#5582

Field Tests on Staircase Pressurization System in Hong Kong

W.K. Chow **L. Lam Wai** **K.P. Cheung** *ASHRAE Member* **K.C. Lam**

ABSTRACT

This paper reports a series of field tests on the performance of staircase pressurization systems. The differential pressure levels across the doors to the staircase, airflow rate, air temperature, and fan characteristics are measured. A review on the present local fire regulations is also presented. The airflow network program ASCOS was also used to simulate the system. By comparing the measured field test results with those simulated by the computer model, modification to the operation is proposed. Recommendations are made for improving the future design of these smoke control systems.

INTRODUCTION

Smoke is a major cause of casualties during a fire because of its toxic nature and optical obstruction effect. Therefore, smoke control is essential in providing safety. The spread of smoke from the fire compartment to other parts of a building is primarily caused by indoor airflow induced by forces such as the buoyancy of hot gases, the stack effect from indoor and outdoor air temperatures difference, etc. In a high-rise building, escape routes are limited to the staircases. Therefore, keeping smoke away from staircases is important. People believe that an effective means of protecting the staircase is to pressurize it (McGuire 1967, Hobson and Stewart 1972, Wakamatsu 1972). Many investigational works have been reported (Evers and Waterhouse 1978, Yoshida *et al.* 1979, Klote 1980, Irving 1981, Klote and Fothergill 1983, Ritter 1985, Cheung 1987, Achakji and Tamura 1988, Klote 1988, Butcher 1989, Chow 1990). However there are still no unified design guides (BS 5588, NFPA 92A) and further work has to done to clarify some uncertainties. In Hong Kong, staircase pressurization systems are now specified by local codes to be installed in a wide range of buildings (FSD 1987). The local industry is interested in two aspects:

- How does a staircase pressurization system perform when in operation?
- What are the design criteria concerned?

Much investigational work must be done before these questions can be answered. Preliminary field tests on existing systems should be carried out to give some physical insight on performance. Field measurements on actual systems have been carried out in other parts of the world (Klote 1988, Clark and Harris 1989, Wong and Wong 1990, Tamura and Klote 1990, Klote 1990), but few results of local systems' evaluation are reported (Chow *et al.* 1990). A series of field tests was therefore performed on the staircase pressurization system installed at an educational institution in Hong Kong. This system was installed nine years ago, before there were tight fire regulations.

This paper reports on the field test for evaluating the system installed in the institution. From it, some guides for future investigational works can be proposed. The system did not perform satisfactorily; the problems encountered are discussed with suggestions for modification. The computer model ASCOS was used to help improve the current design and operation scheme (Klote and Fothergill 1983).

PRINCIPLES OF STAIRCASE PRESSURIZATION

Although fire may be confined in a burning compartment within a reasonable period of time, the smoke generated can spread quickly to other adjacent areas through cracks or opened doors. To avoid this, pressurizing the escape route such as the staircase is believed to be a solution (McGuire 1967, Hobson and Stewart 1972, Wakamatsu 1977). Two important factors must be considered in system design (Klote 1988):

Pressure Differences

It is necessary to consider both a maximum and a minimum allowable pressure difference induced by the mechanical system (*e.g.*, fan) across the doors. The minimum value must be stronger than the driving forces of air movement due to pressure fluctuations, stack effect, smoke buoyancy, and wind. The maximum allowable pressure difference should not make opening the door difficult.

Air Leakage Characteristics

The amount of air flowing from a high-pressure area to a low-pressure area through the leakage paths (*e.g.*, gaps in the doors) depends on the flow resistance and pressure difference concerned. A general expression relating leakage flow rate Q to the static pressure differential across an individual leakage component is (Klote and Fothergill 1983):

W.K. Chow, Principal Lecturer, **L. Lam Wai**, **K.P. Cheung**, and **K.C. Lam**, Department of Building Services Engineering, Hong Kong Polytechnic, Hong Kong.

