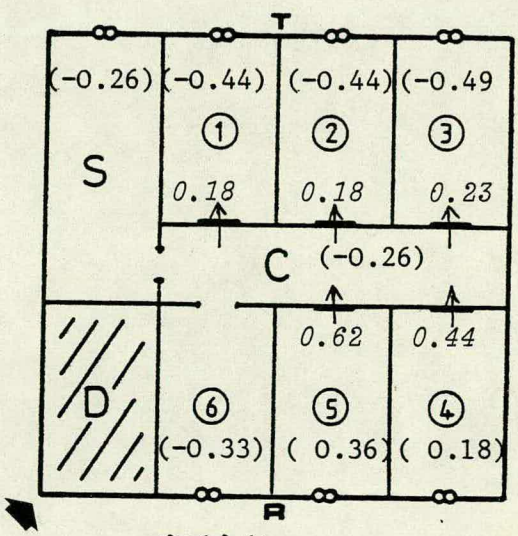
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.8.3: Wind Induced Pressure Distribution, α = 225°

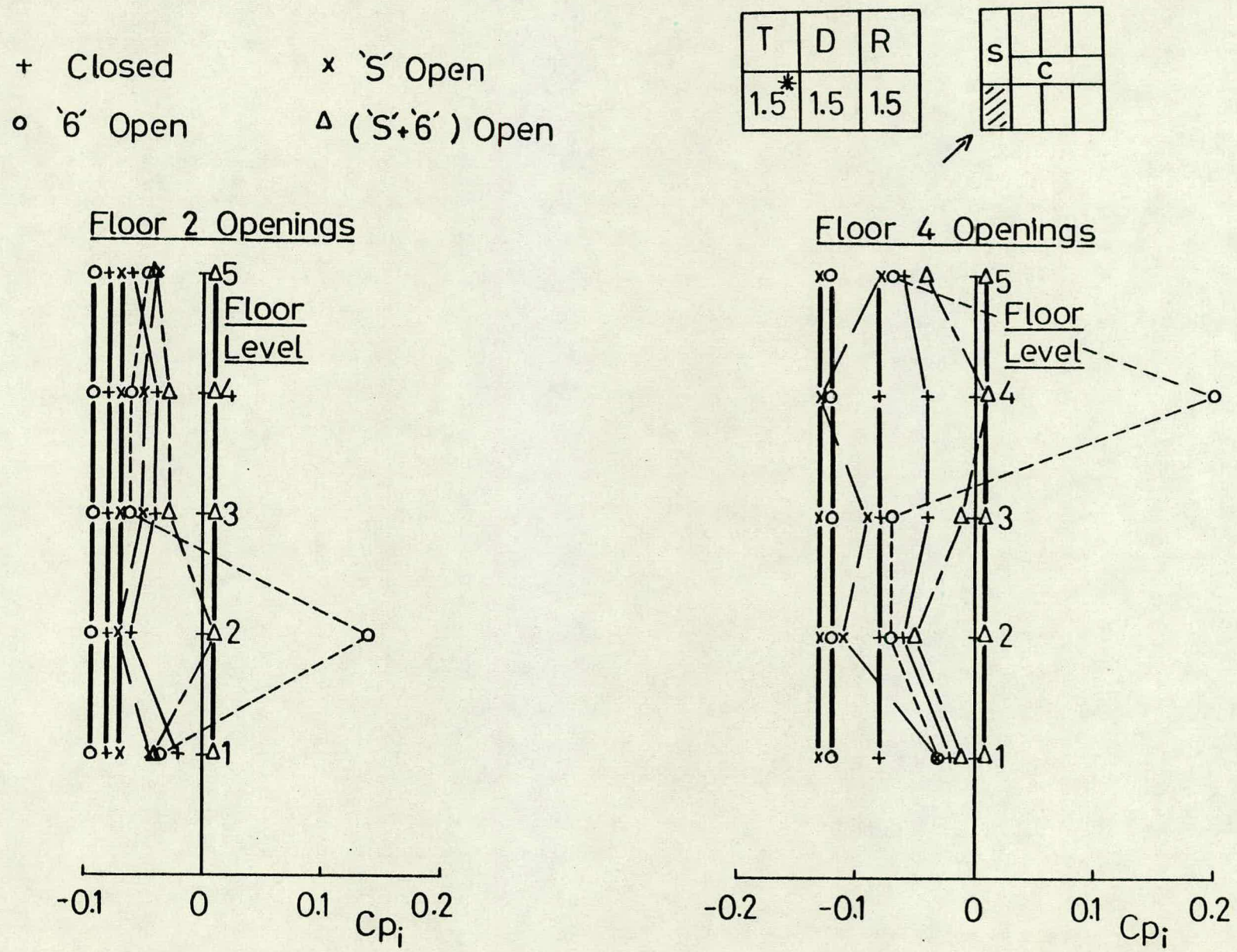


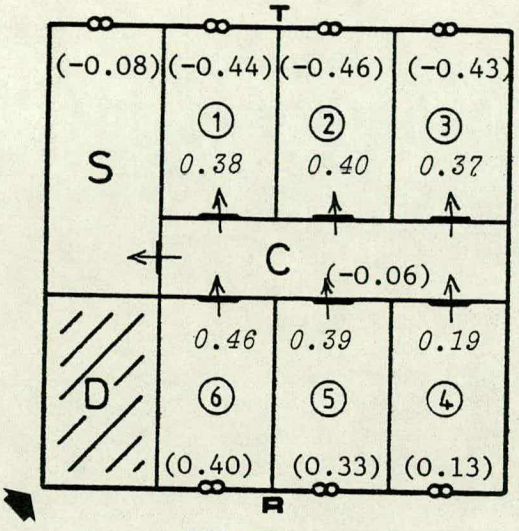
Fig 3.8.4: Shaft and Corridor Wind Induced Pressures, $\alpha=225^{o}$, Leakage (b)

Incidence, α = 224°

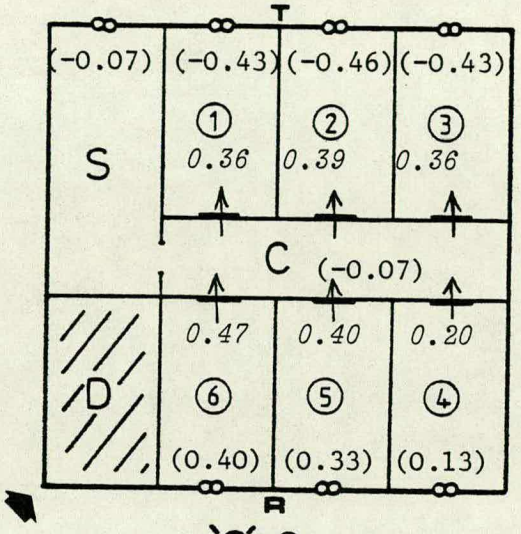
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

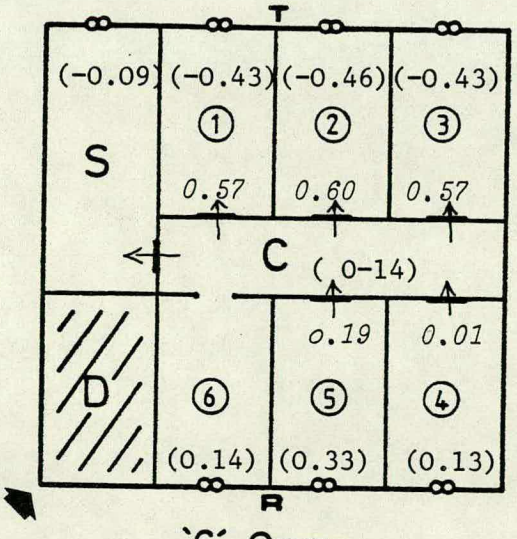
FLOOR 2



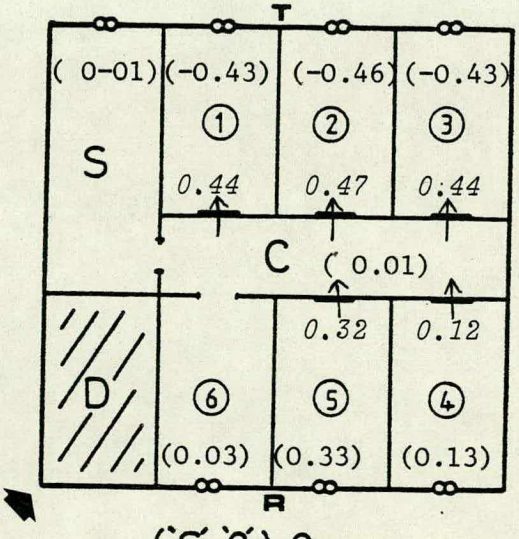
All Closed



'S' Open



'6' Open



('S'+'6') Open

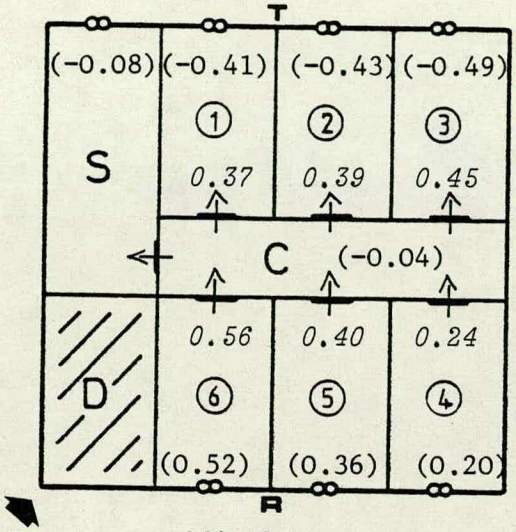
Fig 3.8.5: Wind Induced Pressure Distribution, α = 224°

Incidence, α = 225°

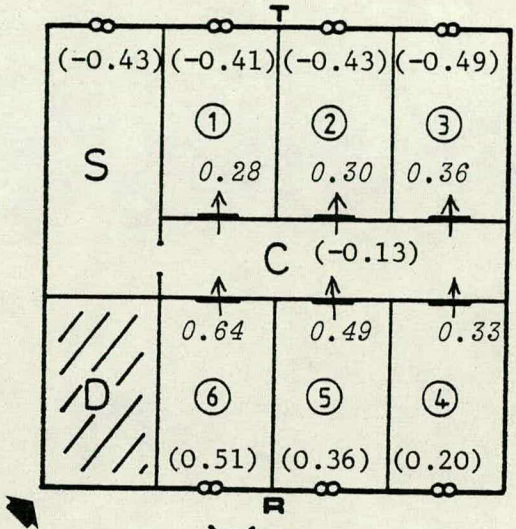
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

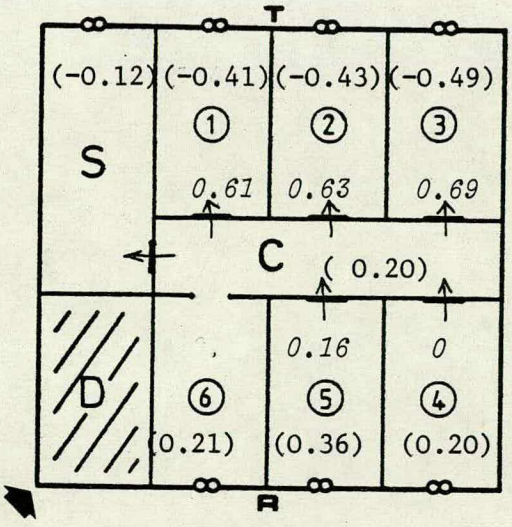
FLOOR 4



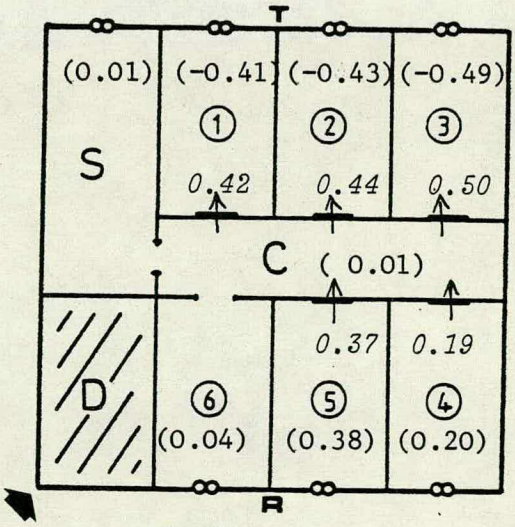
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.8.6: Wind Induced Pressure Distribution, α = 225°

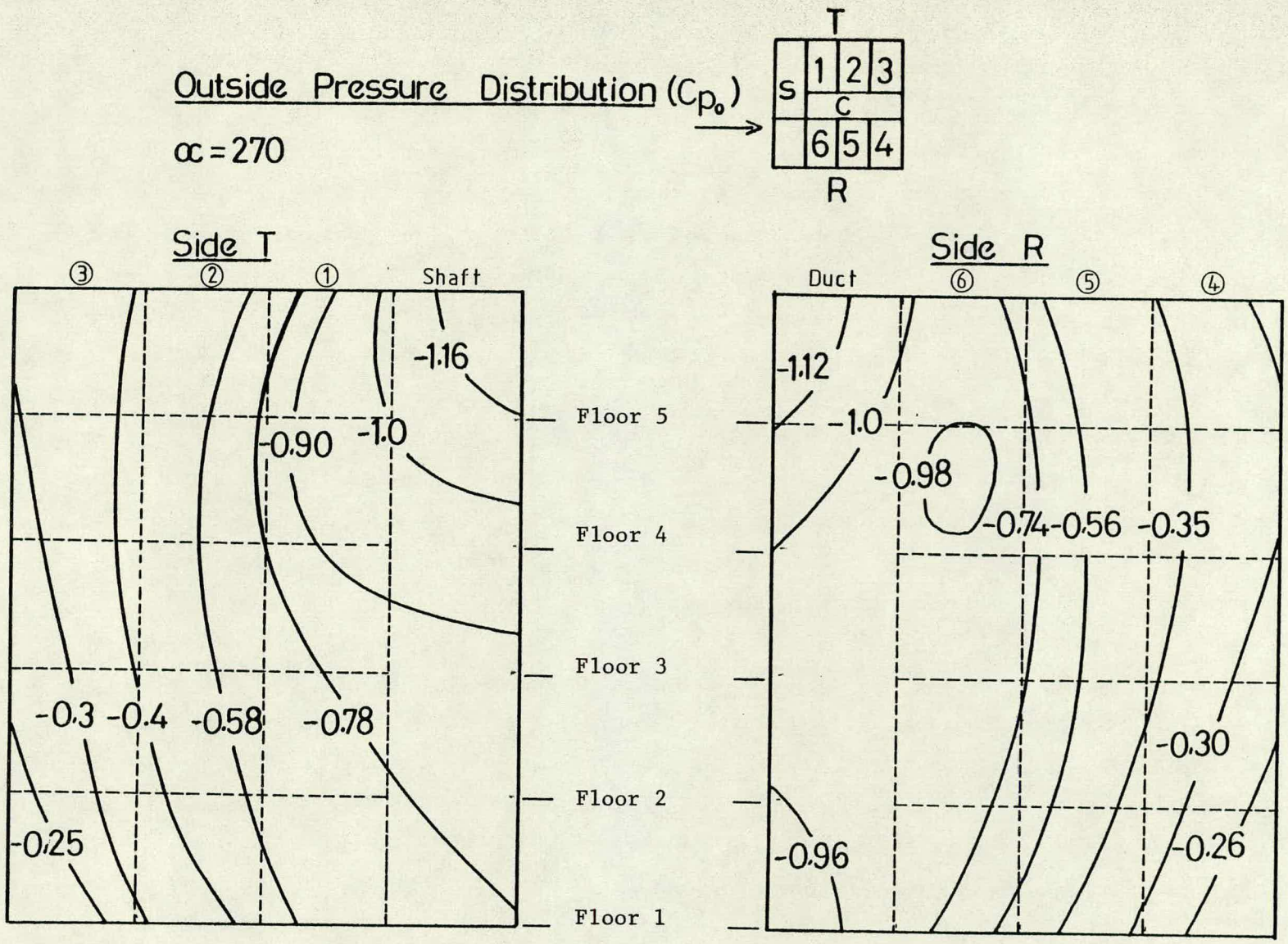


Fig 3.9: Outside pressure distribution (Cp_o), $\alpha = 270^o$

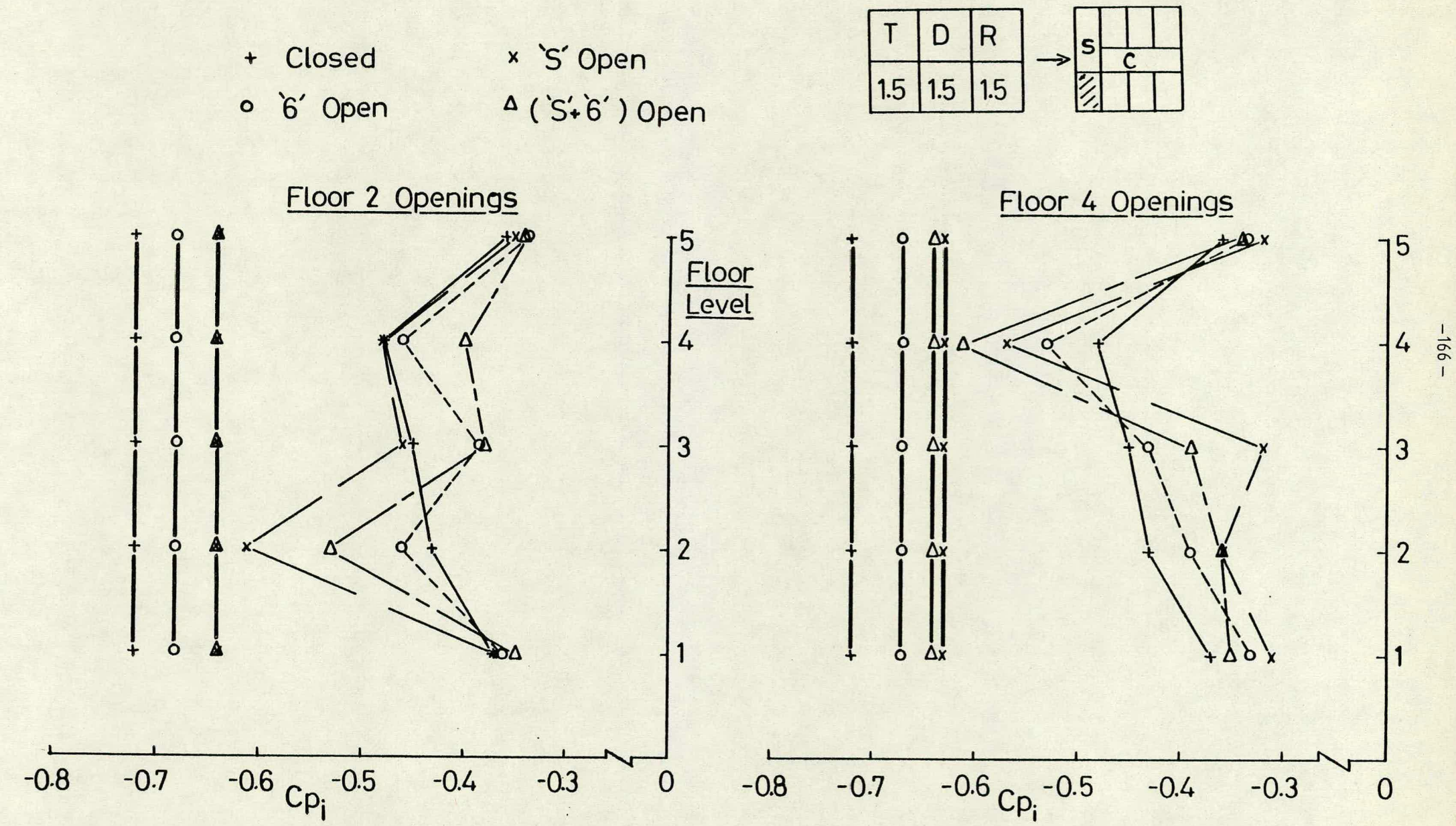
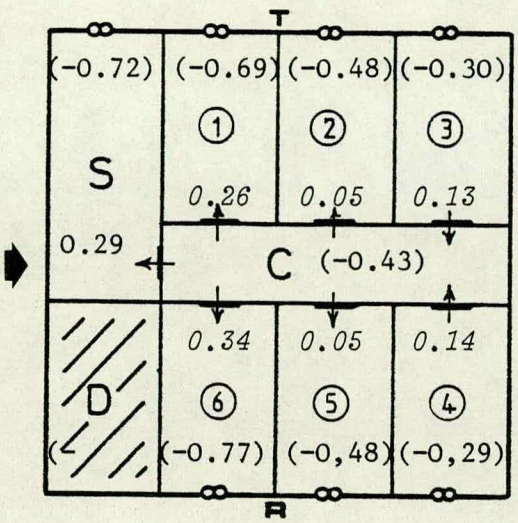


Fig 3.9.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 0^{o}$, Leakage ( ).

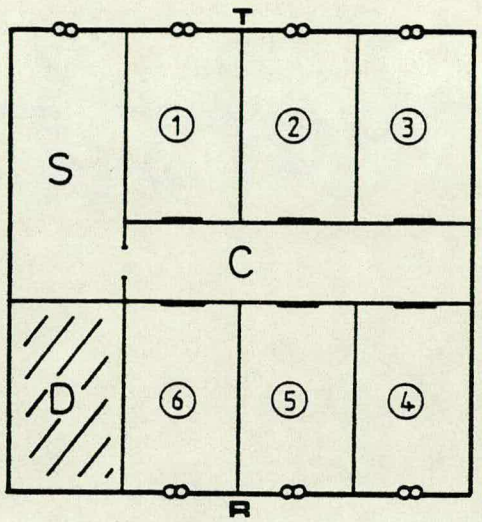
Incidence , α = 270°
Cp_i in ( )

T	D	R
1.5	1.5	1.5

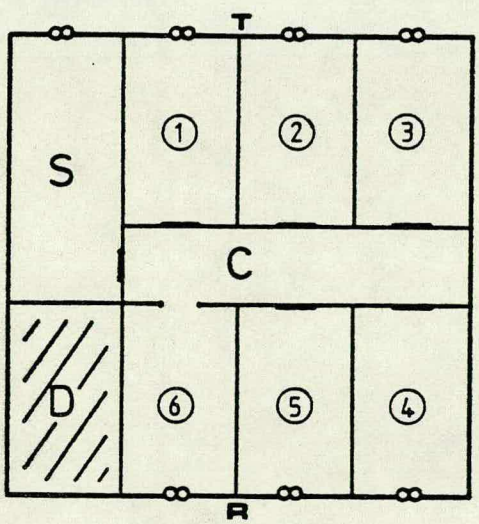
FLOOR 2



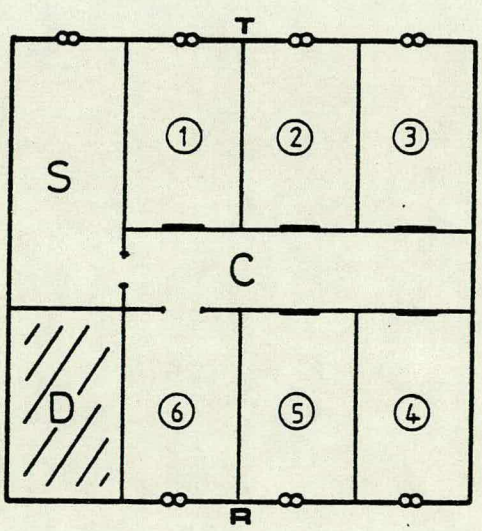
All Closed



'S' Open



'6' Open



('S'+'6') Open

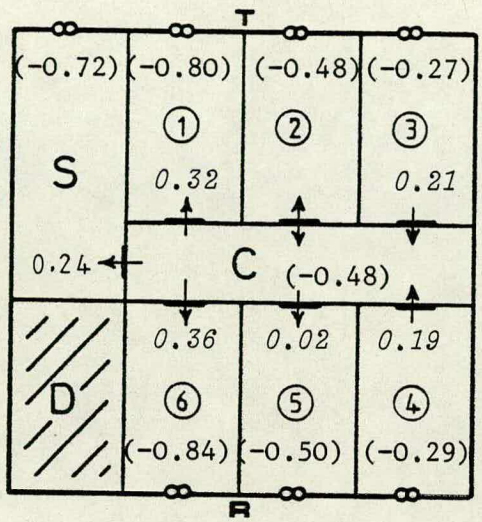
Fig 3.9.2 Wind Induced Pressure Distribution, α = 270°

Incidence, α = 270°

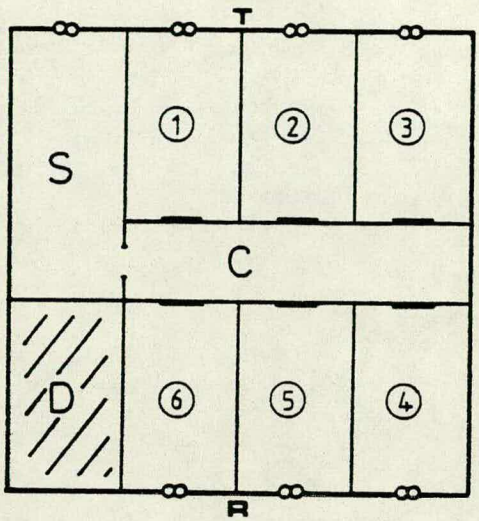
C_{pi} in ( )

T	D	R
1.5	1.5	1.5

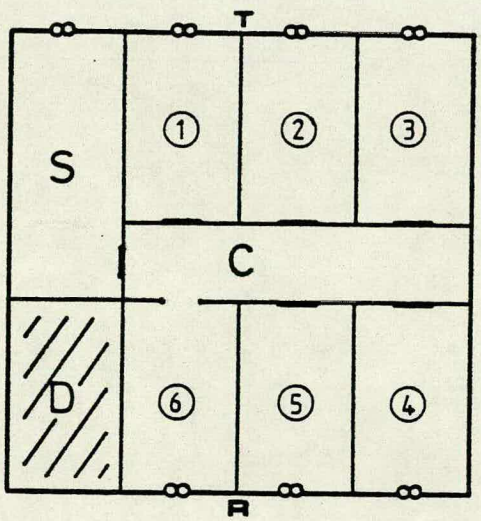
FLOOR 4



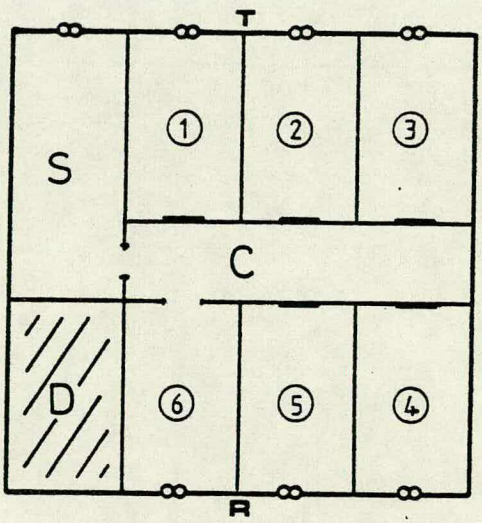
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.9.3: Wind Induced Pressure Distribution, α = 270°

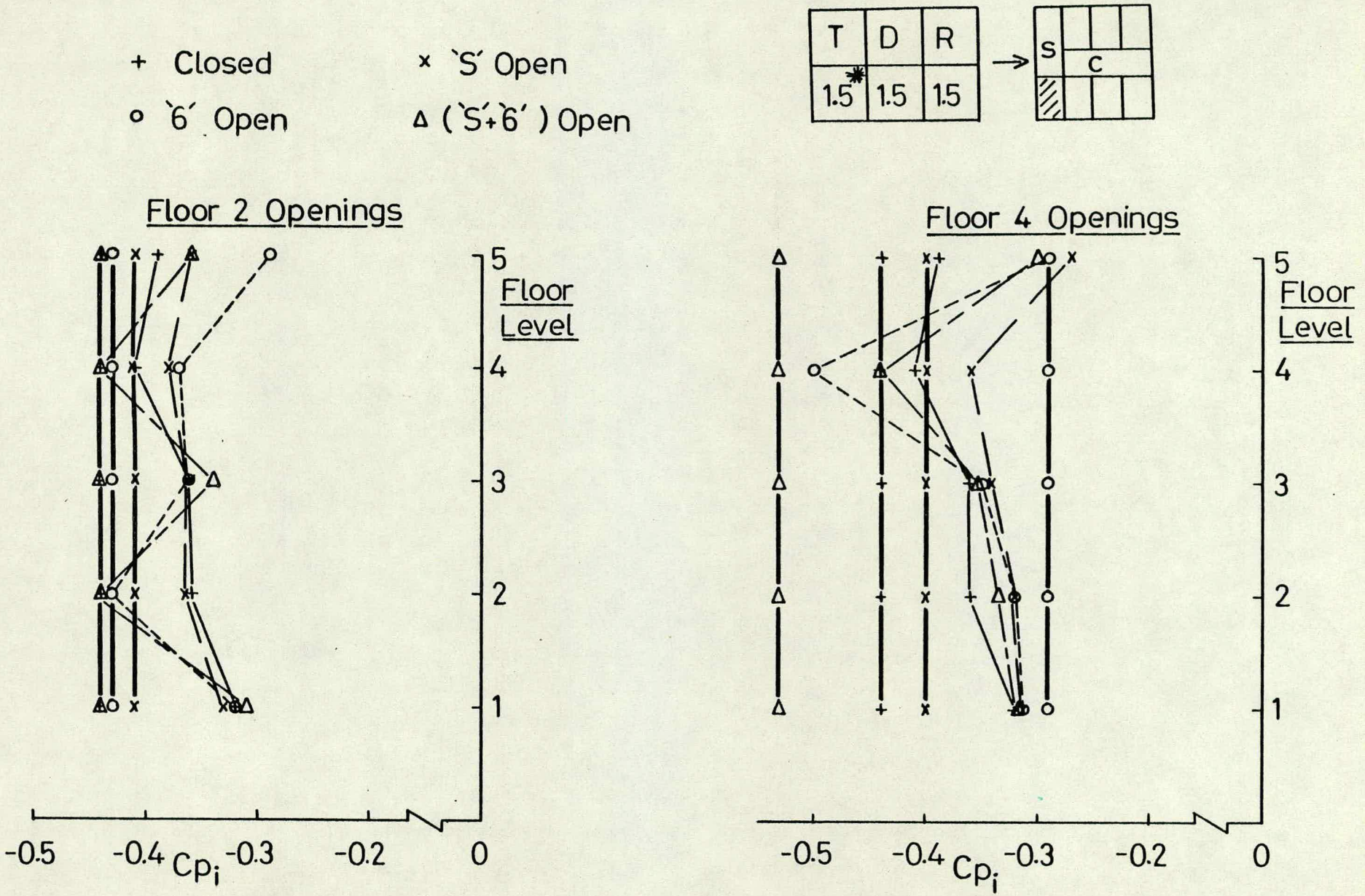


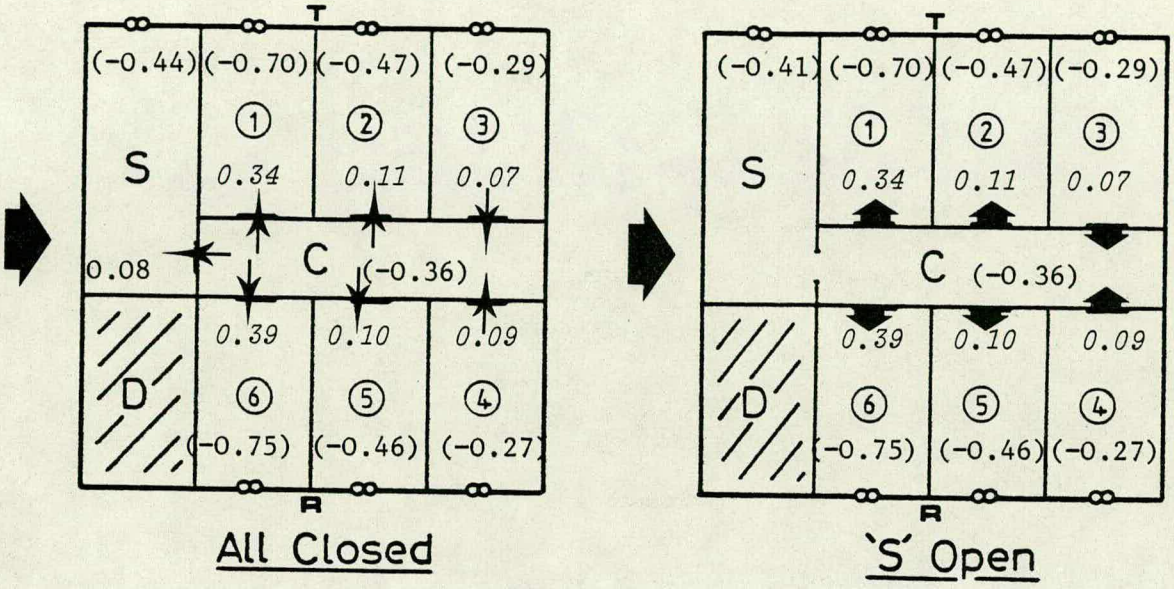
Fig 3.9.4: Shaft and Corridor Wind Induced Pressures, $\alpha = 0^{o}$, Leakage ( ).

Incidence, α = 270°

C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

FLOOR 2



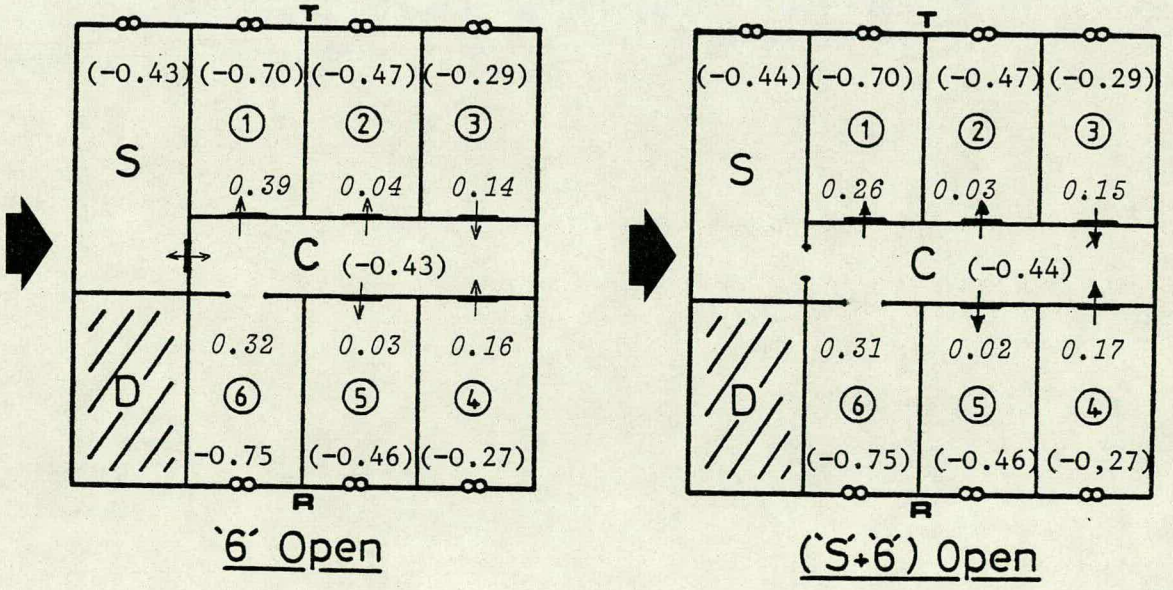


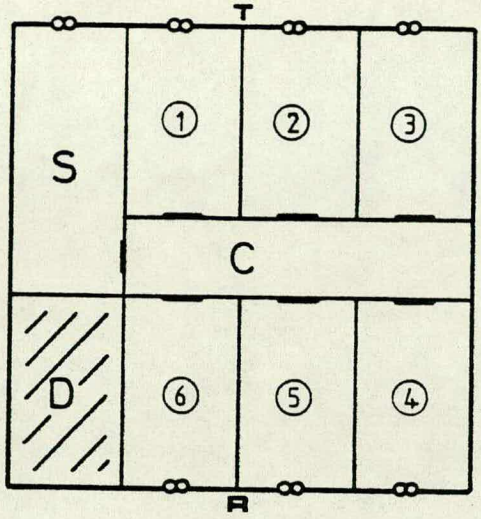
Fig 3.9.5: Wind Induced Pressure Distribution, α = 270°

Incidence , α = 270°

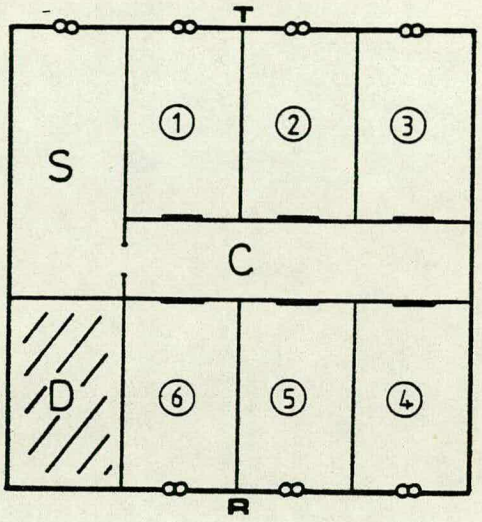
C_{p_i} in ( )

FLOOR 4

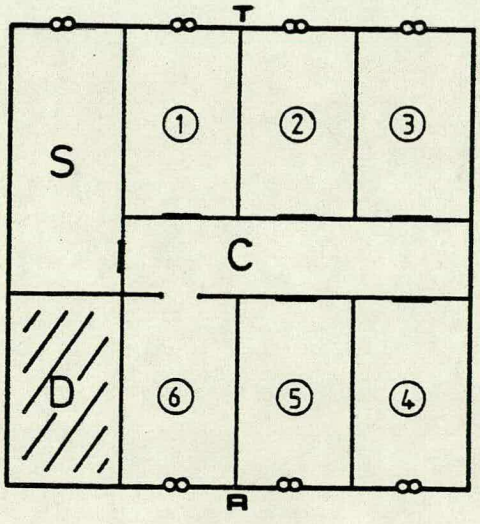
T	D	R
1.5*	1.5	1.5



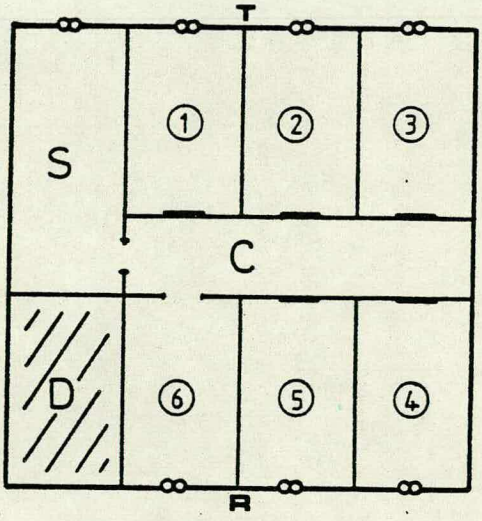
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 3.9.6: Wind Induced Pressure Distribution, α = 270°

CHAPTER FOUR, VOL II

THE EFFECT OF A PROBABLE FIRE PRESSURE IN A ROOM ON INTERNAL PRESSURES

CHAPTER 4, Volume II

THE EFFECT OF A PROBABLE FIRE PRESSURE IN A ROOM ON INTERNAL PRESSURES

4.0

The wind induced pressure measurements for various rooms, shaft and the corridors have been discussed in the previous chapter for seven different outside wind directions. From this discussion it became clear that the internal pressures varied considerably with the wind direction. The results also showed that under certain building leakage configurations and under certain wind conditions the wind induced pressure differences across room and shaft doors were so small that they could easily be altered by a small change in the thermal equilibrium of the kbuilding. Under such conditions the internal flow pattern can change significantly. A fire, since it accompanies very high temperatures, can be a source of that thermal inequilibrium. It was therefore filt necessary to repeat the measurements, this time taking into account the effect of probably fire.

Various experimental studies on the nature of fire show that a fire in a room under calm conditions creates a pressure difference of about $10N/m^2$ at the top of the door. See also Chapter 4 Volume I. Accordingly, fire in the model was simulated by creating such a pressure difference.

A discussion of the results obtained follos, which are compared with the results with such a fire pressure.

4.1 Discussion of Results:

The measurements of Chapter 3 were repeated with a fire pressure in room ⑥ on floors 2 and 4. The results are discussed for one wind direction only.

4.1.1 Wind Incidence, $\alpha=0^{o}$

The outside pressure distribution on sides T and R is discussed in chapter 3. The present discussion is only confined to the internal pressures.

Floor 2: Leakage (a)

When there is no fire pressure in room ⑥, the pressure inside the room is dominated by the prevailing outside wind induced pressure on side R. In this case since corridor pressure is higher than the room pressure, flow of air results into the room.

The introduced fire pressure in room ⑥, combines with the wind induced pressure, which may alter the internal flow pattern. Corridor pressure is directly affected by the new pressure in room ⑥. Since the outflow of air through this room from the corridor is reduced, the corridor pressure readjusts itself to increase the rate of flow through rooms ④ and ⑤ doors. It is this new pressure which

determines the direction of flow across room ⑥ door. Comparison of figures 4.1.2 and 3.3.3 show that for leakage (a), the corridor pressure increases to counteract the fire pressure.

When all doors are closed, and since all door leakages are the same, following relationship for the pressure differences hold

$$\sum_{j=1}^{J} k(\Delta Cp_i)^{\frac{1}{2}} + k(\Delta Cp_i)_{sh}^{\frac{1}{2}} = 0 \qquad \ldots 4.1.1$$

where j= room number

J= total number of rooms

k= a constant, depends on the air-density and the leakage area of door.

Substituting the measured pressure difference values (from fig 4.1.2) shows that the above relationship does not quite hold. In fact the calculations show that there is more inflow than outflow in the corridor. This discrepancy is probably due to an experimental error in the corridor pressure measurement. Comparing the pressure masurements for 'no fire' and 'fire' cases show that, the corridor pressure is the same. This is not expected because of the large change in room ⑥ pressure. The corridor pressure must increase the inflow equal to outflow, accordingly the value is most probably Cp_i=0.33. Assuming then, this to be the true corridor pressure value, equation 4.1.1 is satisfied.

These values show that for leakage (a) the wind induced pressure difference across the shaft door is sufficient to confine smoke to the fire floor, and no shaft pressurisation is required in this case. In fact if the pressurisation system switches on the detection of a fire, it might cause an over pressure across shaft doors, making them difficult to open. Such a situation must be avoided.

For Leakage (b), because of the large drop in the shaft pressure, and also the fact that the corridor pressure is increased due to a fire pressure in room ⑥, the shaft pressurisation is necessary to confine smoke to the fire floor. In this case there will be no danger of over pressure because of the reduced wind induced pressure difference across shaft doors on all floors (see fig 4.1.4).

Most of the smoke generated by kthe fire is drawn out of the windows by the prevailing negative pressures on side R. The rate of this outflow depends on the size of window leakage as well as on the pressure difference developed by fire and wind combined. If the window leakage is very small lot more smoke will be forced to flow into the corridor through the door leakage. Under such conditions leakage (b) will cause the smoke to flow into the shaft, if no shaft pressurisation is present.

From fig 4.1.5 it is clear that other room pressures are not influenced by the fire pressure. The room ⑥ pressures are shown in the table below.

Table 4.1.3.: Floor 2, Fire room Cp_i

	Leakage (a)	Leakage (b)
With 'fire'	0.32	0.32
Without 'fire'	-0.15	-0.18

The effect of Open Doors:

Shaft and corridor pressures go through very small changes due to the opening of shaft door ('s' open). For leakage (a) the shaft pressure is still higher than that of the corridor (fig 4.1.2) and no change in flow direction results. Higher corridor pressure confines smoke to the fire room. In the case of Leakage (b) the opening of the shaft door reduces the corridor pressure slightly, which results in an increased flow rate from the fire room into the corridor.

When room ⑥ door is opened ('6' open) the rate of flow of smoke into the corridor increases dramatically and the corridor pressure drops slightly (see fig 4.1.2). This causes an increase in pressure difference across the shaft door confining smoke to the fire floor. In the case of leakage (b) the measurements shown (fig 4.1.5) that the the shaft pressure is higher than that of the corridor when room ⑥ door is opened. But this difference is very small and requires shaft pressurisation to ensure smoke free shaft.

The opening of shaft and corridor doors together ('s' + '6' open) is most dangerous from the smoke spread point of view as it connects the shaft directly to the fire room. The results in figures 4.1.2 and 4.1.5 show the tendency for the smoke to flow into the shaft. For this door opening configuration shaft pressurisation is required for both leakages (a) and (b).

Floor 4

Considering the corridor as a 'control volume' on this floor, the equality of inflow and outflow can be shown by applying equation 4.1.1 for the 'All doors-closed' case.

The measured results are shown in fig 4.1.3. It shows that since the wind induced pressures are high, the shaft door pressure difference is low, compared with that on floor 2.

ΔCp_i (shaft) = 0.20 Floor 2

ΔCp_i (shaft) = 0.06 Floor 4

It is due to this higher wind induced pressure that the flow direction across the fire room ⑥ door is reversed. It is because of this that the reduced pressure difference across the shaft door does not present any problems.

The opening of doors on this floor has similar effects as on floor 2, but with reduced pressure differences.

Leakage Configuration (b)

The corridor and shaft pressure measurements are shown in fig 4.1.4. It shows that the pressures are reduced considerably due to the reduction in shaft leakage (compare with fig 4.1.1). The pressure difference across the shaft door is also reduced.

Floor 2

The pressure measurements with the fire pressure in room ⑥ are shown in fig 4.1.5. It shows that because of the reduced pressure, the flow direction across the shaft door is easily influenced by the fire pressure. The smoke flowing into the corridor also finds its way into the shaft. It is for this reason that the shaft pressurisation is required. From the measurements it is clear that the presurising fan has only to over come very small opposing pressure, if all doors are closed.

The inflow and outflow cna be calculated for the corridor by applying equation 4.1.1.

The Effect of Door Openings:

Because the presskure difference across the shaft door is very sensitive to the changes in corridor pressure, the opening of doors can influence the flow direction across the shaft door greately.

The opening of shaft door does not have much effect as the pressures in the shaft and corridors, are the same when this door is closed. The results shown in fig 4.1.5 ('s'open) contain some experimental error.

When the fire room ⑥ door is opened, the corridor pressure drops, even though there is a lot more smoke flowing into the corridor. This drop in pressure reverses the flow across the shaft door, confining smoke to the fire floor. If rooms ④ and ⑤ doors are opened, most of the smoke can be taken out of these rooms. Therefore no shaft pressurisation will be required.

When the shaft and rooom ⑥ doors are opened together, the shaft becomes directly connected with the fire room. This must be avoided as higher shaft pressures will be required to keep it smoke free.

Floor 4

The results for this floor are shown in fig 4.1.6. Higher corridor pressures increases the flow into the shaft. Shaft pressurisation will be required. The infiltration rates can be calculated from the pressure measurements using equation 4.1.1.

The effect of opening the doors is similar to that on floor 2, except when fire room door is opened. In this case because of the higher corridor pressure, the flow into the shaft persists

Conclusions:

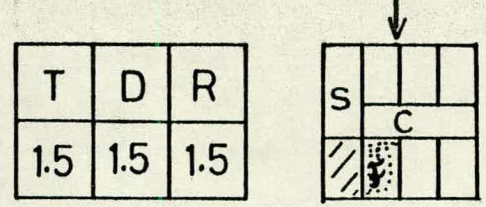
It is clear from these measurements that the fire pressure can have considerable effect on the corridor and shaft pressures. When designing a shaft pressurisation system this kind of study is essential.