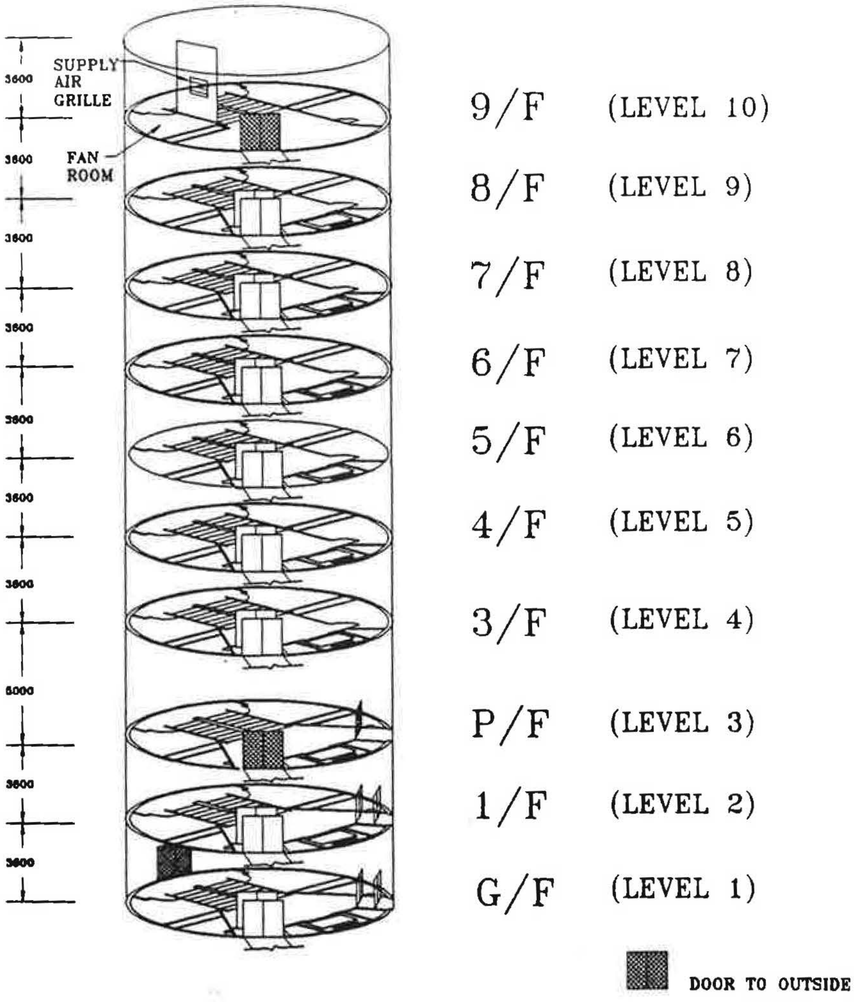


Figure 1 *Site of education institution*

$$Q = K(\Delta P)1/N \quad (1)$$

where:

ΔP = pressure difference, Pa
K = leakage coefficient of the component

For small leakage openings such as cracks or porous structures, the value of N varies between 1 and 2. The leakage coefficient can be expressed in terms of an equivalent leakage area A. The following equation is commonly used for calculating airflow:

$$Q = 0.827\, A(\Delta P)1/2 \quad (2)$$

LOCAL REQUIREMENTS

The Fire Services Department (FSD) of Hong Kong issued the New Code of Practice for Minimum Fire Services Installations and Equipment in 1987. It states that staircase pressurization systems must be installed in a range of buildings. The requirement was further revised in March 1989, and basically followed BS 5588 in order to clarify some points (Millar 1989).

The design differential pressures, with all doors closed and all overpressure relief systems in operation, are:

Minimum pressure = 50 Pa
Maximum pressure = Not fixed

The design airflow rate shall be obtained from having an average egress velocity of 0.75 m/s across three single-leaf entry doors and the largest exit door, which are fully opened. The leakage allowance for all other doors must be taken into account.

The resultant force for opening a door should not exceed 133N.

FIELD MEASUREMENT

The test site is a 10-level core with a combined lobby consisting of an elevator lobby, access to accommodation, access to service rooms, toilets, and switch room as shown in Figure 1. There is no door between the elevator lobby and the stairs. The top level of the core has mechanical and lift machine rooms. There are exit doors on the ground floor (G/F), podium floor (P/F), and the ninth floor (9/F) to outside as shown in the three-dimensional drawing in Figure 1. Double-leaf, bidirectional swing-type doors are used between the staircase and tenants' areas, and the exit doors at P/F as well. Doors exiting to the exterior at G/F and 9/F, the switch room, and the toilets are single-leaf, one-direction swing-type doors with locks. The staircase pressurization system, installed nine years ago, is a single-injection type, with a fan located at the top of the building. The fan is completely enclosed in a 2-h fire-rated en-