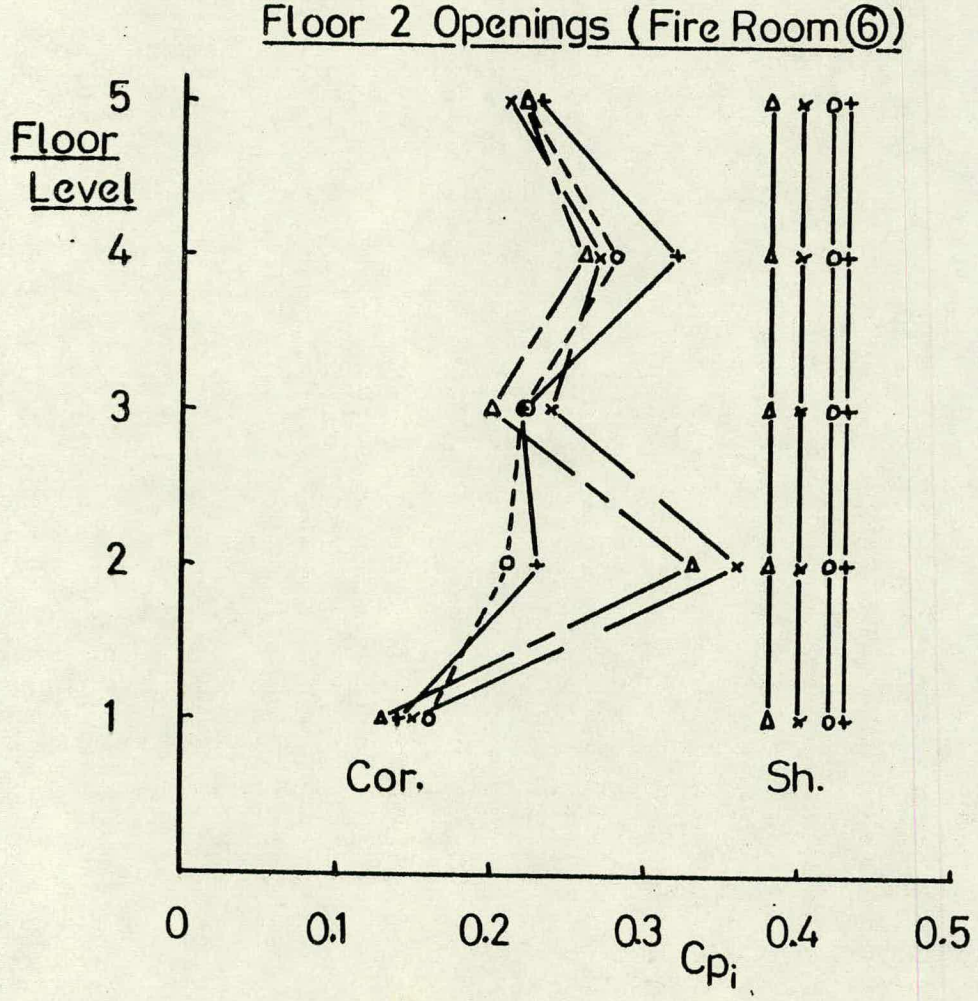
The similar results for other wind angles are given in figs 4.2.1 - 4.7.6. Because of the limitations of space and time they are not discussed here in detail. The main conclusions are summarised in Volume I (chapter 4).

Shaft and Corridor Pressure Distribution

$\alpha = 0$ + Closed × 'S' Open

o '6' Open Δ ('S'+'6') Open





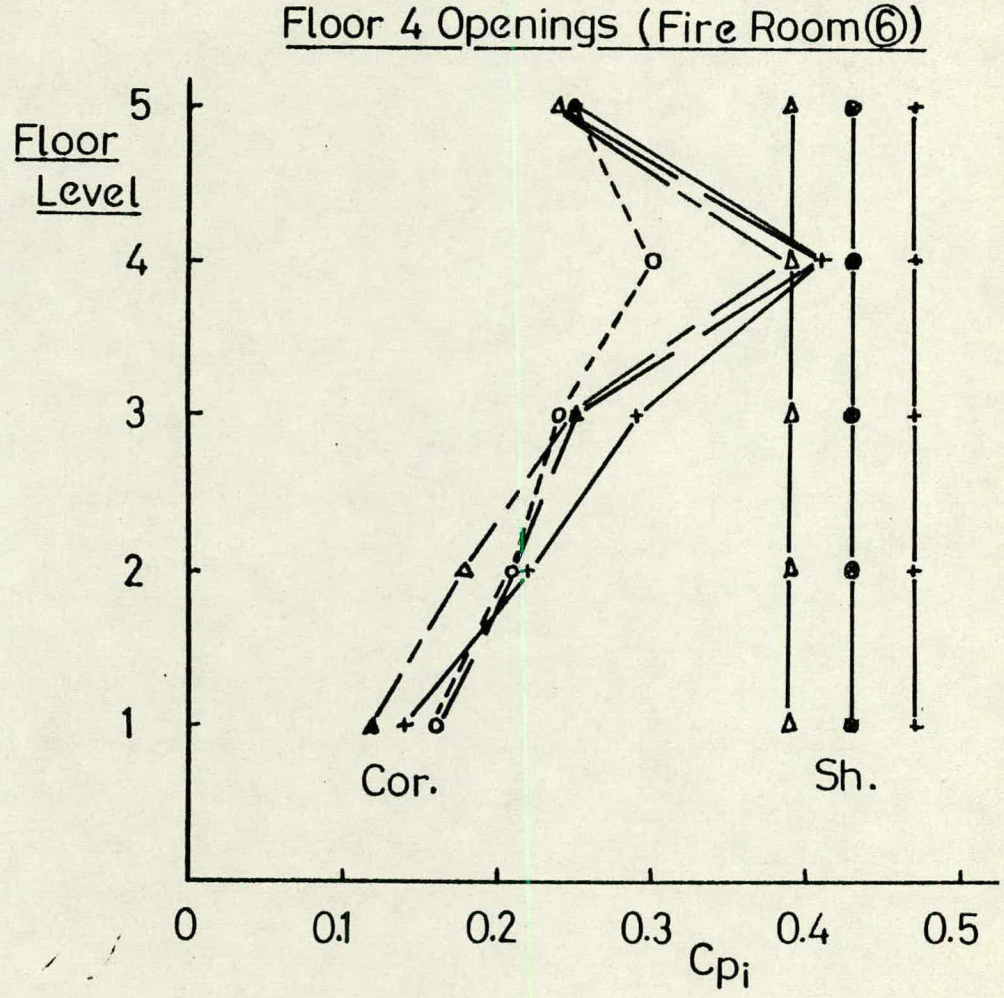
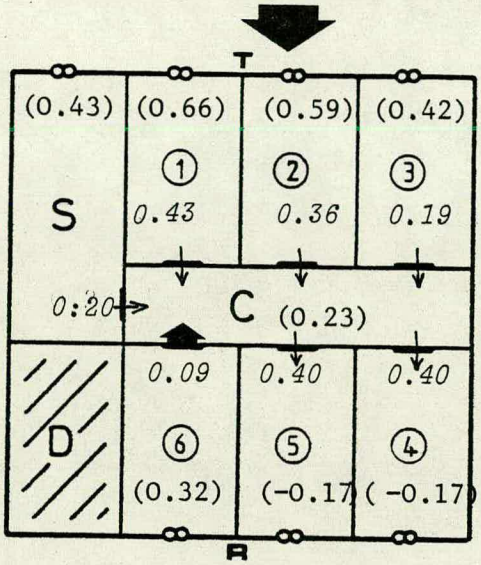


Fig 4.1.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 0^{o}$, Leakage (a), with 'Fire'.

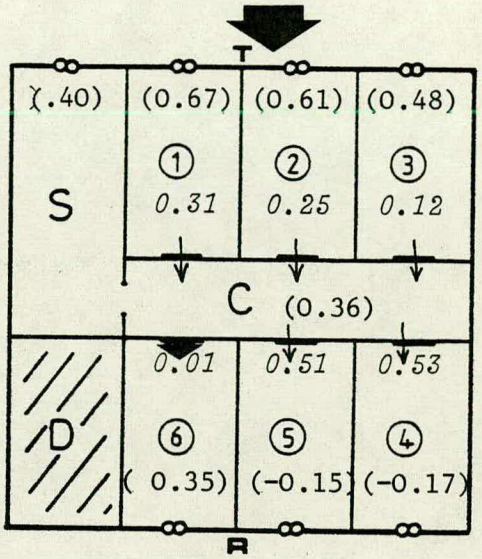
Incidence, α = 0°
Cp_i in ( )

T	D	R
1.5	1.5	1.5

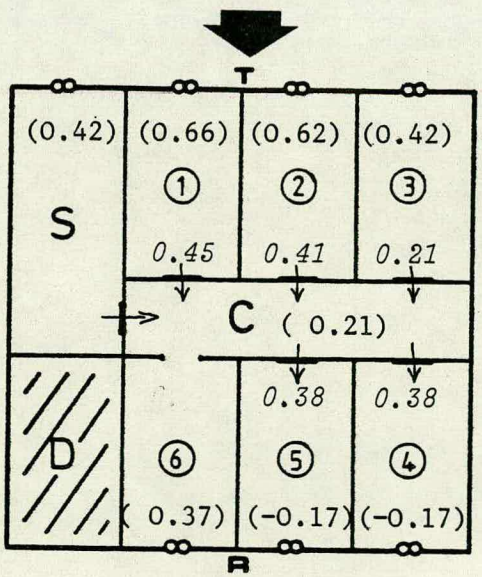
FLOOR 2 (Fire Room ⑥)



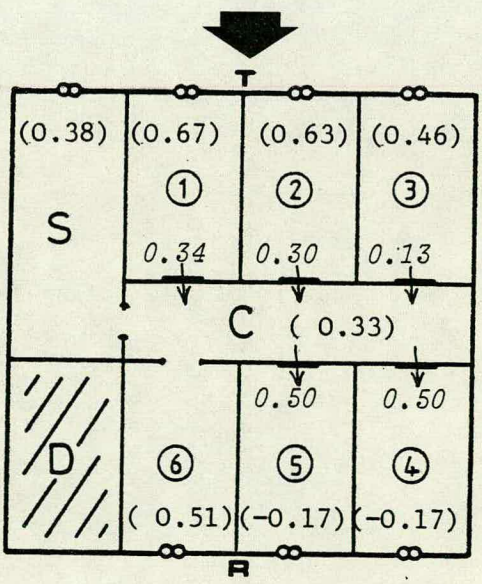
All Closed



'S' Open



'6' Open



('S'+'6') Open

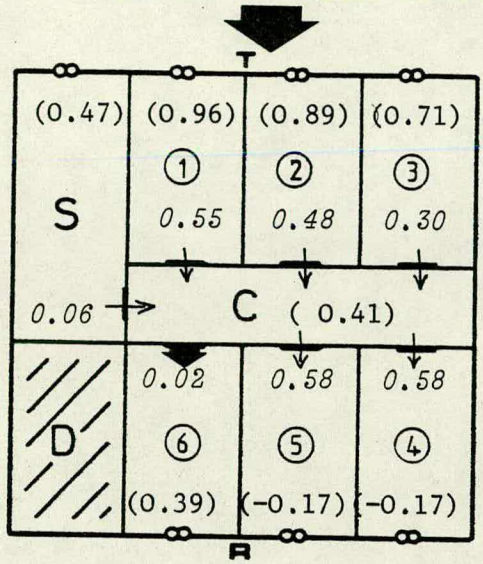
Fig 4.1.2: Wind Induced Pressure Distribution, α = 0°

Incidence, α = 0°

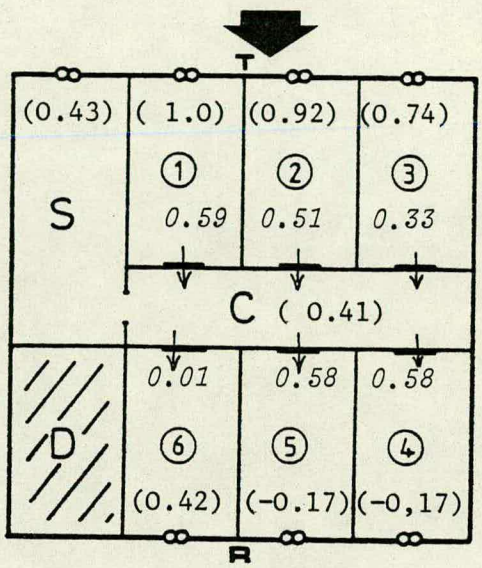
Cp_i in ( )

T	D	R
1.5	1.5	1.5

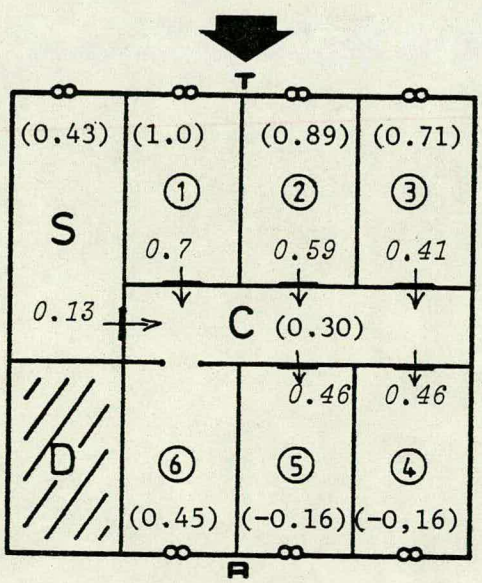
FLOOR 4 (Fire Room ⑥)



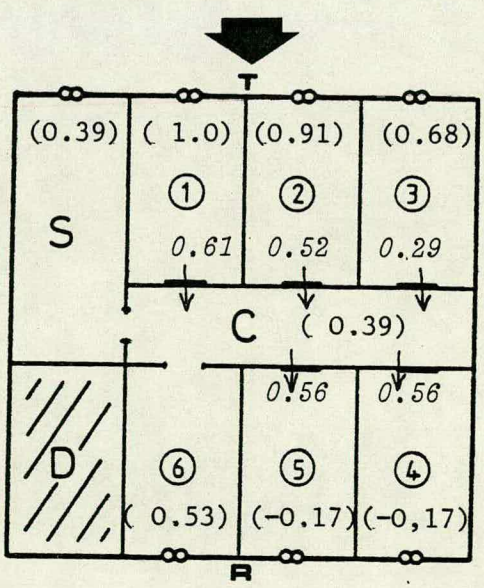
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.1.3: Wind Induced Pressure Distribution, α = 0°

Shaft and Corridor Pressure Distribution

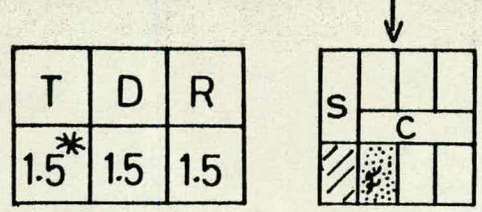
$\alpha = 0$

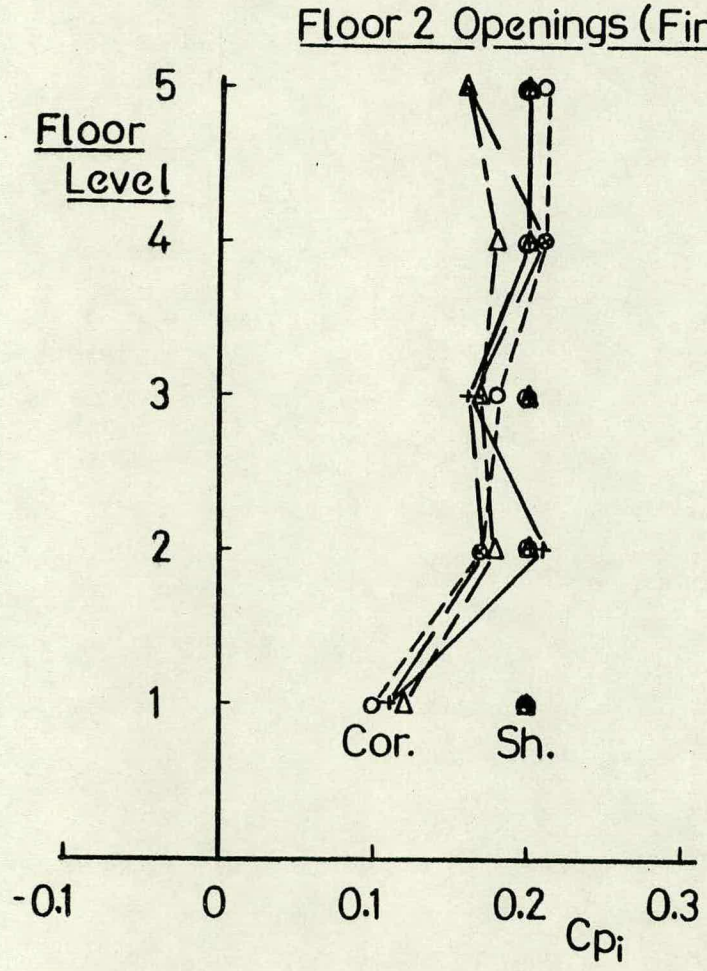
+ Closed

× 'S' Open

o '6' Open

Δ ('S'+'6') Open





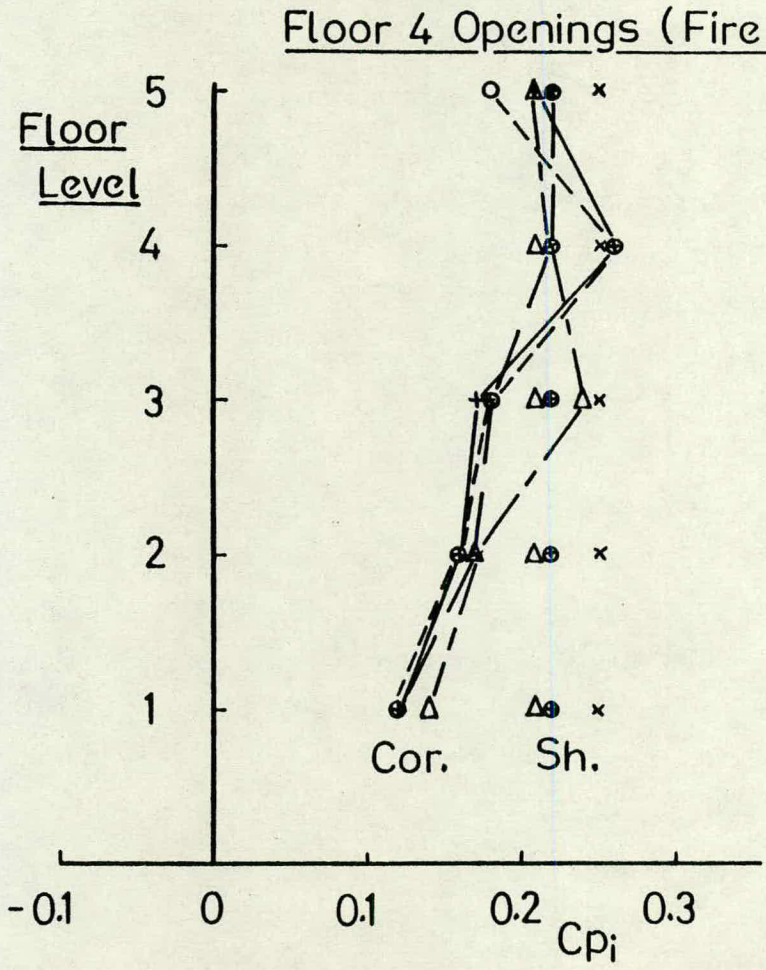


Fig 4.1.4: Shaft and Corridor Wind Induced Pressures, $\alpha = 0^{o}$, Leakage (b), with 'Fire'.

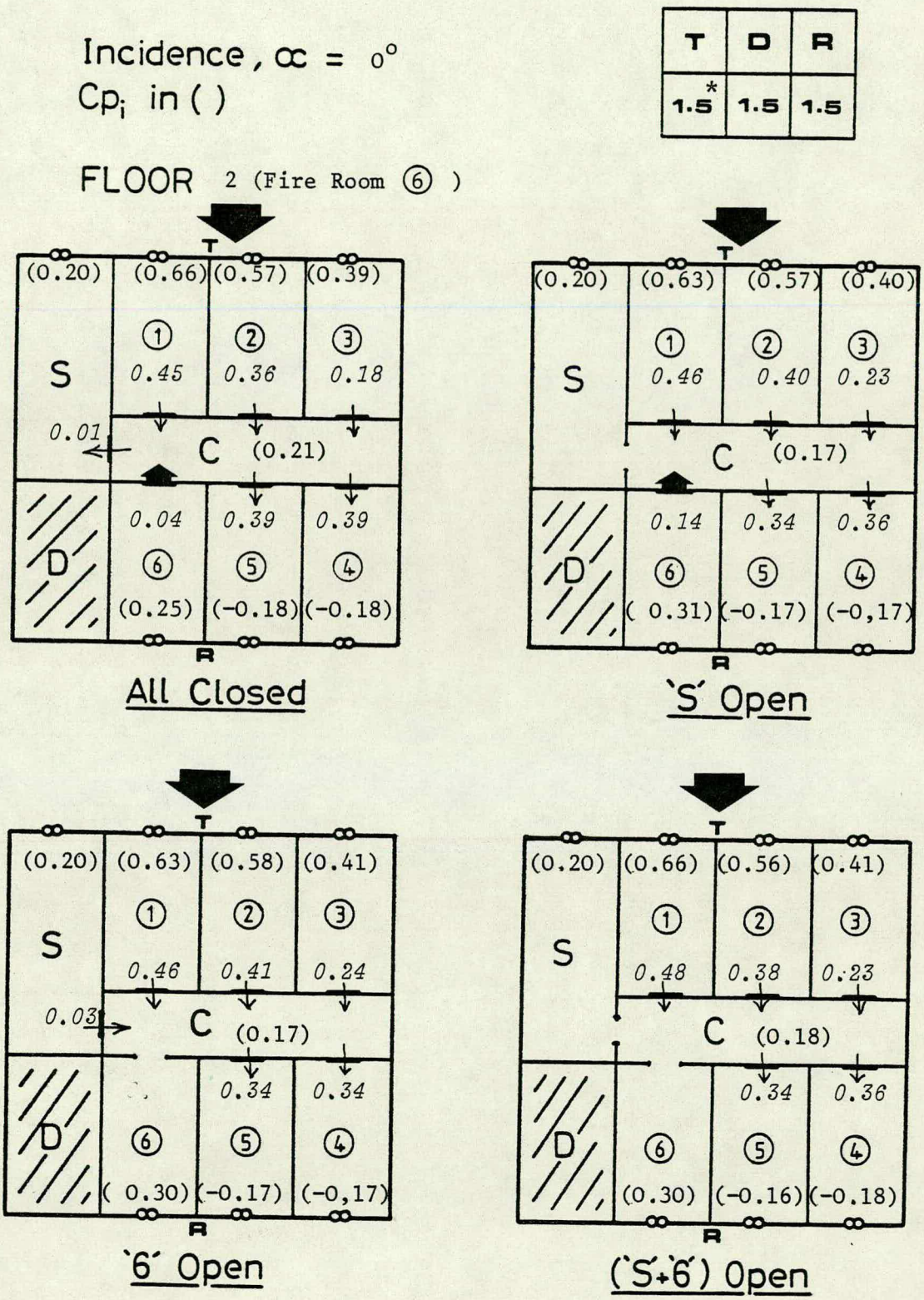


Fig 4.1.5 : Wind Induced Pressure Distribution, $\alpha = 0^\circ$

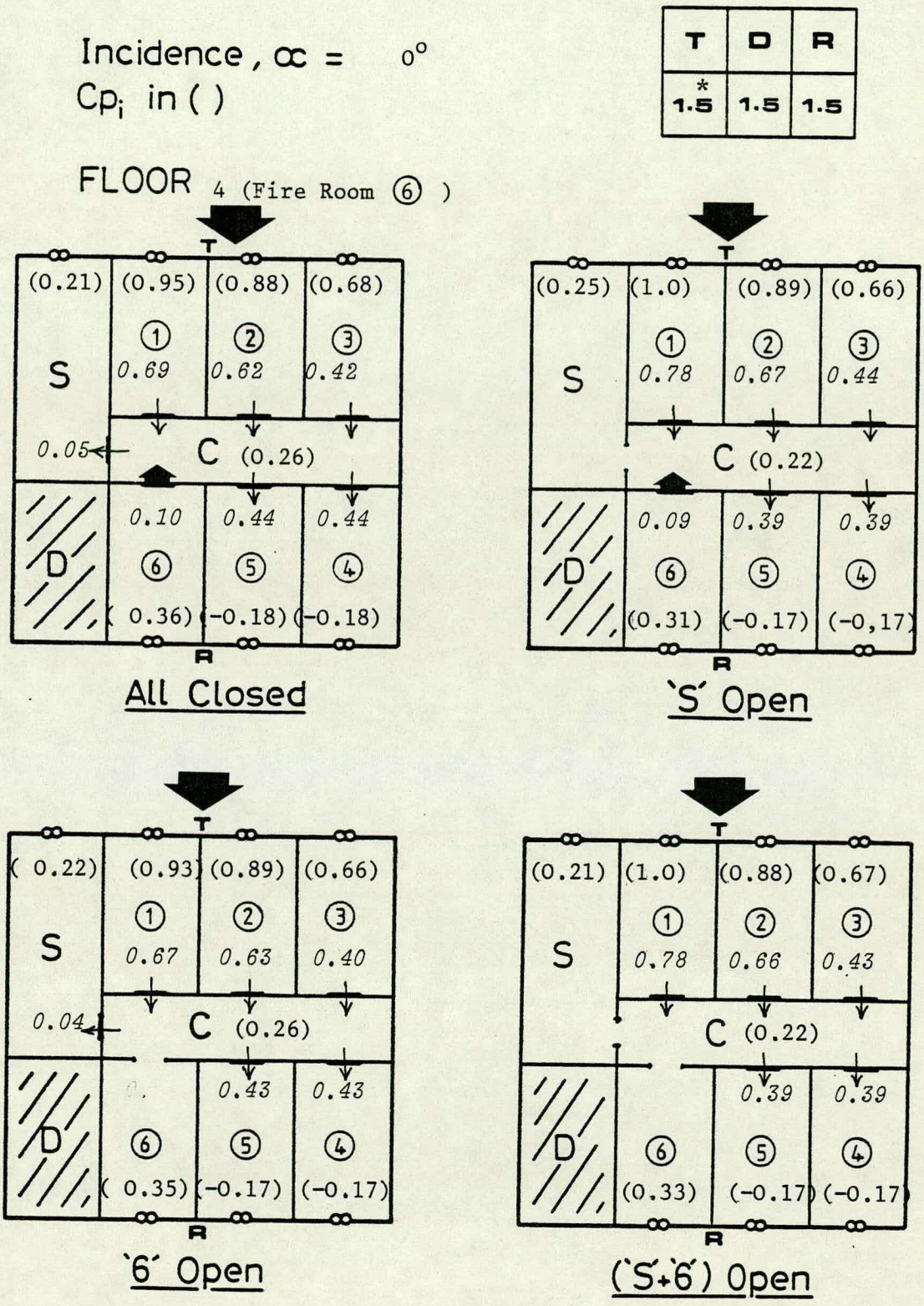


Fig 4.1.6: Wind Induced Pressure Distribution, α = 0°

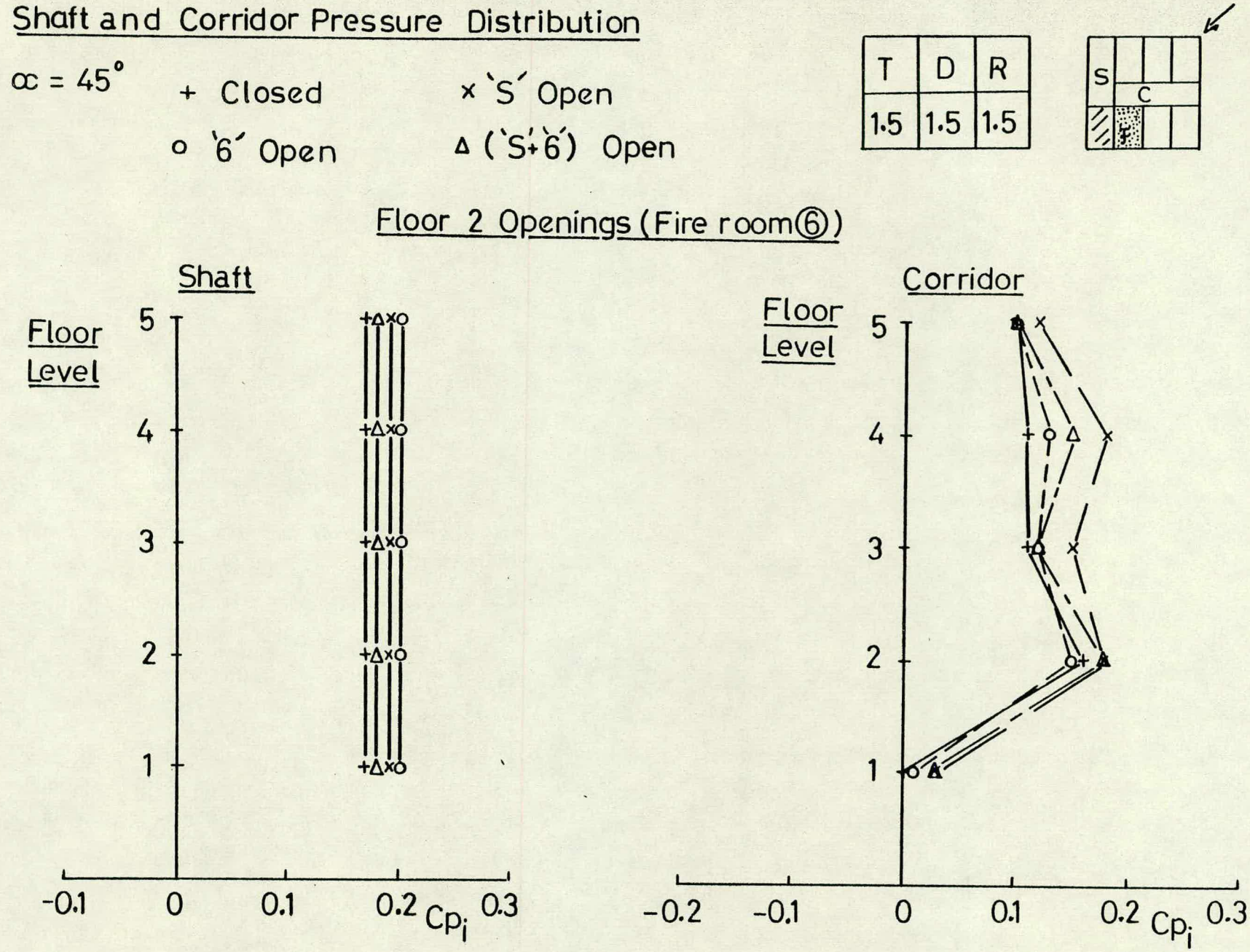
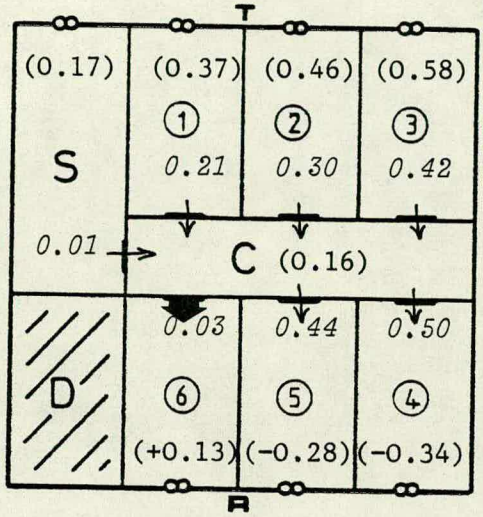


Fig 4.2.1: Shaft and Corridor Wind Induced Pressures, α =45°, Leakage (a), with 'Fire'.

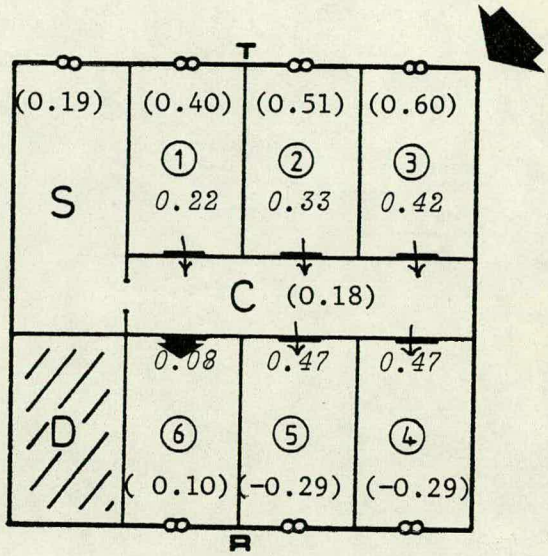
Incidence, α = 45°
Cp_i in ( )

T	D	R
1.5	1.5	1.5

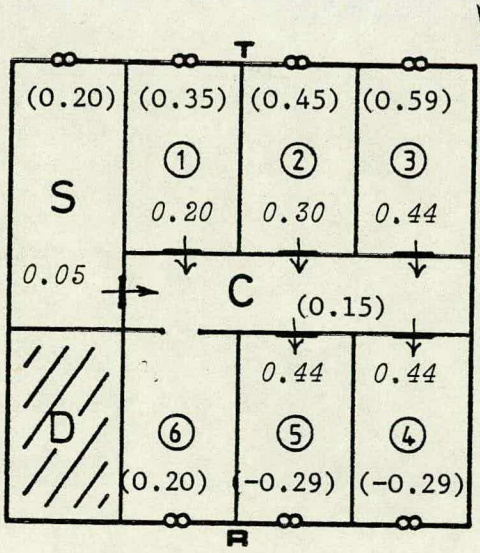
FLOOR 2 (Fire Room ⑥)



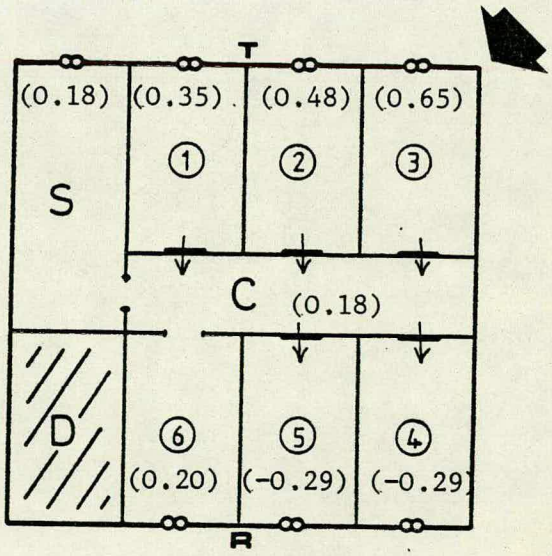
All Closed



'S' Open



'6' Open



('S'+'6') Open

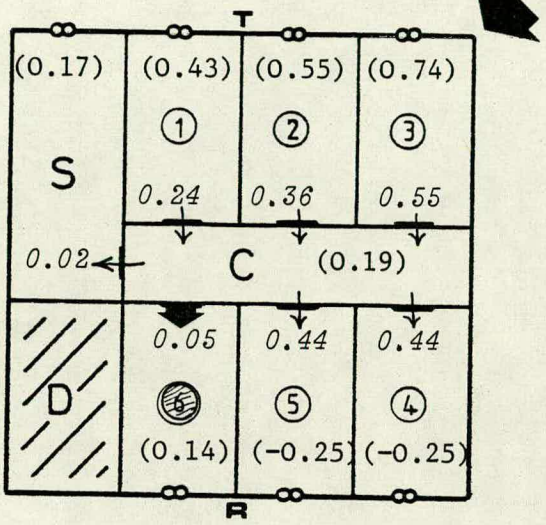
Fig 4.2.3: Wind Induced Pressure Distribution, α = 45°

Incidence, α = 45°

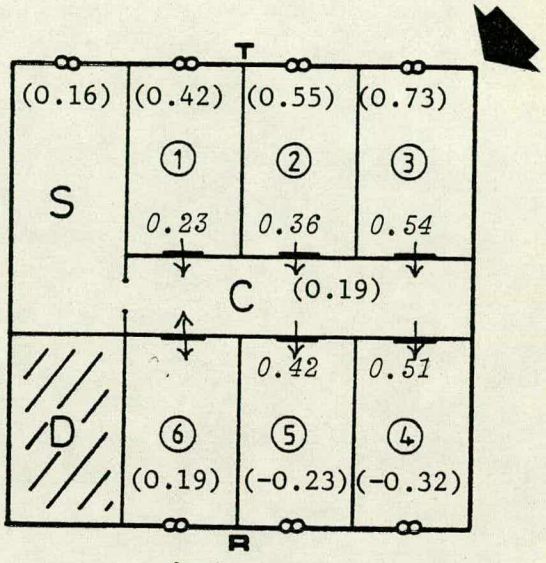
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

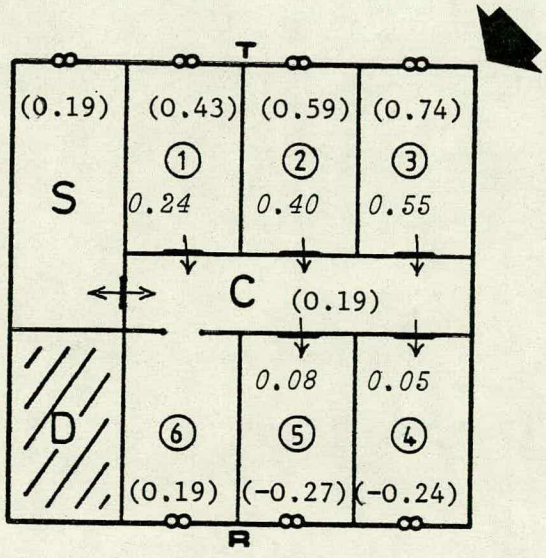
FLOOR 4 (Fire Room ⑥)



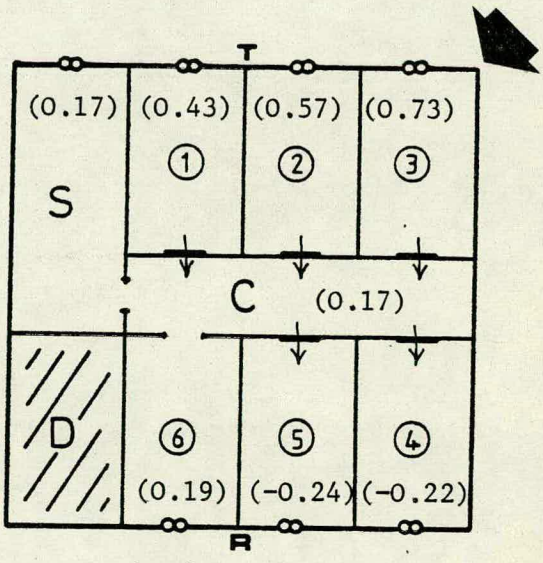
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.2.4 : Wind Induced Pressure Distribution, α = 45°

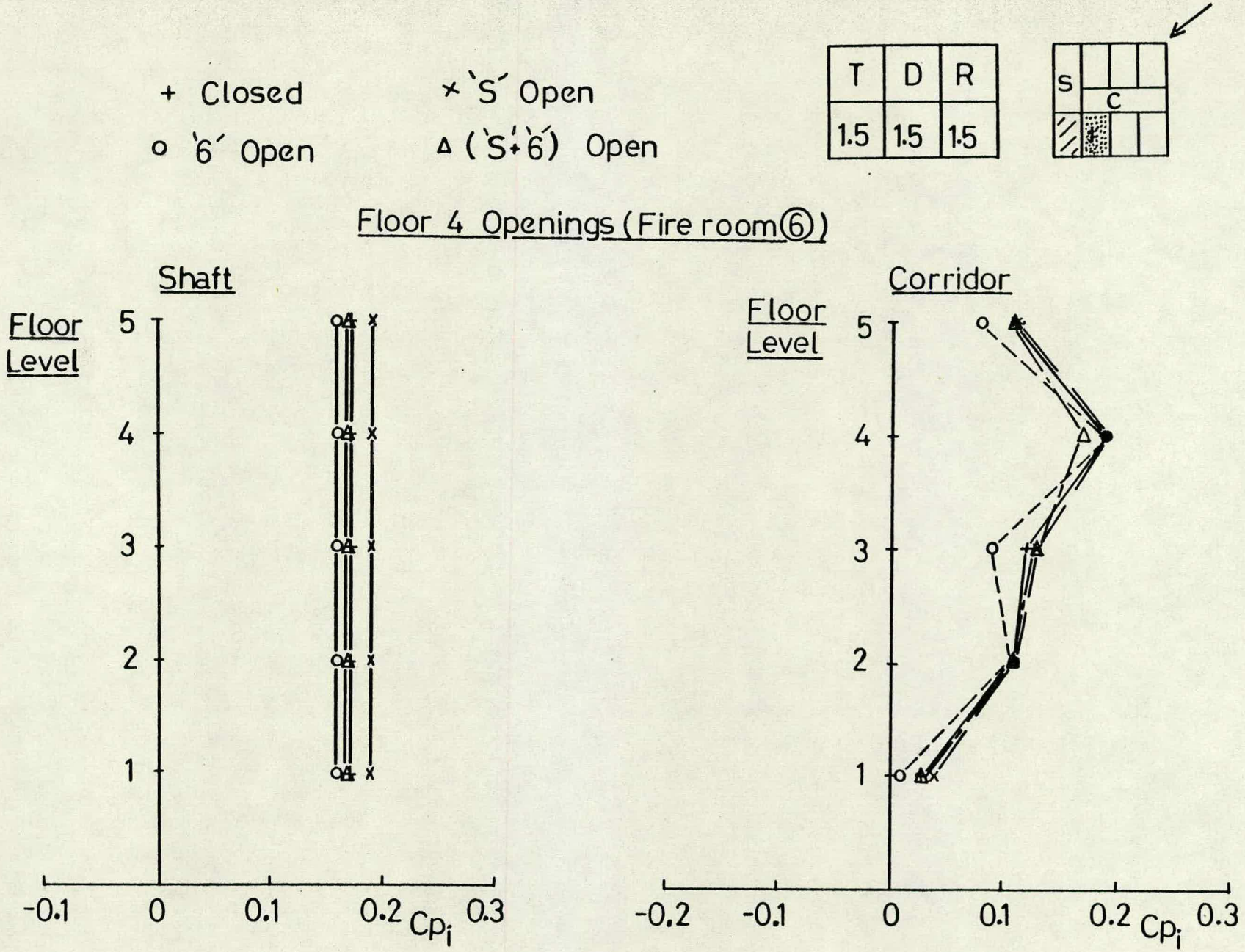


Fig 4.2.2: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (a), with 'Fire'.

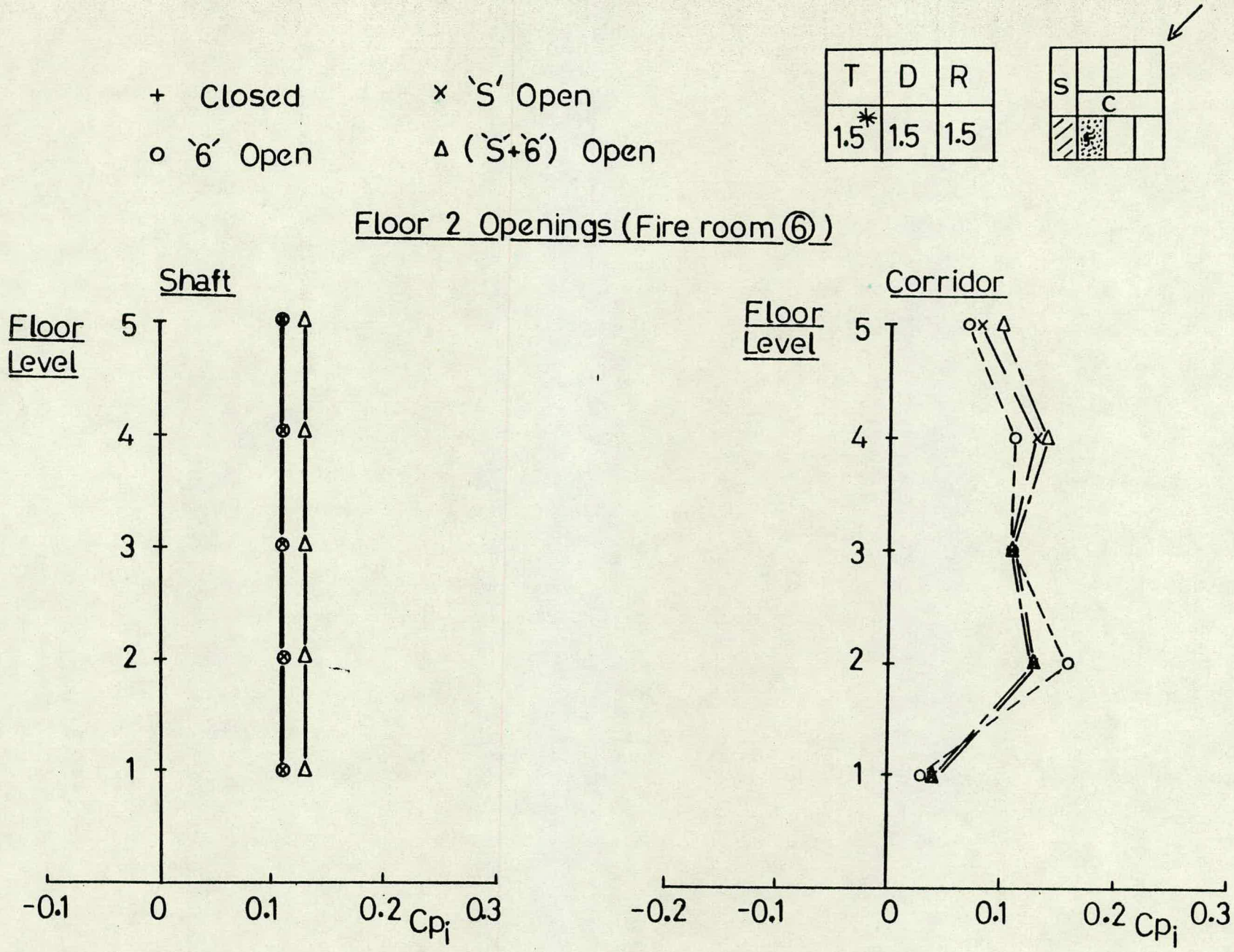
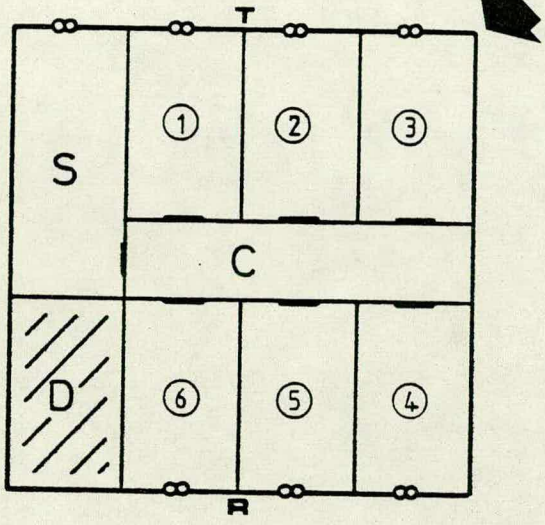


Fig 4.2.5: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (b), with 'Fire'.

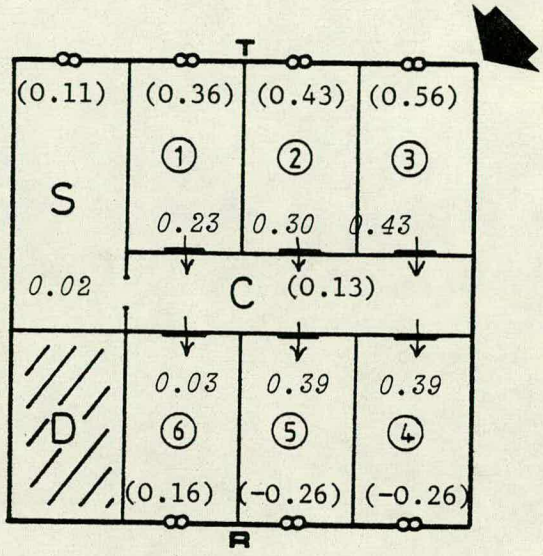
Incidence, α = 45°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

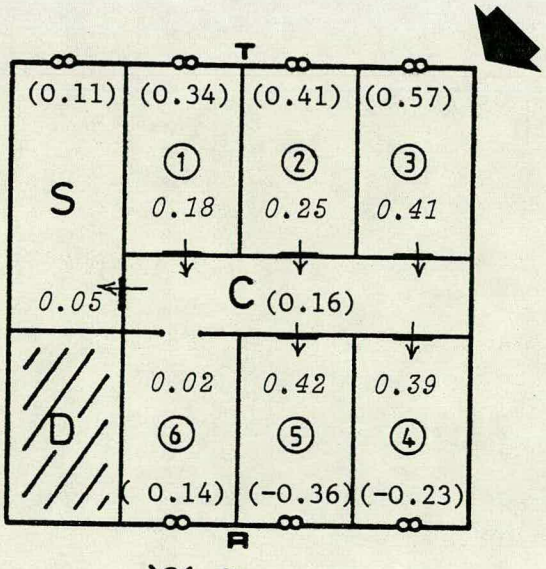
FLOOR 2 (Fire Room ⑥)



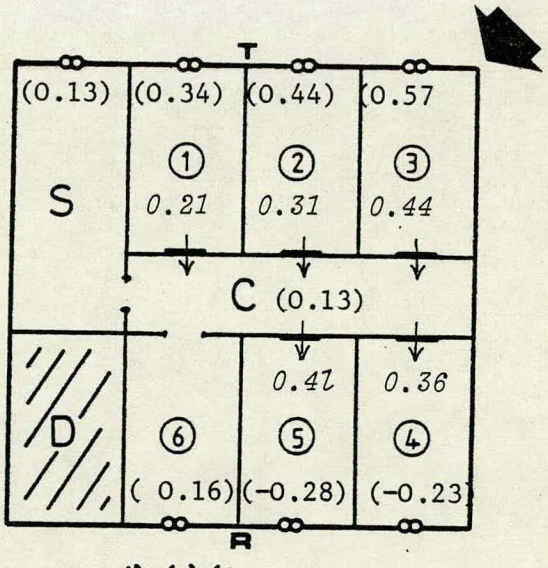
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.2.7: Wind Induced Pressure Distribution, α = 45°

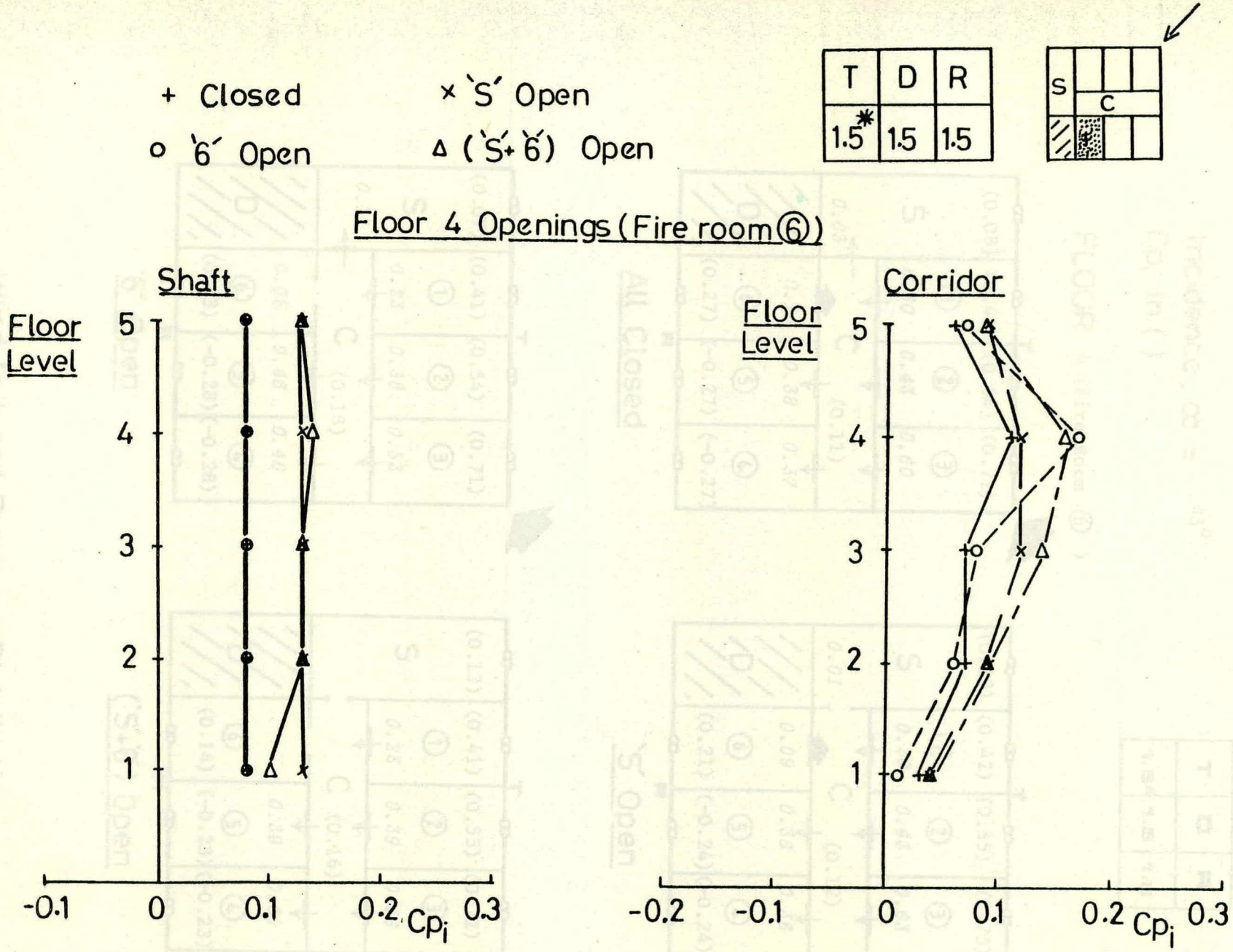


Fig 4.2.6: Shaft and Corridor Wind Induced Pressures, $\alpha = 45^{o}$, Leakage (b), with 'Fire'.

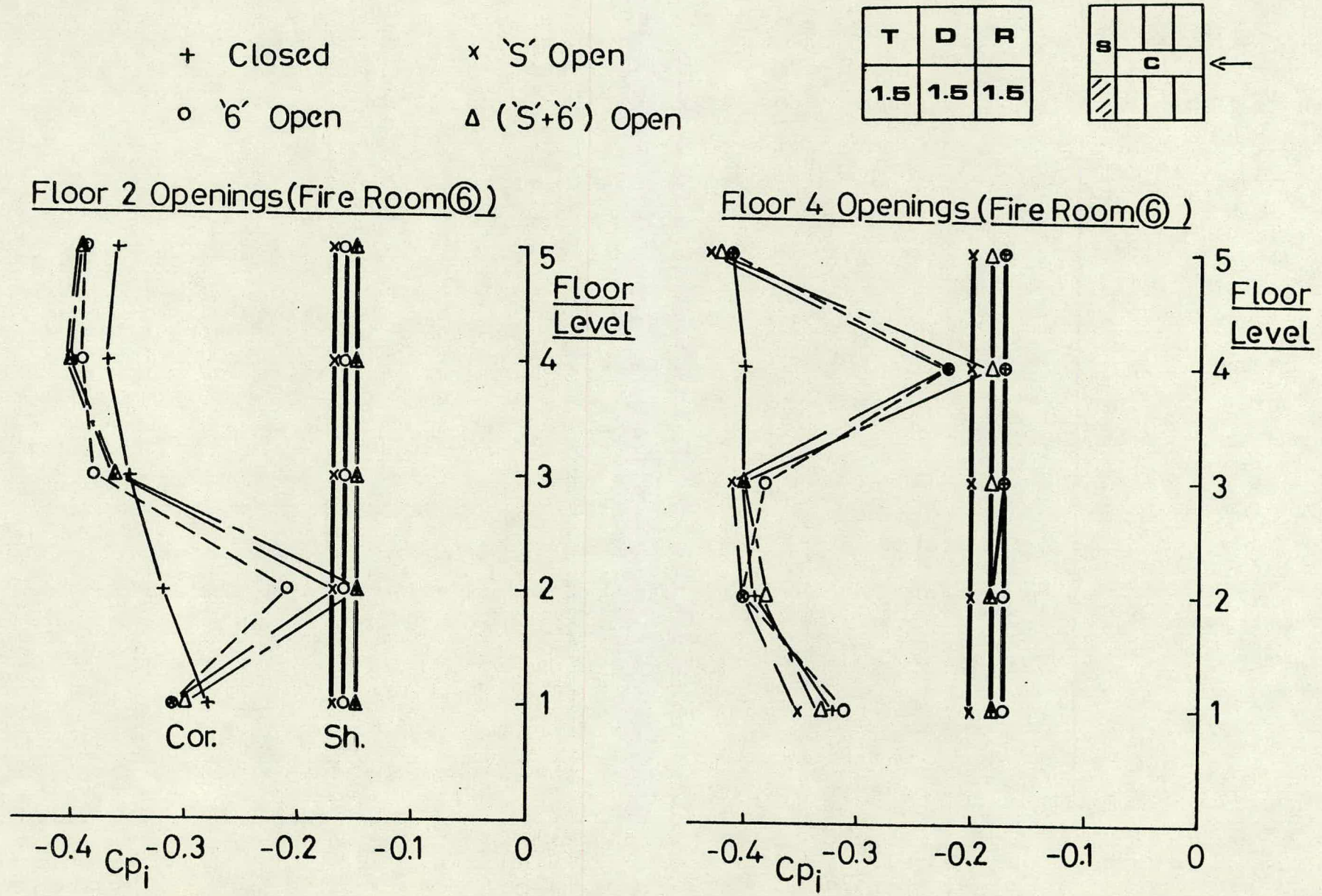
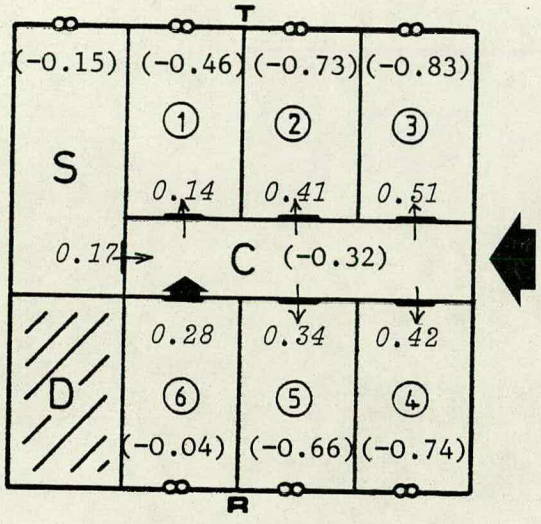


Fig 4.3.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 90^{o}$, Leakage (a), with 'Fire'.

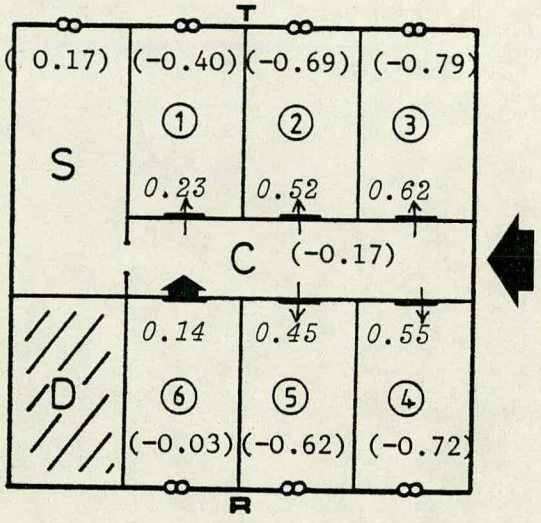
Incidence, α = 90°
Cp_i in ( )

T	D	R
1.5	1.5	1.5

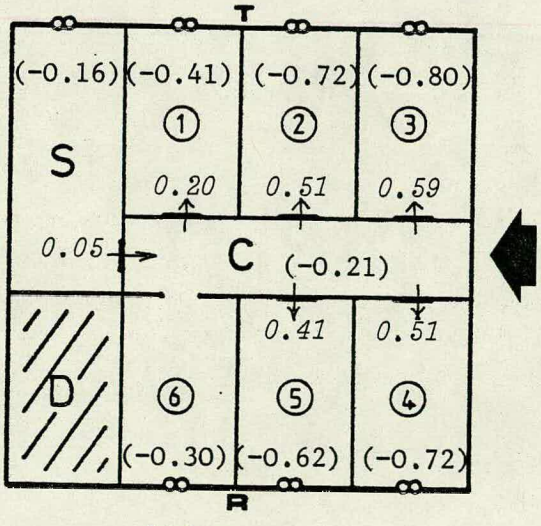
FLOOR 2 (Fire Room ⑥)



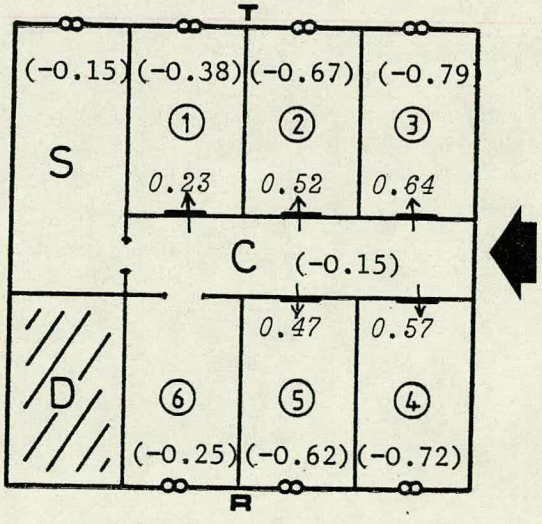
All Closed



'S' Open



'6' Open



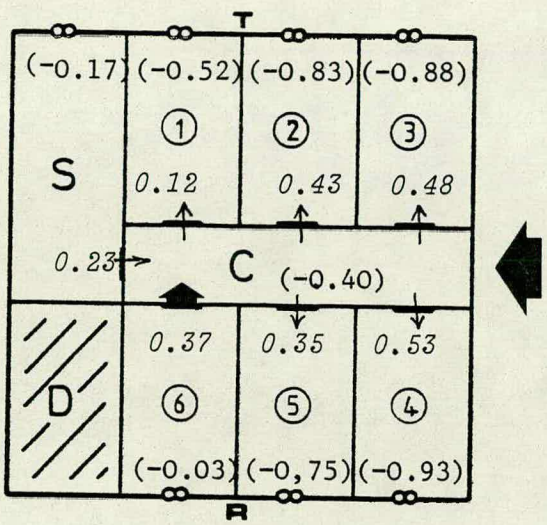
('S'+'6') Open

Fig 4.3.2: Wind Induced Pressure Distribution, α = 90°

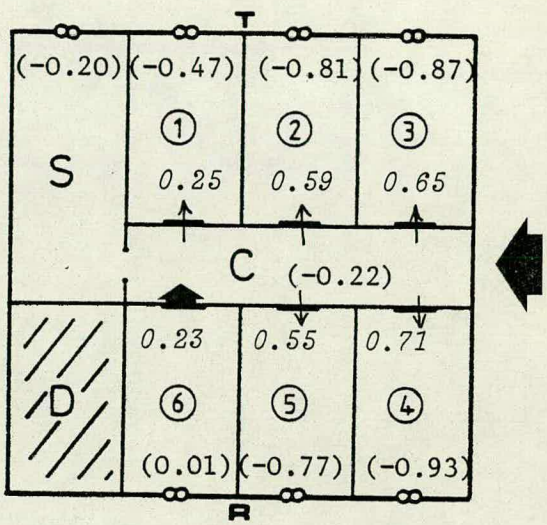
Incidence, $\alpha = 90^\circ$
Cp_i in ( )

T	D	R
1.5	1.5	1.5

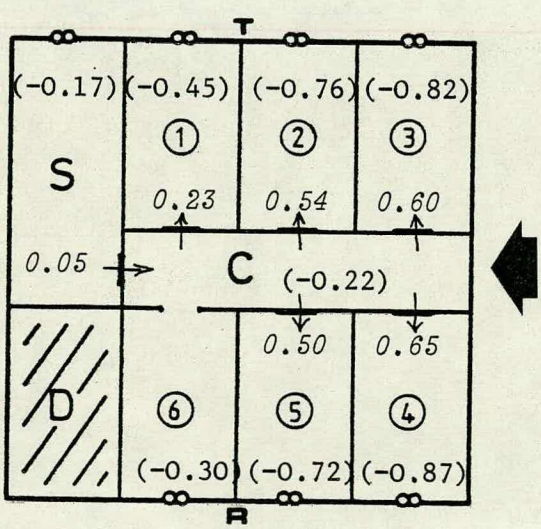
FLOOR 4 (Fire Room ⑥)



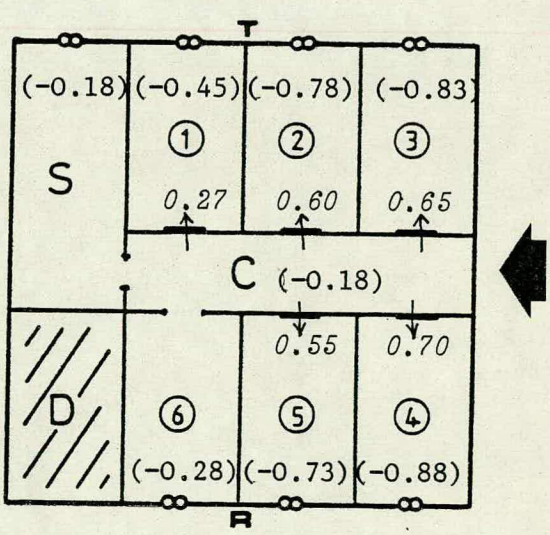
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.3.3: Wind Induced Pressure Distribution, $\alpha = 90^\circ$

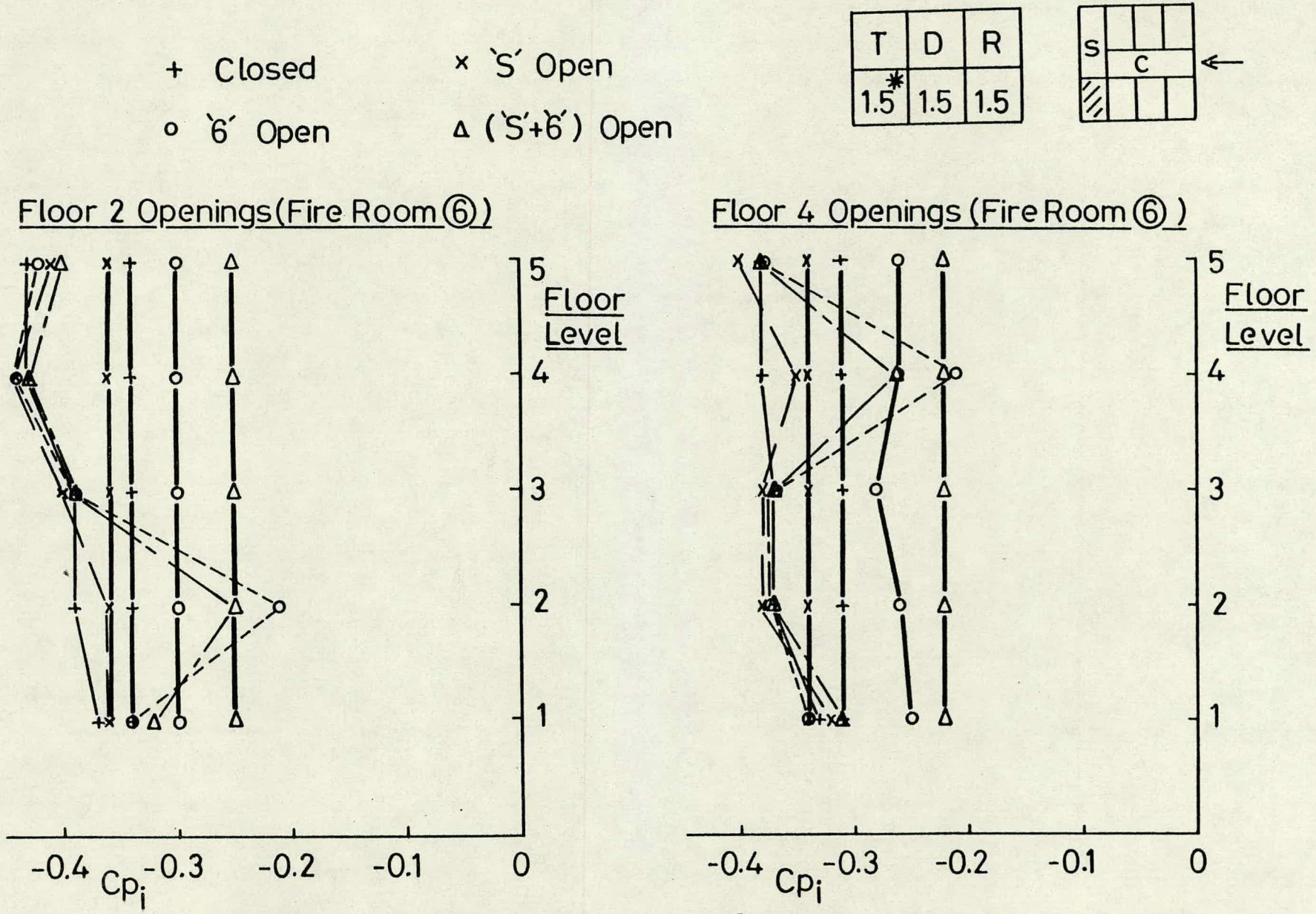
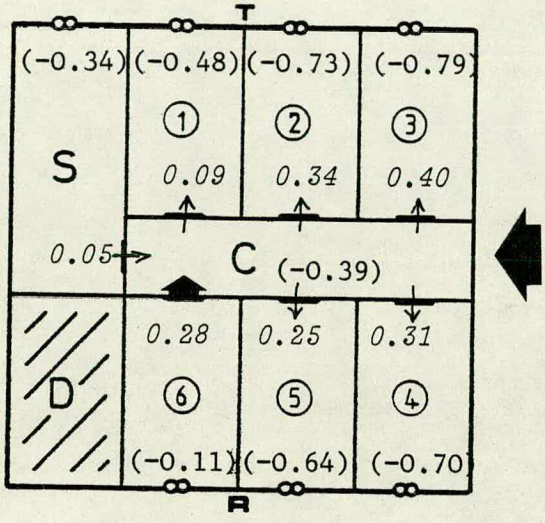


Fig 4.3.2: Shaft and Corridor Wind Induced Pressures, $\alpha \doteq 90^{o}$, Leakage (b), with 'Fire'.

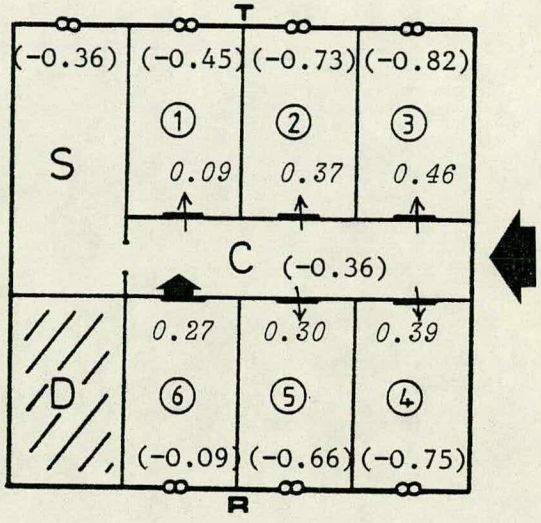
Incidence, α = 90°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

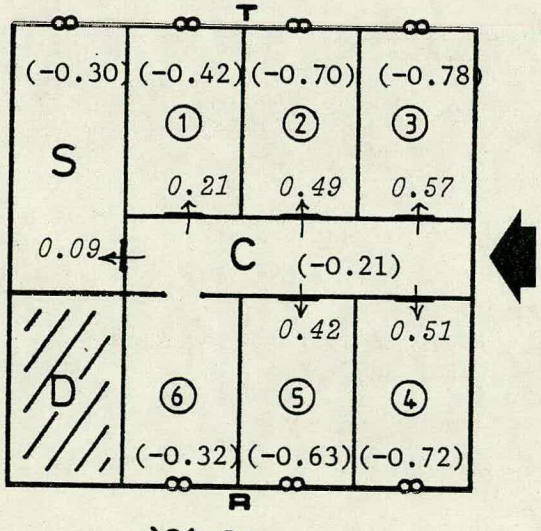
FLOOR 2 (Fire Room ⑥)



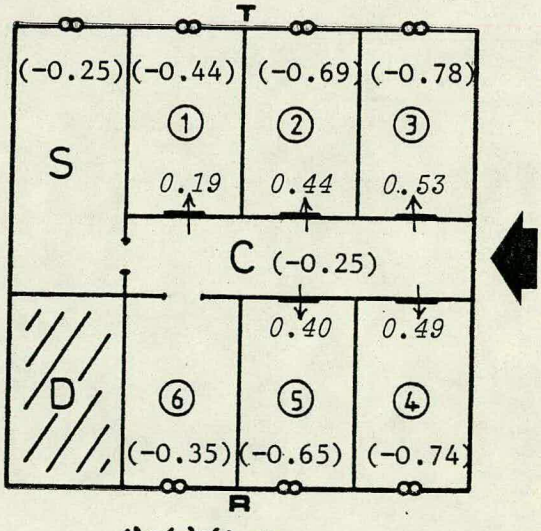
All Closed



'S' Open



'6' Open



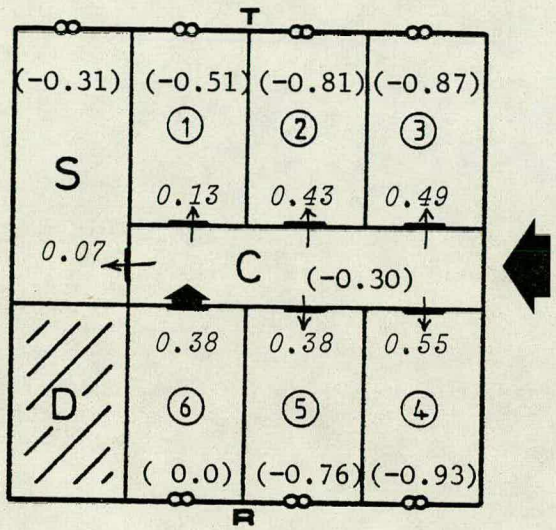
('S'+'6') Open

Fig 4.3.5: Wind Induced Pressure Distribution, α = 90°

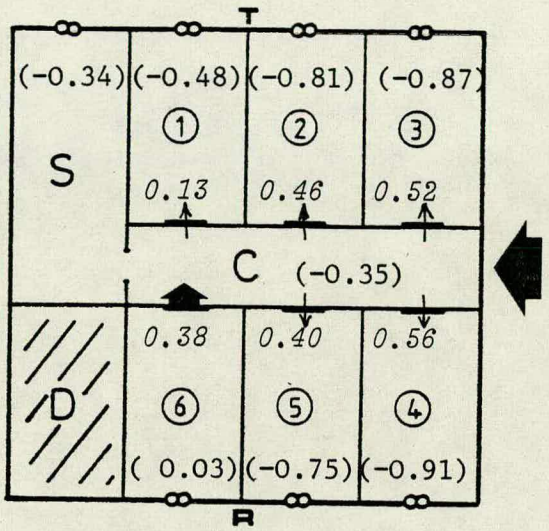
Incidence, α = 90°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

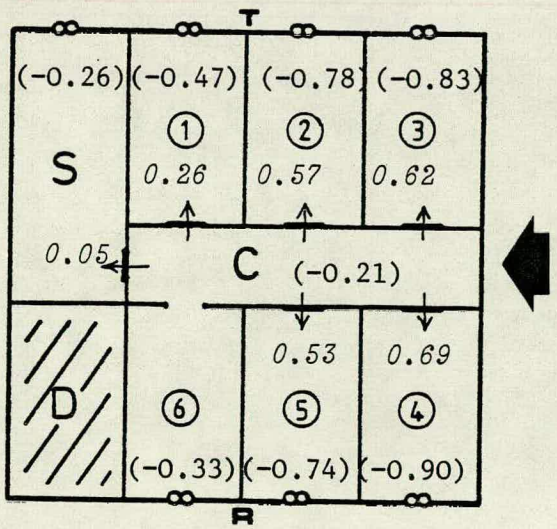
FLOOR 4 (Fire Room ⑥)



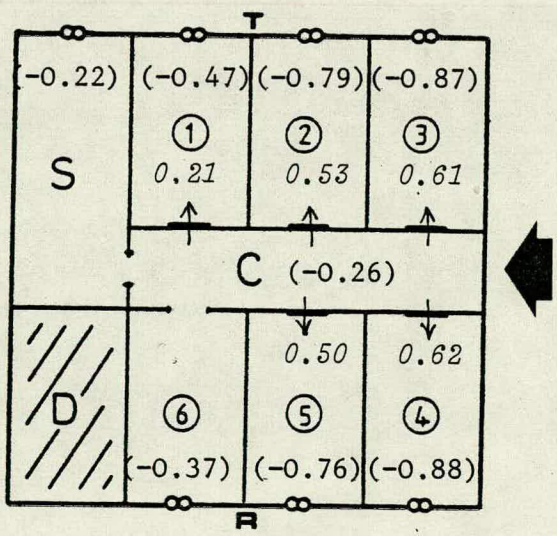
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.3.6: Wind Induced Pressure Distribution, α = 90°

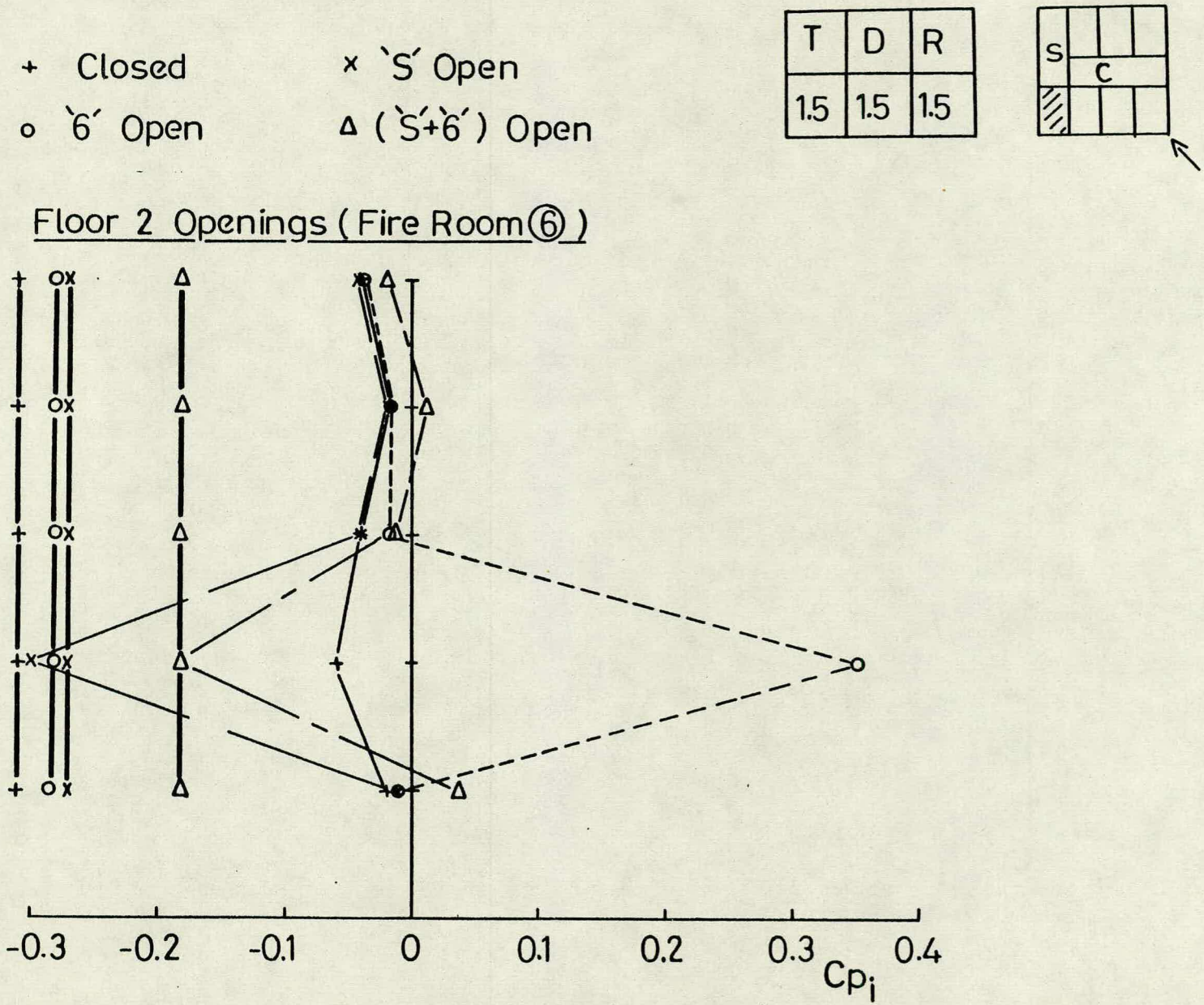


Fig 4.4.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 135^{o}$, Leakage (a), with 'Fire'.

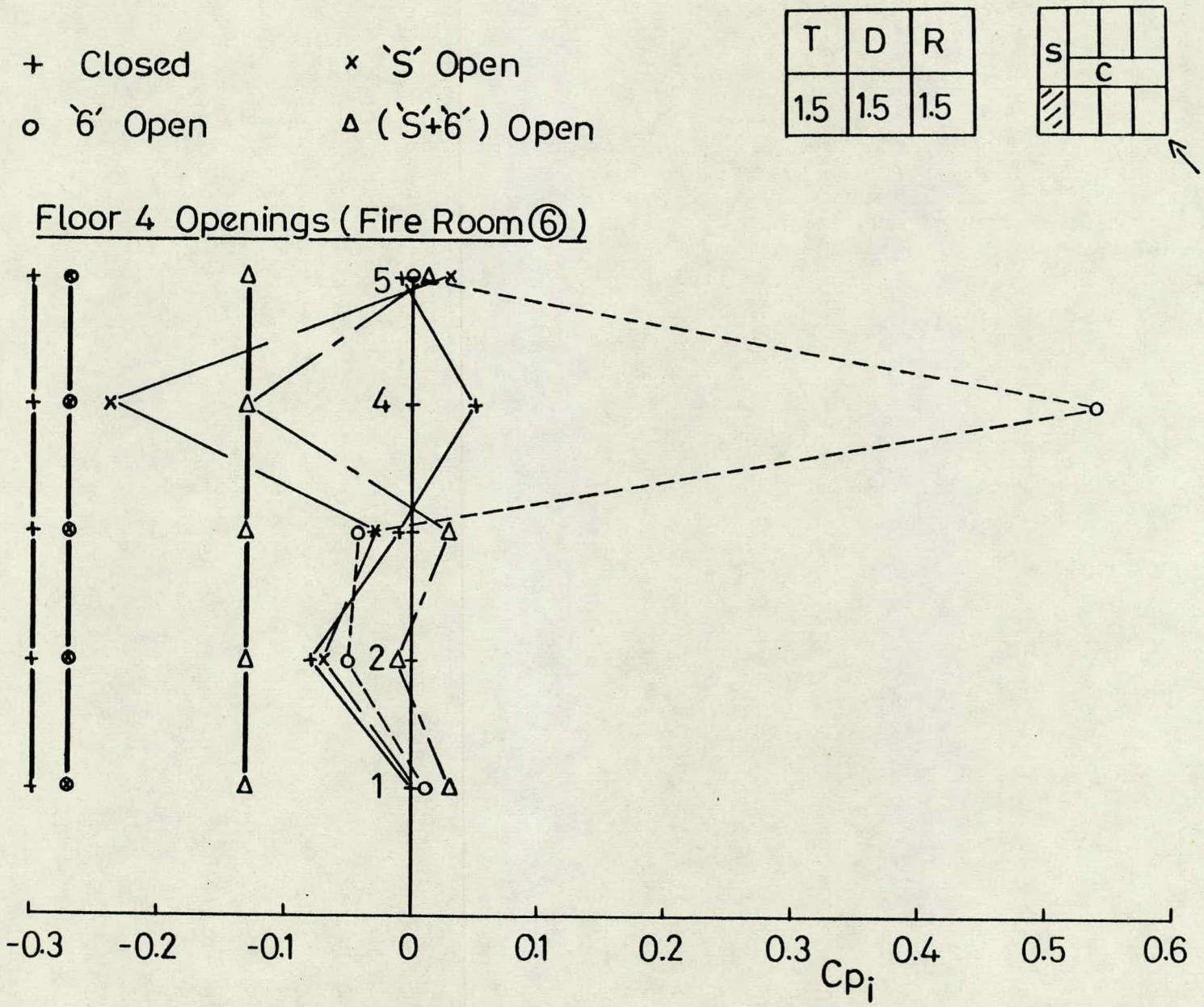


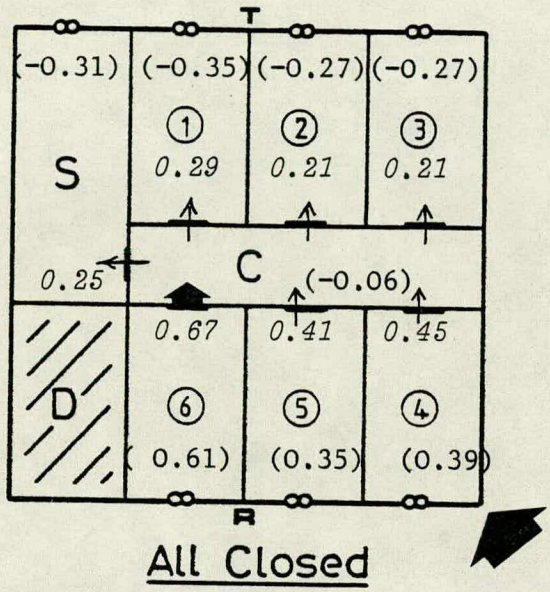
Fig 4.4.2: Shaft and Corridor Wind Induced Pressures, $\alpha = 135^{o}$, Leakage (a), with 'Fire'.

Incidence, α = 135°

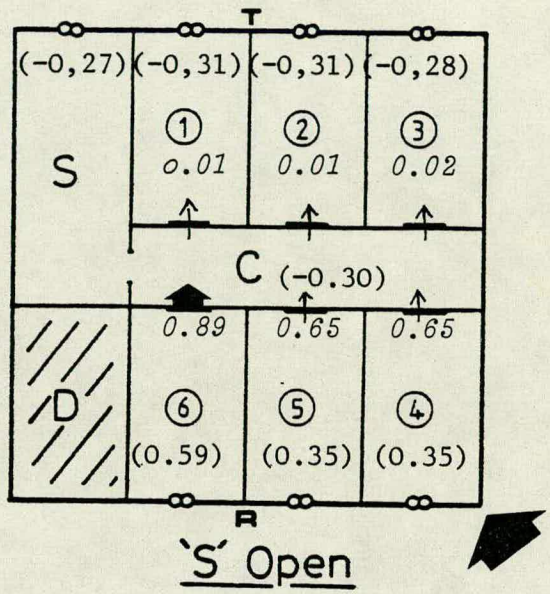
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

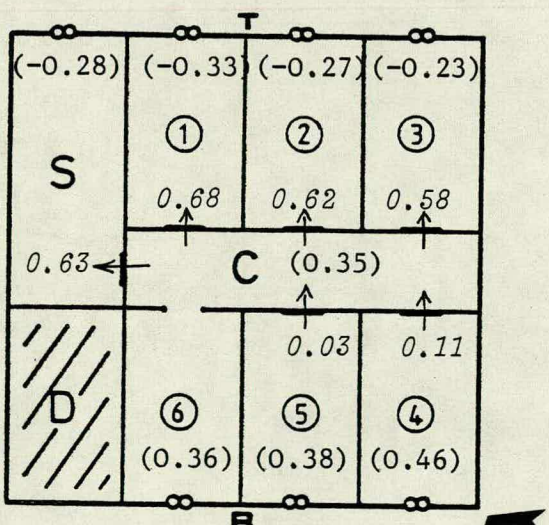
FLOOR 2 (Fire Room ⑥)



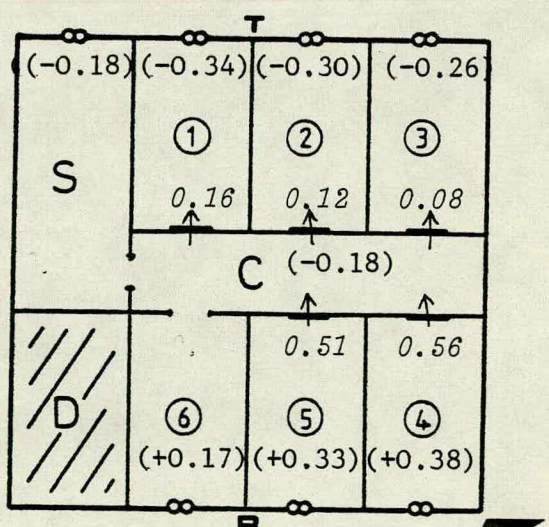
All Closed



'S' Open



'6' Open



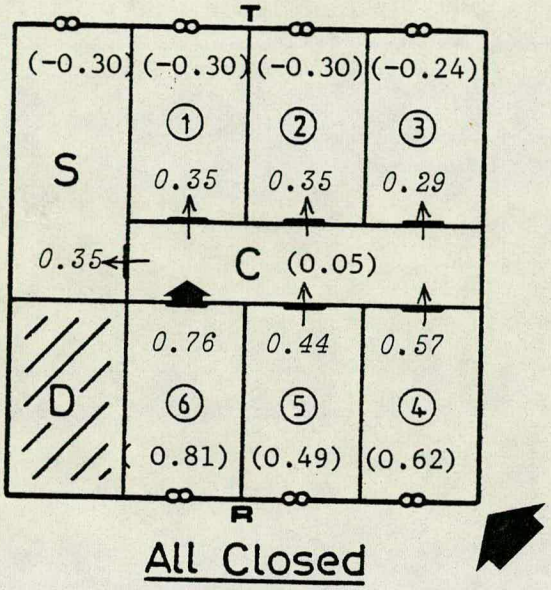
('S'+'6') Open

Fig 4.4.3: Wind Induced Pressure Distribution, α = 135°

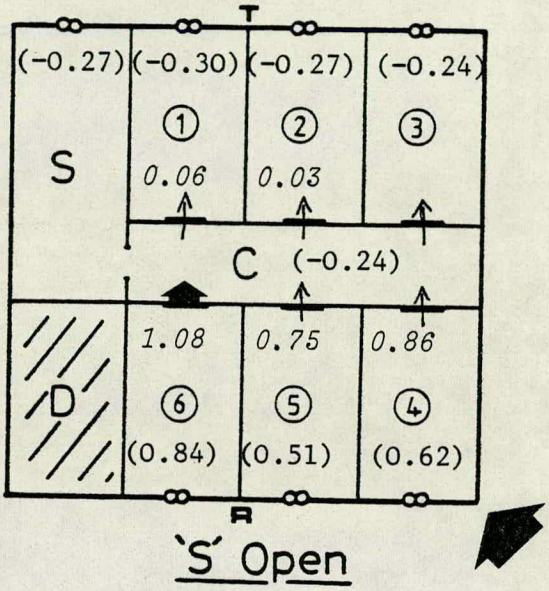
Incidence, α = 135°
C_{pi} in ( )

FLOOR 4 [FIRE ROOM ⑥]

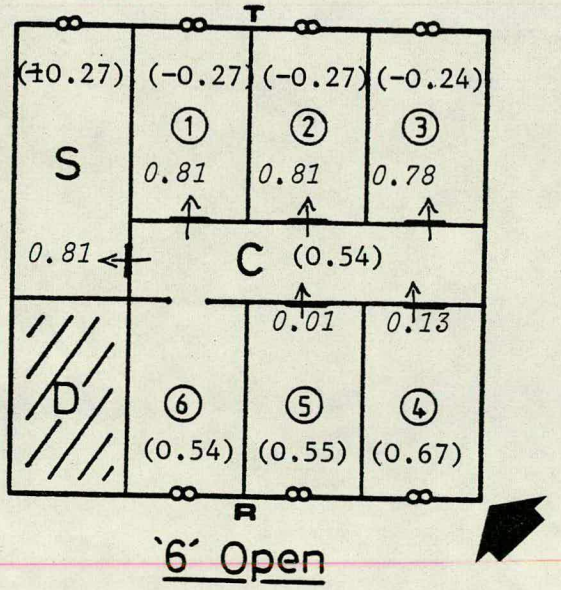
T	D	R
1.5	1.5	1.5



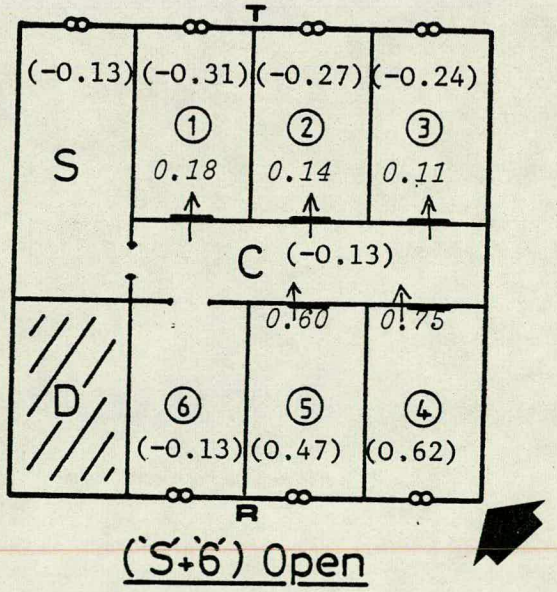
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.4.4: Wind Induced Pressure Distribution, α = 135°

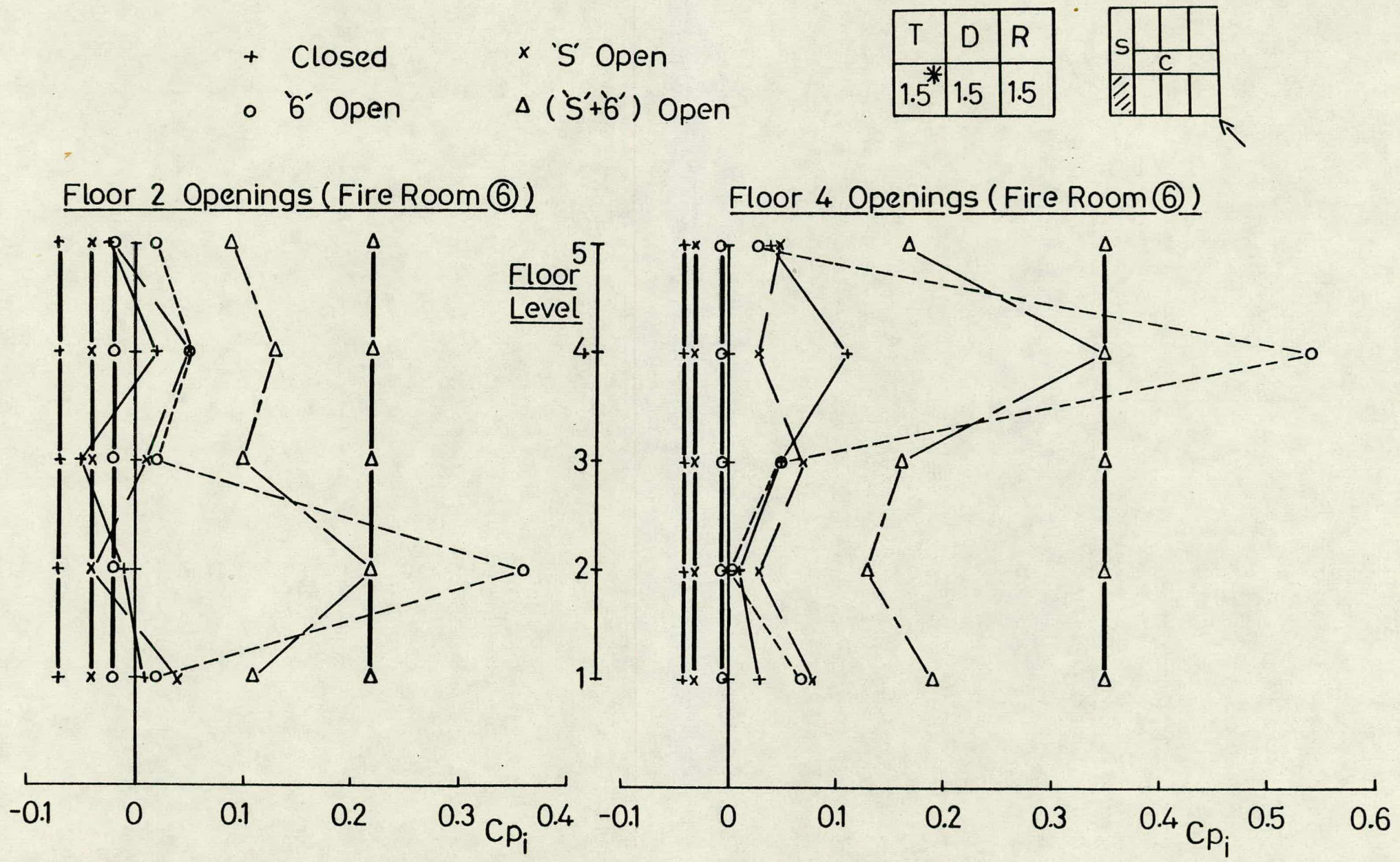
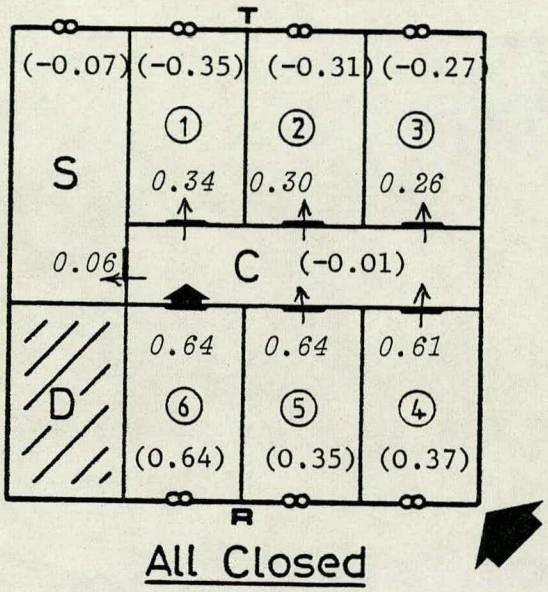


Fig 4.4.5: Shaft and Corridor Wind Induced Pressures, $\alpha = 135^{o}$, Leakage (b), with 'Fire'.