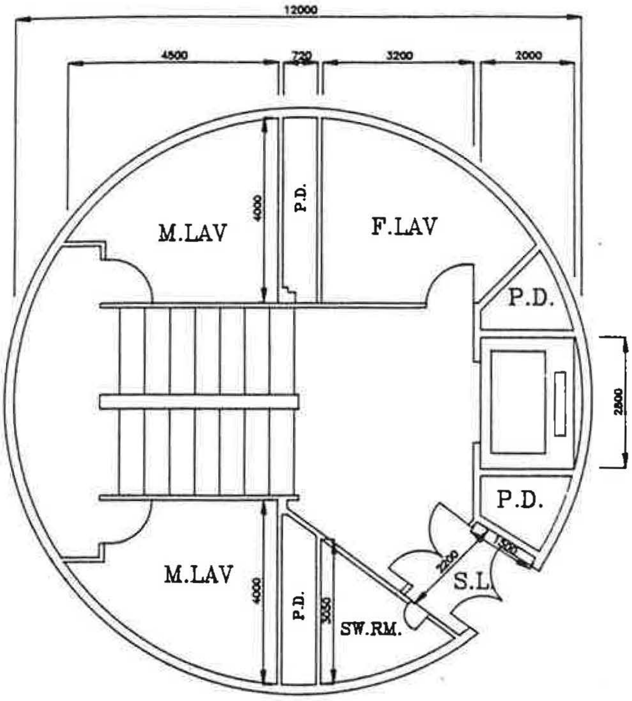


Figure 2 *Staircase detail of typical floor*

closure with nominal flow rate 10 m^3/s and 150 Pa static pressure, and supplies air to the staircase through the air grille on the top floor. Figure 2 shows a typical plan of a floor in the core.

Several points in the system are found to be not very good. The staircase lobby also serves as an elevator lobby with a number of doors leading to different services rooms, such as toilets, switch room, etc. These potential leakage paths provide low resistance paths for the supply air to escape instead of flowing through the door gaps leading to the accommodation. There are numerous leakage paths that allow supply air to leak elsewhere than to the intended path. Therefore, the airflow is lower than the value to maintain the required pressurization level between the lobby and the accommodation. In addition, the physical size of those door gaps are quite large which means that a larger volume of air must be supplied to maintain the required pressurization level. Before turning on the fan, the following were measured:

1. The differential pressure levels across the door between staircase and lobby; and the door between the lobby and the tenant area at each floor level.
2. The force required to open these doors.
3. The outside wind velocity and the outdoor temperature.

The following tests were performed when the fan was turned on:

Test 1. All the doors were closed with the fan turned on.
Test 2. The door at the 9/F (level 10) was opened.
Test 3. The door at the P/F (level 3) was opened.
Test 4. The doors at the P/F (level 3), 3/F (level 4), 4/F (level 5), and 5/F (level 6) were opened. Both stair doors and stair lobby doors at the 3/F (level 4), 4/F (level 5), and 5/F (level 6) were opened.

In addition to the parameters measured when the fan was turned off, the airflow velocity at the supply air grille was measured at nine different positions across the section. Further, the width of the door gaps at each door at different positions was also measured.

EXPERIMENTAL RESULTS

The differential pressure levels measured are summarized in Figures 3 to 6 with the measured leakage area from the staircase shown in Table 1. The pressure levels between staircase and lobby for test 1 lies below 30 Pa; the values between the lobby and tenant area were less than 20 Pa. For test 2, the pressure levels were much lower, *i.e.*, less than 3 Pa between the staircase and lobby. This result is because the system is a top-injection type and opening a door at the high level causes a serious drop in pressure levels at the other floors. The pressure level for test 3 with a lower level door opened is a little bit higher, *i.e.*, up to 10 Pa in the level closed to the fan. This is also due to the fact that the system is a top-injection one. For test 4, four doors were opened and the pressure levels at the top floors were not too low (*i.e.*, up to 6 Pa). This result is because air was injected at the upper floor. The airflow rate at the opened doors for each test are computed from the measured velocities and are shown in Table 2. The forces required for opening the door were measured for all the tests and shown in Figures 7a and 7b. The maximum value for all the tests lie below 100 N, which satisfies the local requirement.