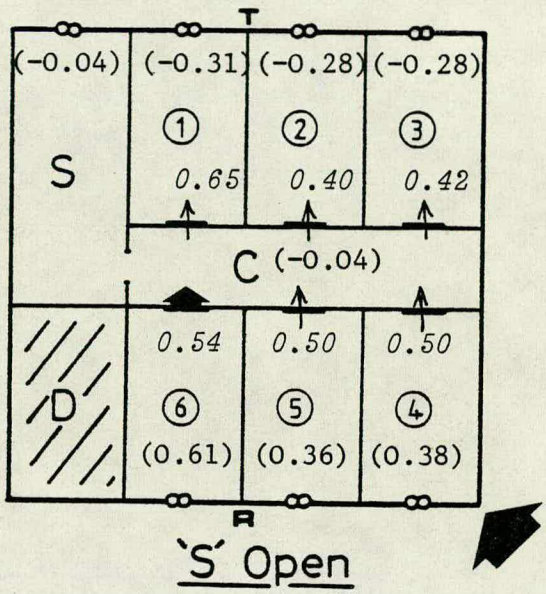
Incidence, α = 135°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

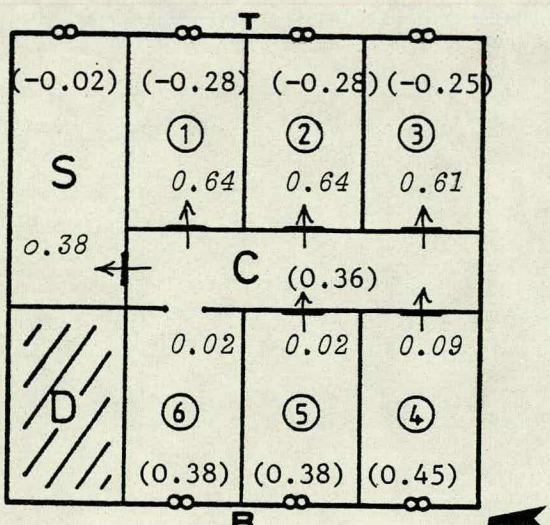
FLOOR 2 (Fire Room ⑥)



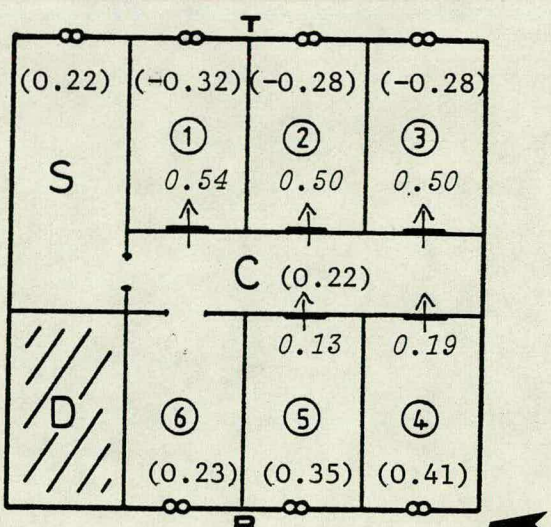
All Closed



'S' Open



'6' Open



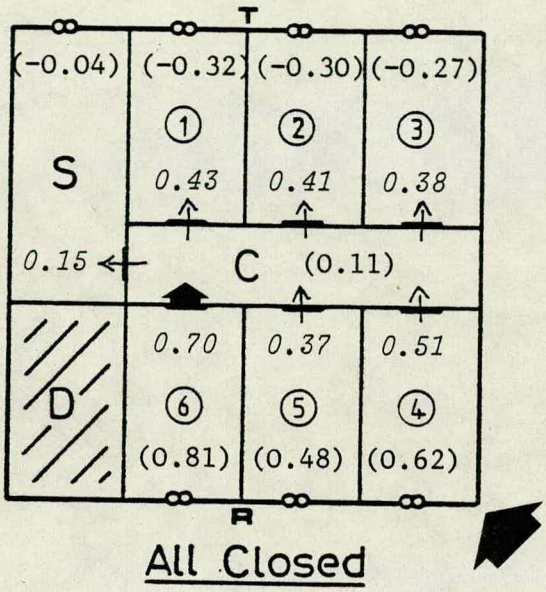
('S'+'6') Open

Fig 4 4 6: Wind Induced Pressure Distribution, α = 135°

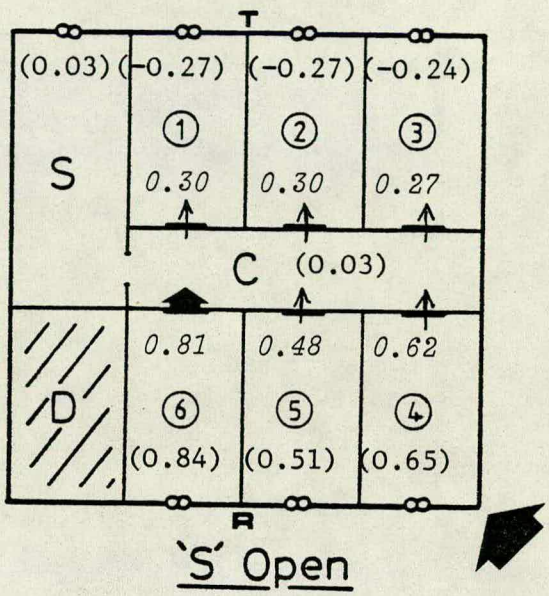
Incidence , α = 135°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

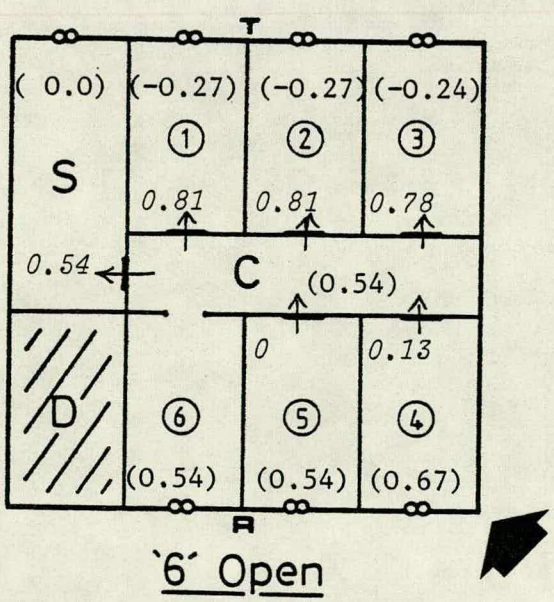
FLOOR 4 (Fire Room ⑥)



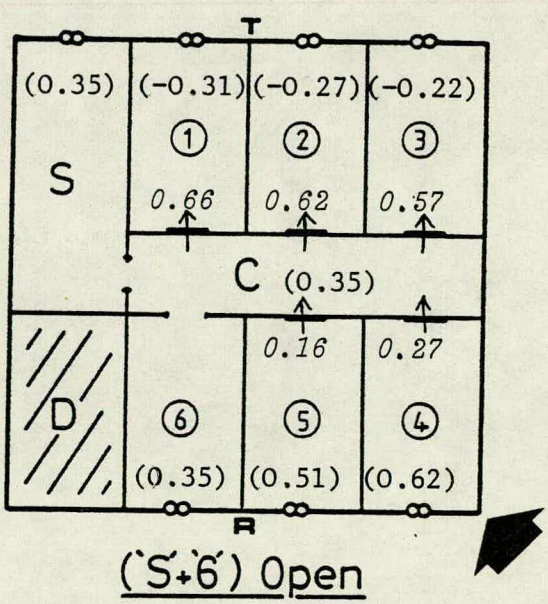
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.4.7: Wind Induced Pressure Distribution, α = 135°

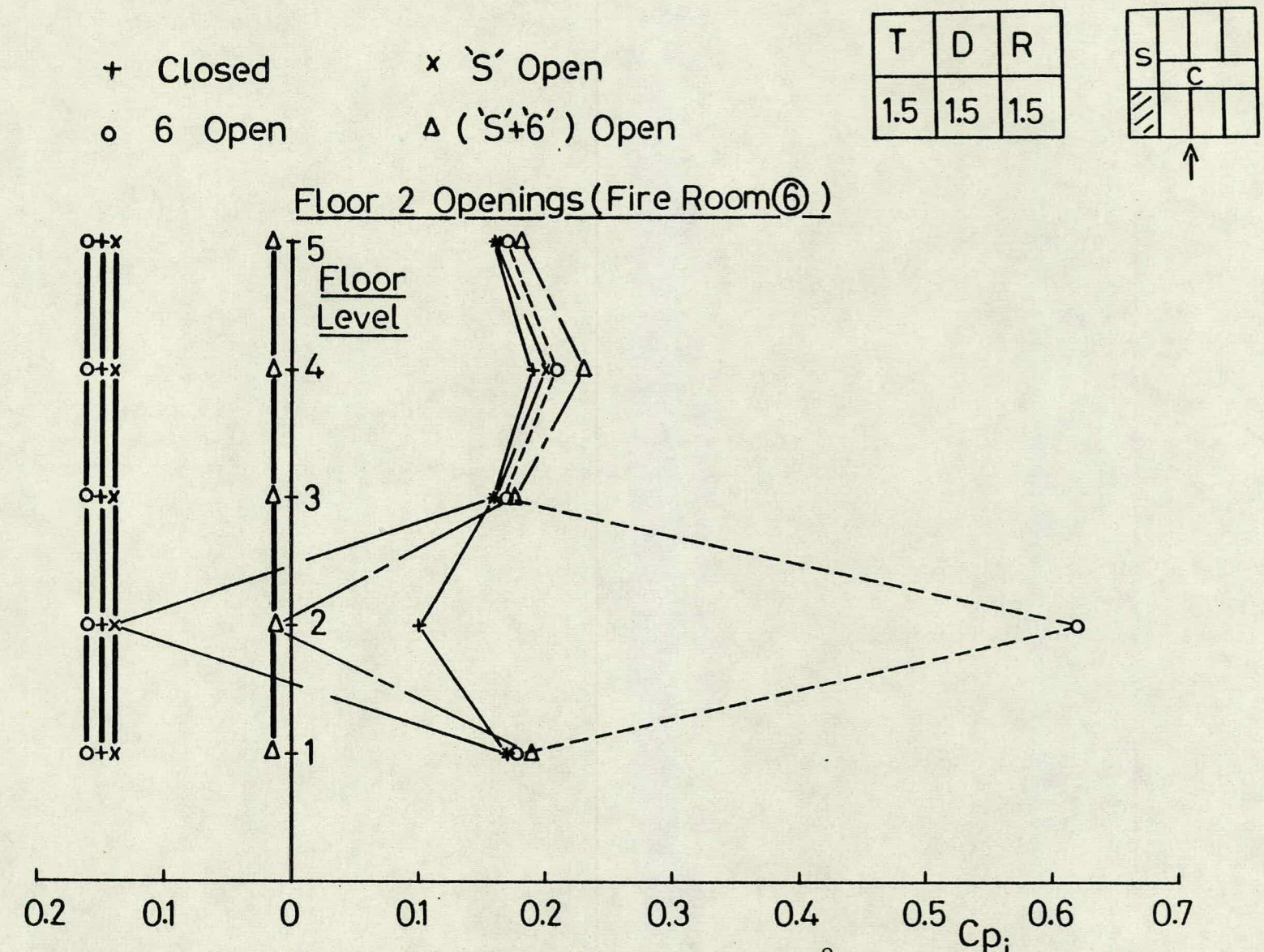


Fig 4.5.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 180^{o}$, Leakage (a), with 'Fire'.

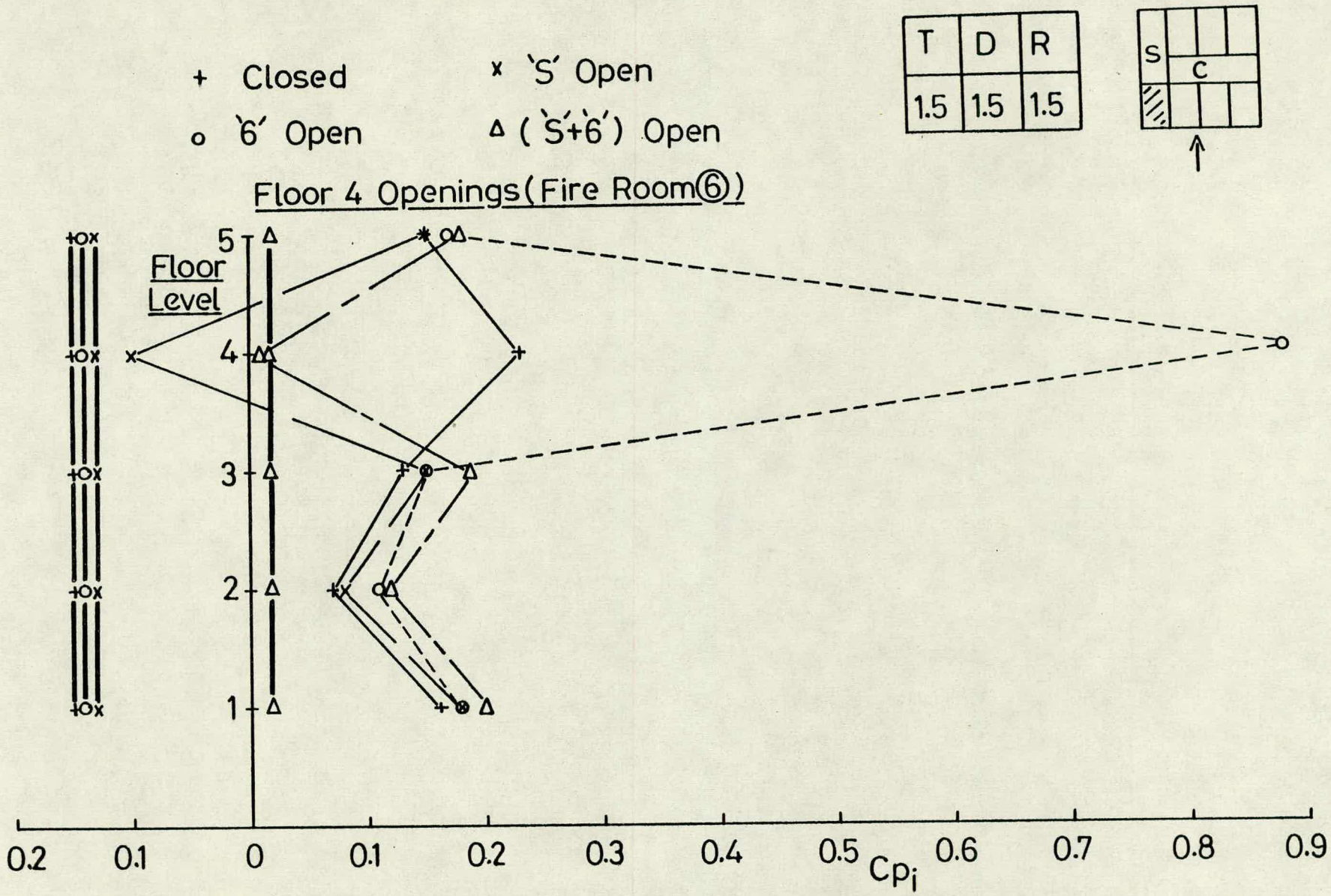
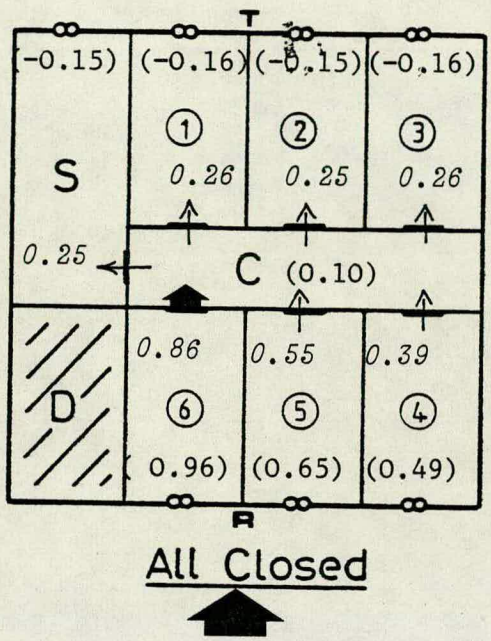


Fig 4.5.2: Shaft and Corridor Wind Induced Pressures, $\alpha = 180^{o}$, Leakage (a), with 'Fire'.

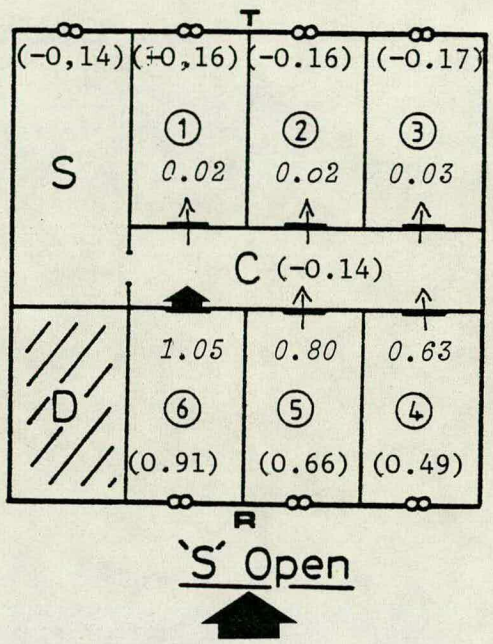
Incidence, α = 180°
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

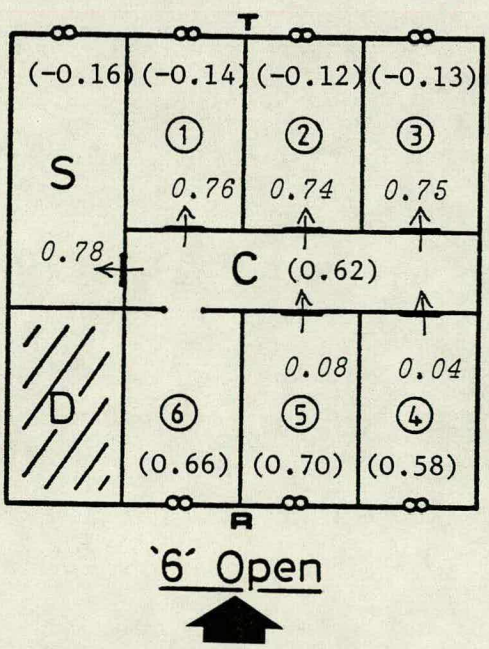
FLOOR 2 (Fire Room ⑥)



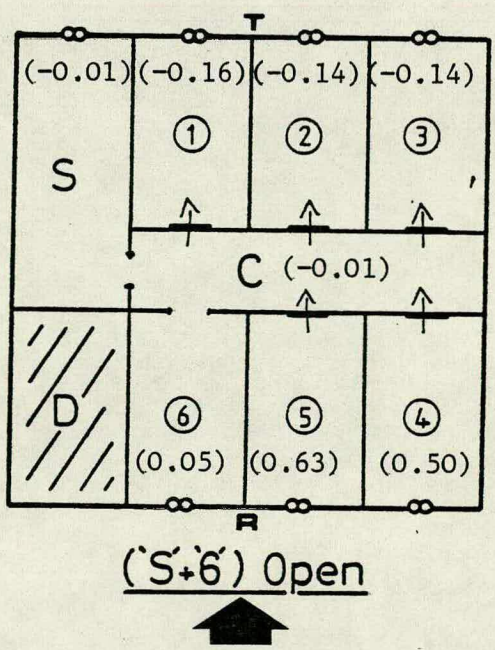
All Closed



'S' Open



'6' Open



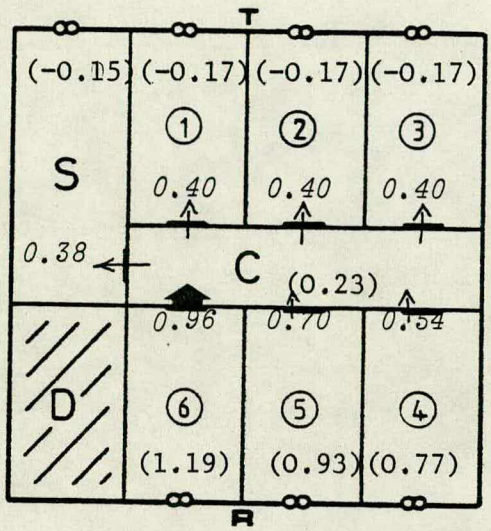
('S'+'6') Open

Fig 4.5.3: Wind Induced Pressure Distribution, α = 180°

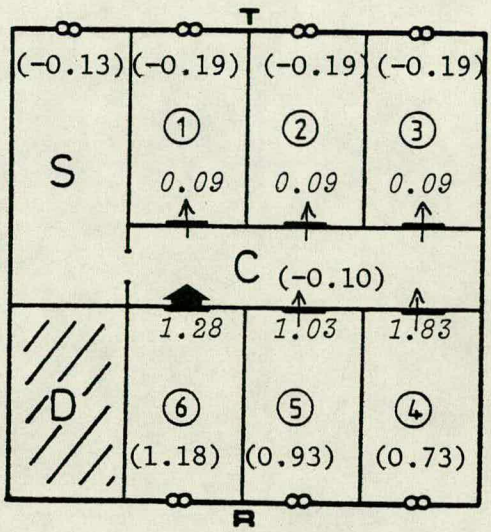
Incidence, α = 180°
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

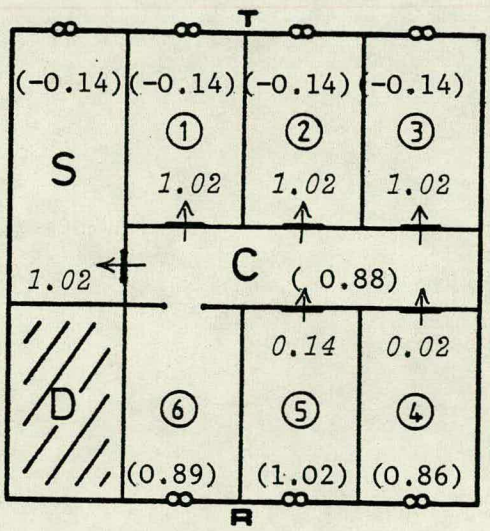
FLOOR 4 (Fire Room ⑥)



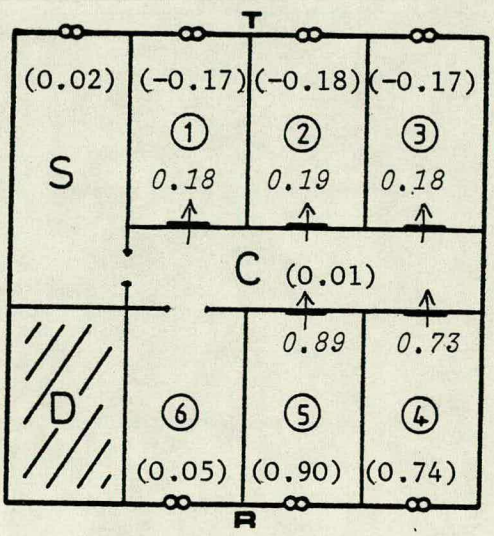
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.5.4: Wind Induced Pressure Distribution, α = 180°

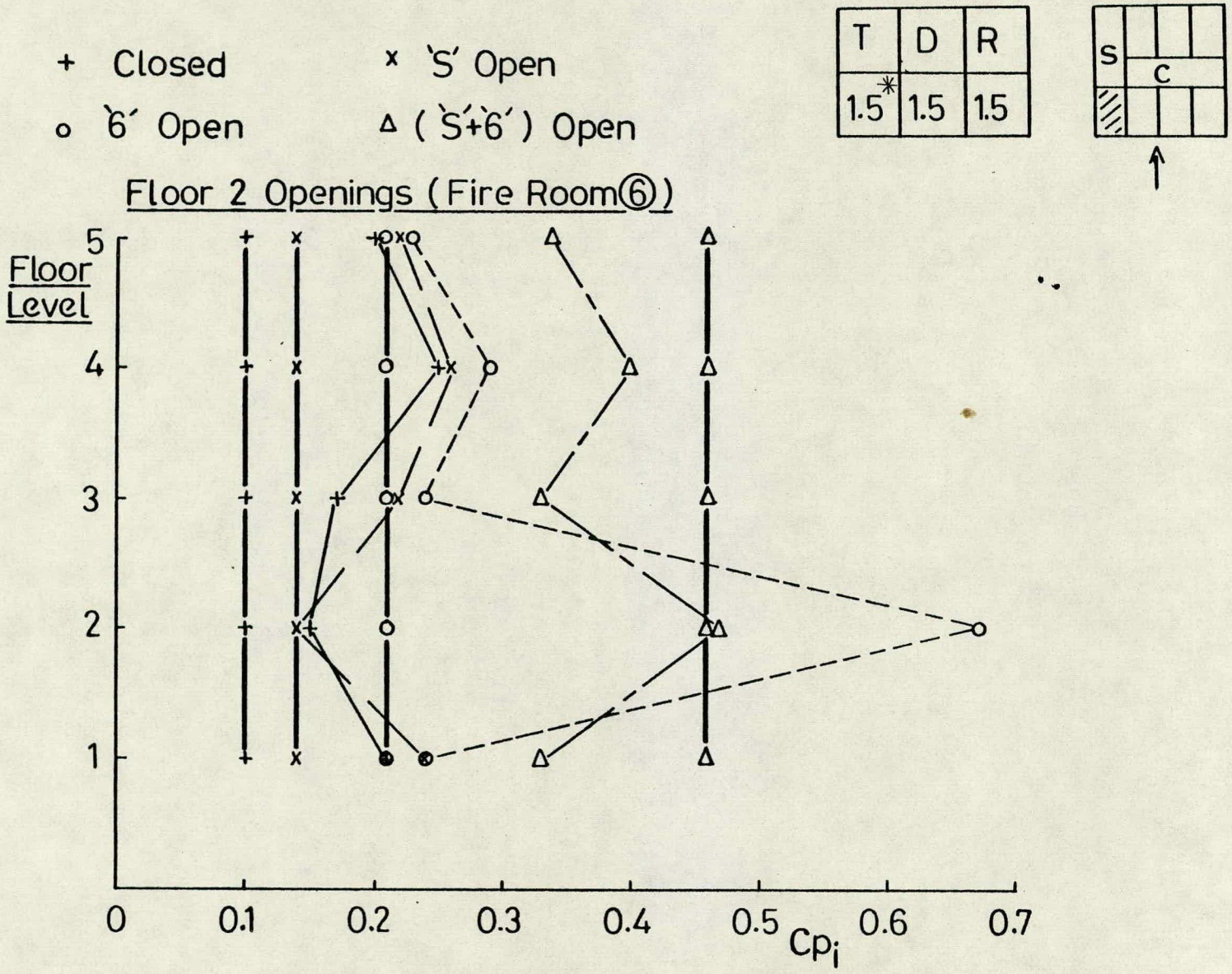


Fig 4.5.5: Shaft and Corridor Wind Induced Pressures, $\alpha = 180^{o}$, Leakage (b), with 'Fire'.

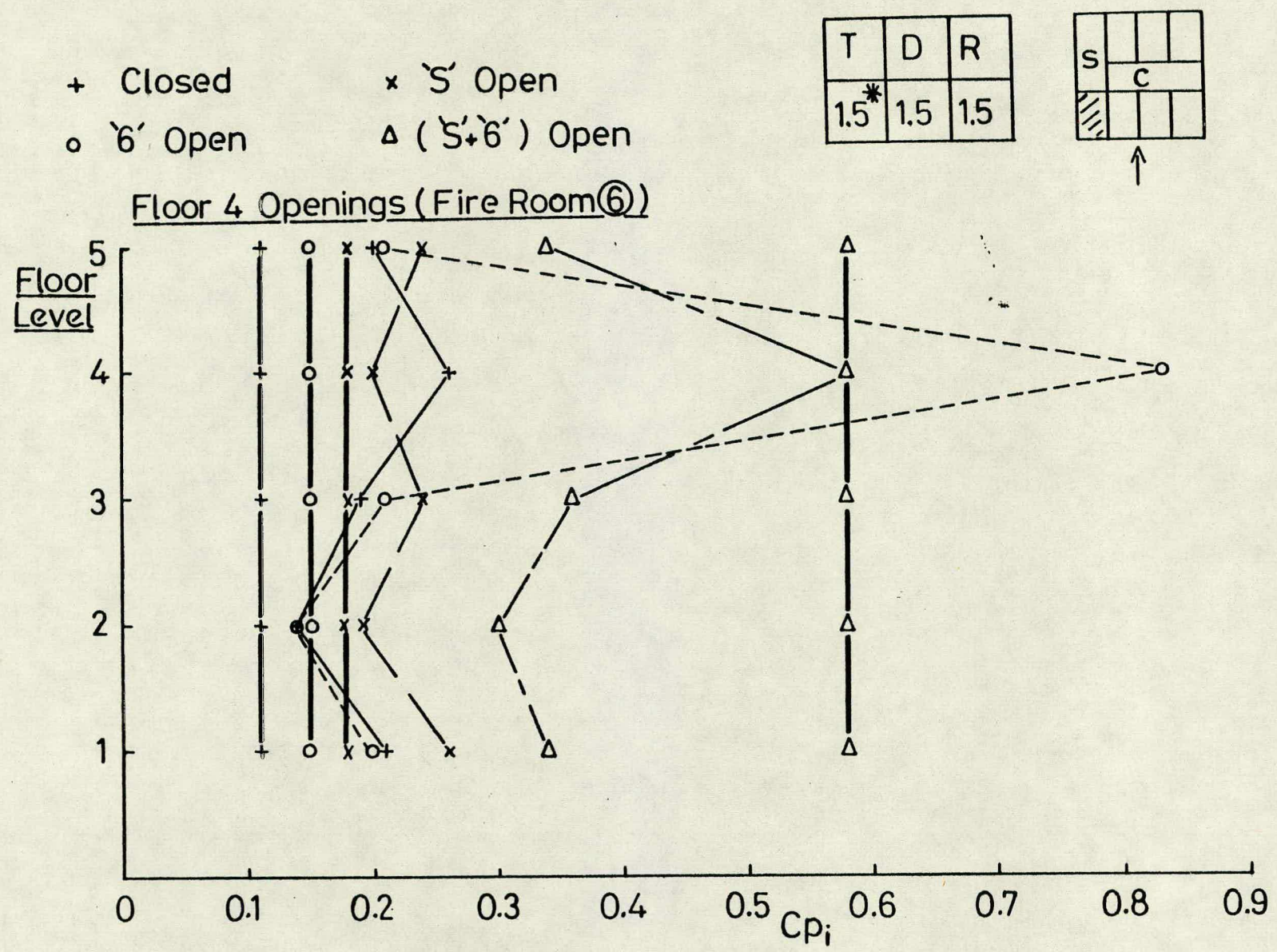


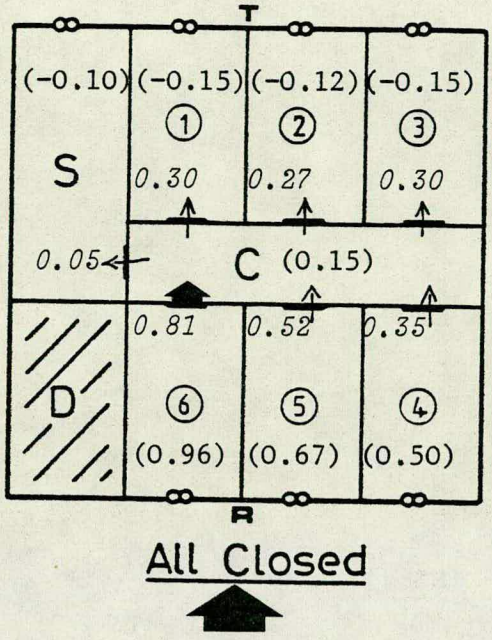
Fig 4.5.6: Shaft and Corridor Wind Induced Pressures, $\alpha = 180^{o}$, Leakage (b), with 'Fire'.

Incidence , α = 180°

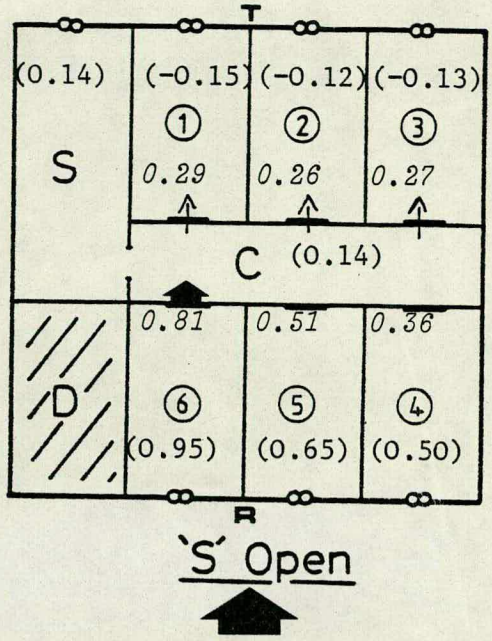
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

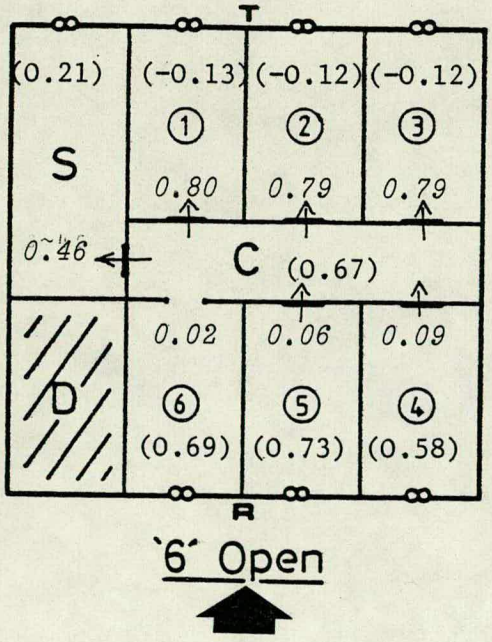
FLOOR 2 (Fire Room ⑥)



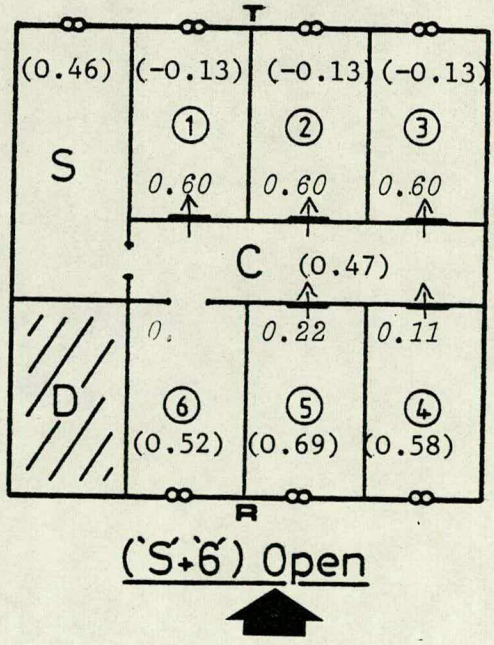
All Closed



'S' Open



'6' Open



('S'+'6') Open

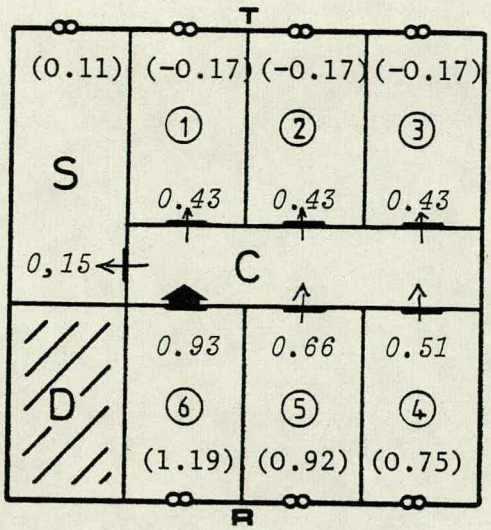
Fig 4.5.7: Wind Induced Pressure Distribution, α = 180°

Incidence, α = 180°

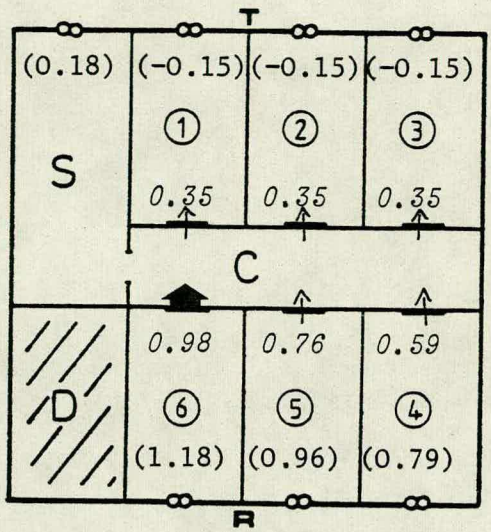
C_{pi} in ( )

T	D	R
1.5*	1.5	1.5

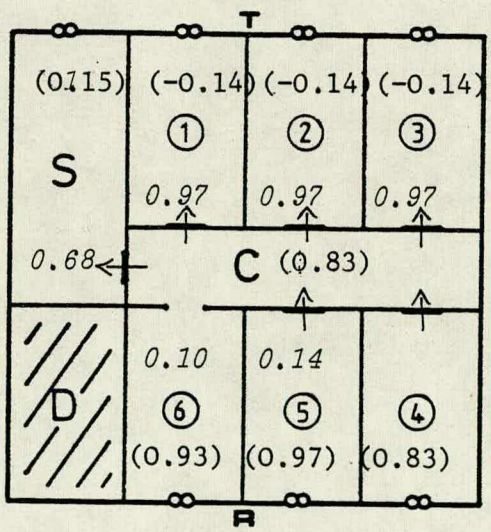
FLOOR 4 (Fire Room ⑥)



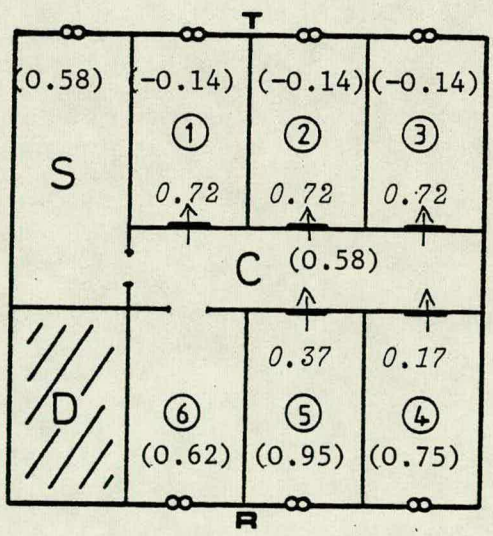
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.5.8: Wind Induced Pressure Distribution, α = 180°

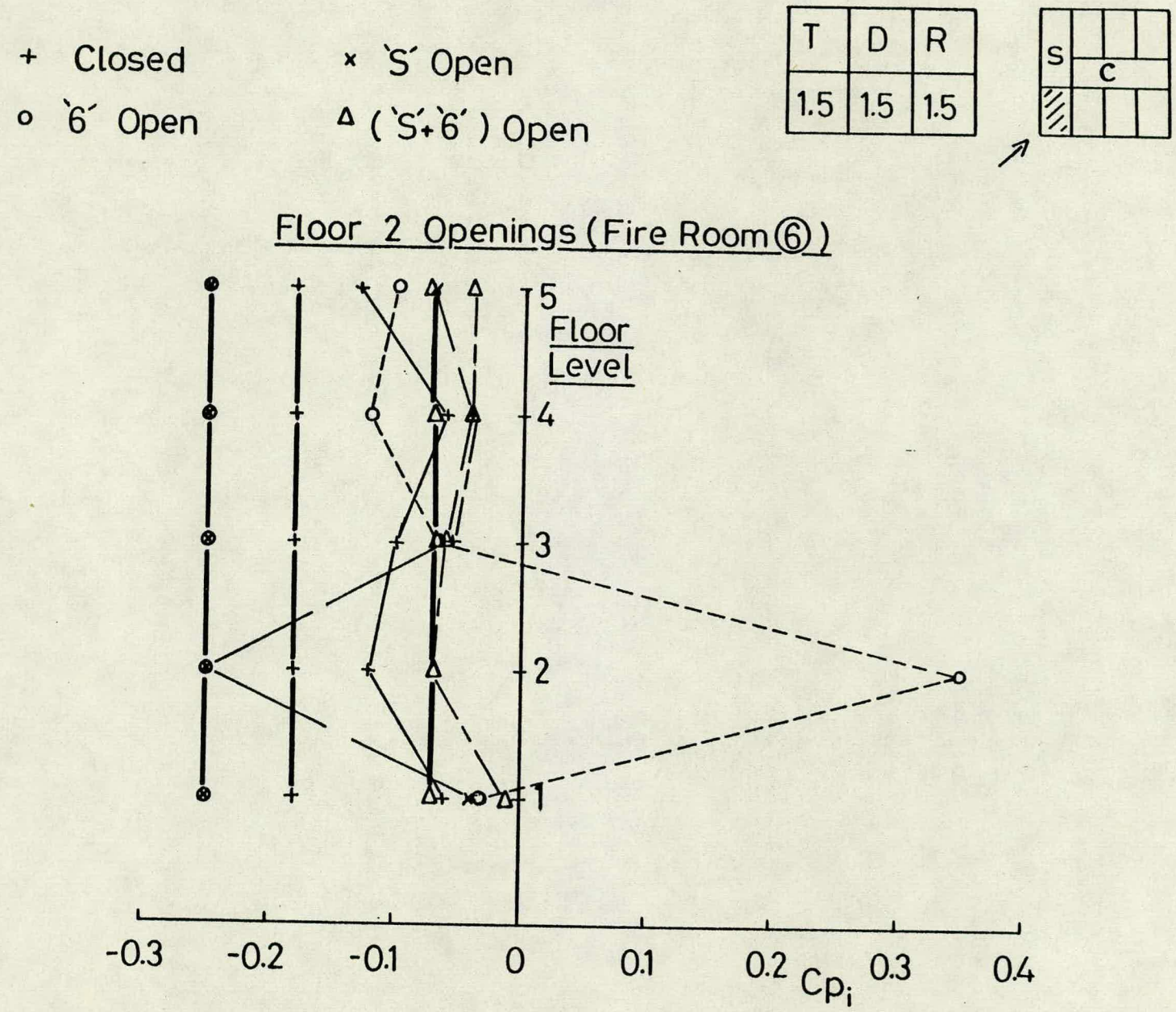


Fig 4.6.1.: Shaft and Corridor Wind Induced Pressures, $\alpha = 225^{o}$, Leakage (a), with 'Fire'.

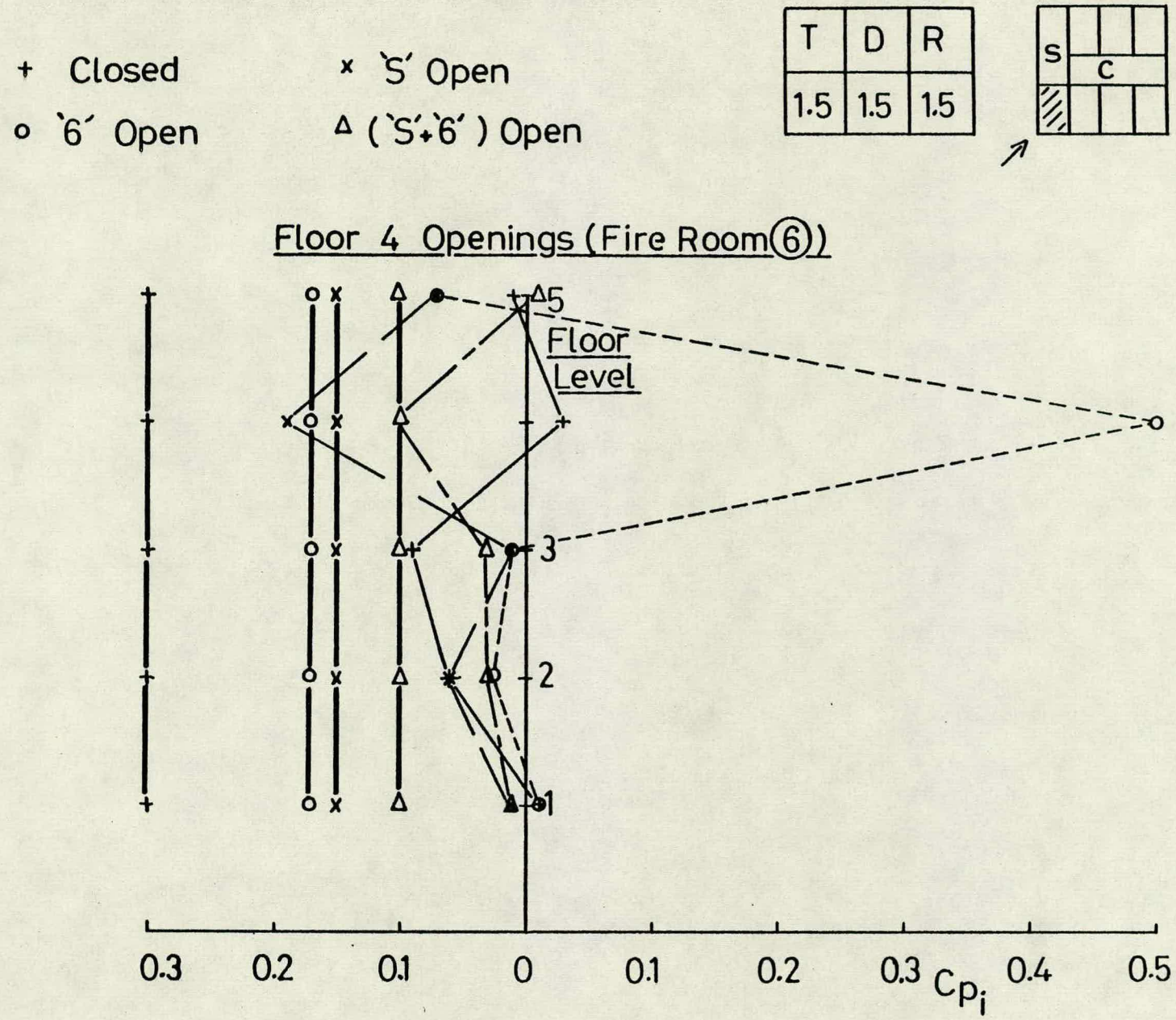
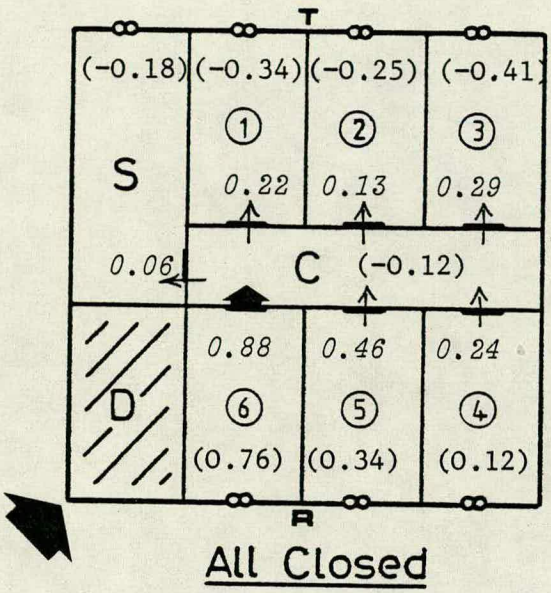


Fig 4.6.2: Shaft and Corridor Wind Induced Pressures, $\alpha = 225^{o}$, Leakage (a), with 'Fire'.

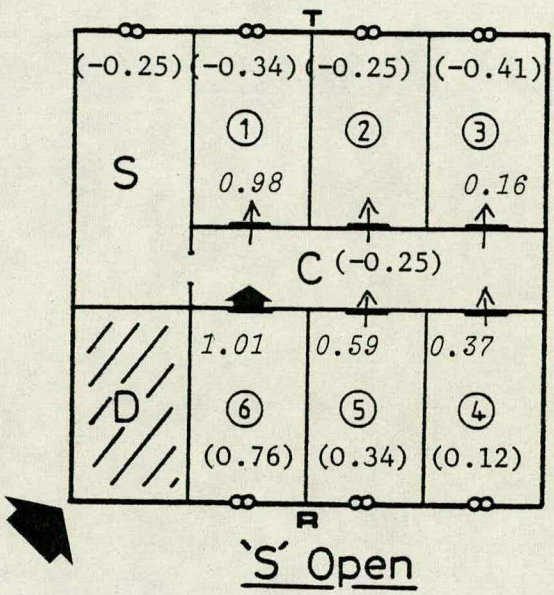
Incidence , α = 225°
Cp_i in ( )

T	D	R
1.5	1.5	1.5

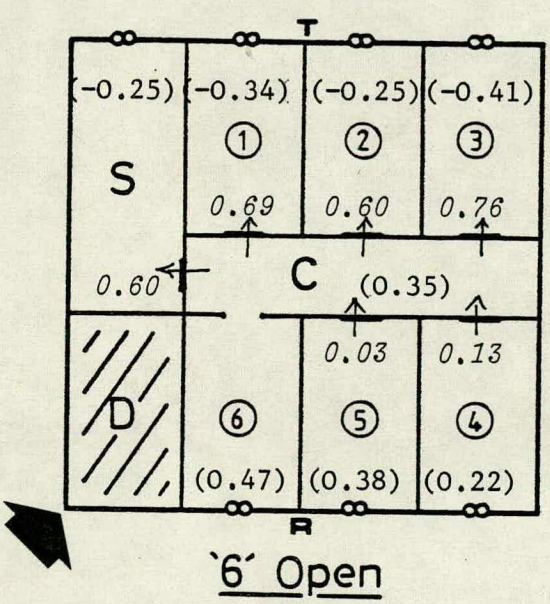
FLOOR 2 (Fire Room ⑥)



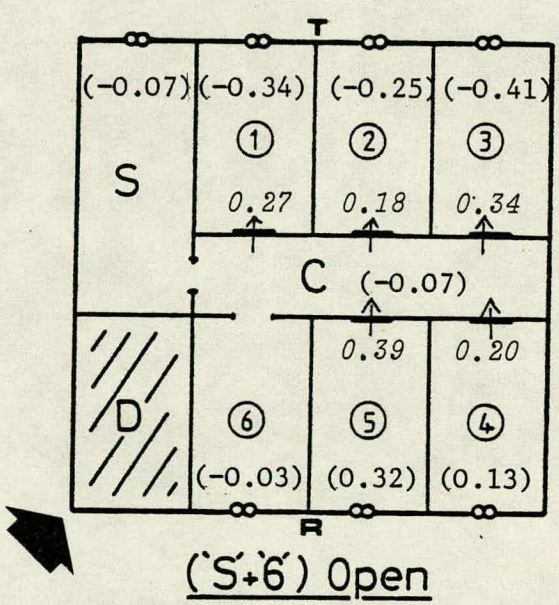
All Closed



'S' Open



'6' Open



('S'+'6') Open

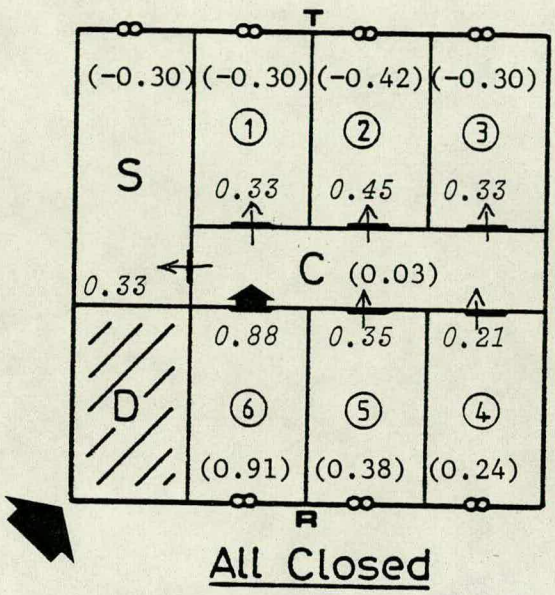
Fig 4.6.3: Wind Induced Pressure Distribution, α = 225°

Incidence, α = 225°

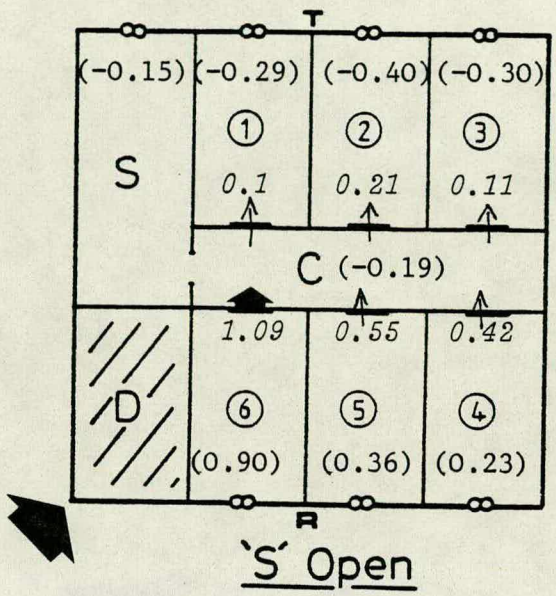
C_{pi} in ( )

T	D	R
1.5	1.5	1.5

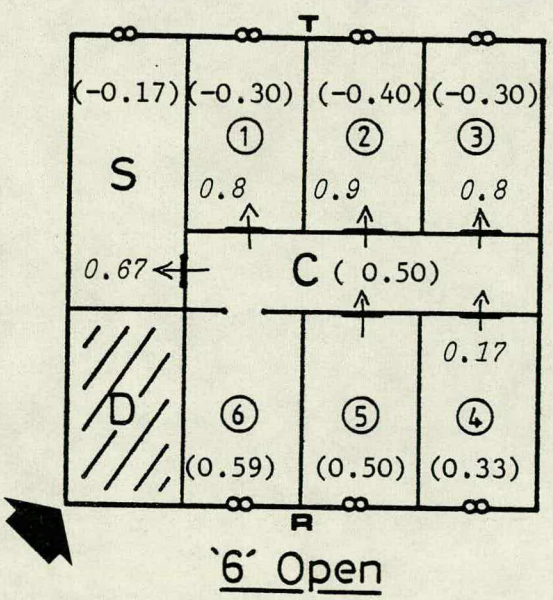
FLOOR 4 (Fire Room ⑥)



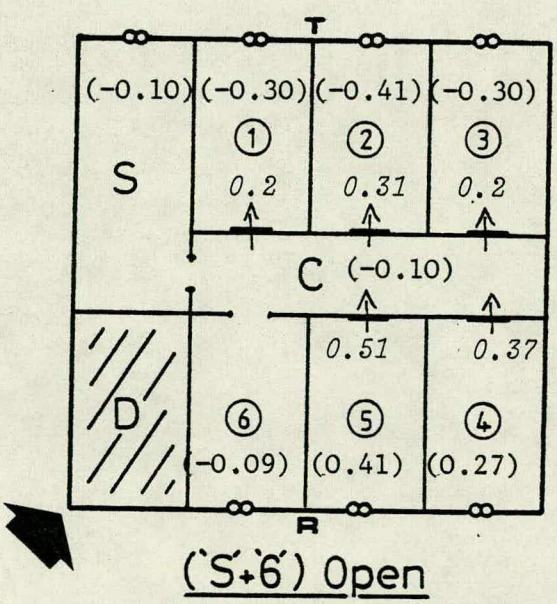
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.6.4: Wind Induced Pressure Distribution, α = 225°

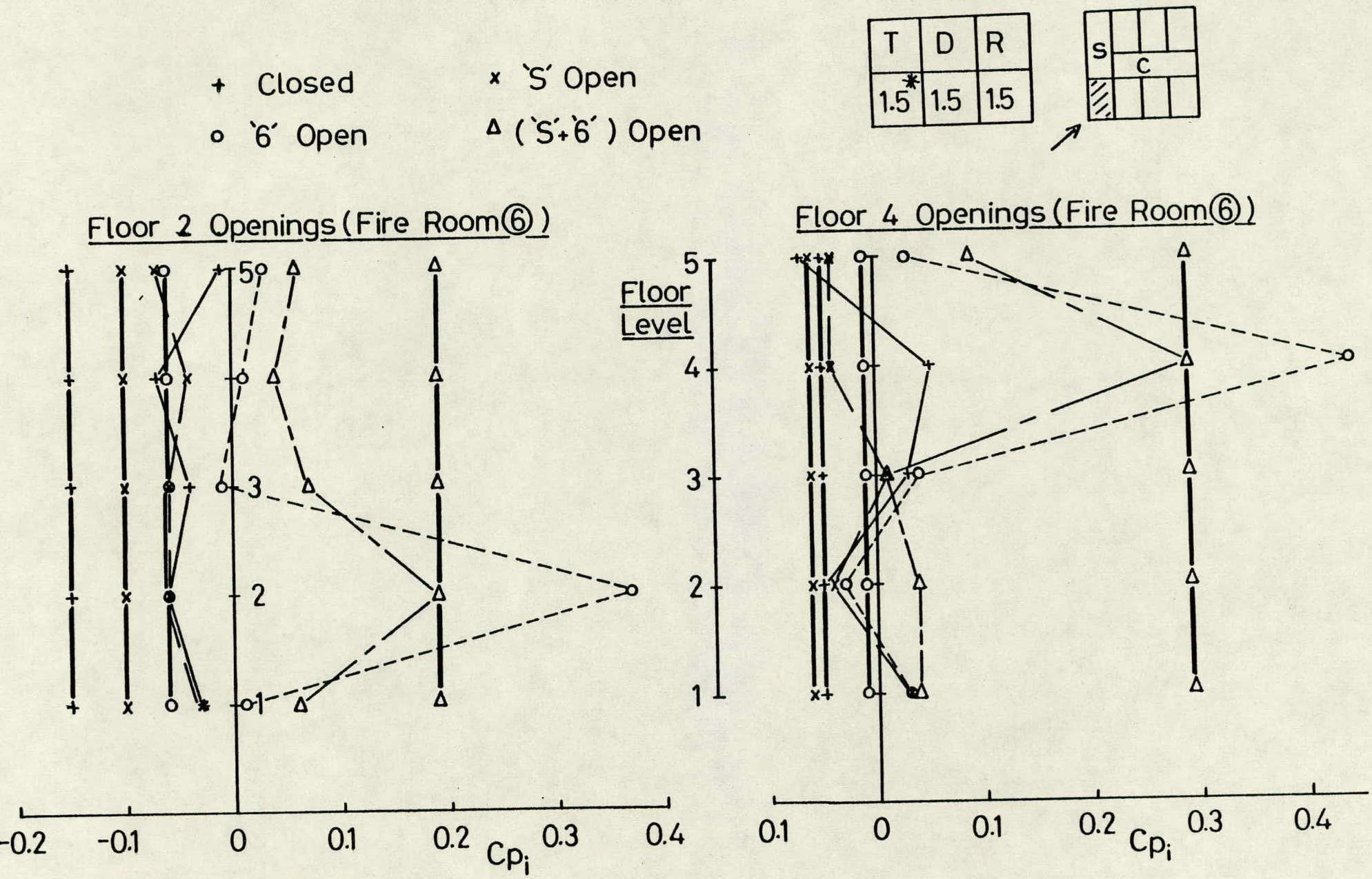


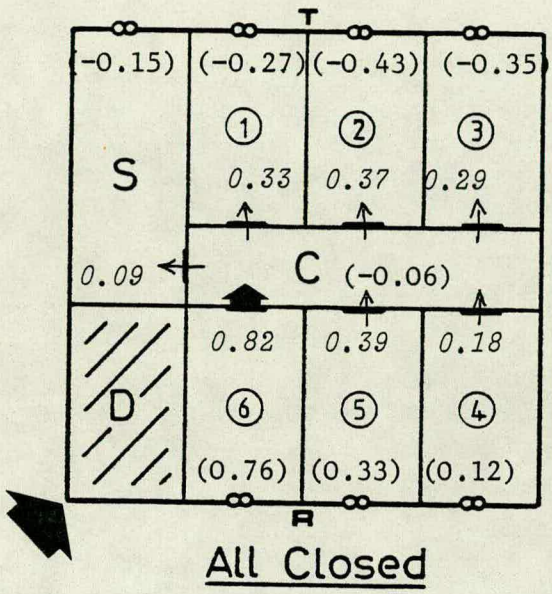
Fig 4.6.5: Shaft and Corridor Wind Induced Pressures, $\alpha = 225^{o}$, Leakage (b), with 'Fire'.

Incidence, α = 225°

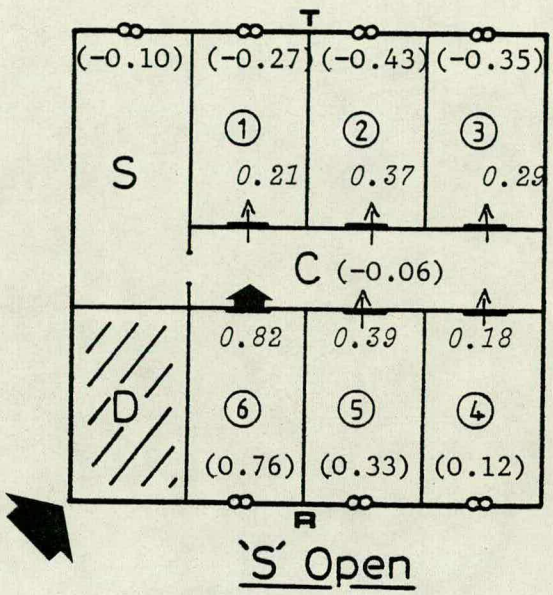
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

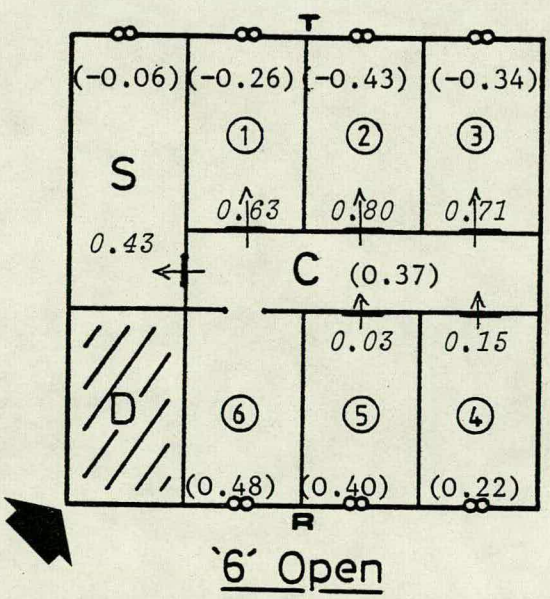
FLOOR 2 (Fire Room ⑥)



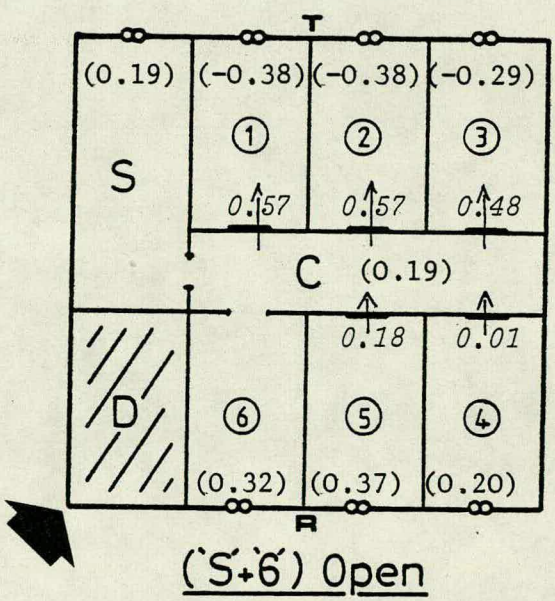
All Closed



'S' Open



'6' Open



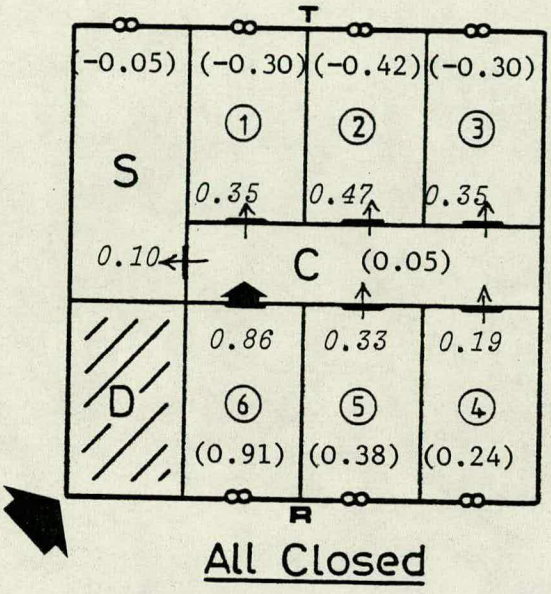
('S'+'6') Open

Fig 4.6.6: Wind Induced Pressure Distribution, α = 225°

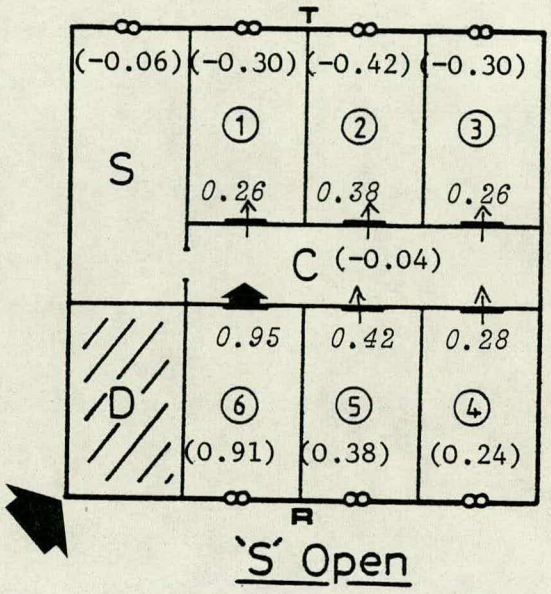
Incidence, α = 225°
Cp_i in ( )

T	D	R
1.5*	1.5	1.5

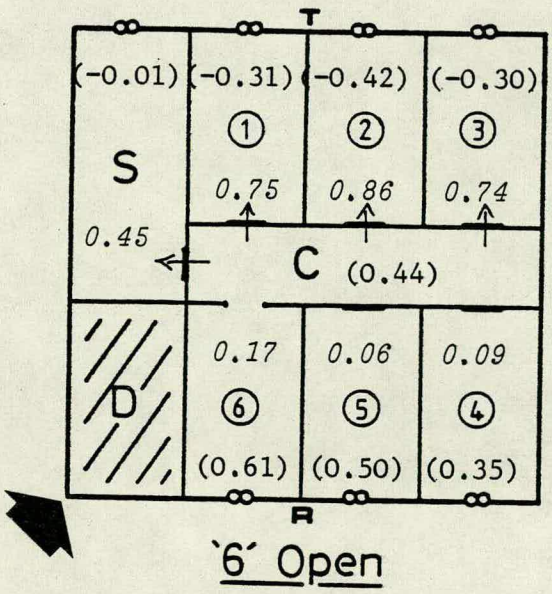
FLOOR 4 (Fire Room ⑥)



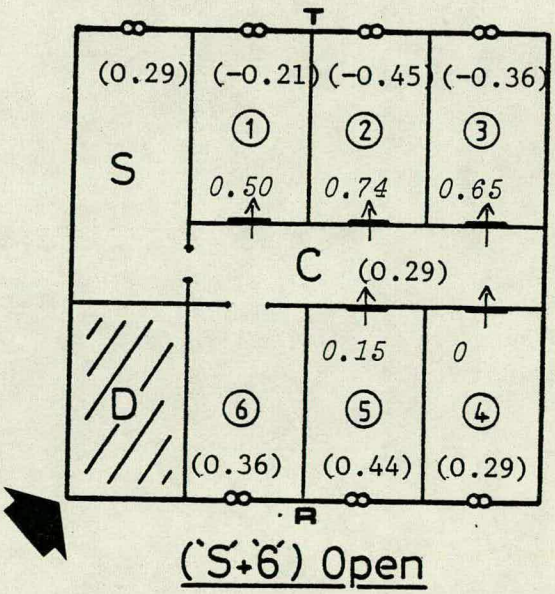
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.6.7: Wind Induced Pressure Distribution, α = 225°

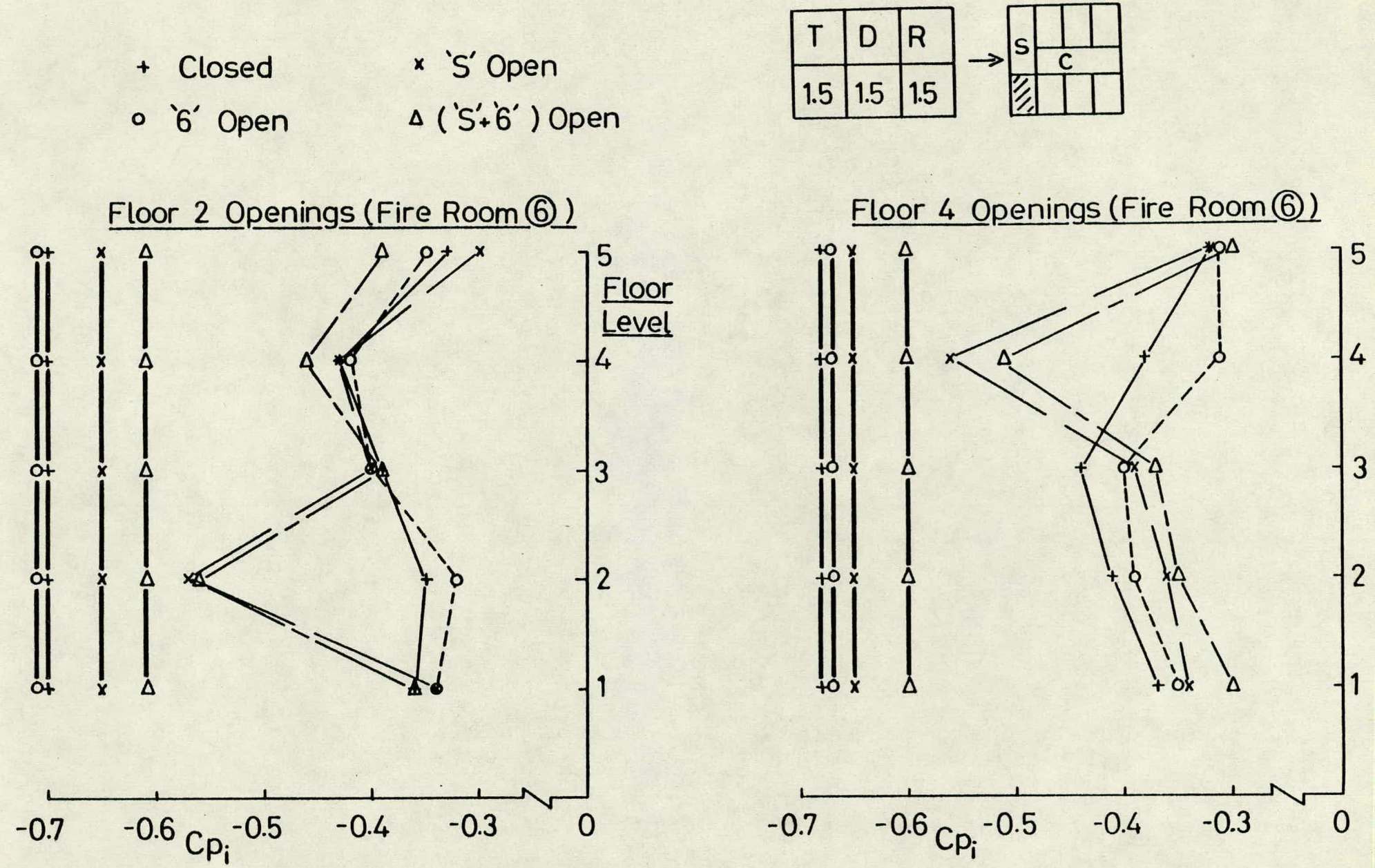
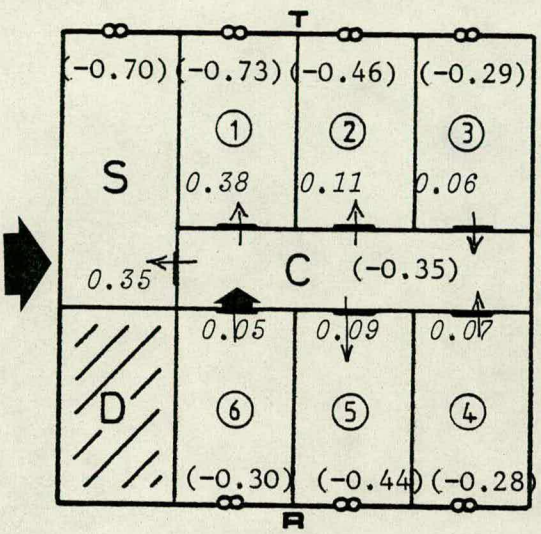


Fig 4.7.1: Shaft and Corridor Wind Induced Pressures, $\alpha = 270^{o}$, Leakage (a), with 'Fire'.

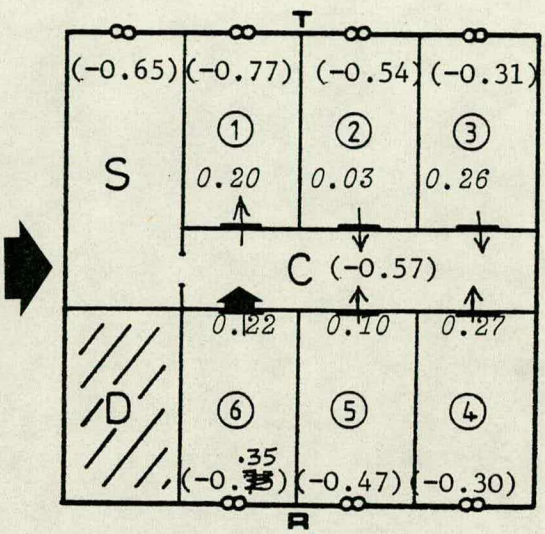
Incidence, α = 270°
C_{p_i} in ( )

T	D	R
1.5	1.5	1.5

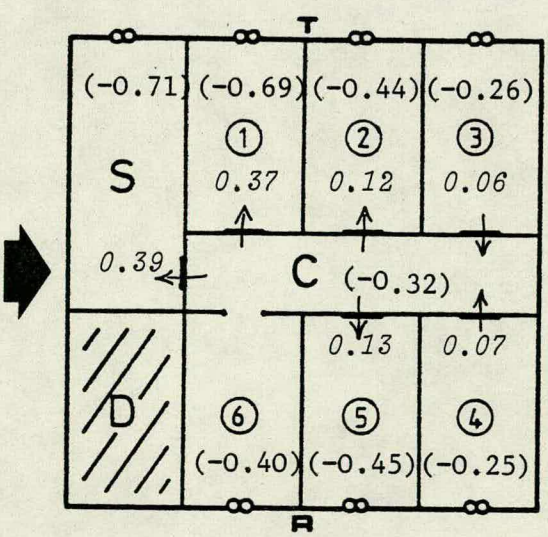
FLOOR 2 (Fire Room ⑥)



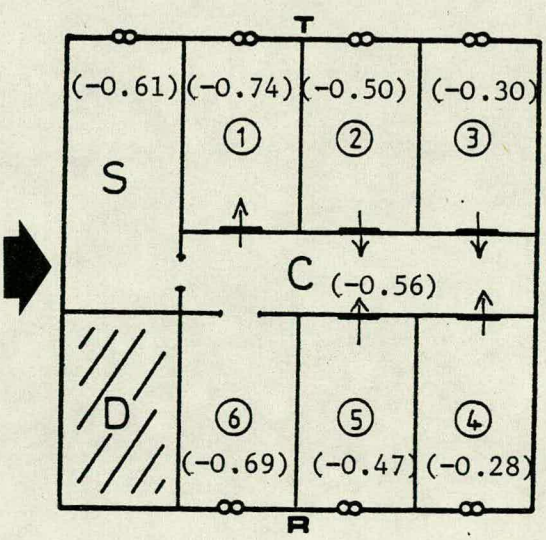
All Closed



'S' Open



'6' Open



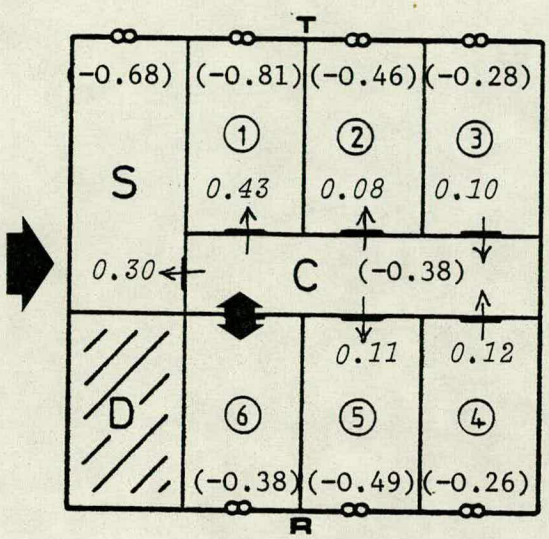
('S'+'6') Open

Fig 4.7.2: Wind Induced Pressure Distribution, α = 270°

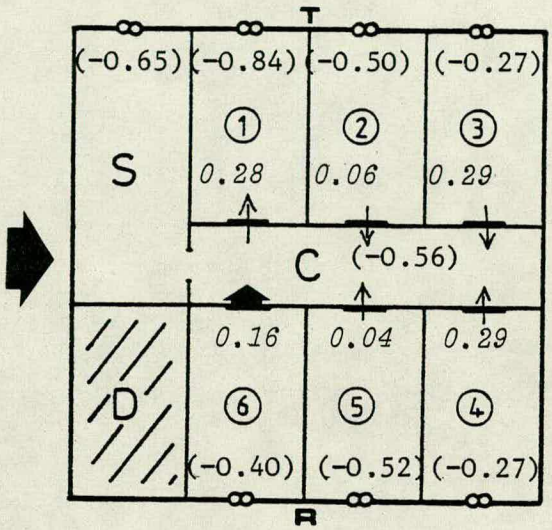
Incidence, α = 270°
C_{pi} in ( )

T	D	R
1.5	1.5	1.5

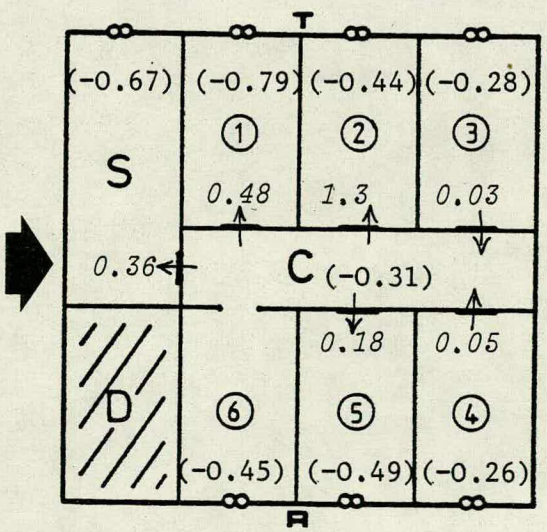
FLOOR 4 (Fire Room ⑥)



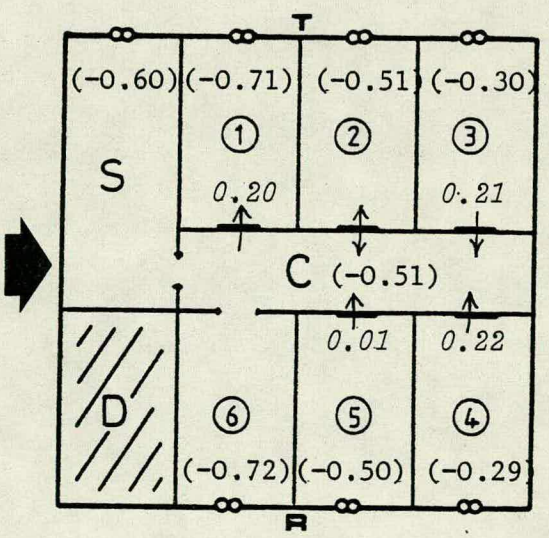
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.7.3: Wind Induced Pressure Distribution, α = 270°

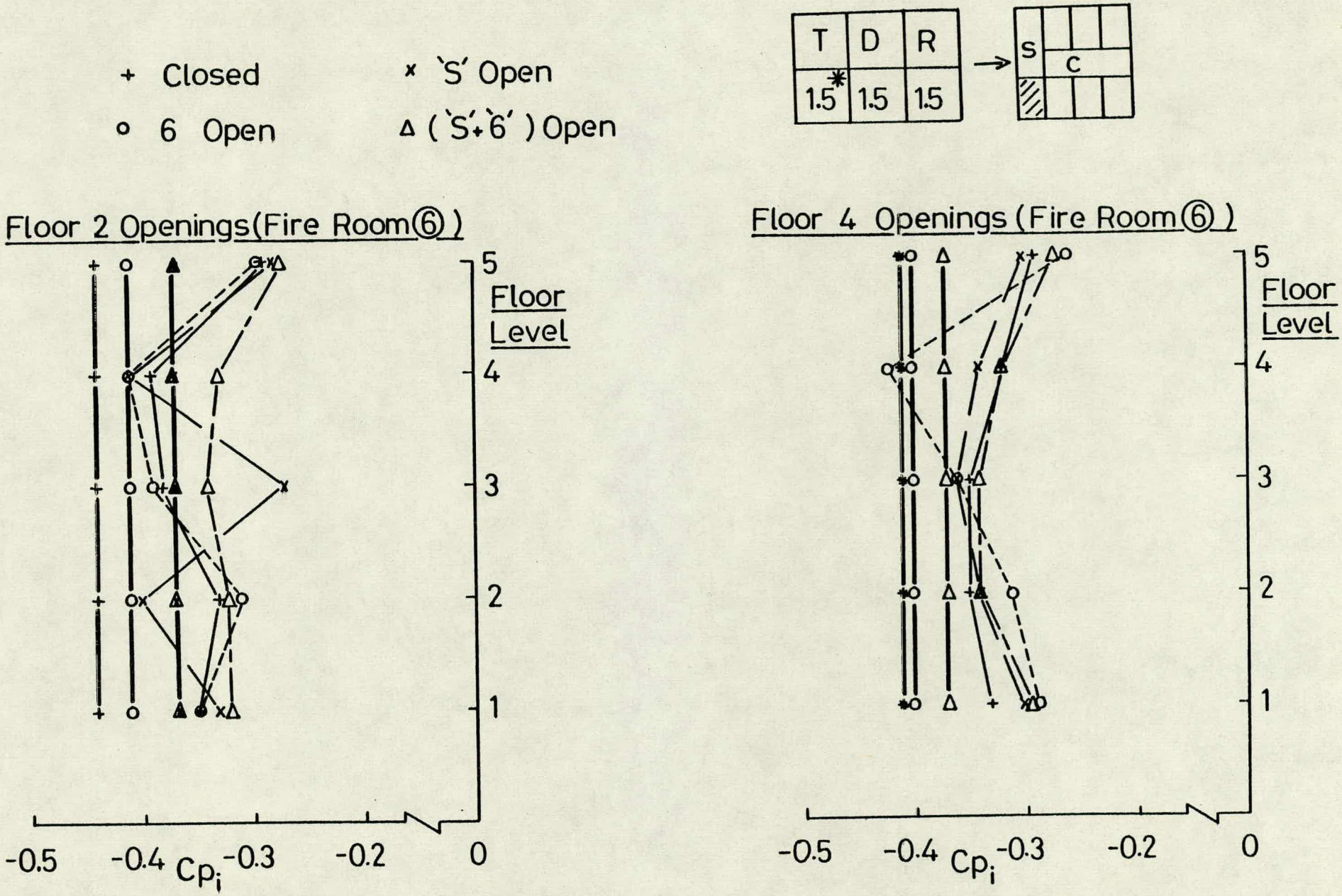
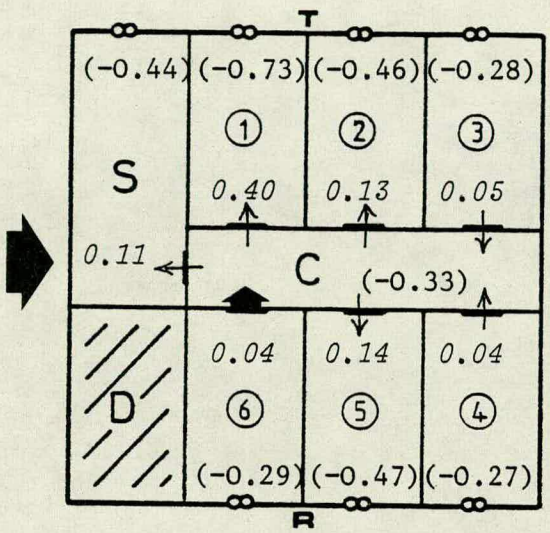


Fig 4.7.4: Shaft and Corridor Wind Induced Pressures, $\alpha = 270^{o}$, Leakage (b), with 'Fire'.

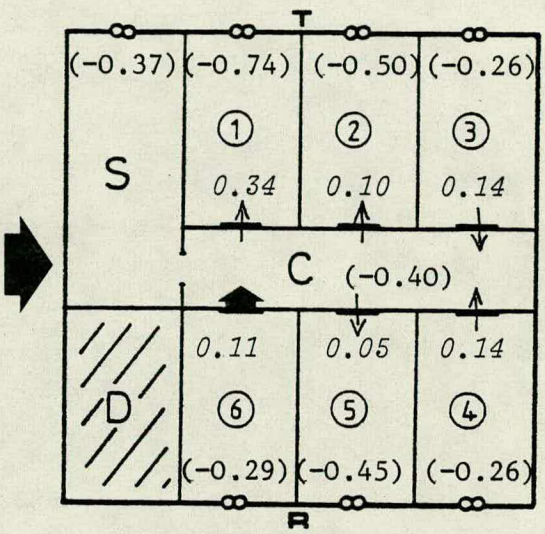
Incidence, α = 270°
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

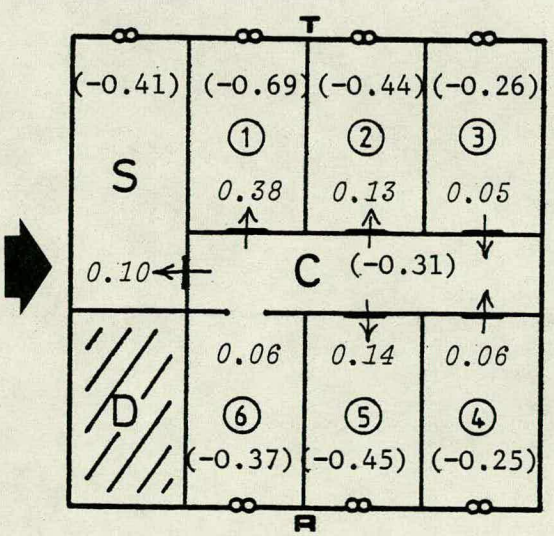
FLOOR 2 (Fire Room ⑥)



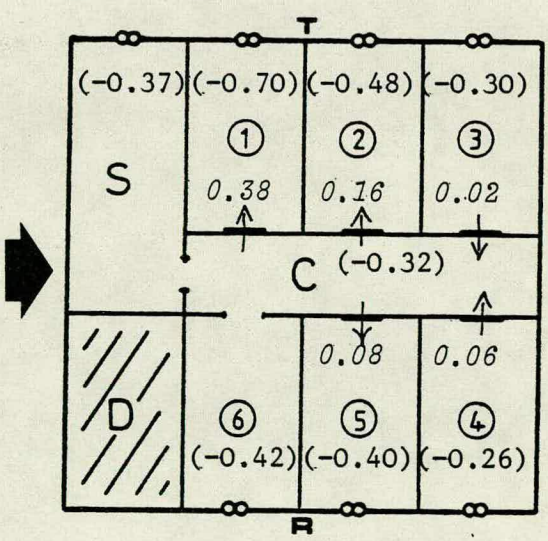
All Closed



'S' Open



'6' Open



('S'+'6') Open

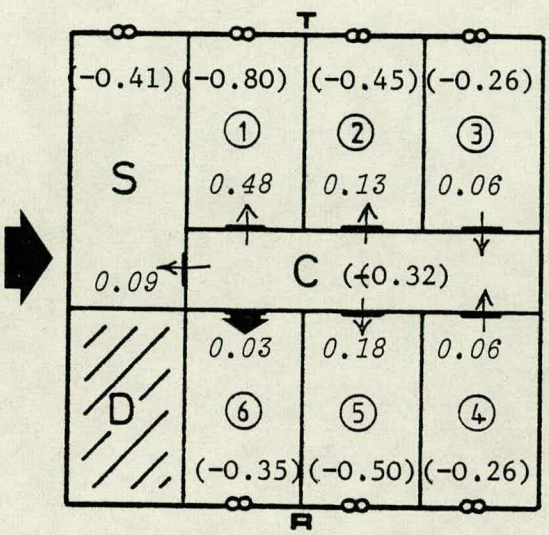
Fig 4.7.5: Wind Induced Pressure Distribution, α = 270°

Incidence, α = 270°

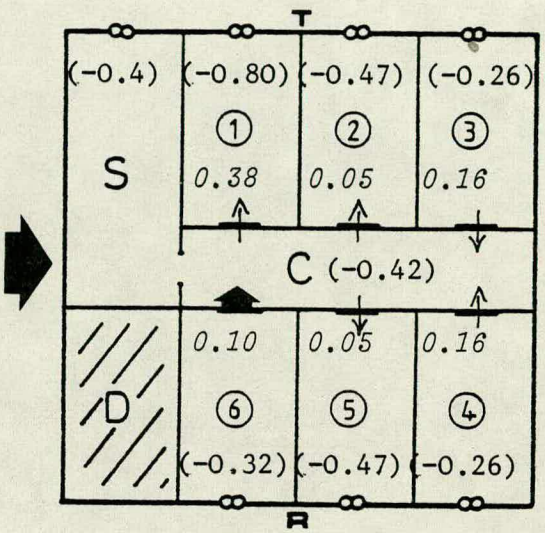
C_{p_i} in ( )

T	D	R
1.5*	1.5	1.5

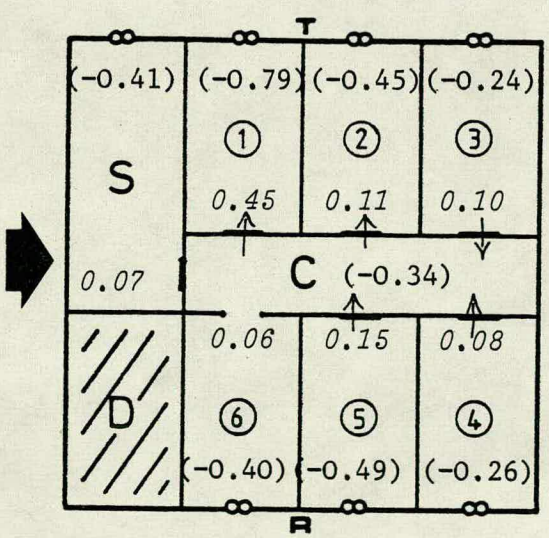
FLOOR 4 (Fire Room ⑥)



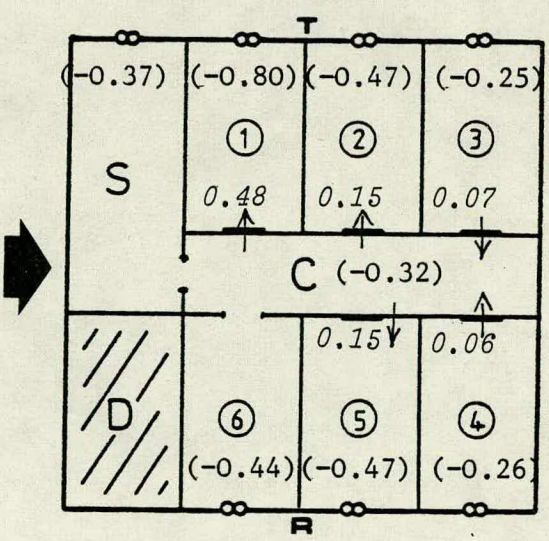
All Closed



'S' Open



'6' Open



('S'+'6') Open

Fig 4.7.6: Wind Induced Pressure Distribution, α = 270°

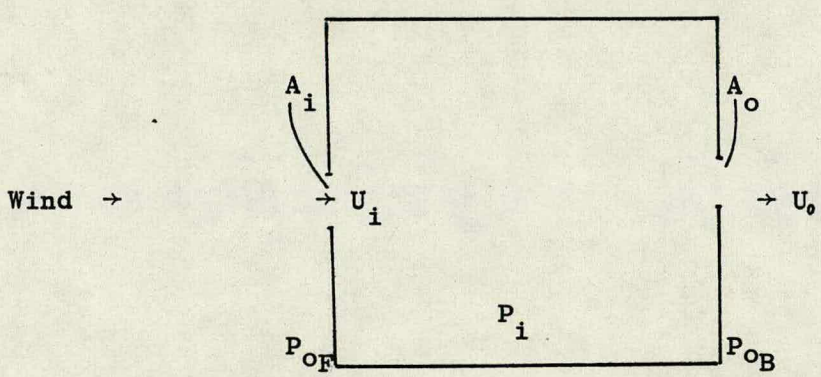
APPENDIX A

APPENDIX A

Wind Effect

The foregoing is a very simplified theory for vent design as it does not take wind effects into consideration. Almost all such buildings are subject to wind pressures. In some cases (for large buildings) such pressures can be much larger than the buoyancy pressures.