TABLE 1
Airflow Leakage Area at Site, m^2

Floor Level	Door between Staircase and Lobby	Door between Lobby and Tenant Area	Leakage to Floor Above	Leakage Area to Outside	Leakage to Elevator
1	0.1150	0.1153	0.08	0.4125	0.035
2	0.0908	0.0905	—	0.205	0.035
3	0.1514	—	—	100	0.035
4	0.0654	0.0543	0.08	0.205	0.035
5	0.0646	0.0538	0.08	0.125	0.035
6	0.0583	0.0541	0.08	0.125	0.035
7	0.0696	0.0635	0.08	0.125	0.035
8	0.0539	0.0509	0.08	0.125	0.035
9	0.0457	0.0308	—	0.205	0.035
10	0.1620	—	—	3.5	0.035
	0.0643 (Exit Door)				0.36 (Opening in Lift Room)

TABLE 2
Airflow Velocity and Flow Rate through Doors

Test No.	Opened Door on Level	Measured Velocity, m/s	Flow Rate, l/s	Computed Velocity, m/s	Flow Rate, l/s
1	—		—		—
2	10	1.58	5533	1.63	5697
3	3	1.34	5122	1.50	5728
4	3	1.30	4969	1.35	5141
	4	0.25	463	0.16	287
	5	0.23	423	0.13	237
	6	0.41	760	0.22	421

DISCUSSION

The ASCOS program designed for analyzing pressurized staircases and simulating the associated airflow was used (Klote and Fothergill 1983). In this program, the building is translated into a network of spaces or nodes, with a specified pressure and temperature. Vertical shafts, such as staircases and elevator shafts, are modelled by a series of spaces, with one for each floor. Airflow through these paths is a function of the pressure difference across them. Outside pressures incorporate the effects of air temperature and wind. The friction losses in vertical shafts are also considered. The flows and leakage paths are assumed to occur at mid-height at each level. The details of the computer program have been described in Klote and Fothergill (1983) and will not be repeated here. An idealized airflow network for this staircase was established for simulation and is shown in Figure 8. In the network, there was a flow path between staircase and accommodation throughout the building (Figure 9). All the physical data, *i.e.*, the fan characteristics, flow area, etc., are keyed in. Results on the differential pressure levels are also shown in Figures 3 to 6. The predicted results agree reasonably well with the measured values.

Although satisfying the old local requirement (since staircase pressurization is not specified in the old code), the system might not be particularly successful, as the present criteria are not satisfied (Figure 2 and Table 2). The pressure level dropped significantly when a door was opened. The pressure level became extremely small when a door at a higher level was opened. Modification is necessary, but at the present time, it is too expensive to carry out a field test by changing the actual system. However, the ASCOS computer program can be used to simulate the design operating point for a revised system.

There are several ways of modifying the design. Distributing air through a multiple injection system using the existing pressurizing fan might be a solution. The existing duct void can be used to accommodate the distribution ductwork. Air grilles could be installed on each floor to ensure uniform pressurization of each lobby, so that the adverse effect of opening doors on other floors can be minimized. However, this system will be too expensive. Another alternative is to change the leakage area. The smaller the leakage area, the higher the differential pressure will be. But it is not feasible to replace all the doors.

If the single-injection system is still preferred, a higher fan airflow rate is needed to maintain the pressure in case of a door opening. Trial runs of varying both the inflow and exhaust airflow rates are again entered in the ASCOS program (Klote and Fothergill 1983). To maintain the pressure levels at other floors above 50 Pa when there is an opened door, the flow rate has to be increased to 35000 13/s. Obviously, this is not feasible for operation.

A suggested modification is made by injecting air in and extracting air out with a smaller flow rate. Subject to having a reasonable fan size for uniform pressure distribution, three pressurization fans rated 13 m^3/s, 10 m^3/s, and 12 m^3/s suggested for installation at level 3 (P/F), level 7 (6/F), and level 10 (9/F), respectively. Furthermore, two exhaust fans each rated 13.5 m^3/s are required at level 1 and level 5 (G/F and 4/F) to cater to the overpressure problem when all doors are closed. The simulated differential pressure levels under different door opening conditions are shown in Table 3 and Figures 10 to 13. In this way, the system has high enough pressure (*i.e.*, > 50 Pa) even when a door is opened.

CONCLUSION

A series of preliminary field measurements were carried out to determine the airflow pattern induced by the pressurization system in a staircase at an educational institution. These tests were conducted to assess the performance of the system installed. The system did not satisfy the new local requirement. There is no guarantee that the system can work successfully when there are open doors. From the test results, when all the doors were closed, the pressure level can be maintained above 50 Pa. When a door was opened, the pressure level at other floors dropped significantly. This condition is even worse when a door at an upper level was opened. Also, the pressure levels dropped more when more doors were opened. Poor distribution of supply air is the key factor.