Consider a simple case: a building with two leakage openings on the opposite sides.



Further, suppose that wind blows normal to one of the walls, as shown above.

Define leakage ratio, R, as

$$R_L = \frac{\Sigma \text{ Front wall leakages}}{\Sigma \text{ Back wall leakages}} = \frac{A_i}{A_o} \qquad \text{.....(A1)}$$

Applying Bernoull's relation to the front wall opening

$$P_{o_F} - P_i = \tfrac{1}{2} \rho U_i^2 \qquad \text{..... (A2)}$$

where P_{o_F} - outside pressure on the front wall

P_i - pressure inside the building.

∴ Mass of air flowing into the building is

$$M_i = \rho A_i U_i C_i \qquad \text{..... (A3)}$$

where C_i is the discharge coefficient.

From (A2) $$U_i = \sqrt{\frac{2(P_{o_F} - P_i)}{\rho}} \qquad \text{.....(A4)}$$

$$\therefore M_i = C_i \rho A_i \sqrt{\frac{2(P_{o_F} - P_i)}{\rho}} \qquad \text{..... (A5)}$$

Similarly for the back wall

$$M_o = C_o \rho A_o U_o \qquad \text{..... (A6)}$$

or $$M_o = C_o \rho A_o \sqrt{\frac{2(P_i - P_{o_B})}{\rho}} \qquad \text{..... (A7)}$$

In the steady state condition, inflow must equal outflow, i.e.

$$M_i = M_o \qquad \text{..... (A8)}$$

provided two openings are similar, then $C_i = C_o$.

$$\therefore A_i \sqrt{P_{o_F} - P_i} = A_o \sqrt{P_i - P_{o_B}} \qquad \text{..... (A9)}$$

or $$\frac{P_{o_F} - P_i}{P_i - P_{o_B}} = \frac{A_o^2}{A_i^2} \qquad \text{..... (A10)}$$

or in terms of pressure coefficients

$$\frac{Cp_{o_F} - Cp_i}{Cp_i - Cp_{o_B}} = \left(\frac{A_o}{A_i}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (A11)$$

$$\text{or} \quad Cp_i = \frac{\left(Cp_{o_B} + \frac{A_i^2}{A_o^2} Cp_{o_F}\right)}{\frac{A_i^2}{A_o^2} + 1} \quad \ldots\ldots\ldots\ldots\ldots \quad (A12)$$

$$\text{or} \quad Cp_i = \left(\frac{Cp_{o_B} + R_L^2 \, Cp_{o_F}}{R_L + 1}\right) \quad \ldots\ldots\ldots\ldots\ldots \quad (A13)$$

Therefore, for this particular case, we have a simple relationship to work out the inside pressure coefficient. This depends highly on the leakage ratio, R_L, and the pressures on the walls on which these leakages are situated.

APPENDIX B

APPENDIX B

Computer Program for Smoke Flow Analysis

A number of computer programs dealing with the smoke movement within buildings are used in the United States, Japan and here in Britain: they are very similar. The one used in the States was reported by Barrett and Locklin (1) some time ago. Their program enables them to study -

a) Air flow quantities through all flow paths

b) Pressure difference across doors

c) Pressure in all spaces

d) Infiltration and exfiltration through exterior walls

e) Smoke concentration with time at any location.

The computer technique used is very similar to the one described presently.

The Japanese program reported by Wakamatsu (4) was also developed on the same lines.

With the increasing number of high rise buildings here in this country, the Fire Research Station, in collaboration with Scientific Controls Ltd in 1973, developed a similar program. A modified version of that program is used in the Department of Fire Safety Engineering at Edinburgh University to study the smoke control problem in high-rise buildings. At the moment a ten-storey high building belonging to the University is being used for this purpose. The results obtained will be discussed later.

Smoke Movement in Buildings

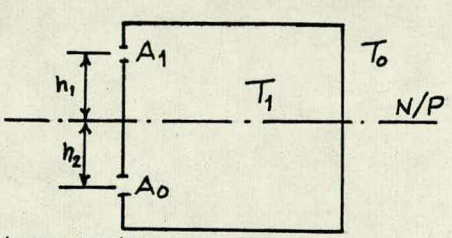
The factors that influence the movement of air within a building are:

1. Stack effect
2. Wind
3. Ventilation systems
4. Fire.

If we have a building with the inside temperature higher than the surroundings, then the density of the inside air is lower than that of the outside environment. This inside warmer air rises up through the shafts, and as a result, outside cool air rushes into the building through the door and window cracks, or any other leakages. This happens at the lower half of the building. At the upper levels the opposite is true with the air rushing out of the building. The air flow pattern resulting this way is called the 'stack effect'.

Such inflows and outflows suggest that there must be a level at which air neither flows into the building nor out of it. In other words, the inside and outside pressures at that level are the same. This is referred to as the neutral pressure plane. The height of this neutral pressure plane depends on the relative leakage areas at the high and low levels. In fact it can easily be shown that -

$$\frac{h_1}{h_2} = \frac{T_1 A_o^2}{T_o A_1^2}$$

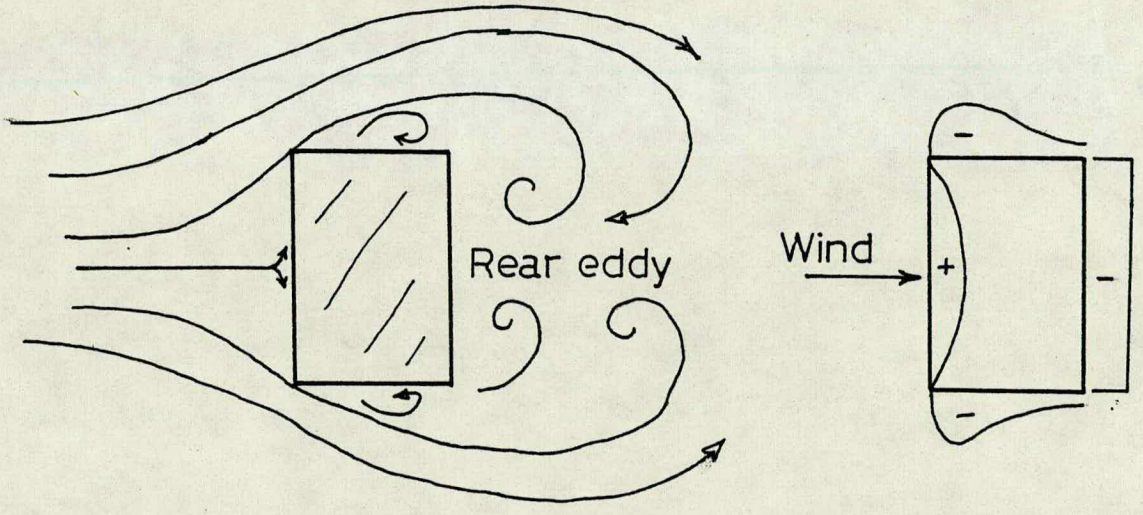


It also depends on the inside and outside temperatures.

Wind Effect

Air flow around and over a building causes variations in pressure around it. Distribution of pressures over building surfaces depends on wind speed and direction, height and shape of the building and surrounding terrain.

When wind blows normally to one face of a building, it is slowed down against that face which experiences a build up of pressure. At the same time it is deflected and accelerated around the end walls and over the roof with a consequential reduction of pressure, i.e. suction, exerted on these areas. A large eddy is created behind the building which exerts a suction on the rear face.



The figures above illustrate the qualitative flow pattern. As can be seen, except for the back wall, the pressures are not constant over the surfaces. In fact the measurements made here in the Department of Fire Safety Engineering on simple models show that the

Cp_o variations are as follows:

Front Wall	Side Walls	Back Wall
1.0 to 0.4	-1.0 to-0.2	-0.3

These values change with the change in wind direction.

The pressure coefficient, Cp_o, is defined as -

$$Cp_o = \frac{P - P_o}{\frac{1}{2}\rho U^2}$$

where P = total pressure at a level

P_o = static pressure at that level

U = wind speed

ρ = air density.

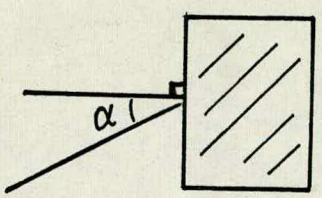
For the complete analysis it is assumed that -

$Cp_o = 0.75$ $\quad 0^o < |\alpha| \leqslant 30^o$

$Cp_o = -0.021\,\alpha + 1.38$ $\quad 30^o < |\alpha| \leqslant 90^o$

$Cp_o = -0.5$ $\quad |\alpha| > 90^o$

where α is defined as



and the form of the velocity profile is

$$U \propto h^{\gamma}$$

where γ = 0.17 open country

γ = 0.35 urban areas.

Ventilation Systems

In such systems air is fed into and extracted from various parts of the building at fixed flow rates. In the event of a fire, this system could considerably accelerate the circulation of smoke to other parts of the building. It is common practice, on the automatic detection of fire, to switch off the system. For this reason the effect of mechanical ventilation is ignored in the program.

Fire Compartment

The whole of the fire compartment is assumed to be at a uniform high temperature. Because of the temperature differential between the compartment and the air outside it, a neutral axis exists at each opening. Cold air flows into the compartment below the neutral axis and hot gases flow out above this axis. In the program it is assumed that the height of this neutral plane is the same for all openings as that at the door of the room. Again, this height is determined by the relative leakage areas above and below the neutral axis.

Any mass production by the fire is neglected and it is assumed that the temperature has reached a steady - i.e. initial expansion ignored. Therefore fire is specified by two parameters.

1. Temperature of the fire compartment.
2. Some measure of concentration of smoke emerging from the fire compartment.

Flow Paths

Air flows from the regions of high pressure to regions of low pressure. The flow rate depends on the resistance offered by the openings. In buildings these openings are the doors and windows. Leakage flow also occurs through roof and walls but it is very small compared with that through doors and windows and it is ignored.

In general, if the pressure difference across an opening is ΔP, then the mass flow rate through the opening is

$$M \propto (\Delta P)^{1/n}$$

where n depends on the shape of the opening, e.g.

n = 2 for cracks around closed doors

n = 1.6 for cracks around closed windows.

For simplicity, n is assumed to be equal to 2 in the program. Therefore the mass flow rate, M, can be written as -

$$M = \sqrt{\frac{\Delta P}{R_f}}$$

where R_f = flow resistance of the opening

$$= \frac{1}{2\rho\ (Cd\ A)^2}$$

where Cd = flow coefficient of the opening

ρ = density of air

A = area of the opening.

The value of Cd is assumed to be 0.65.

Smoke Spread and Concentration

Using the above relationships between flow rate and pressure difference across each flow path, the values of M and ΔP are known at all openings.

In order to estimate the safety of occupants in different parts of the building, it is important to know the length of time smoke takes to reach different parts and how it spreads or how concentration builds up after this time.

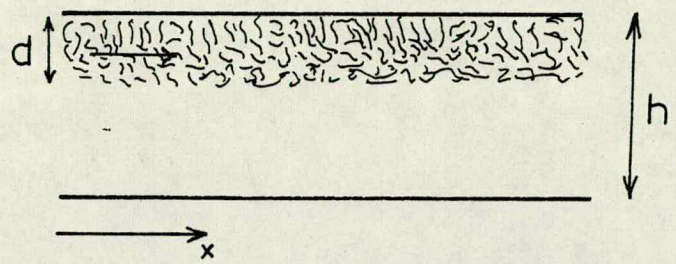
During the initial stages of the fire, smoke spread is exceedingly complex, because the air flow system is in a very unsteady state due to the transient temperatures in the vicinity of the fire. It is therefore assumed that the flow is in a steady state throughout the fire. In other words, this implies that the temperatures in all parts of the building, including the fire compartment, are stable.

The knowledge of M and ΔP, enables the smoke concentration to be calculated in all parts of the building. To do this, two assumptions are made -

1. The smoke diffuses instantaneously in all compartments except vertical shafts and the corridor outside the fire room.
2. The smoke head flows initially in vertical shafts at the same velocity as the flow in the steady state.

The concentration is determined relative to the concentration in the fire room.

Smoke Flow in the Corridor on the Fire Floor



As smoke flows out from the fire room it forms a layer under the ceiling in the corridor. Cool air enters the fire room at the bottom of the door and hot air leaves from the top.

The temperature of the layer is the function of distance, x, along the corridor from the fire room. In the program the form assumed is

$$\theta_x = K_1 \, \theta_f \, \ell^{-K_2 x}$$

where θ_x = temperature above ambient at x

θ_f = temperature above ambient in fire room, where K_1 and K_2 are constants.

K_1 = 0.05 fire door closed

K_1 = 0.5 fire door open

and K_2 is the measure of heat transfer to the walls

$$K_2 = \frac{H \, W \, K_1}{\dot{M}_o \, Cp}$$

where H = Newtonian heat transfer coefficient = 20 W/m^2 deg C.

W = width of the corridor

$\dot{M}_o$ = mass rate of flor of hot gases into the corridor

Cp = specific heat of smoke.

The depth, d, is assumed constant throughout the length of the corridor and is given by

$$d = 0.5\ h$$

The time taken for this layer to establish is given by

$$t = \frac{\ell\ W\ d\ K_1\ \rho_o}{m_o}$$

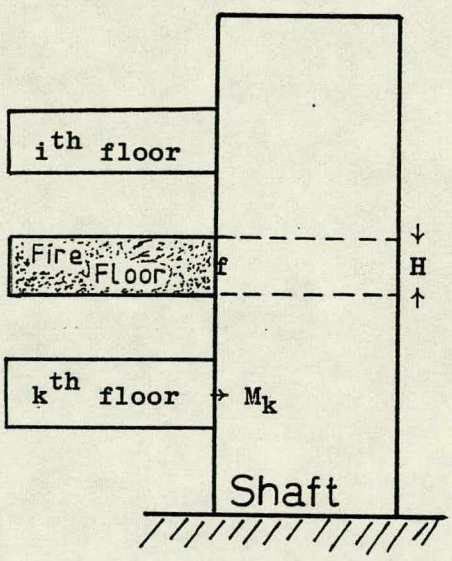
where ℓ = length of the corridor.

Smoke Flow in Vertical Shafts

In order to calculate the time for the smoke to reach other floors, we examine the way in which smoke moves in vertical shafts (stair and lift shafts). It is assumed that the smoke heat flows initially in the shaft at the same velocity as the flow in the steady state.

Suppose the mass rate of flow from the k^{th} floor into the shaft is M_k, then the total mass flowing into the shaft below the fire floor is

$$\sum_{k=1}^{f} M_k$$



Let us now consider the fire floor level. The amount of air (smoke) contained at that level is -

$$\rho HA$$

where ρ is the density at that level, and

A is the cross-sectional area of the shaft.

Divide this by the nett amount of air moving into the shaft to get the time at which the smoke will reach the i^{th} floor.

$$\therefore \quad T_i = \sum_{\eta=f}^{i-1} \frac{\rho HA}{\sum_{k=1}^{\eta}} \qquad i > f$$

Similarly if air is flowing into the building from the shaft at floors below the fire floor,

$$\text{i.e.} \quad \sum_{k=1}^{f-1} M_k < 0$$

then

$$T_i = \sum_{\eta=1}^{f-1} \frac{\rho HA}{-\sum_{k=1}^{i} M_k} \qquad i < f$$

and the concentration C_i at the i^{th} level is given by

$$C_i = \frac{\sum_{k=1}^{i} C_k M_k}{\sum_{k=1}^{i} M_k}$$

C_k is the concentration of smoke flowing into or out of the k^{th} floor.

Computer Technique

From the relationship derived earlier, i.e. from Bernoulh, which relates the pressure difference and mass flow rate, it is relatively simple to work out one unknown when others are known. In large buildings with hundreds of flow paths, the task is not so easy, hence the computers. To solve such large networks of flow paths, we make use of electrical network theory. In electrical theory, if the voltage drop, V, across a resistance, R, through which a current, I, is flowing, the flowing relationship holds,

$$\text{i.e.} \quad V = IR$$

This is somewhat similar to our equation relating pressure differences and mass flow rates.

For our flow network, we can obtain equations by the application of two laws -

(a) The law of constancy of mass at each node.

(b) Bernoulh's law.

These two are analogous to Kirchoff's first and second laws of electrical circuit theory.

If the building is divided into N nodes, and n flow paths, then the first law gives us (N-1) linearly independent equations of the form

$$\sum_{j=1}^{n} a_{ij} M_j = 0$$

where M_j = mass flow rate through j^{th} flow path.

$$a_{ij} \begin{cases} 0 \text{ if } j^{th} \text{ flow path is not incident on } i^{th} \text{ node} \\ \pm 1 \text{ otherwise} \end{cases}$$

Bernoulli's Law gives

$$\sum_{j=1}^{n} b_{ij} P_j = 0$$

where

P_j = pressure difference across the j^{th} flow path

b_{ij} $\begin{cases} = 0 \text{ if the } j^{th} \text{ flow path is not included in the } i^{th} \text{ circuit} \\ = \pm 1 \text{ otherwise.} \end{cases}$

This relationship gives (n - N + 1) linearly independent equation.

In addition we have terminal relations of the form -

$$P_j = \pm r_j M_j^2$$

giving us n equations.

∴ we have

$$(N-1) + (n-N+1) + n = 2n$$

linearly independent equations.

∴ In a building with let up of, say, one hundred flow paths, we have to solve two hundred equations: hence the computer.

If we compare the electrical relation of V = IR with our terminal relation $P_j = r_j M_j^2$, we see that ours is a non-linear equation, meaning that we cannot apply the electrical solution directly.

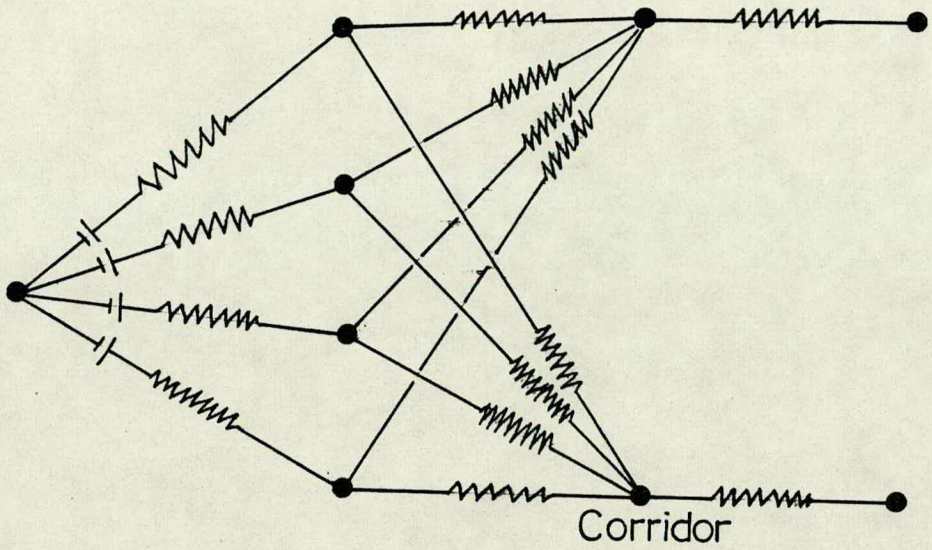
To get over this difficulty we use the linearisation technique which is iterative -

$$f(z) = f(a) + (z-a) f^1(a) _ _ _$$

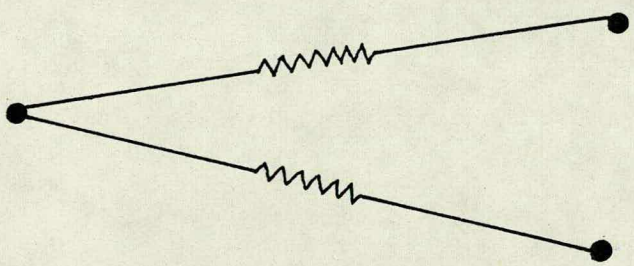
i.e. we start off assuming a solution and see if it converges or not after so many iterations.

We consider each floor in turn and write down the relationships for the flowpaths.

As the changing conditions on one floor affect what happens on other floors, the above solution is not good enough. To take into account the effect of other floors, we consider each floor as a unit and work out the relationship for the simplified network, relating outside with the shafts.

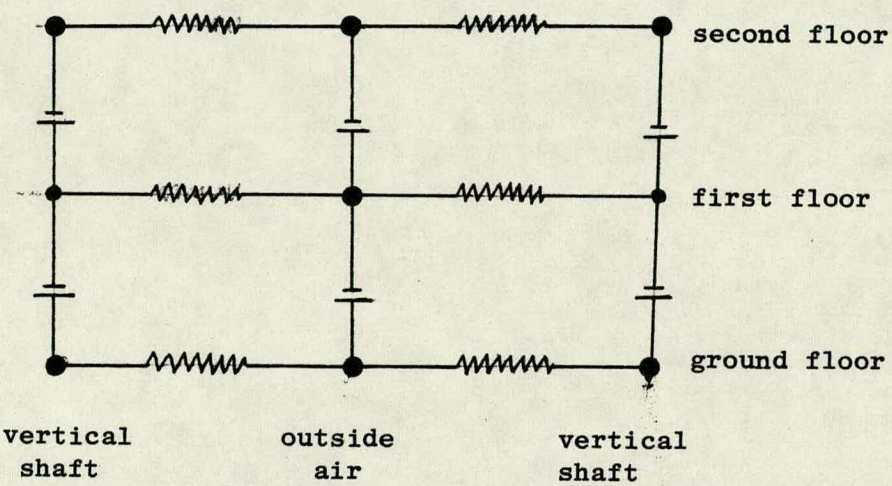


Sub-Network



Simplified Network

We put these networks together as each floor is only connected by the outside air and the shafts to form skeleton network.



Skeleton Network

We, then, return to each floor in turn to obtain a complete solution for the original elements.

Data Input

$	Segment declaration
*	Program control declaration
$INP	Input data document follow
$SIM	Execute the simulation: option follows
$REP	Generate reports as requested on the following cards
$END	End of current segment
$FIN	End of program.

Data Documents

*BUILD	Details of the nodes follow
*PATHS	Details of the flow paths follow
*OPEN	Doors or windows open or closed
*NEWVAL	New values for dictionary variables follow
*EOD	End of current data document

Building Data

Specified floor by floor.

*BUILD

FLØØR n_1

Node Type	Details
RØØM	Volume
CØRDØR	Volume
SHAFT	Cross-sectional area
ØUTAIR	-
SUBDCT	Cross-sectional area.

Flow Path Data

Again specified floor by floor. The first card is -

*PATHS

FLØØR n_1

Each card describes one flow path and contains the following items in the order:

(i) Data card identifier

(ii) Node numbers of the end points

(iii) Flow path type

(iv) Details of the flow path.

The first item on each data card is the word NODE. The program recognises six different flow path types:-

Flow path type	Identifier
Outside door	3
Inside door	4
Window	5
Ventilation opening (to outside air)	6
Ventilation opening (to duct)	7
Ventilation path (subduct to duct)	8

For each particular flow path type certain details must be given:-

Flow path type	Details
3 (outside door)	Height, width, crack width, direction faced.
4 (inside door)	Height, width, crack width, distance from end of corridor.

5 (Window)	Height, width, crack width, direction faced, height of window sill above floor.
6 (Vent.to outside)	Area of opening, height above floor, direction faced.
7	Area of opening, mass flow rate, height above floor, distance from vertical duct, area of subduct, flay indication whether closed off on detection of fire.
8	Area of opening.

Open Doors or Windows

*ϕPEN

FLϕϕR f NODES n_1 n_2

*EϕD

New Values

*NEWVALS

Variable name value

*EϕD

Simulation Control

$SIM

*EVALS n (number of simulations)

*NODES

FLØØR f_1 NODES n_1 n_2 n_3

FLØØR f_2 NODES n_4 n_5

} NODE numbers for output.

*TIMES t_1 t_2 t_3 - times for recording of smoke

*DEBUG $NAME_1$ $NAME_2$ $NAME_3$

SEND

Report Generation

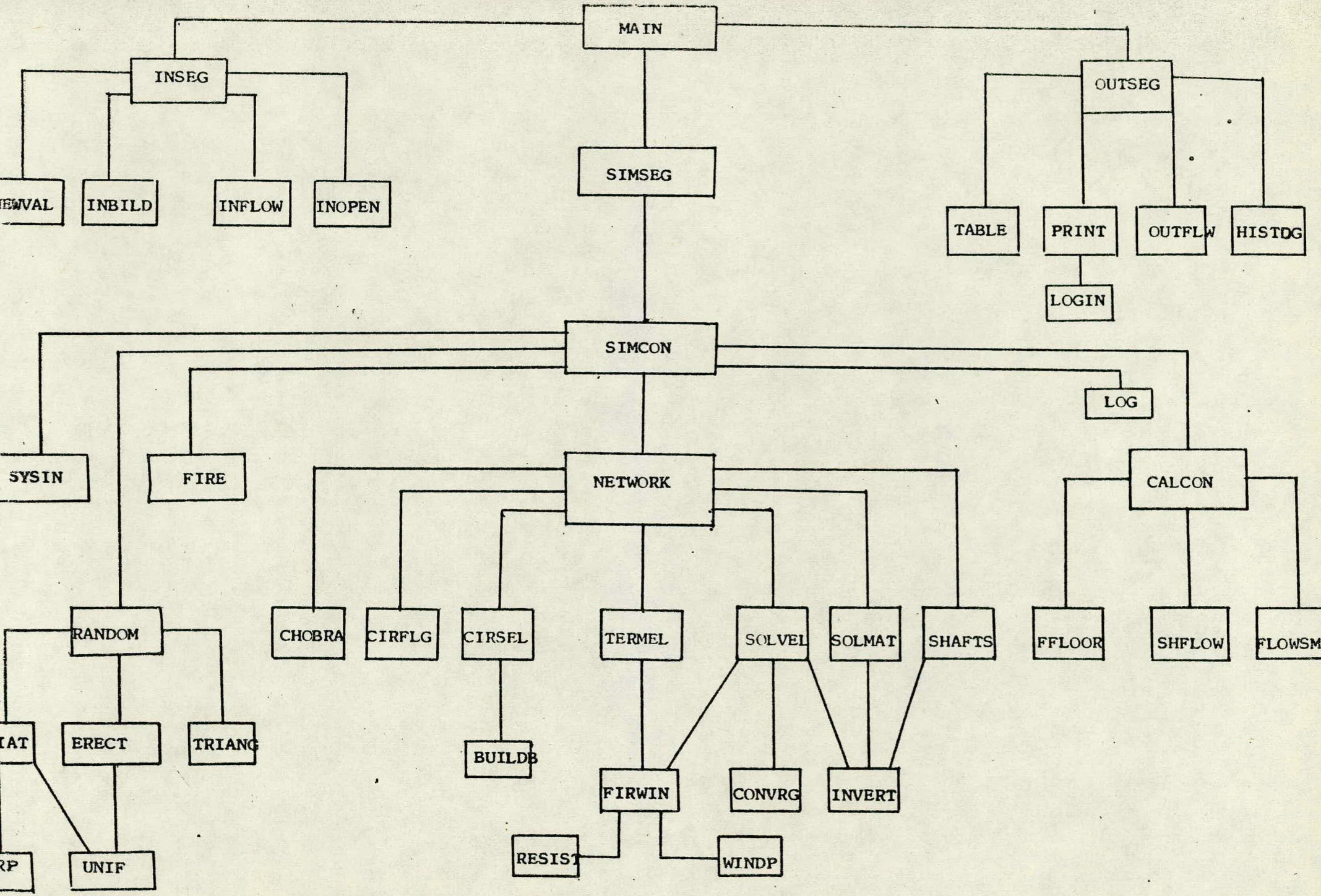
$REP

*FLØWS - mass flow rates and pressure differences.

*DNSITY - table of smoke densities

$END

$FIN.


MAIN
INSEG
OUTSEG
SIMSEG
INVAL
INBILD
INFLOW
INOPEN
TABLE
PRINT
OUTFLW
HISTDG
LOGIN
SIMCON
LOG
SYSIN
FIRE
NETWORK
CALCON
RANDOM
CHOBRA
CIRFLG
CIRSEL
TERMEL
SOLVEL
SOLMAT
SHAFTS
FFLOOR
SHFLOW
FLOWSM
IAT
ERECT
TRIANG
BUILDB
FIRWIN
CONVRG
INVERT
RESIST
WINDP
RP
UNIF

Input Data

Darwin Building

```
      SMOKE MOVEMENT IN DARWIN BUILDING
C     VERSION 1
C     EDINBURGH NOV. '76
*INP
*BUILD
FLOOR     1
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      11929
ROOM      9      18788
ROOM      10     4613
ROOM      11     18094
ROOM      12     5071
ROOM      13     5909
ROOM      14     18140
ROOM      15     33794
ROOM      16     8563
FLOOR     2
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      23102
ROOM      9      5771
ROOM      10     5569
ROOM      11     15036
ROOM      12     7951
ROOM      13     7951
ROOM      14     8208
ROOM      15     21357
ROOM      16     729
ROOM      17     7425
ROOM      18     8748
ROOM      19     408
FLOOR     3
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      28741
ROOM      9      11323
ROOM      10     9056
ROOM      11     9059
ROOM      12     11117
ROOM      13     3048
ROOM      14     12125
ROOM      15     10088
ROOM      16     7796
ROOM      17     3628
ROOM      18     3628
ROOM      19     3628
ROOM      20     6804
FLOOR     4
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      14391
ROOM      9      4009
ROOM      10     7459
ROOM      11     1782
ROOM      12     5386
ROOM      13     4252
ROOM      14     2693
ROOM      15     7796
ROOM      16     2612
ROOM      17     3193
ROOM      18     2612
ROOM      19     2612
ROOM      20     49275
ROOM      21     2248
ROOM      22     2248
ROOM      23     2248
ROOM      24     2248
ROOM      25     2126
ROOM      26     1282
ROOM      27     6385
FLOOR     5
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      15511
ROOM      9      1185
ROOM      10     2734
ROOM      11     4752
ROOM      12     7128
ROOM      13     2470
ROOM      14     6885
ROOM      15     4374
ROOM      16     2467
ROOM      17     2612
ROOM      18     3193
ROOM      19     6676
ROOM      20     49275
ROOM      21     4813
ROOM      22     1782
ROOM      23     1367
ROOM      24     3678
ROOM      25     1693
FLOOR     6
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      196
ROOM      9      400
ROOM      10     367
ROOM      11     163
ROOM      12     255
ROOM      13     255
ROOM      14     864
ROOM      15     870
ROOM      16     304
ROOM      17     827
ROOM      18     152
ROOM      19     139
ROOM      20     612
ROOM      21     246
ROOM      22     290
ROOM      23     391
ROOM      24     232
ROOM      25     145
ROOM      26     109
ROOM      27     444
ROOM      28     269
ROOM      29     780
ROOM      30     269
FLOOR     7
OUTAIR    1
SHAFT     2      198
SHAFT     3      56
SHAFT     4      56
SHAFT     5      168
SHAFT     6      25
SHAFT     7      25
CORDOR    8      2379
ROOM      9      3591
ROOM      10     2693
ROOM      11     2308
ROOM      12     2308
ROOM      13     4567
ROOM      14     2308
ROOM      15     3334
ROOM      16     2248
ROOM      17     2248
ROOM      18     1124
ROOM      19     1124
```

FLOOR	8	
OUTAIR	1	
SHAFT	2	198
SHAFT	3	56
SHAFT	4	56
SHAFT	5	168
SHAFT	6	25
SHAFT	7	25
CORDOR	8	13257
ROOM	9	2612
ROOM	10	19649
ROOM	11	3098
ROOM	12	834
ROOM	13	898
ROOM	14	7624
ROOM	15	2821
ROOM	16	2896
ROOM	17	2551
ROOM	18	850
ROOM	19	74250
ROOM	20	1215
ROOM	21	1282
FLOOR	9	
OUTAIR	1	
SHAFT	2	198
SHAFT	3	56
SHAFT	4	56
SHAFT	5	168
SHAFT	6	25
SHAFT	7	25
CORDOR	8	16014
ROOM	9	2902
ROOM	10	19926
ROOM	11	2700
ROOM	12	2565
ROOM	13	9234
ROOM	14	2302
ROOM	15	5488
ROOM	16	810
ROOM	17	13365
ROOM	18	21195
ROOM	19	13176
ROOM	20	8562
ROOM	21	270
ROOM	22	1603
ROOM	23	834
ROOM	24	1282
ROOM	25	1147

FLOOR	10	
OUTAIR	1	
SHAFT	2	198
SHAFT	3	56
SHAFT	4	56
SHAFT	5	168
SHAFT	6	25
SHAFT	7	25
CORDOR	8	25647
ROOM	9	2079
ROOM	10	1350
ROOM	11	7978
ROOM	12	3240
ROOM	13	2916
ROOM	14	2160
ROOM	15	3996
ROOM	16	1377
ROOM	17	2052
ROOM	18	2447
ROOM	19	2410
ROOM	20	8302
ROOM	21	7938
ROOM	22	17810
ROOM	23	1026
ROOM	24	20591
ROOM	25	337
ROOM	26	1620
ROOM	27	1552
ROOM	28	2767
ROOM	29	1033
ROOM	30	1262
ROOM	31	1114
ROOM	32	1519
ROOM	33	2329
*EOD		

```
*PATHS
FLOOR    1
NODE     1     8     3     7     4    31   180
NODE     1    12     3     7     4    31     0
NODE     1     8     3     7     4    31     0
NODE     1    11     3     8     8    31    90
NODE     1     9     3    11     4    31    90
NODE     8    14     4     8     6    31   114
NODE     8    13     4     7     3    31   102
NODE     8    12     4     7     5    31    94
NODE     8    11     4    11     4    31    78
NODE     8    11     4     7     4    31    70
NODE     8    10     4     7     4    31    54
NODE     8     9     4     7     4    31    48
NODE     8    16     4     7     4    31     4
NODE     8    15     4     7     4    31    41
NODE     8     2     4     7     3    31    83
NODE     8     3     4     7     3    31   105
NODE     8     4     4     7     3    31   113
NODE     8     6     4     7     2    31    21
NODE     8     7     4     7     2    31     7
NODE     1    14     5     2    23    10     0     9
NODE     1    13     5     2     9    10     0     9
NODE     1    11     5     2    27    10     0     9
NODE     1    11     5     2    27    10    90     9
NODE     1    10     5     2     5    10    90     9
NODE     1     9     5     2    32    10    90     9
NODE     1     9     5     2    27    10   180     9
NODE     1    16     5     2    23    10   180     9
FLOOR    2
NODE     1     8     3     7     4    31   270
NODE     1     8     3     7     4    31   180
NODE     1    14     5     2    27    10     0     9
NODE     1    13     5     2    27    10     0     9
NODE     1    12     5     2    27    10     0     9
NODE     1    12     5     2    18    10    90     9
NODE     1    11     5     2    27    10    90     9
NODE     1    10     5     2     9    10    90     9
NODE     1     9     5     2    18    10    90     9
NODE     1     9     5     2    23    10   180     9
NODE     1     8     5     2     4    10   180     9
NODE     1    17     5     2    18    10   180     9
NODE     8    14     4     7     3    31    30
NODE     8    13     4     7     3    31    36
NODE     8    12     4     7     3    31    60
NODE     8    11     4     7     4    31    68
NODE     8    10     4     7     3    31   114
NODE     8     9     4     7     4    31   120
NODE     8    17     4     7     4    31   133
NODE     8    19     4     7     3    31   114
NODE     8    18     4     7     4    31   106
NODE     8    16     4     7     3    31    26
NODE     8    15     4     7     4    31    32
NODE     8     2     4     7     4    31    48
NODE     8     3     4     7     3    31    46
NODE     8     4     4     7     3    31    37
NODE     8     6     4     7     2    31   121
NODE     8     7     4     7     2    31   128
```

```
FLOOR     3
NODE      1      8      3      7      4     31     270
NODE   1      8      3      7      4     31     180
NODE      8     14      4      7      4     31      34
NODE      8     14      4      7      3     31      58
NODE      8     13      4      7      3     31      63
NODE      8     12      4      7      3     31      71
NODE      8     11      4      7      3     31      92
NODE      8     10      4      7      3     31     104
NODE      8      9      4      7      3     31     122
NODE      8     20      4      7      4     31     129
NODE      8     20      4      7      3     31     173
NODE      8     19      4      7      3     31     132
NODE      8     19      4      7      3     31     141
NODE      8     18      4      7      3     31     151
NODE      8     17      4      7      3     31     161
NODE      8     16      4      7      3     31     168
NODE      8     15      4      7      3     31     163
NODE      8      2      4      7      4     31      51
NODE      8      3      4      7      4     31      49
NODE      8      4      4      7      4     31      40
NODE      8      6      4      7      3     31     128
NODE      8      7      4      7      3     31     136
NODE      1      8      5      2     18     10     270      9
NODE      1     14      5      2     18     10     270      9
NODE      1     14      5      2     50     10       0      9
NODE      1     13      5      2      5     10       0      9
NODE      1     12      5      2     27     10       0      9
NODE      1     12      5      2     18     10      90      9
NODE      1     11      5      2     18     10      90      9
NODE      1     10      5      2     18     10      90      9
NODE      1      9      5      2     18     10      90      9
NODE      1      9      5      2     27     10     180      9
NODE      1     19      5      2     13     10     180      9
NODE      1     18      5      2      9     10     180      9
NODE      1     17      5      2      9     10     180      9
NODE      1     16      5      2     18     10     180      9
NODE      1     16      5      2     18     10     270      9
NODE      1     15      5      2     18     10     270      9
NODE      2      5      8      1      0      0      0      0
```

```
FLOOR    4
NODE     1     8     3     7     4    31   180
NODE     1    27     5     2    24    10   180     9
NODE     1     9     5     2    13    10   180     9
NODE     1    10     5     2    13    10   180     9
NODE     1    10     5     2    13    10    90     9
NODE     1    11     5     2     5    10    90     9
NODE     1    12     5     2    18    10    90     9
NODE     1    13     5     2     9    10    90     9
NODE     1    14     5     2     9    10    90     9
NODE     1    15     5     2    18    10    90     9
NODE     1    15     5     2    18    10     0     9
NODE     1    16     5     2     9    10     0     9
NODE     1    17     5     2     5    10     0     9
NODE     1    18     5     2     9    10     0     9
NODE     1    19     5     2     9    10     0     9
NODE     1    20     5     2    32    10     0     9
NODE     1    20     5     2    72    10   270     9
NODE     1    20     5     2    27    10   180     9
NODE     8     2     4     7     4    31    15
NODE     8     3     4     7     3    31    12
NODE     8     4     4     7     3    31     4
NODE     8     6     4     7     2    31   110
NODE     8     7     4     7     2    31   117
NODE     8     9     4     7     3    31    96
NODE     8    10     4     7     3    31   108
NODE     8    11     4     7     3    31   104
NODE     8    12     4     7     3    31    86
NODE     8    13     4     7     3    31    66
NODE     8    14     4     7     3    31    51
NODE     8    15     4     7     3    31    43
NODE     8    16     4     7     3    31    41
NODE     8    17     4     7     3    31    26
NODE     8    18     4     7     3    31    20
NODE     8    19     4     7     3    31    10
NODE     8    20     4     7     4    31     0
NODE     8    20     4     7     4    31   132
NODE     8    21     4     7     3    31   126
NODE     8    22     4     7     3    31   117
NODE     8    23     4     7     3    31   110
NODE     8    24     4     7     3    31   100
NODE     8    25     4     7     3    31    57
NODE     8    26     4     7     3    31    30
NODE     8    27     4     7     3    31   126
```

```
FLOOR    5
NODE     1     8     3     7     4    31   180
NODE     1    10     5     2    13    10   180     9
NODE     1    11     5     2    13    10   180     9
NODE     1    11     5     2    18    10    90     9
NODE     1    12     5     2    18    10    90     9
NODE     1    14     5     2    18    10    90     9
NODE     1    15     5     2    18    10    90     9
NODE     1    15     5     2     9    10     0     9
NODE     1    16     5     2     9    10     0     9
NODE     1    17     5     2     9    10     0     9
NODE     1    18     5     2     5    10     0     9
NODE     1    19     5     2    23    10     0     9
NODE     1    20     5     2    27    10     0     9
NODE     1    20     5     2    72    10   270     9
NODE     1    20     5     2    27    10   180     9
NODE     1    21     5     2    23    10   180     9
NODE     8     2     4     7     4    31    15
NODE     8     3     4     7     3    31    12
NODE     8     4     4     7     3    31     4
NODE     8     6     4     7     3    31    88
NODE     8     7     4     7     3    31    97
NODE     8     9     4     7     3    31    92
NODE     8    10     4     7     3    31    97
NODE     8    11     4     7     3    31   100
NODE     8    12     4     7     3    31   100
NODE     8    13     4     7     3    31    75
NODE     8    14     4     7     3    31    47
NODE     8    15     4     7     3    31    52
NODE     8    16     4     7     3    31    46
NODE     8    17     4     7     3    31    40
NODE     8    18     4     7     3    31    25
NODE     8    19     4     7     3    31    20
NODE     8    20     4     7     4    31     0
NODE     8    20     4     7     4    31   111
NODE     8    21     4     7     4    31   108
NODE     8    22     4     7     3    31    92
NODE     8    23     4     7     3    31   104
NODE     8    24     4     7     3    31    95
NODE     8    25     4     7     3    31    88
```

```
FLOOR      6
NODE       1       8       3       7       4      31     180
NODE       1       9       5       2      13      10     180       9
NODE       1      10       5       2      13      10     180       9
NODE       1      10       5       2      13      10      90       9
NODE       1      11       5       2       5      10      90       9
NODE       1      12       5       2       9      10      90       9
NODE       1      13       5       2       9      10      90       9
NODE       1      14       5       2      18      10      90       9
NODE       1      15       5       2      18      10      90       9
NODE       1      15       5       2      27      10       0       9
NODE       1      16       5       2       5      10       0       9
NODE       1      17       5       2      23      10       0       9
NODE       1      18       5       2      27      10       0       9
NODE       1      18       5       2      27      10     270       9
NODE       1      19       5       2      27      10     270       9
NODE       1      20       5       2      18      10     270       9
NODE       1      20       5       2      13      10     180       9
NODE       1      21       5       2       9      10     180       9
NODE       1      22       5       2       5      10     180       9
NODE       1      23       5       2      13      10     180       9
NODE       1      24       5       2       9      10     180       9
NODE       8       9       4       7       3      31     118
NODE       8      10       4       7       3      31     115
NODE       8      11       4       7       3      31     111
NODE       8      12       4       7       3      31      90
NODE       8      13       4       7       3      31      83
NODE       8      14       4       7       4      31      62
NODE       8      15       4       7       4      31      48
NODE       8      16       4       7       3      31      32
NODE       8      17       4       7       4      31      14
NODE       8      18       4       7       4      31       0
NODE       8      19       4       7       3      31     177
NODE       8      19       4       7       3      31     158
NODE       8      20       4       7       3      31     160
NODE       8      21       4       7       3      31     157
NODE       8      22       4       7       3      31     148
NODE       8      23       4       7       3      31     129
NODE       8      24       4       7       3      31     135
NODE       8       2       4       7       4      31      22
NODE       8       3       4       7       3      31      18
NODE       8       4       4       7       3      31       9
NODE       8       6       4       7       2      31     118
NODE       8       7       4       7       2      31     127
NODE       8      25       4       7       3      31     136
NODE       8      26       4       7       3      31     128
NODE       8      27       4       7       4      31     120
NODE       8      27       4       7       4      31     160
NODE       8      28       4       7       4      31     109
NODE       8      29       4       7       3      31      73
NODE       8      30       4       7       3      31      61
NODE       2       5       8       1       0       0       0       0
```

```
NODE    1    9    5    2   27   10  180    9
NODE    1    9    5    2   72   10   90    9
NODE    1    9    5    2   27   10    0    9
NODE    1   10    5    2    5   10    0    9
NODE    1   11    5    2    9   10    0    9
NODE    1   12    5    2    9   10    0    9
NODE    1   13    5    2   32   10    0    9
NODE    1   13    5    2   72   10  270    9
NODE    1   13    5    2   27   10  180    9
NODE    1   14    5    2    9   10  180    9
NODE    1   15    5    2   13   10  180    9
NODE    8    9    4    7    4   31   54
NODE    8    9    4    7    4   31   36
NODE    8   10    4    7    3   31   25
NODE    8   11    4    7    3   31   20
NODE    8   12    4    7    3   31    9
NODE    8   13    4    7    4   31    0
NODE    8   13    4    7    4   31  114
NODE    8   14    4    7    3   31  107
NODE    8   15    4    7    3   31  101
NODE    8   15    4    7    3   31  109
NODE    8   16    4    7    3   31  109
NODE    8   17    4    7    3   31  101
NODE    8   18    4    7    3   31   75
NODE    8   19    4    7    3   31   65
NODE    8    2    4    7    4   31   16
NODE    8    3    4    7    3   31   12
NODE    8    4    4    7    3   31    4
NODE    8    6    4    7    2   31   91
NODE    8    7    4    7    2   31   98
FLOOR   8
NODE    1    8    3    7    4   31  180
NODE    1    9    5    2    9   10  180    9
NODE    1   10    5    2   18   10  180    9
NODE    1   10    5    2   54   10   90    9
NODE    1   14    5    2   18   10   90    9
NODE    1   14    5    2   18   10    0    9
NODE    1   15    5    2    9   10    0    9
NODE    1   16    5    2    5   10    0    9
NODE    1   17    5    2   13   10    0    9
NODE    1   19    5    2   36   10    0    9
NODE    1   19    5    2   72   10  270    9
NODE    1   19    5    2   54   10  180    9
NODE    8    2    4    7    4   31   16
NODE    8    3    4    7    3   31   12
NODE    8    4    4    7    3   31    4
NODE    8    6    4    7    2   31   91
NODE    8    7    4    7    2   31   98
NODE    8    9    4    7    3   31   90
NODE    8   10    4    7    4   31   95
NODE    8   11    4    7    3   31   90
NODE    8   10    4    7    4   31   63
NODE    8   12    4    7    3   31   59
NODE    8   13    4    7    3   31   39
NODE    8   14    4    7    3   31   48
NODE    8   10    4    7    3   31   51
NODE    8   14    4    7    3   31   47
NODE    8   15    4    7    3   31   38
NODE    8   16    4    7    3   31   25
NODE    8   17    4    7    3   31   21
NODE    8   18    4    7    3   31   18
NODE    8   19    4    7    4   31    0
NODE    8   19    4    7    4   31    4
NODE    8   19    4    7    4   31   82
NODE    8   20    4    7    3   31   64
NODE    8   21    4    7    4   31   73
NODE    2    5    8    1    0    0    0    0
```

```
FLOOR    9
NODE     1     8     3     7     4    31   180
NODE     1     9     5     2     9    10   180   9
NODE     1    10     5     2    18    10   180   9
NODE     1    10     5     2    54    10    90   9
NODE     1    13     5     2    18    10    90   9
NODE     1    13     5     2    27    10     0   9
NODE     1    14     5     2     5    10     0   9
NODE     1    15     5     2    23    10     0
NODE     1    17     5     2    27    10     0   9
NODE     1    17     5     2    18    10   270   9
NODE     1    18     5     2    32    10   270   9
NODE     1    19     5     2    23    10   270   9
NODE     1    19     5     2    27    10   180   9
NODE     1    20     5     2    23    10   180   9
NODE     8     9     4     7     3    31    96
NODE     8    10     4     7     4    31    83
NODE     8    11     4     7     3    31    76
NODE     8    10     4     7     4    31    58
NODE     8    12     4     7     3    31    38
NODE     8    13     4     7     3    31    46
NODE     8    14     4     7     3    31    28
NODE     8    15     4     7     3    31    13
NODE     8    16     4     7     3    31     4
NODE     8    17     4     7     4    31     0
NODE     8    18     4     7     4    31     4
NODE     8    18     4     7     4    31   118
NODE     8    19     4     7     4    31   121
NODE     8    20     4     7     3    31    93
NODE     8    21     4     7     3    31    89
NODE     8    22     4     7     3    31   104
NODE     8    23     4     7     3    31    98
NODE     8    24     4     7     3    31    76
NODE     8    25     4     7     3    31    68
NODE     8     2     4     7     4    31    17
NODE     8     3     4     7     3    31    13
NODE     8     4     4     7     3    31     5
NODE     8     6     4     7     3    31    93
NODE     8     7     4     7     3    31   100
```

```
FLOOR      10
NODE        1      8      3      7      4     31    180
NODE        8     13      4      7      3     31     75
NODE        8     24      4      7      3     31    146
NODE        1      9      5      2     13     10    180      9
NODE        1     11      5      2     13     10    180      9
NODE        1     11      5      2     27     10     90      9
NODE        1     12      5      2      9     10     90      9
NODE        1     13      5      2     13     10     90      9
NODE        1     14      5      2      5     10     90      9
NODE        1     15      5      2     18     10     90      9
NODE        1     15      5      2      9     10      0      9
NODE        1     16      5      2      9     10      0      9
NODE        1     17      5      2      9     10      0      9
NODE        1     18      5      2      5     10      0      9
NODE        1     19      5      2      9     10      0      9
NODE        1     20      5      2     23     10      0      9
NODE        1     21      5      2     18     10      0      9
NODE        1     21      5      2     18     10    270      9
NODE        1     22      5      2     45     10    270      9
NODE        1     24      5      2      9     10    270      9
NODE        1     24      5      2     20     10    180      9
NODE        8      2      4      7      4     31     32
NODE        8      3      4      7      3     31     17
NODE        8      4      4      7      3     31     10
NODE        8      6      4      7      2     31    138
NODE        8      7      4      7      2     31    145
NODE        8      9      4      7      3     31    145
NODE        8     10      4      7      3     31    119
NODE        8     11      4      7      4     31    113
NODE        8     12      4      7      3     31     95
NODE        8     14      4      7      3     31     67
NODE        8     15      4      7      3     31     68
NODE        8     16      4      7      3     31     74
NODE        8     17      4      7      3     31     72
NODE        8     18      4      7      3     31     42
NODE        8     19      4      7      3     31     34
NODE        8     20      4      7      4     31     27
NODE        8     20      4      7      4     31      8
NODE        8     21      4      7      4     31      0
NODE        8     22      4      7      4     31    190
NODE        8     23      4      7      3     31    182
NODE        8     24      4      7      4     31    184
NODE        8     24      4      7      3     31    141
NODE        8     25      4      7      3     31    134
NODE        8     26      4      7      3     31    185
NODE        8     27      4      7      3     31    142
NODE        8     28      4      7      3     31     96
NODE        8     29      4      7      3     31    129
NODE        8     30      4      7      3     31    104
NODE        8     31      4      7      3     31     87
NODE        8     32      4      7      3     31     79
NODE        8     33      4      7      3     31     70
```

```
*EOD
*NEWVAL
HFLOOR      14
ITSOL       60
IFROOM       11
TMPIN       20.0
TMPOUT      20.0
VW       65.617
FTEMP       1000.0
*EOD
ΠEND
ΠSIM
*DEBUG       SHAFTS
*TIMES      300         600         900
ΠEND
ΠREP
*FLOWS
*DNSITY
ΠEND
ΠFIN
```

Input Data

32-Cell Model

```
      SMOKE MOVEMENT IN SMALL OFFICE BUILDING (32 Cell Model)
C     FIVE STOREY FULL SIZE MODEL
C      DOOR LEAKAGE =1.5%      1.5      1.5      1.5
C     WINDOW LEAKAGE CRACK WIDTH  =(T) = 0.114FT.  , (R) =0.150FT..
C     DOOR      "        "       "     = 0.027FT.
C      FIRE ROOM DOOR LEAKAGE CRACK WIDTH = 0.075FT.
C     WINDOW SIZE                      = 3FT X 13FT
C      DOOR   "                        = 5FT X 11FT
C       ROOM  "                        = 16FT X 15FT X 26FT
C     ROOM DOORS ..............CLOSED
C     SHAFT DOORS..............CLOSED
C      NO STACK EFFECT
C     DEPARTMENT OF FIRE SAFETY ENGINEERING
C     UNIVERSITY OF EDINBURGH
C     DEC. '78
$INP
*BUILD
FLOOR       1
OUTAIR        1
SHAFT         2        612
SHAFT         3        423
CORDOR        4         7590
ROOM         5         6345
ROOM          6        6345
ROOM          7        6345
ROOM          8        6345
ROOM          9        6345
ROOM          10       6345
FLOOR       2        TO       5
OUTAIR       1
SHAFT        2        612
SHAFT        3        423
CORDOR       4        7590
ROOM         5        6345
ROOM         6        6345
ROOM        7         6345
ROOM         8        6345
ROOM         9        6345
ROOM         10       6345
*EOD
*PATHS
FLOOR       1
NODE      1       2       3       11      5              9      0
NODE      1       2       5       3       13      114      0      10
NODE      1       5       5       3       13      114      0      10
NODE      1       6       5       3       13      114      0      10
NODE      1       7       5       3       13      114      0      10
NODE      1       8       5       3       13      150      180      10
NODE      1       9       5       3       13      150      180      10
NODE      1       10      5       3       13      150      180      10
NODE      2      3       8       1       0       0       0       0
NODE      2       4       4       11      5      27      46
NODE      4       5       4       11      5      27      39
NODE      4       6       4       11      5      27      23
NODE      4       7       4       11      5      27      10
NODE      4       8       4       11      5      27        10
NODE      4       9       4       11      5      27      23
NODE      4       10      4      11       5       27      39
```

```
FLOOR     2
NODE    1     2     5     3    13    114     0    10
NODE      1     5     5     3    13    114     0    10
NODE    1     6     5     3    13    114     0    10
NODE    1     7     5     3    13    114     0    10
NODE    1     8     5     3    13    150   180    10
NODE    1     9     5     3    13    150   180    10
NODE    1    10     5     3    13    150   180    10
NODE    2     3     8     1     0     0     0     0
NODE    2     4     4    11     5    27    46
NODE    4     5     4    11     5    27    39
NODE    4     6     4    11     5    27    23
NODE    4     7     4    11     5    27    10
NODE    4     8     4    11     5    27    10
NODE    4     9     4    11     5    27    23
NODE    4    10     4    11     5    75    39
FLOOR   3    TO     5
NODE    1     2     5     3    13   114     0    10
NODE    1     5     5     3    13   114     0    10
NODE    1     6     5     3    13   114     0    10
NODE    1     7     5     3    13   114     0    10
NODE    1     8     5     3    13   150   180    10
NODE    1     9     5     3    13   150   180    10
NODE    1    10     5     3    13   150   180    10
NODE    2     3     8     1     0     0     0     0
NODE    2     4     4    11     5    27    46
NODE    4     5     4    11     5    27    39
NODE    4     6     4    11     5    27    23
NODE    4     7     4    11     5    27    10
NODE    4     8     4    11     5    27    10
NODE    4     9     4    11     5    27    23
NODE    4    10     4    11     5    27    39
*EOD
*OPEN
FLOOR     2       NODES      4      10
*EOD
*NEWVAL
HCEIL     14
HFLOOR    15
IFROOM    20
ITSOL     30
TMPIN     15
TMPOUT    15
CORWID    11
VW        20.01
WH        0.0
FTEMP     1000
*EOD
$END
$SIM
*DEBUG      FIRE      FIRWIN
*TIMES      300       600       900
$END
$REP
*FLOWS
*DNSITY
$END
$FIN
```

APPENDIX C

APPENDIX C

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WIND EFFECTS ON BUILDINGS WITH VARYING LEAKAGE CHARACTERISTICS — WIND-TUNNEL INVESTIGATION

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Summary

A wind-tunnel investigation has been conducted on a simple cubical model to see the effect of outside wall leakage on internal and external pressures. Three wind directions have been studied. The results have been extended to smoke-control problems. A method has been developed to modify the roof-vent design calculations to take wind effects into account. It is also shown that failure of vent systems may be more common than would be expected from current design methods.

1. Introduction

Effects of wind on buildings and tall structures have been investigated over the past few decades. A considerable amount of useful information has been gathered on the full-scale measurements on existing buildings [1,2] and wind-tunnel experiments conducted on models. The studies so far have been concerned largely with the estimation of wind loads that a building is likely to experience in an environment of varying turbulent-flow regimes. Such information is necessary from the structural safety point of view.

The wind-induced pressures on the sides and the roof of a building depend on the characteristics of the approaching wind, the building surroundings and on the shape and size of the building. The total wind loads acting on the walls are determined by the difference in internal and external pressures.

In the case of a simple tall building of rectangular cross-section, the external pressures vary with the magnitude and direction of the wind. If the air flows normally to one side of such a building, then the windward side is subjected to positive pressures, while other sides experience negative pressures (suction).

The internal pressures, on the other hand, depend on building-leakage characteristics. In buildings with openable windows (unsealed), an uncontrolled flow of air results between the interior and exterior, through such paths as doors and windows. This air leakage has the effect of changing the interior environmental conditions such as humidity and temperature. It also acts as the most important source of fresh air for buildings without any mechanical ventilation.

Air leakage also plays an important role in the fire safety of a building. Movement of air resulting from the inside pressure variations affects the spread of smoke within a building. It is important, therefore, in smoke-control problems, to understand the pressure variations within a building enclosure resulting from leakage. In large single-cell buildings, such as high-bay warehouses, department stores and factories, it is necessary to clear them of smoke to prevent any damage to the stock. To do this, a knowledge of the external pressure distribution is also essential for locating roof vents.

The problem of roof vent design has previously been investigated [3,4]. In these studies the wind effects have been ignored. The extraction rate through the vents has been calculated considering the buoyancy effects alone. As the majority of large buildings are situated out in the open, the wind effects become quite significant as numerous studies have shown [1,5,6] not only the suction on the roof that changes the extraction rate but the internal pressure variations resulting from leakage characteristics also have considerable effect.

The importance of wind-induced pressures is evident from the wind-tunnel studies on models [7]. The internal pressure variations are functions of both the wind direction and the relative leakage of walls.

The present experimental investigation, on a simple cubical model building with a partition, attempts to determine these effects to see how the design calculations can be modified by taking wind effects into account.

2. Description of the model

The experiments were conducted on a 25-cm cubical model manufactured out of clear acrylic plastic. The cube contained a partition wall dividing the inner space into two regions, as shown in Fig. 1 (dotted line represents partition wall).

The leakage characteristics of two walls (front and back) and the partition were varied. For this purpose ten holes were drilled on each wall with their centres lying, equally spaced, on a circle of 12.5-cm diameter with its centre at the centre of each wall (see Fig. 1). The area of each hole was 0.1 percent of the wall area (i.e. 0.625 cm^2), so that when all ten holes were open it gave total leakage on one per cent of the wall area. This choice was based on the typical measured values for buildings.

For the purpose of outside pressure measurements, each wall was provided with seventeen static pressure holes. The details of the arrangements of these holes are shown in Fig. 1. The inside pressures were simply tapped by placing the pressure measuring tubes on either side of the partition.

3. Experimental technique

The measurements were taken in the low-speed open-jet type wind tunnel at the Department of Civil Engineering and Building Science, University of

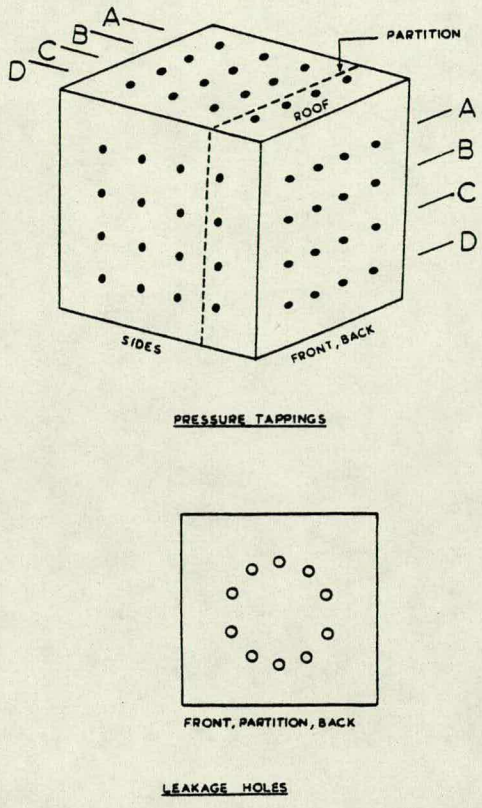


Fig. 1. Arrangement of pressure tappings and leakage holes on the box.

Edinburgh. The open jet was 1.07 m by 1.52 m and the working table was 1.75 m by 1.53 m. A uniform section 1.75 m long was added to the outlet of the original tunnel to accommodate the elliptical wedge turbulence generators. These turbulence generators were used to produce the same wind turbulence as found in the real atmosphere. The turbulent velocity profile was as shown in Fig. 2. The model was placed at the centre of the table with measuring tubes running through a hole in the table to a 48-way pressure scanner.

The test programme was designed to investigate the effect of leakage on the inside and outside pressure distribution for the cases of three wind directions (0°, 45°, 90°), with constant wind velocity. The leakages on the front and back walls were varied in a systematic manner, keeping the partition leakage constant to its maximum value (i.e. 1%).

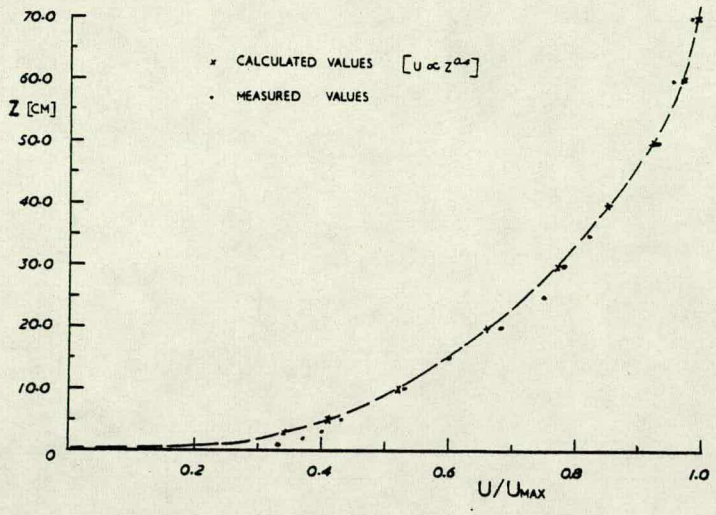


Fig. 2. Wind tunnel velocity profile.

4. Measurements

The pressure measurements were taken in order to investigate:
(a) External pressure variations with
  (i) front and back wall leakage combinations,
  (ii) wind direction.
(b) Internal pressure variations with .
  (i) front and back wall leakage combinations,
  (ii) wind directions.

4.1 Procedures

Measurements were made for numerous lekaage combinations. Results for five such combinations, at wind directions of 0°, 45°, 90°, are presented here.

Leakage combinations were:

F	P	B	Code
0	1.0	0	+
0.4	1.0	0.4	○
0.4	1.0	1.0	□
1.0	1.0	0.4	△
1.0	1.0	1.0	●

where F = front wall; P = partition; B = back wall; "Code" refers to the points in the figures. Numbers refer to percentage leakage area on each wall.

In order to see how the pressure varied over the wall surface, graphs were plotted for four different levels (A, B, C and D) on each wall. The arrangement is shown in Fig. 3.

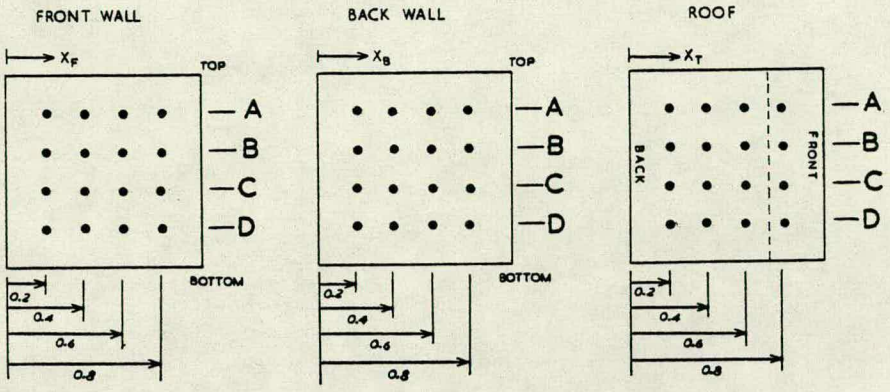


Fig. 3. Relative position of measurement levels A, B, C, D.

5. Results

Measurements for the front-wall pressures are shown in Fig. 4. It shows the pressure variations for different leakage combinations at heights marked A, B, C and D above the floor level, as indicated in Fig. 3. This is done to see if any leakage hole openings on the front wall have any appreciable effect on outside pressures in the vicinity of the hole. Figures 5 and 6 show the similar results for wind incidences 45° and 90°.

As the air which infiltrates through the openings in the front wall leaves through the back-wall openings, it is important to find out if this infiltration has any effect on the back wall pressures. Similar graphs, as for front wall, are drawn for the back wall, Figs. 7, 8 and 9. The positions A, B, C and D correspond to those in Fig. 3 for the back wall.

The pressure variations on the roof are significant for vent calculations. Figure 10 shows this variation for three wind directions investigated (0°, 45°, 90°). The similarity of contours at $\alpha = 0°$ and at $\alpha = 90°$ is noticeable. This is due to the symmetry of the model.

Figure 11 shows the actual pressure measurements on the roof for different wind direction. Again, the results are presented for lines A, B, C and D as shown in Fig. 3 for the roof. As there are no leakage holes in the roof, this figure only shows the curves for three wind directions.

The wind direction and leakage characteristics of the building have considerable effect on the internal pressures. The internal pressure variations with incidence at different leakage combinations are shown in Figs. 12 and 13 for two compartments labelled I and II.

To combine the front and back wall leakages, a parameter R, the leakage ratio, is defined as

$$R = \frac{\text{front-wall leakage area}}{\text{back-wall leakage area}}$$

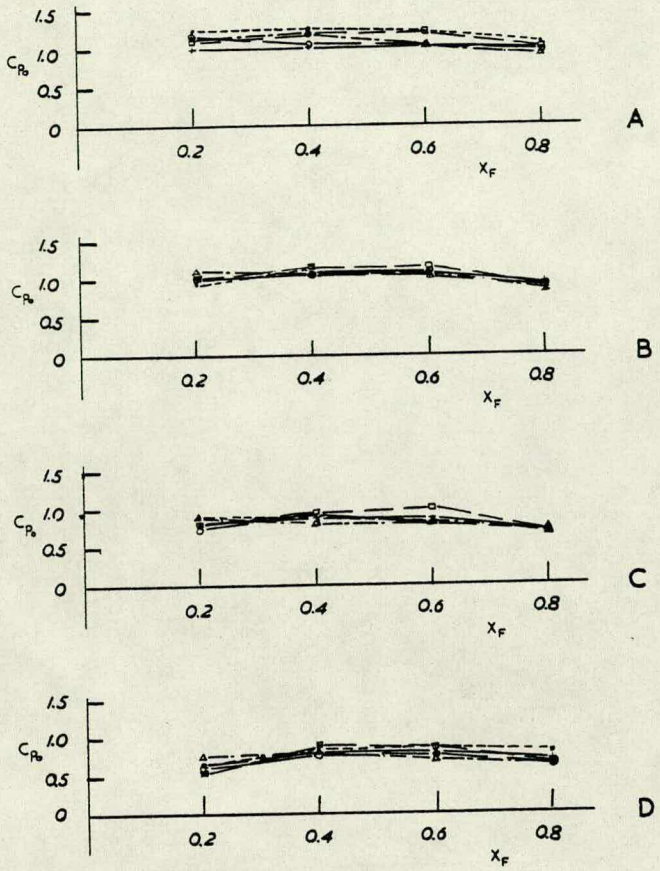


Fig. 4. Front wall outside pressure (C_{p_o}) variation with leakage $\alpha = 0°$.

The variation of internal pressure with R is shown in Fig. 14 for different wind directions.

6. Analysis and calculations

When fire occurs in a large single-cell building, such as a high-bay warehouse, the hot gases and smoke rising from the fire form a layer under the ceiling. This layer grows in depth with time, unless the gases are removed. The most efficient and convenient way of removing them is by making holes (vents) in the roof. For natural ventilation (i.e. no powered extract), the shape, size and location of these vents are the important factors which determine their efficient functioning. Assuming that the layer is fully stratified (i.e. there is no mixing between the hot layer and the cold air underneath), the mass rate of flow of hot gases through the vents must be such that it is

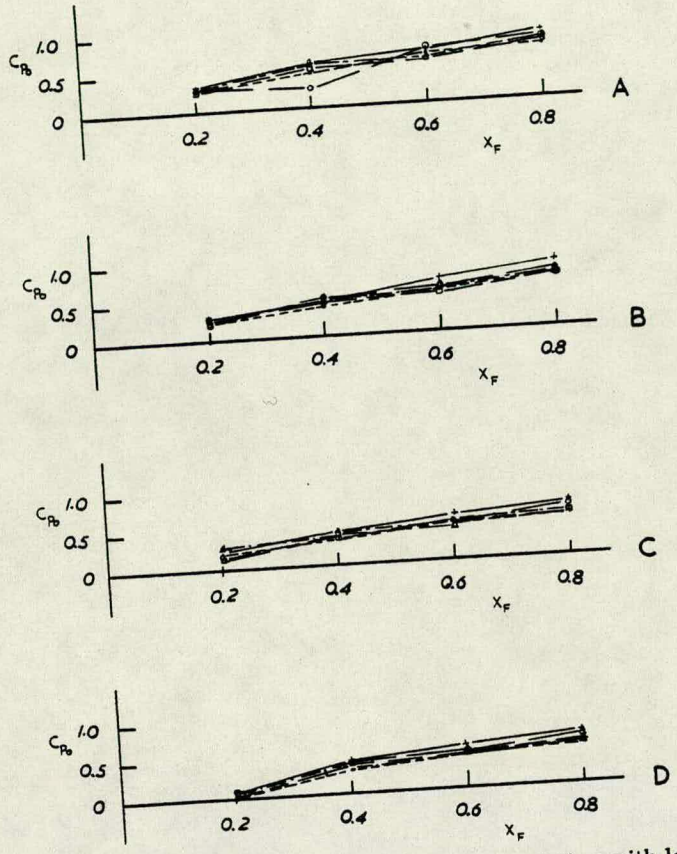


Fig. 5. Front wall outside pressure (C_{p_o}) variation with leakage $\alpha = 45°$.

not extracting cold air under the layer. In that case the efficiency of the vents will drop.

If the temperature of the hot layer is known, and, for the safe limit of the layer thickness, the critical volume flow ($V_{v_{crit}}$) through the vent is given by [4]:

$$V_{v_{crit}} = \frac{2.0(gd^5\theta_c T_0)^{\frac{1}{2}}}{(\theta_c + T_0)} \tag{1}$$

where g = acceleration due to gravity, d = layer thickness, θ_c = excess temperature above ambient below the ceiling, T_0 = ambient air temperature. The excess temperature above ambient (θ_c) of the hot layer is determined from the knowledge of the fire size (i.e. heat output) and the application of plume theory [3].

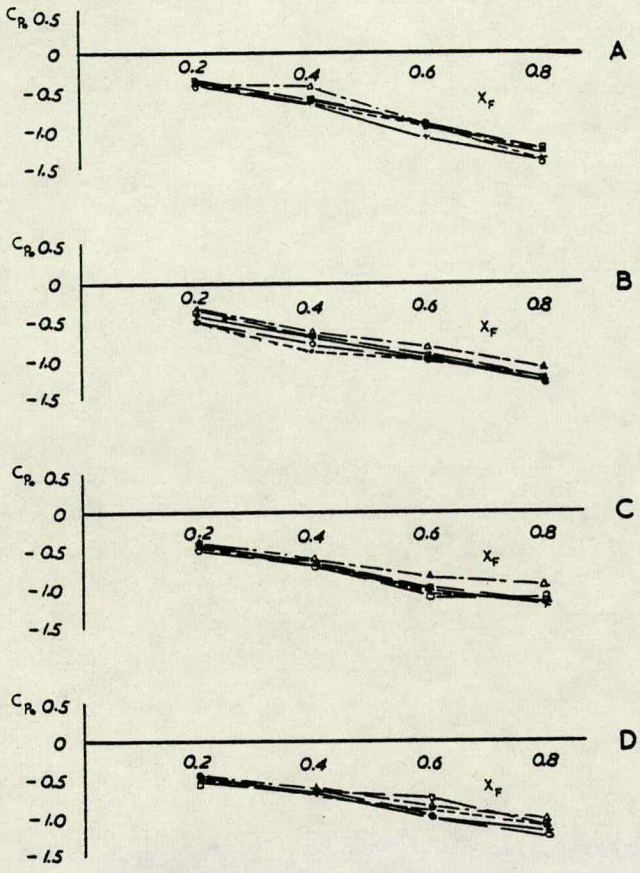


Fig. 6. Front wall outside pressure (C_{p_o}) variation with leakage $\alpha = 90°$.

Suppose the velocity of gases through the vent is u_v, then from Bernoulli's relation:

$$q\Delta C_{p_{roof}} = \frac{1}{2}\rho_c u_v^2 \tag{2}$$

where q = dynamic head at the building height and $\Delta C_{p_{roof}}$ = pressure coefficient difference across the roof. The total internal pressure is given by:

$$C_{p_i} = C_{p_{iw}} + C_{p_T} \tag{3}$$

where $C_{p_{iw}}$ = internal pressure coefficient due to wind and $C_{p_{iT}}$ = buoyancy pressure coefficient below the ceiling. Then the pressure difference across the roof is:

$$\Delta C_{p_{roof}} = C_{p_i} - C_{p_r} \tag{4}$$

where C_{p_r} = wind pressure coefficient on the roof. From eqs. (3) and (4):

$$\Delta C_{p_{roof}} = C_{p_{iw}} - C_{p_r} + C_{p_{iT}} \tag{5}$$

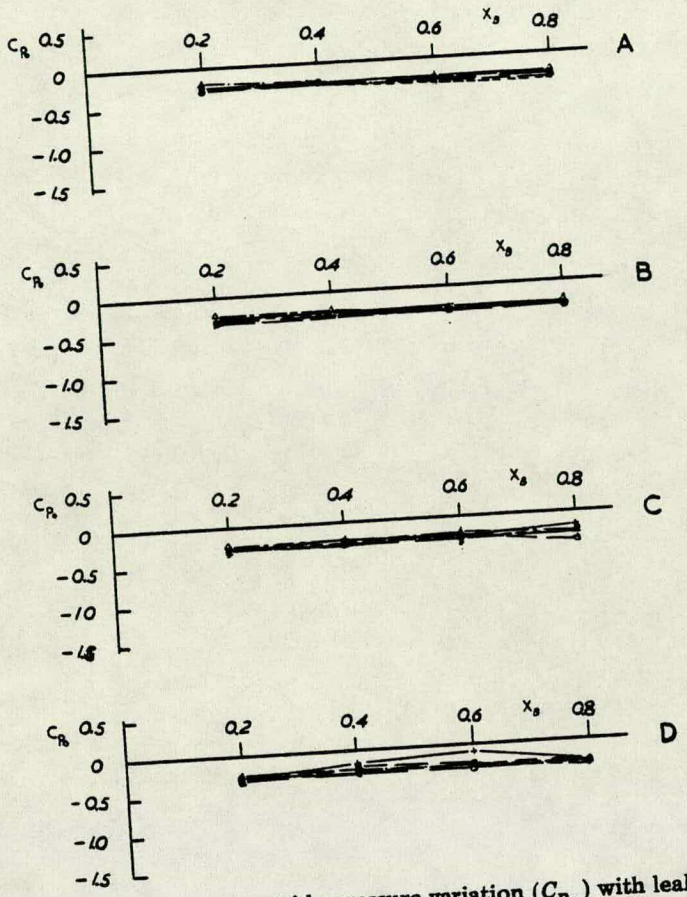


Fig. 7. Back wall outside pressure variation (C_{p_o}) with leakage $\alpha = 0°$.

C_{p_r} is always negative for all wind directions, $C_{p_{iT}}$ is always positive, and $C_{p_{iw}}$ can either be positive or negative depending on the relative leakage of the walls and the wind direction. So the conditions for vent failure or otherwise are:

$|C_{p_r}| + C_{p_{iT}} + C_{p_{iw}} > 0$ no failure

$|C_{p_r}| + C_{p_{iT}} - C_{p_{iw}} < 0$ failure

This means that if $C_{p_{iw}}$ is negative and its value is greater than $|C_{p_r}| + C_{p_{iT}}$, the vents will fail as the air is sucked into the building through the vents. On the other hand if $C_{p_{iw}}$ is positive, the rate of smoke flow through the vent is increased. The value of $C_{p_{iw}}$ determines the efficiency of the vent. $C_{p_{iw}}$ and C_{p_r} are known from the wind tunnel measurements, $C_{p_{iT}}$ is known from the plume theory. Thus $C_{p_{roof}}$ is known.

Now, eq. (2) gives

$$u_v = (2q\Delta C_{p_{roof}}/\rho_c)^{\frac{1}{2}} \qquad (6)$$

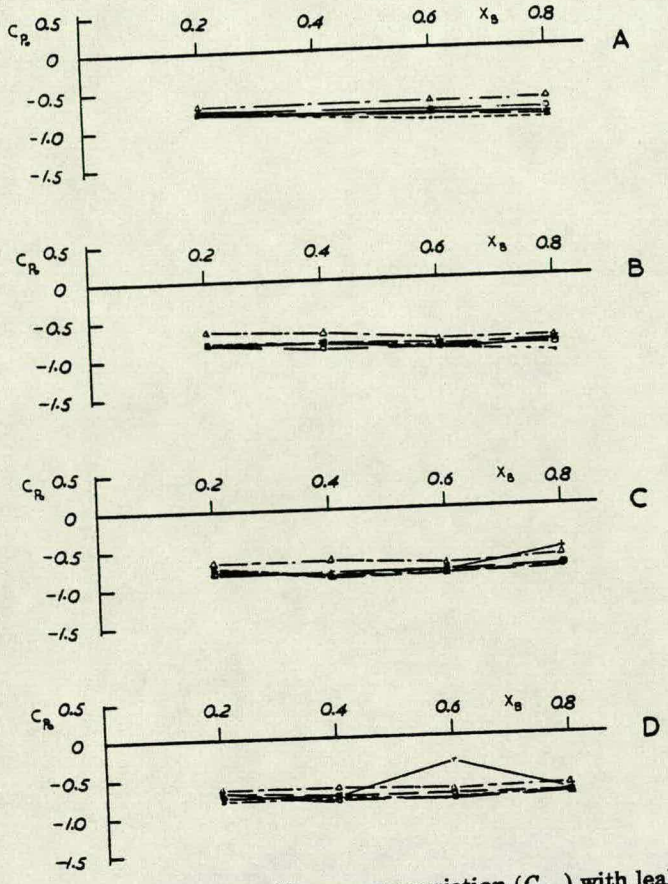


Fig. 8. Back wall outside pressure variation (C_{p_o}) with leakage $\alpha = 45°$.

The critical mass flow rate of hot gases through the vent is:

$$M_{v_{crit}} = \rho_c V_{v_{crit}} \tag{7}$$

or in terms of extract velocity:

$$M_{v_{crit}} = C_v \rho_c A_{v_{crit}} u_v \tag{8}$$

where $A_{v_{crit}}$ = critical vent area, C_v = discharge coefficient for the vent, ρ_c = gas density below the ceiling. Substituting for u_v from (6), we get:

$$M_{v_{crit}} = C_v \rho_c A_{v_{crit}} (2q\Delta C_{p_{roof}} / \rho_c)^{\frac{1}{2}} \tag{9}$$

or

$$A_{v_{crit}} = \frac{M_{v_{crit}}}{C_v \rho_c} \left(\frac{\rho_c}{2q\Delta C_{p_{roof}}} \right)^{\frac{1}{2}}$$

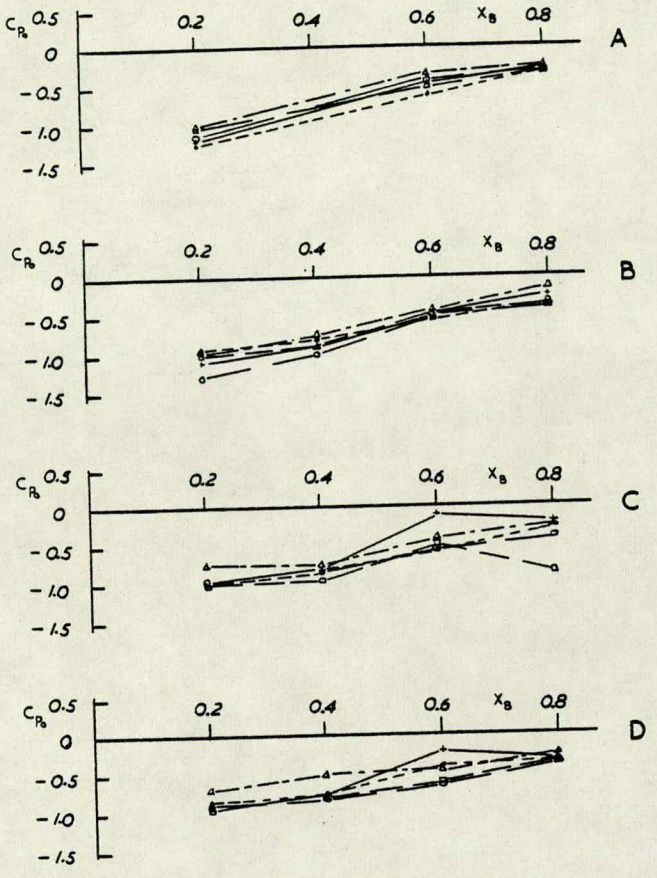


Fig. 9. Back wall outside pressure variation (C_{p_o}) with leakage $\alpha = 90°$.

Critical mass flow through a vent is known from eqs. (7) and (1). Therefore critical vent area required can be calculated from eqn. (10). From the knowledge of total mass to be extracted, number of such vents required can easily be worked out.

6.1 Sample calculation

Let us assume that the building is 50 m × 50 m cube, and that the wind speed at that height is 20 m/s, then

$$q = \tfrac{1}{2}\rho U^2 = \tfrac{1}{2} \times 1.22 \times 400 = 244 \text{ N/m}^2$$

For a fire of total heat output 1260 Btu/s (317.55 kcal/s), and layer depth 3 m, the initial mass flow rate is 16.88 kg/s (from Ref. [3]). Considering the building to be at wind incidence $\alpha = 0$.

For leakage ratio $R = 1$ (from Fig. 14).

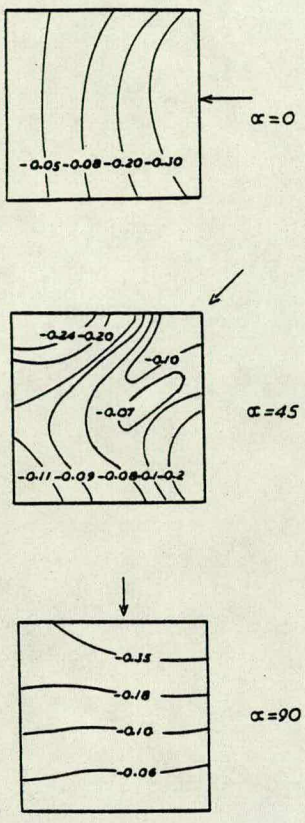


Fig. 10. Pressure contours on the roof (C_{p_o}) for wind directions $\alpha = 0°$, $\alpha = 45°$, and $\alpha = 90°$.

$$C_{p_i} = 0.2$$

$$C_{p_{iT}} = 0.772/244 = 0.00316$$

$$C_{p_r} = -0.16$$

$$\therefore \Delta C_{p_{roof}} = 0.2 + 0.00316 + 0.16$$

$$= 0.363$$

$$\therefore A_{v_{crit}} = \frac{16.88}{0.6 \times 1.19} \left(\frac{1.19}{2 \times 244 \times 0.363}\right)^{\frac{1}{2}}$$

$$= 1.937 \text{ m}^2$$

Similar calculations can be done for other leakage combinations at various incidences. The results are plotted in Fig. 15.

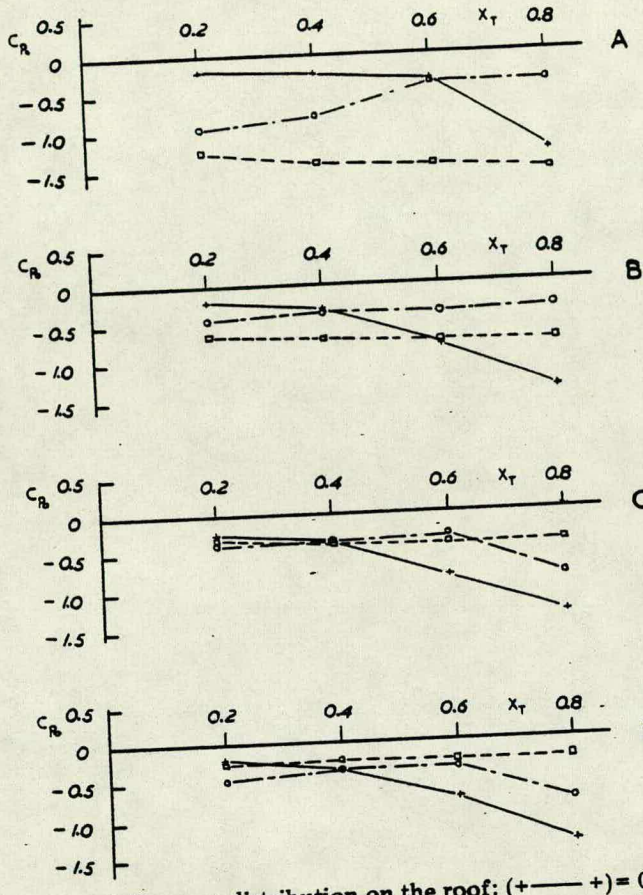


Fig. 11. Pressure distribution on the roof: (+—— +)= 0°; (o------o) = 45°; (□-------□) = 90°.

7. Discussion

7.1 Leakage effects on outside pressures

One of the objects of this exercise was to see if any measurable changes occur in the outside pressures on the walls with variation in leakage. The leakage characteristics of the front and back walls were varied to give maximum leakage of 1 per cent on each wall. The results for three wind directions are shown in Figs. 4, 5 and 6, for the wall labelled as Front Wall. These figures (in particular Fig. 4) show that the pressures are unaffected by the leakage. The scatter can be attributed to the turbulence itself. No marked change is detectable due to opening of the holes. When the model is rotated through 90°, the front wall becomes one of the side walls, and experiences negative pressures (suction). This is clear from Fig. 6. Again, no change in pressures is detectable due to opening of the holes.

The other wall on which the leakage was varied was the Back Wall. The

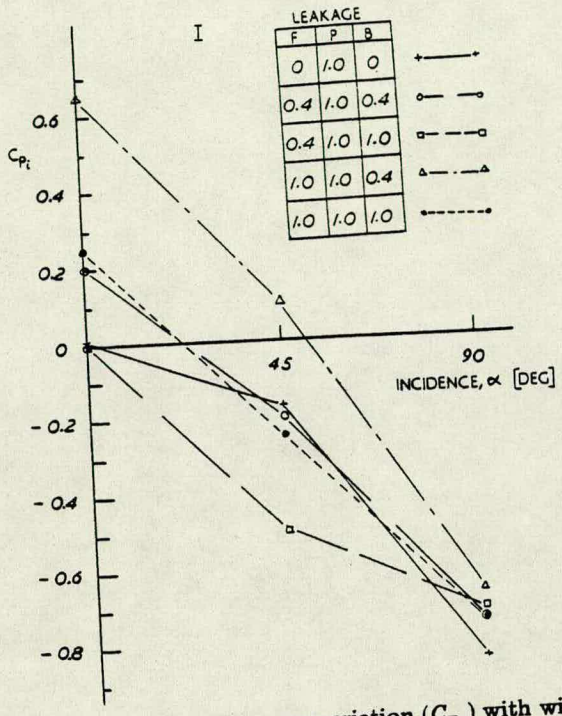


Fig. 12. Internal pressure variation (C_{p_i}) with wind direction for different leakage combinations, Region 1.

results are summarised in Figs. 7, 8 and 9. As Fig. 7 shows clearly, no apparent change occurs in pressure measurements and the pressure is uniform over the whole surface ($C_{p_o} \doteqdot -0.26$). But, as the model is rotated through 45°, the suction increases (Fig. 8) and still further increase occurs when the back wall becomes one of the side walls ($\alpha = 90°$) Fig. 9. The scatter at levels C and D is very likely due to turbulence. These measurements therefore indicate that any changes in leakage characteristics of a building have no effect on the outside pressures acting on the building.

7.2 Pressure distribution on the roof

In case of a fire, such buildings become smoke logged easily. To clear the building of smoke, ventilation holes are required in the roof. A knowledge of the wind-induced pressure distribution on the roof is therefore necessary for better design of these holes.

Wind-induced pressure on the roof is highly dependent on the wind direction. Figure 10 shows the pressure contours for three wind directions investigated. In the regions of the roof near the windward side (when air flows normal to one of the walls), the suction increases as air is accelerated when it rounds the corner: as air slows down towards the leeward wall, the suction is decreased. This is clear from Fig. 10, for $\alpha = 0$ and 90°. The similar-

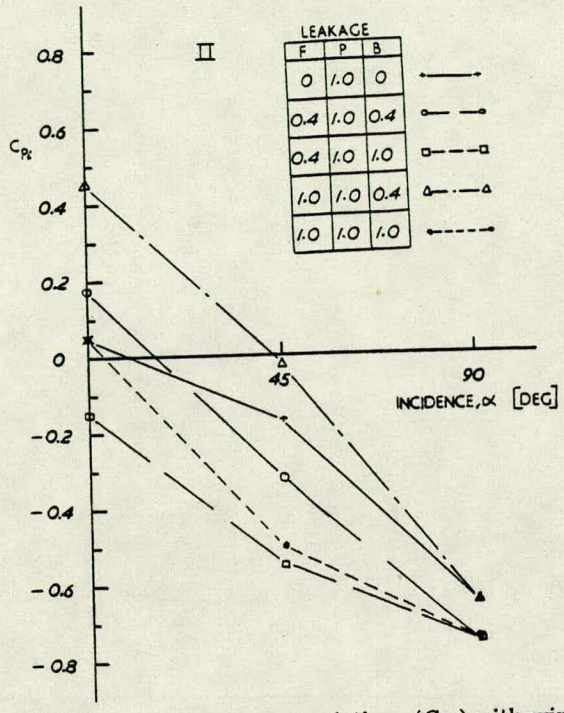


Fig. 13. Internal pressure variations (C_{p_i}) with wind direction for different leakage combinations, Region II.

ity of contours in these two wind directions is due to the symmetry of the model (being cubical). For any other direction the pattern is quite complex as is clear from the case of $\alpha = 45°$.

The actual measurements are shown in graphical form in Fig. 11. Here the variable parameter is only the wind direction. For $\alpha = 0°$, the outside pressure coefficient varies from -0.3 (windward wall) to -1.4 (leeward wall). The magnitude for $\alpha = 90°$ is the same.

$-0.3 < C_{p_o} < -1.4$ for $\alpha = 0°$

$-0.3 < C_{p_o} < -1.5$ for $\alpha = 90°$

7.3 Internal pressures

Because of the leakage, air enters the building at positive pressure areas and leaves at negative pressure areas. As a result, change in the inside pressures occurs so that inflow equals outflow. This inflow and outflow, depend on the leakage characteristics, as well as the wind direction (for a given wind profile and building shape). Any vent-design calculations must take the inside pressure variations into account, as it is the pressure difference across the roof that drives the hot gases out.