A multiple-injection system is recommended, which will supply air to each floor uniformly. Another consideration is to include air curtains in the doorways for preventing smoke from spreading into the escape route (Chen 1986). However, this system is very expensive and also causes discomfort to the occupants.

For identifying future design criteria, long-term measurement is necessary. An important point to be considered

TABLE 3
Airflow Velocity and Flow Rate through Doors for Trial Simulation for Suggested System

Test No.	Opened Door on Level	Simulated Velocity, m/s (Fan 35 m^3/s)	Simulated Flow, m^3/s (Fan 35 m^3/s)	Simulated Velocity, m/s (Suggest System)	Simulated Flow, m^3/s (Suggest System)
1	—	—	—	—	—
2	10	8.09	28.321	8.02	28.080
3	3	7.47	28.540	7.61	29.100
4	3	6.70	25.616	6.90	26.389
	4	0.79	1.459	0.83	1.519
	5	0.64	1.179	0.62	1.147
	6	1.07	1.966	0.93	1.701

is the differential pressure level to be maintained when there are doors opened. Also, the number of doors designed to be opened and their location for different systems (*e.g.*, single-injection, bottom-injection, multiple-injection) is critical. The fan size, intake airflow rate, and the exhaust air rate for regulating pressure in the system are to be studied. More practically, a local design guide for such a system and a way of assessing the performance of such a system is essential (Klote 1988). All these elements have to be clarified in future, preferably using a full-scale physical model with hot smoke.

ACKNOWLEDGMENT

The authors wish to thank the Estate and Development Office for their cooperation while performing the field test.

REFERENCES

Achakji, G.Y., and Tamura, G.I. 1988. "Pressure drop characteristics of typical stairshafts in highrise buildings." *ASHRAE Transactions*, Vol. 94, Part 1.

BS 5588. 1978. *Fire precautions in the design and construction of building*, Part 4: Code of practice for smoke control in protected escape routes using pressurization.

Butcher, G. 1989. "Pressurization: A method of keeping escape routes in building clear of smoke." *Hong Kong Engineer*, February.

Chen, M.L. 1986. "A look at pressurization." *ASHRAE Journal*, April.

Cheung, K.P. 1987. "Staircase pressurization—The rationale and the alternatives." *ASHRAE Transactions*, Vol. 93, Part 2, Paper No. 3111.

Chow, W.K. 1990. "Staircase pressurization systems." *Transactions of the HKIE*, Vol. 2, Group 1, pp. 33-38.

Chow, W.K.; Wong, F.K.; Lo, T.T.; and Lau, K.M. 1990. "Field tests on a staircase pressurization system installed in a commercial building." *ASHRAE Transactions*, Part 2A, Vol. 96, pp. 393-398.

Clark, J.A., and Harris, J.W. 1989. "Stairwell pressurization in a cold climate." *ASHRAE Transactions*, Part 1, Vol. 95, p. 847.

Fire Services Department. 1987. "Minimum fire services installations and equipments." FSD Hong Kong.

Evers, E., and Waterhouse, A. 1978. "A computer model for analysing smoke movement in buildings." Current Paper 69/78, Building Research Establishment, U.K.

Hobson, P.J., and Stewart, L.J. 1972. "Pressurization of escape routes in buildings." *Fire Research Note* 958, Fire Research Station, Borehamwood, U.K.

Irving, S.J. 1981. "Validation of a smoke movement program." *Building Services Engineering Research and Technology*, Vol. 2, p. 151.

Klote, J.H. 1980. "Stairwell pressurization." *ASHRAE Transactions*, Part 2A, Vol. 86.

Klote, J.H. 1988a. "An overview of smoke control technology." *ASHRAE Transactions*, Vol. 94, Part 1, Paper DA-88-13-1.

Klote, J.H. 1988b. "Inspecting and testing air moving systems for fire safety." *Heat/Piping/Air Conditioning*, April, 77.

Klote, J.H. 1988c. "Project plan for full scale smoke movement and smoke control tests." NBSIR 88-388. Gaithersburg, MD: National Bureau of Standards.

Klote, J.H. 1990. "The Plaza hotel fire experiments." *ASHRAE Journal*, Vol. 32, No. 10, pp. 25-29.

Klote, J.H., and Fothergill, J.W. 1983. *Design of smoke control systems of building*. Atlanta, GA: ASHRAE.