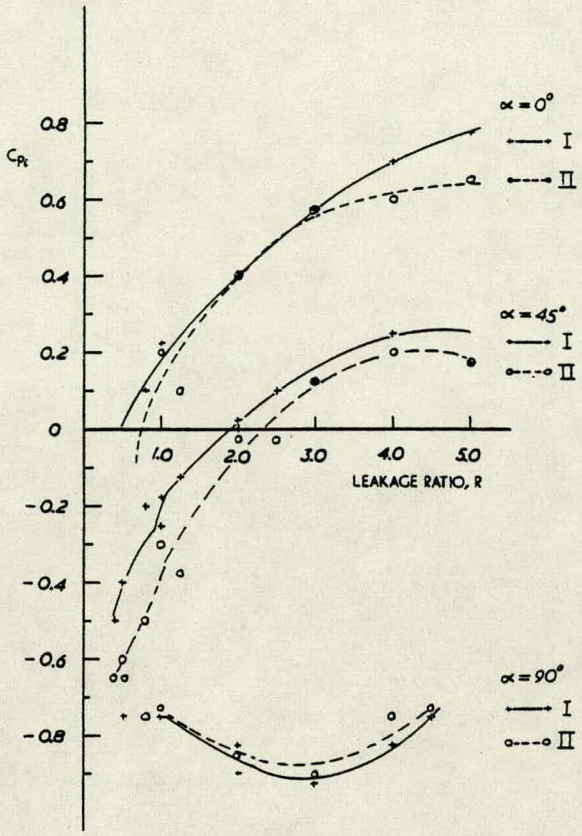


Fig. 14. Variation of internal pressure (C_{p_i}) with leakage ratio R, for wind direction $\alpha = 0°, 45°, 90°$.

The measured internal pressures, for different leakage combinations and wind directions, are shown in Figs. 12, 13 and 14, where I and II are the sections on either side of the partition (I towards the front wall, II towards the back wall).

In Figs. 12 and 13, the results for no external leakage (sealed cube) are interesting. It is expected that when the building (box) is completely sealed, the inside pressures are independent of outside wind. But this is not what the figures show. Solid lines are the result for this case and they show that pressure becomes negative as the wind direction changes from $\alpha = 0°$ to $\alpha = 90°$, in fact the corresponding C_{p_i} values are $C_{p_i} = 0$, $C_{p_i} = -0.85$, respectively. This was found to be due to the change in volume of the cube, resulting from the wind force acting on the flexible walls of the cube.

When $\alpha = 0°$ and the front-wall leakage is greater than the back-wall, there is a build-up of pressure inside the cube in order to adjust the back-wall pressure difference so that inflow equals outflow, and the inside pressure is lowered when the front wall leakage is less than the back wall. The comparison of the curves for △ and □ in Figs. 12 and 13 shows this clearly.

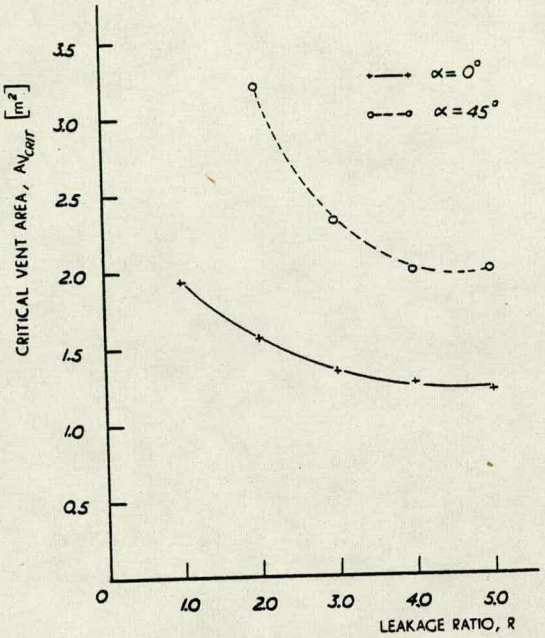


Fig. 15. Variation of critical vent area ($A_{v_{crit}}$) with leakage ratio R, for α = 0°, 45°.

When α = 90°, in this extreme case both the leaky walls are subjected to negative pressures (being now side walls). Therefore the inside pressure also drops and becomes negative as is clear from Figs. 12 and 13. This inside negative pressure will have the effect of drawing in air through the holes in the roof, and the vent failure will occur.

Figure 14 shows clearly the effect of leakage and wind direction on internal pressure. For α = 0° it is clear that internal pressure increases with R. But for $R < 1$ the curves change as shown in p. 51 of [5]. For $\alpha > 0°$, the curve shifts downwards and at 90° C_{p_i} is negative for all $R > 1$. Hence failure of vents.

Using these results, calculation for the vent sizes can be made, remembering that the negative pressures on the roof and positive pressures inside the cube add to the buoyancy pressures to increase the volume flow rate through the vent. The critical vent area for such a building is calculated and the results for different configurations are shown in Fig. 16. It shows that the critical vent size required decreases with the wind direction for any particular leakage ratio ($R > 1$). In fact, for α = 90°, all vents will fail when the wind speed (U) is significantly greater than zero. To overcome this, the building leakage characteristics must be adjusted to give positive internal pressure.

8. Conclusions

The leakage characteristics of a building do not have any appreciable effect on the outside wind-induced pressures on the building surface.

The internal pressures on the other hand are highly dependent on the leakage characteristics as well as the direction of the approaching wind. In fact the success or failure of the vents on the roof is determined by these effects. Higher leakage on the windward side improves the efficiency of the vents, and the efficiency drops if the leakage is higher on the leeward side.

For a complete solution (i.e. one solution for all wind directions) adjustment in the leakage distribution around the walls is required.

The results of this investigation are applicable directly to some existing building types if the walls of zero leakage and the internal division are regarded as fire-resisting construction and the leaky walls are regarded as curtain of glazing or light-weight metal cladding walls.

Acknowledgement

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APPENDIX D

WIND INDUCED MOVEMENT OF SMOKE WITHIN AND AROUND BUILDINGS - A WIND TUNNEL INVESTIGATION.

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ABSTRACT

This paper presents the results of pressure measurements on the external and internal surfaces and in the spaces of a model building. The model had defined barrier leakages and a fire pressure simulation facility. The objective of these measurements was to provide data for the prediction of potential smoke flow paths. The generation of adverse pressures by the natural wind, that is those causing flow into escape routes, need early, pre-construction identification and the partial study presented shows some of the probable flow patterns. It is suggested that appropriate analysis of building designs will lead to the provisions of smoke control systems of greater effectiveness than hitherto.

PURPOSE OF INVESTIGATION

The experimental work presented in this paper is part of a larger research project on smoke control problems in buildings. The main purpose of the total project is to correlate the behaviour of air flow and smoke flow in full size buildings with experimental model and a predictive computer program which is intended for calculating potential smoke movement in buildings.

This paper presents part of the experimental investigation into the wind induced air flows that can be expected in ordinary buildings. The flow potentials generated by wind induced pressures are analysed with respect to the possible movement of smoke within a building.

DESCRIPTION OF MODEL

A 32-cell, 5-storey perspex model scaled to approximately 1/25 full size. Each floor is arranged as shown in Figure 1 (see also Plate 1). The overall dimensions are 425 x 425 x 505 mm high.

D is a sealed vertical duct which contains measuring tubes and air input ducts. These are required for fire pressure simulation and corridor (C) or staircase shaft (S) pressurization. Walls R and T have variable leakage and T contains a sealed doorway. The other two sides are sealed effectively but do contain pressure taps for external pressure movements and sealed removeable panels for the necessary manipulation of internal doors. Spaces 1-6 represent a set of rooms each having

the same volume. 'Doors' to the corridor contain holes to represent defined leakage areas and each door is sealed to the corridor wall by a tubular seal (PVC) and kept in place by a turnbuckle arrangement. All doors are removeable. 'Windows' to each room are represented by removeable perspex panels, each with three holes which simulate representative leakage areas. Walls T and R contained the leakage areas; all other wall, floor and roof surfaces were regarded as impermeable.

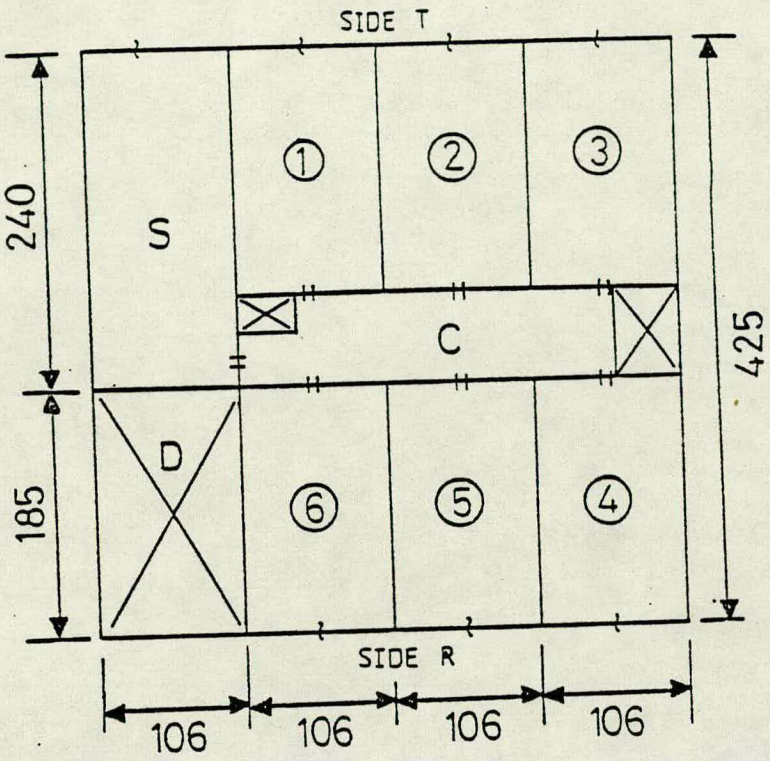


Figure 1: Floor plan of model (dimension:mm).

PRESSURE MEASUREMENT

Pressures inside the model were measured by installing about 200 tubes which ended on surfaces or in the spaces of the model. The tubes were connected to multi-channel pressure scanners then the pressures measured by a micro-manometer and recorded on pen chart recorders. The wind tunnel used was a low velocity open jet tunnel (1070 x 1525 mm), the air being given a turbulent velocity profile by elliptical vortex generators. The increase in velocity with height follows a power law profile having an exponent of 0.4, which is representative of natural wind in urban areas.

LEAKAGES USED

In the results presented, only two air leakage configurations were used. For both configurations the window and door leakages were kept the same, but the leakage available to the stair shaft (S) was changed. The leakage to the shaft represents either that due to windows throughout its height (Leakage (a)) or that due to a single closed entrance door (Leakage (b)).

Table 1

Leakage (a)

T	D	R
1.5	1.5	1.5

Leakage (b)

T	D	R
1.5*	1.5	1.5

The configuration for leakage (a) was that wall T had a leakage equal to 1.5 per cent of the total area of wall T, and wall R the same percentage leakage of wall R but with the outer part of duct (D) excluded. D:1.5 represents the leakage equal to 1.5 per cent of the area of all doors onto the corridor (C).

MEASUREMENTS MADE

Pressure measurements were made on all external surfaces and inside all spaces. These results were normalised to pressure coefficients (Cp) and these were used to calculate differential pressure coefficients (ΔCp) where these are the algebraic difference of the pressure coefficients across a barrier. Cp is defined as the ratio of the actual measured pressure (P) to the dynamic pressure (q) at the building height.

$$Cp = \frac{P}{q} \quad ; \quad \text{where } q = 0.5\ \rho\ U^2$$

ρ = density of air; U = velocity of air at height of model.

All relevant pressures were measured with and without a simulated fire pressure. This was simulated in room ⑥ on floor 2 or floor 4. In addition the measurements were repeated for wind incidence 0° to 270° at intervals of 45°. For 0° ($\alpha = 0$) the airflow is normal to wall T.

The fire pressure was simulated by introducing air into a room and generating a pressure across the room door ≒ 7.5; ≒ 10 Pa (≒ 11 x 10^{-4}; ≒ 14.5 x 10^{-4} psi) in still air conditions (1). This range of pressure was chosen because available evidence suggests that fire induced pressure differences do not exceed about 7.5 Pa (11 x 10^{-4} psi) in ordinary buildings (1).

PRESSURE DISTRIBUTION AROUND MODEL BUILDING

Figures 2 to 8 give the Cpo results for the model. Where possible they are presented as contours. These show that the external pressure distribution is not unusual when compared with any other work on bluff bodies.

The variation in stairshaft pressure coefficients with wind incidence for both leakage configurations are presented in Figure 9. With leakage (a) all angles of incidence greater than 60° give a negative pressure whichcould create dangerous conditions for escapers in a real building fire. With reduced leakage (b) the situation is improved but the shaft pressures are not sufficiently positive to overcome adverse pressures elsewhere in the building.

Figures 10-13 are plots of the corridor pressure coefficients for both leakage configurations and all angles of incidence both with and without fire simulation.

With a fire on floor 4 (Figures 10 and 11) the effect of the fire pressure in the corridors is confined to the fire floor, but the pressure is reversed and the ΔCp corridor stair shaft (C/S) is increased which suggests a greater flow potential for smoke to move into the normal escape route.

easurements for a similar fire on floor 2 show a similar change in flow potential ut the pressures differential was less because of the lower values of Cp_o. igures 12 and 13 give the corridor pressure variations for leakage (b). For ngles of incidence between 135° and 225° the potential flow of smoke into the tairshaft is reduced (compared with that for leakage (a)) because of the reduced eakage area from the stairshaft. (Compare Figures 11 and 13 with respect to igure 9 for $\alpha = 180°$).

DISCUSSION OF RESULTS

Leakage (a) (When T = 1.5; D = 1.5; R = 1.5)

Wind Direction $\alpha = 0°$

Figure 2 (for side T) shows that the wind pressures vary vertically and horizontally, the maximum pressure occurring at 0.8 of the model height. At this level the highest room and corridor pressures are expected when all doors, throughout the model, have the same leakage areas and are closed. This is confirmed by reference to Figure 10 ($\alpha = 0°$) for the corridor pressures.

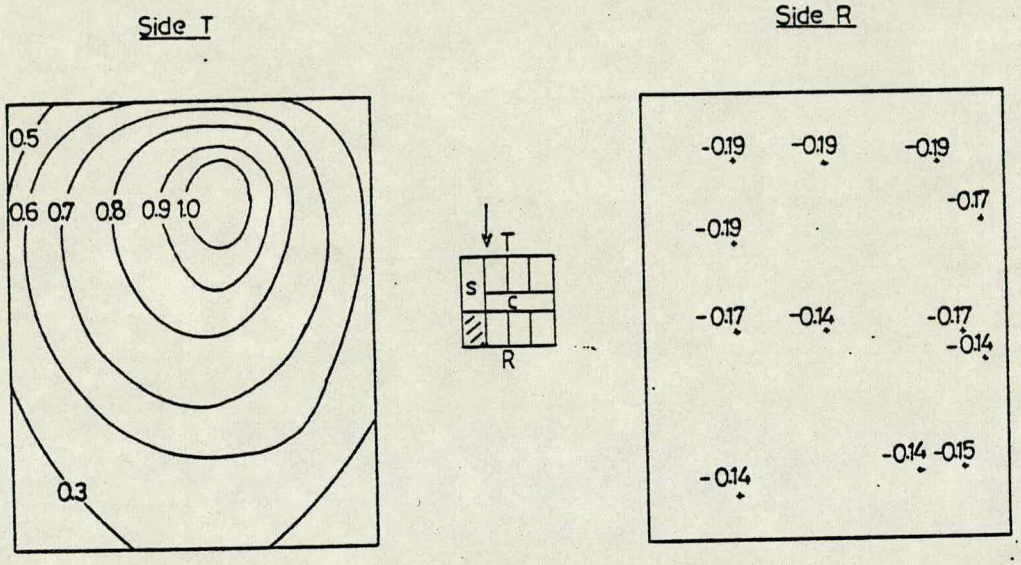


Figure 2: Outside pressure distribution (Cp_o), $\alpha = 0°$.

Table 2: Room Pressures on Floor 4 ($\alpha = 0°$)

Room	①	②	③	Shaft	④	⑤	⑥
Cp_i	0.97	0.90	0.65	0.5	-0.19	-0.19	-0.20

The leeward room ④⑤⑥ pressures relate directly to the external pressures on side R (Figure 2) both exhibiting small pressure variations only. Measurements on other floors showed similar small variations. Subsequent calculations showed that the use of a single value for Cp on side R ($\alpha = 0°$) was not inappropriate for smoke flow prediction.

Wind Direction $\alpha = 45^{\circ}$

Rotation to 45° gave a marked change in pressure pattern for wall T (Figure 3). There was no definite stagnation point although a pressure gradient is maintained with highest values at 0.8 of the height. The maximum values are somewhat less than when $\alpha = 0^{\circ}$.

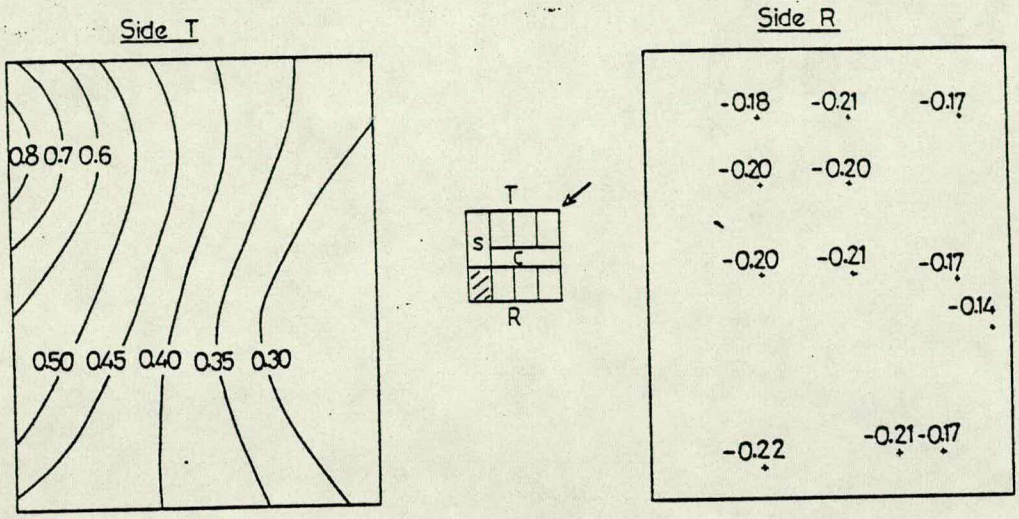


Figure 3: Outside pressure distribution (Cp_o), $\alpha = 45^{\circ}$.

Table 3: Room Pressures on Room 4 ($\alpha = 45^{\circ}$)

Room	①	②	③	Shaft	④	⑤	⑥
Cpi	0.44	0.59	0.76	0.15	-0.23	-0.23	-0.29

Table 3 shows that the highest pressure was developed in Room ③ as expected from the skew pressure distribution on wall T. Wall R remained in the wake region but the negative pressure values are higher than when $\alpha = 0^{\circ}$, because of the larger eddies, of greater velocity, generated at the windward end of the wall. The average external Cp_o is about -0.2 and can be assumed to be uniform. The room pressures were fairly uniform and this supports the former assumption. Reference to Figure 10 ($\alpha = 45^{\circ}$) shows that the corridor pressures are similar to those when $\alpha = 0^{\circ}$, although the values are less. Similarly the shaft pressures (Tables 2 and 3) are reduced also.

Wind Direction $\alpha = 90^{\circ}$

For this wind angle both leaky walls (T and R) had a negative pressure gradient where the maximum values are near the top of each leading end (Figure 4). Table 4 indicates that the highest negative pressure values were found in Rooms ③ and ④.

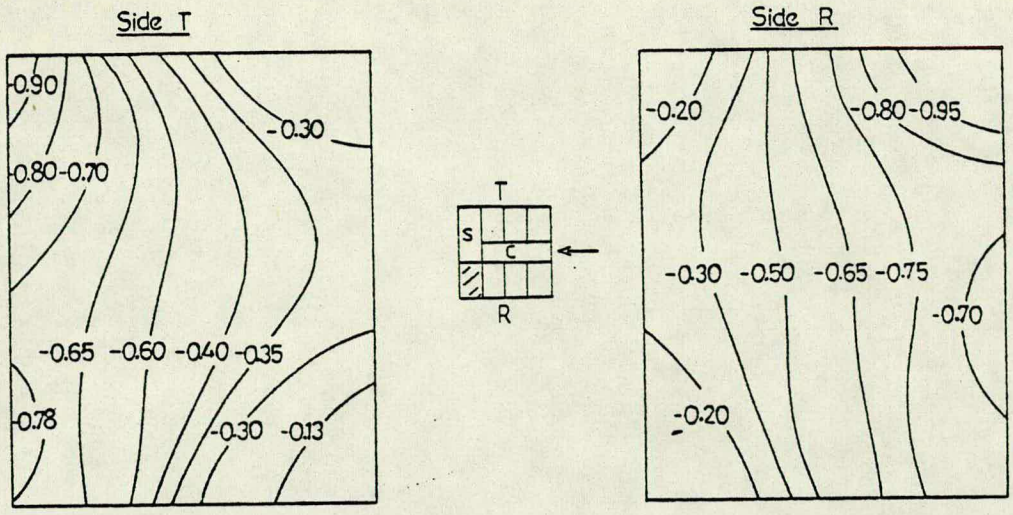


Figure 4: Outside pressure distribution (Cp_o), $\alpha = 90$

Table 4: Room Pressures on Floor 4 ($\alpha = 90^o$)

Room	①	②	③	Shaft	④	⑤	⑥
Cp_i	-0.44	-0.77	-0.81	-0.19	-0.84	-0.73	-0.4

Other measurements showed a similar pressure distribution for other floors which indicated a direct influence of the horizontal pressure gradient.

The corridor pressure for floor 4 (-0.4, Figure 10) is nearly equal to the pressures in rooms ① and ⑥. These volumes are almost in equilibrium so any potential smoke flow would be dictated by other pressure forces. The shaft pressure (-0.19) is greater than those for corridor and room spaces enabling an air flow from the shaft through the corridor and into the various rooms. As it may be assumed that smoke, once disassociated from the fire room, will tend to follow pre-existing air flow paths, this particular configuration would be dangerous for escapers.

Wind Direction $\alpha = 135^o$

The external pressure patterns (Figure 5) should be similar to those for $\alpha = 45^o$. The differences are due to a small experimental error and a comparison of Figures 3 and 5 show that the wind angle is less than 135^o. This resulted in greater negative pressures for side T and lower positive values for side R. As a consequence, the corridor pressures (Figure 10) are always negative compared with the values when $\alpha = 45^o$.

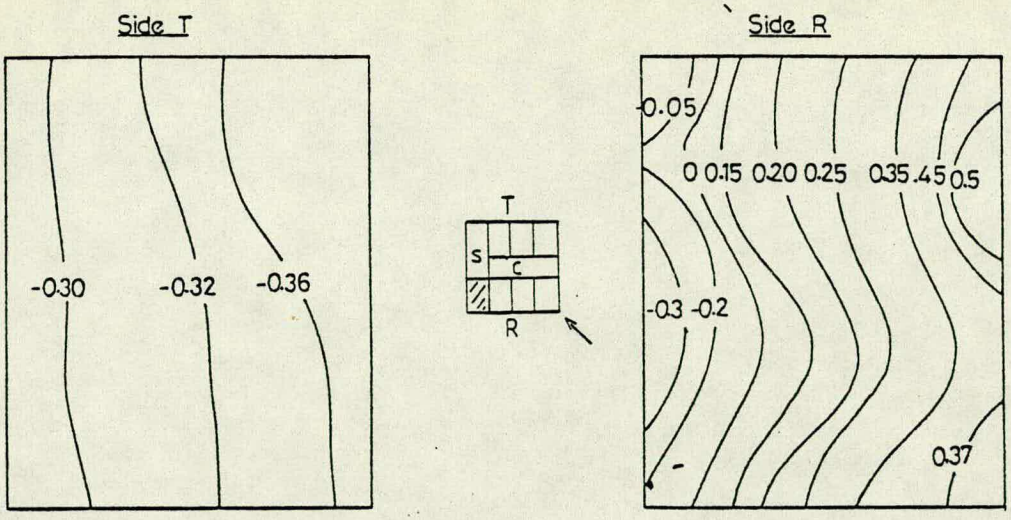


Figure 5: Outside pressure distribution (Cp_o), $\alpha = 135°$

Table 5: Room Pressures on Floor 4 ($\alpha = 135°$)

Room	①	②	③	Shaft	④	⑤	⑥
Cp_i	-0.32	-0.32	-0.29	-0.27	0.62	0.44	0.37

Comparing Tables 3 and 5, the rooms have similar pressures but the shaft has a negative pressure when $\alpha = 135°$. This pressure distribution would allow any smoke produced in Room ④, ⑤ or ⑥ to flow into the corridor, opposite rooms and into the shaft.

Wind Direction $\alpha = 180°$

For this direction the external pressures are similar to those when $\alpha = 0°$ (Figures 6 and 2). The room pressures were similar also. The major difference is the shaft pressure (Figure 10) which is negative when $\alpha = 180°$ as its leaky surface is on the leeward side of the model.

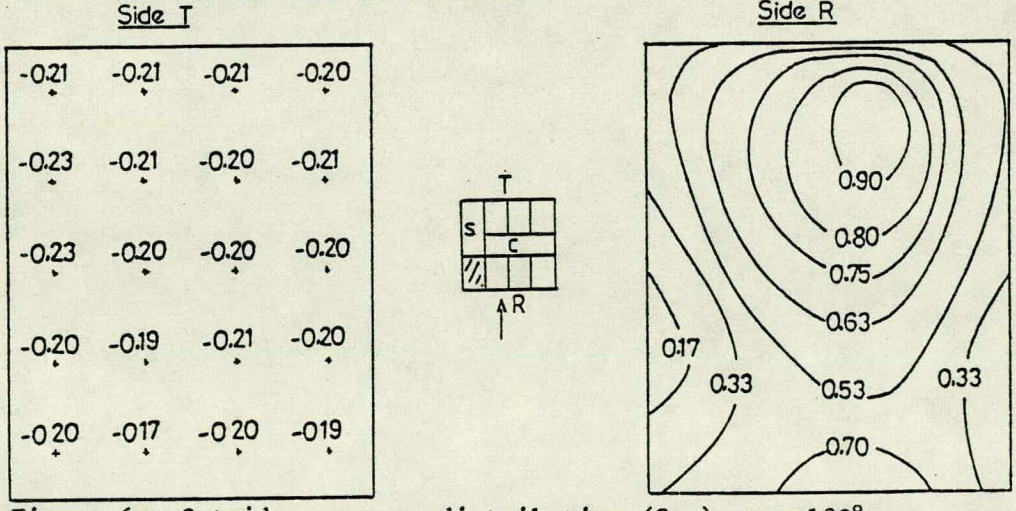


Figure 6: Outside pressure distribution (Cp_o), $\alpha = 180°$.

Wind direction $\alpha = 225^{\circ}$

The outside pressure distribution on the two leaky walls is shown in Figure 7. Comparison with Figure 5 shows that the outside pressures are similar. The corridor and the shaft pressures are still negative and air flows from corridor into the shaft. (Compare Figs 9 and 10).

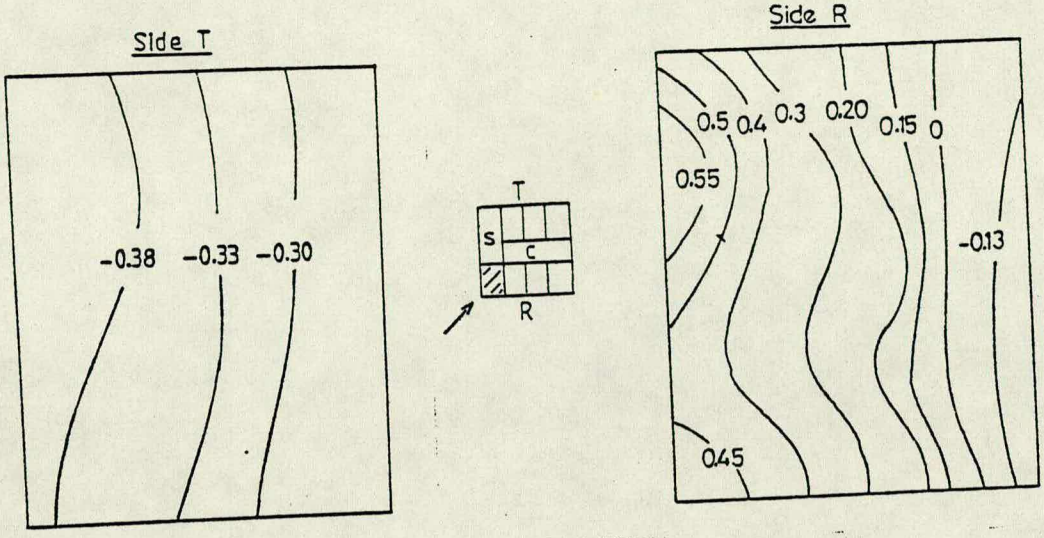


Figure 7: Outside pressure distribution (Cp_o), $\alpha = 225^{\circ}$

Wind direction $\alpha = 270^{\circ}$

The external pressures (Figure 8) are similar to those for when $\alpha = 90^{\circ}$. However the internal pressure distribution is not a reflection of those when $\alpha = 90^{\circ}$ because of the asymmetry of the internal spaces. A potential flow from the corridor into the staircase (see Figures 9 and 10) would be generated.

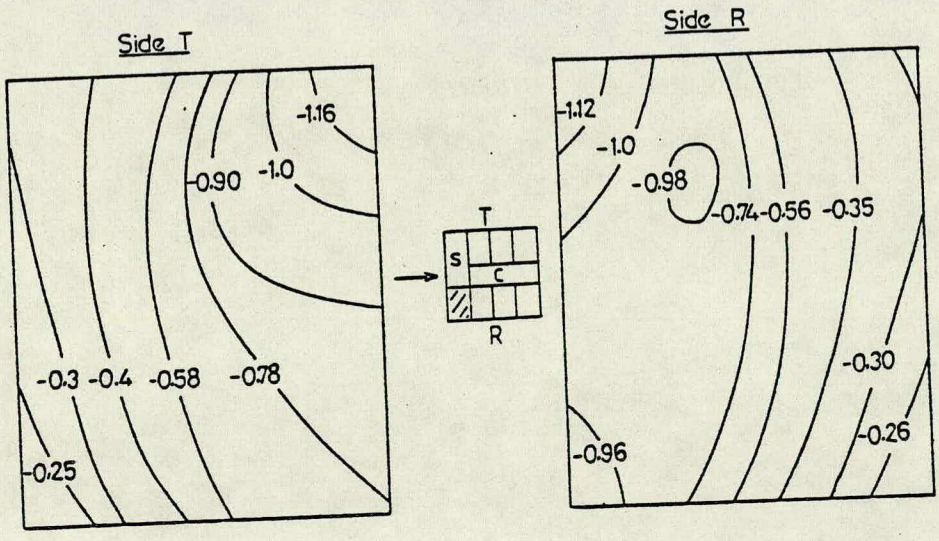


Figure 8: Outside pressure distribution (Cp_o), $\alpha = 270^{\circ}$

Leakage (b) (When T=1.5*; D=1.5; R=1.5)

All pressure measurements were repeated for this leakage configuration. For the rooms no significant changes were observed when the results were compared with those from leakage (a). With the reduced leakage to the shaft (staircase) the value of most of the pressure coefficients was reduced (see Figure 9) and this caused the changes in corridor pressures (compare Figures 10 and 12). The implications of such pressure changes is discussed later.

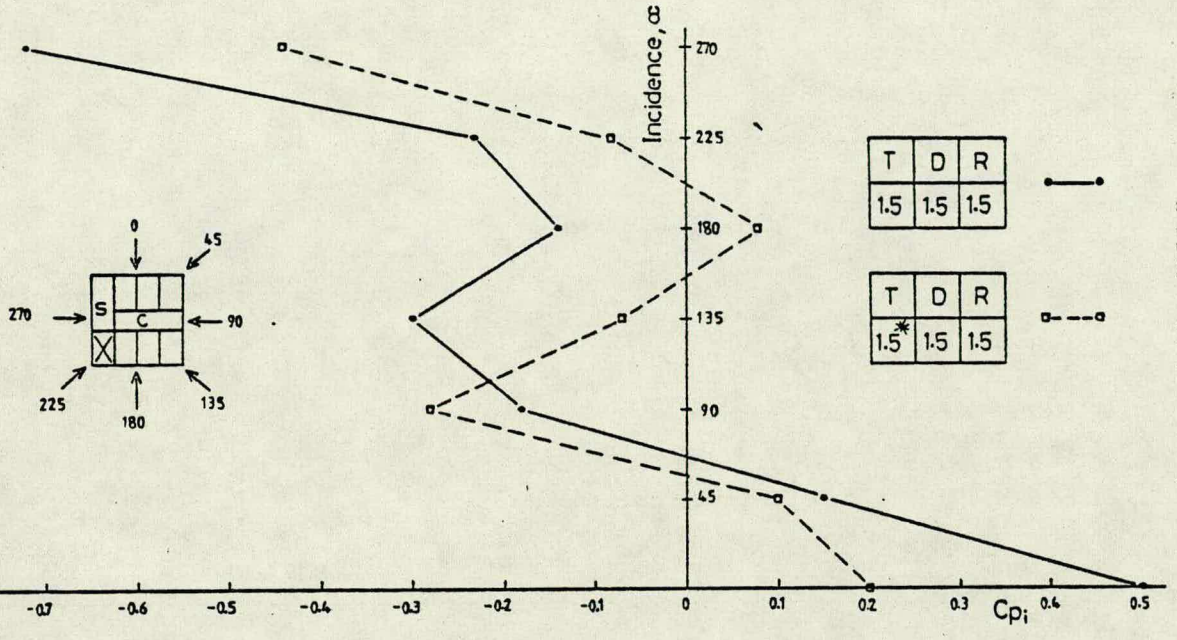


Figure 9: Shaft Pressure Variation with Wind Incidence Leakage (a) and (b)

Changes in Pressure Patterns with Simulated Fire

(i) Leakage (a)

All relevant pressure measurements were repeated with a simulated fire on floor 4 in Room (6). It was observed from the detailed results that there was little change from the "no fire" condition anywhere in the model building except on the fire floor. A comparison of Figures 10 and 11 shows the marked changes in measured pressures for the fire floor corridor at all wind angles except when $\alpha = 90^{\circ}$. Most measurements showed an increase in pressure which changes the ΔCp values between contiguous spaces.

(ii) Leakage (b)

The corridor pressure results for this reduced leakage configuration (Figures 12 and 13) show that the greatest effect remains on the fire floor but because the reduced staircase pressures (Figure 9) increase the ΔCp value across the corridor to staircase doors, there is a greater flow potential from the fire floor into this shaft. (The detailed implications of the increased flow potential are discussed in the next section).

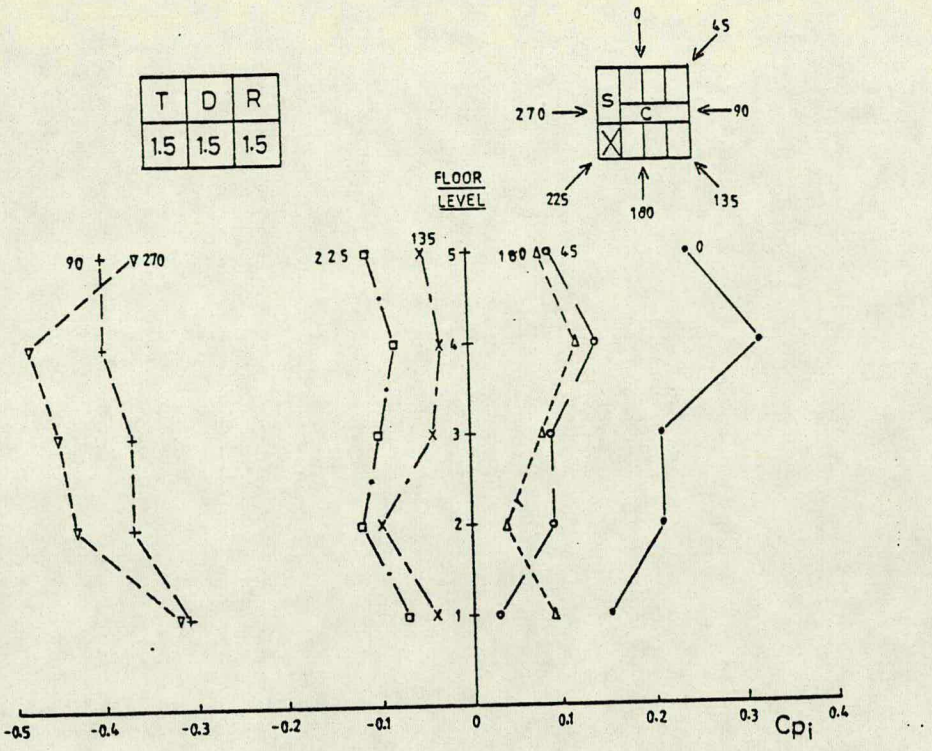


Figure 10: Corridor Pressure Variation with Wind Incidence (Leakage (a)).

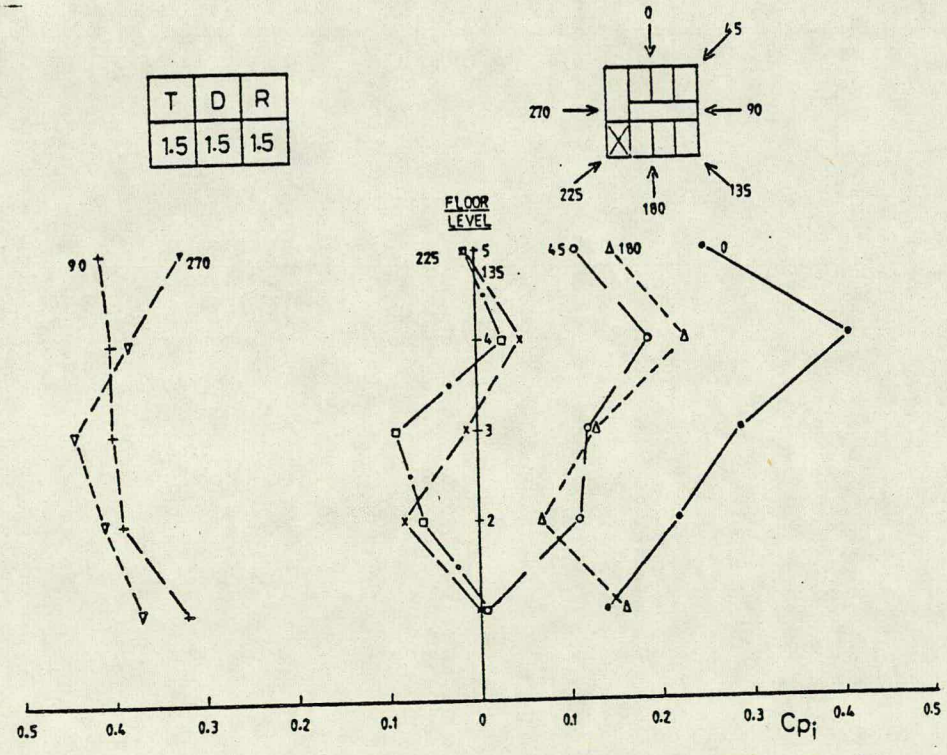


Figure 11: Corridor Pressure Variation with Wind Incidence Leakage (a). Fire Room (6), Floor 4

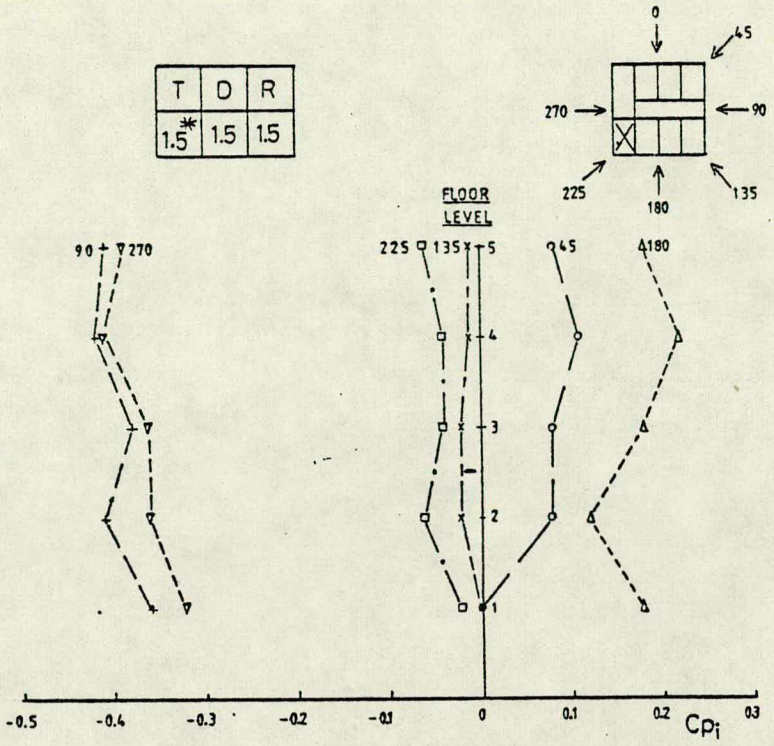


Figure 12: Corridor Pressure Variation with Wind Incidence (Leakage (b)).

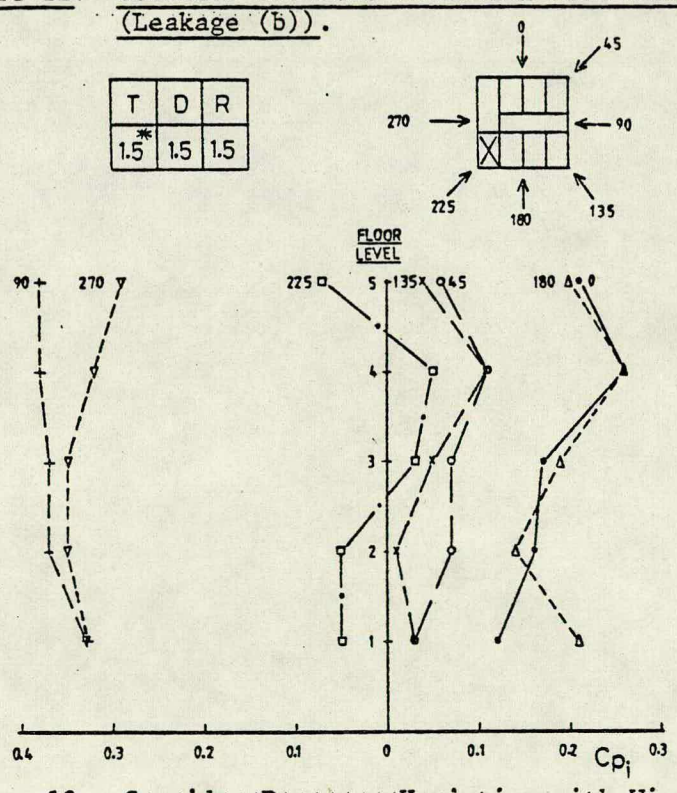


Figure 13: Corridor Pressure Variation with Wind Incidence (Leakage (b)): Fire Room (6), Floor 4.

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WIND INDUCED FLOW PATTERNS

The foregoing results concentrate on the response of building volumes to external wind forces. In this section, emphasis is placed on the changes in internal ΔCp values caused by the external wind and fire pressures. The flow patterns resulting from these ΔCp values are presented in Figures 14-17 and are discussed with respect to potential smoke flow into or through the notional escape route (i.e. corridors and shaft). It is assumed that the flow directions are represented by the arrows in the diagram.

Figure 14(b) (leakage (a)) shows that without a fire and when $\alpha = 90^{o}$, the flow was from the shaft into the corridor. This suggested that a shaft fire would threaten all escape routes and that a fire in another volume would threaten spaces on that particular floor only. When $90^{o} < \alpha < 270^{o}$, the flow is reversed, allowing a fire on any floor to be a threat to the shaft volume (i.e. the staircase).

With a simulated fire in Room ⑥, the resulting pressure differences are presented in Figure 15(b). With $\alpha = 0^{o}$ or 45^{o}, the corridor/staircase differential is reduced and because of the small overpressure due to the wind, the flow is reversed when $\alpha = 45^{o}$, which indicated flow into the shaft. Similarly when $90^{o} < \alpha < 270^{o}$, the flow paths are the same but the potential flow is increased. Comparing Figures 14(a) and 15(b) for $\alpha = 45^{o}$, it is interesting to note that any smoke in the shaft will enter this lower corridor and other levels also. An examination of Figure 15(a) and (b) for $\alpha = 45^{o}$ shows that because of the lower corridor pressures on Floor 2 smoke is likely to be confined to Room ⑥.

Comparing Figures 14(b) and 16(b) the ΔCp corridor/shaft is reduced significantly with the lower shaft leakage (Figure 16(b)). This has the general effect of allowing any fire pressure to overcome the naturally induced wind pressures in the shaft. When $135^{o} < \alpha < 270^{o}$, the flow potential is increased by the fire pressure. This would allow smoke to penetrate the shaft and to threaten Rooms ①, ② and ③. When $\alpha = 90^{o}$, the rooms ④ and ⑤ adjacent to Room ⑥ would be threatened also.

CONCLUSIONS

The results of this partial study serve to emphasise the importance of wind induced pressures on the possible behaviour of smoke in buildings.

The detailed results indicate that a fire in a shaft will threaten all levels when $\alpha < 90^{o}$ and when $90^{o} < \alpha < 270^{o}$ it is fairly certain that a fire in a windward space will threaten escape routes. Therefore, for the first case, the confinement of smoke to a shaft is possibly by presssurization of the corridor and/or lobby.

For the second case (reduced leakage) the smoke needs to be confined to the fire floor, or better still, the fire room, by: (a) shaft pressurization; (b) corridor pressurization; or (c) lobby pressurization.

A knowledge of the pressure difference distribution throughout a building for all wind directions is essential input to the definition of design pressure differentials for any pressurization system.

The actual pressures developed in a building will depend on the wind climate at a particular geographical location. An analysis of such a climate with a knowledge of the naturally developed pressure differentials will give the possible limits of problems across such barriers as doors (2). The probable maximum pressures developed will dictate the problems associated with opening and closing doors in escape paths, the selection of control mechanisms for effective pressurization systems and the probable failure potential for smoke control systems, which rely

on natural forces for their effective operation.

ACKNOWLEDGEMENT

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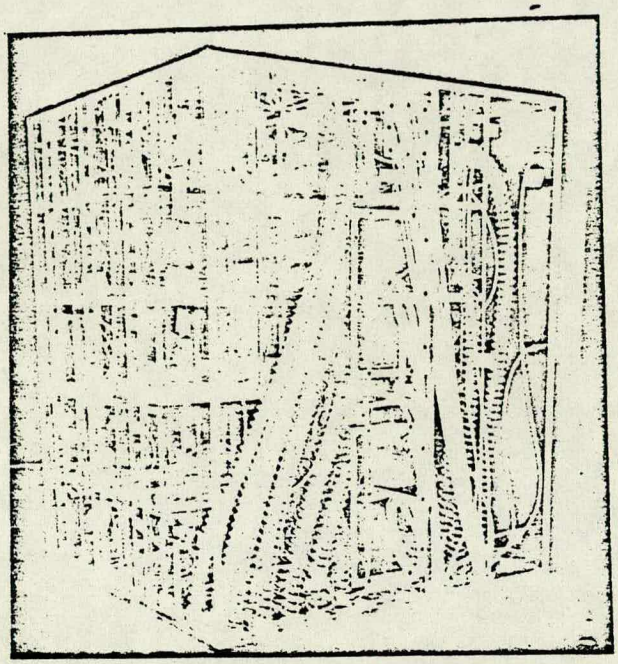


Plate 1: General view of model.