McGuire, J.H. 1967. "Control of smoke in buildings." Fire Technology, Vol. 3, No. 3, p. 281.

Millar, I.S. 1989. "Pressurization of staircases—An explanation of the requirements." Paper presented at the HKIE/CIBSE/ASHRAE Conference on Fire Regulation, Hong Kong, March.

NFPA 92A. 1988. "Recommended practice for smoke control systems." Quincy, MA: National Fire Protection Association, Section 2-2.1.

Ritter, W.T. 1985. "Review of a smoke control system." *ASHRAE Transactions*, Part 1.

Tamura, G.T., and Klote, J.H. 1990. "Experimental fire tower studies on controlling smoke movement caused by stack and wind action." NRCC 31682. Ottawa: National Research of Canada.

Wakamatsu, T. 1977. "A computer technique for predicting smoke movement in building fires and designing smoke control systems." *Fire Standards and Safety*—ASTM, STP614, 168.

Wong, Y.W., and Wong, K.M. 1989. "Development of smoke control regulations for high rise buildings in Singapore." ASHRAE Far East Conference on Air-Conditioning in Hot Climates, Kuala Lumpur, Malaysia, pp. 105-113.

Yoshida, H.; Shaw, C.Y.; and Tamura, C.T. 1978. "FORTRAN IV program to simulate air movement in multi-storey buildings." DBR 45. Ottawa: National Research Council of Canada.

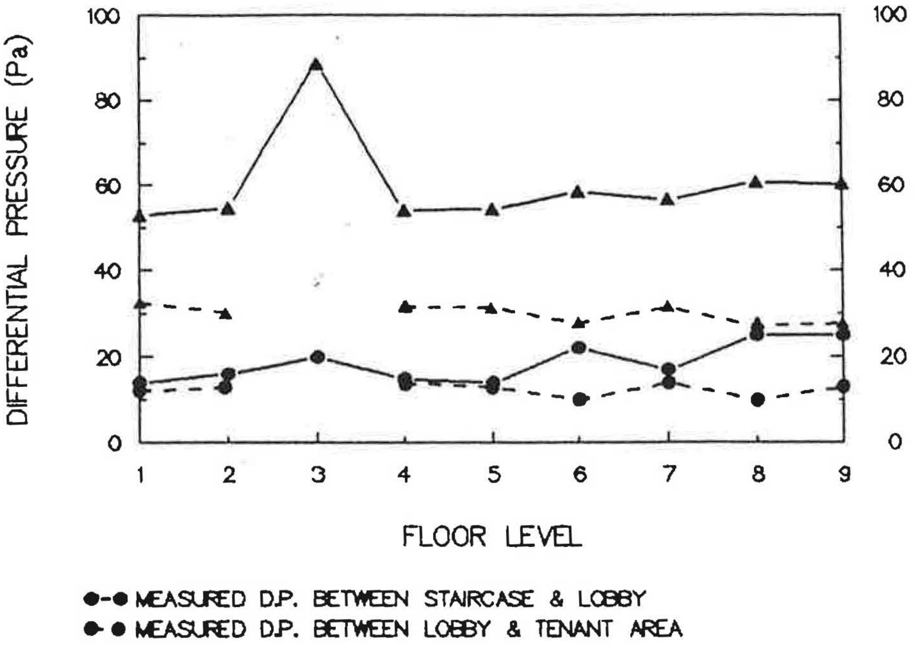
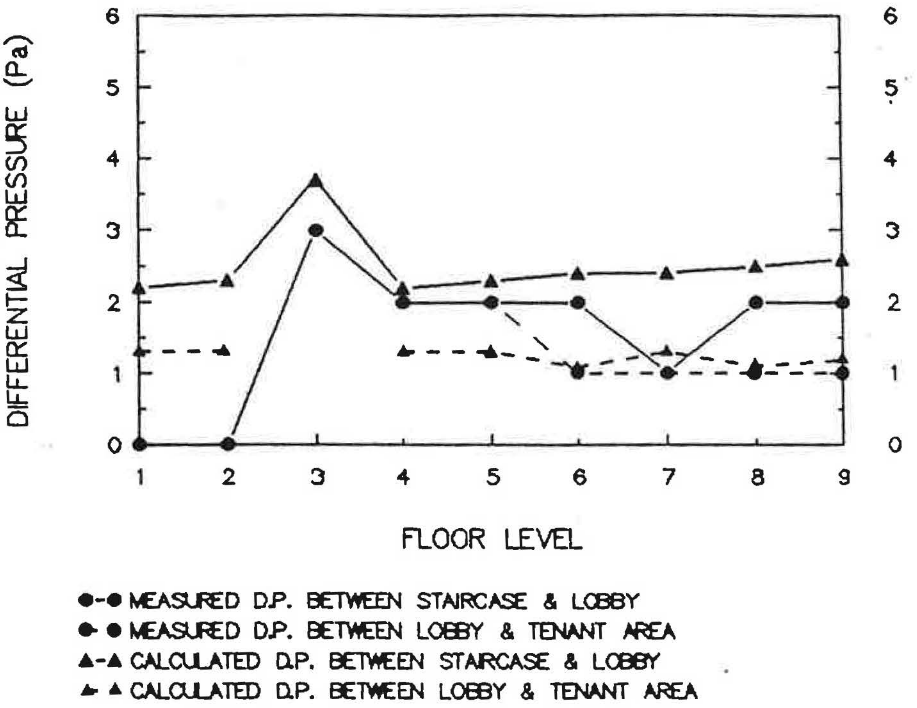


Figure 3 All doors closed



NOTE : LEVEL 3 IS EXIT TO OUTSIDE

Figure 4 Level 10 exit door open

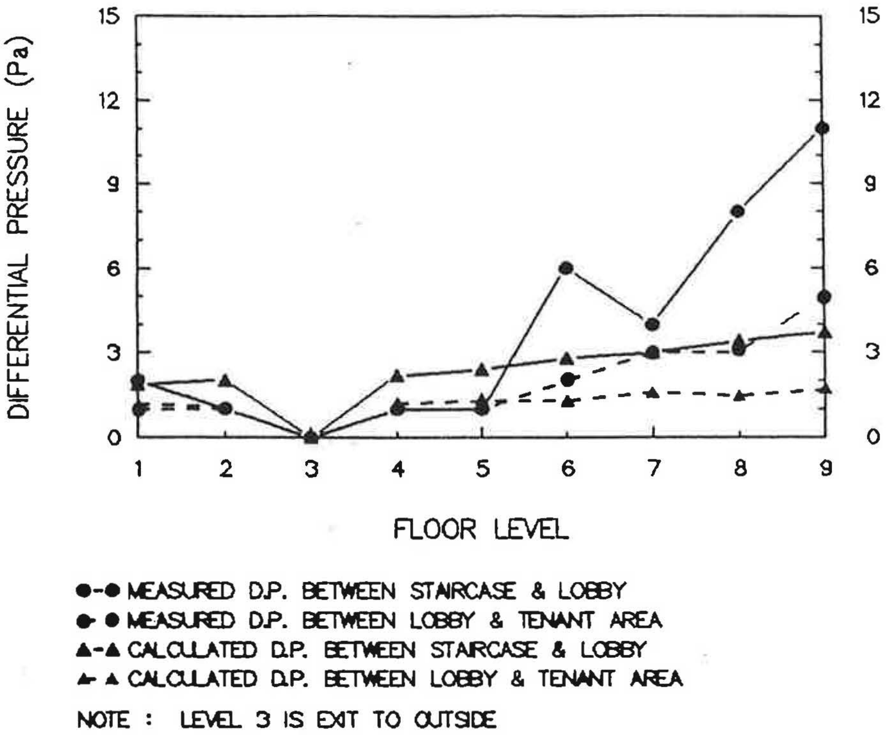


Figure 5 *Level 3 door open*

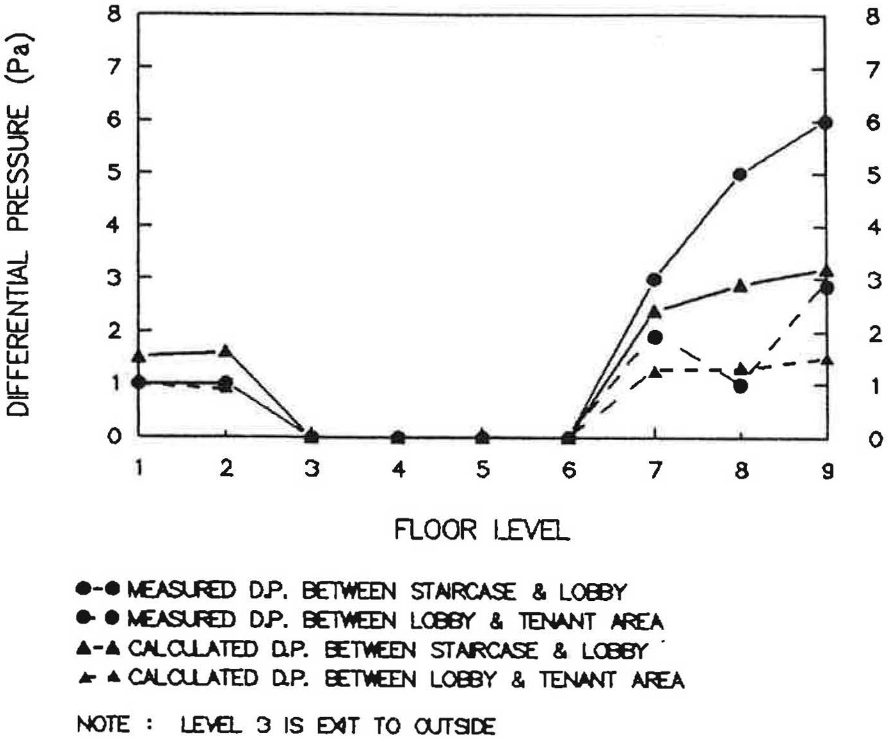


Figure 6 *Levels 3, 4, 5, and 6 doors open*

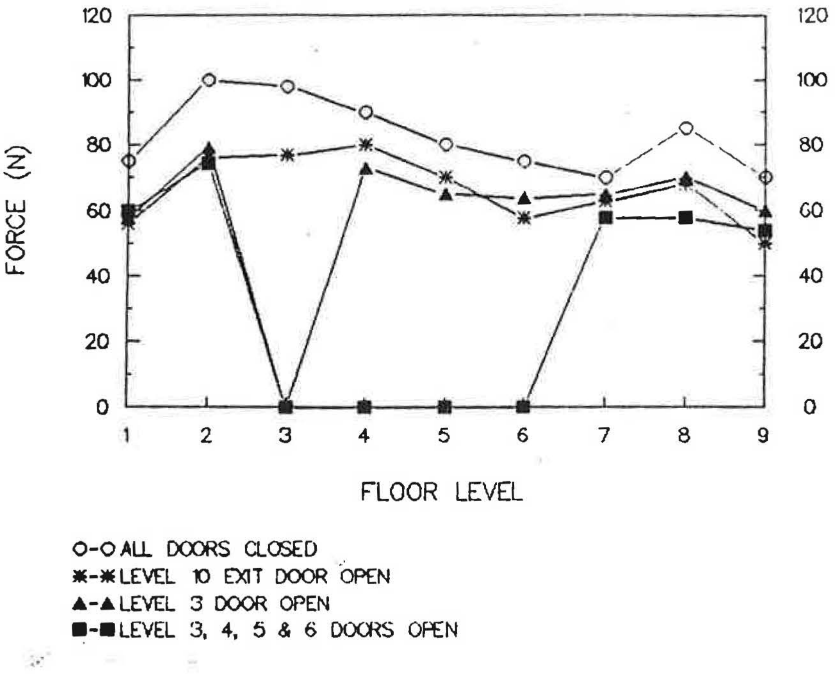


Figure 7a *Measured door opening force for door between staircase and lobby*

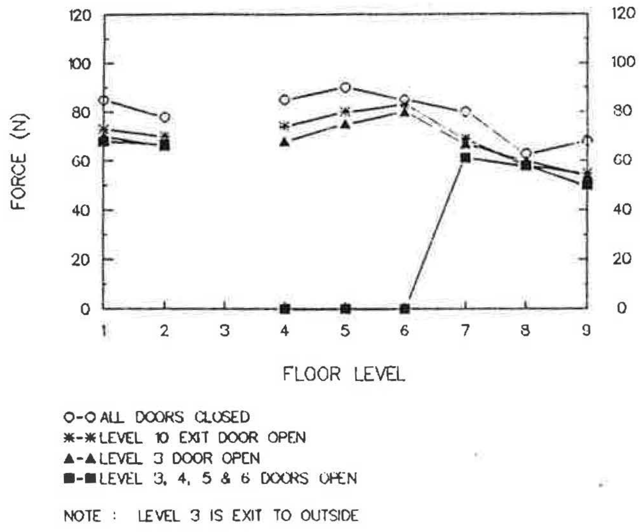
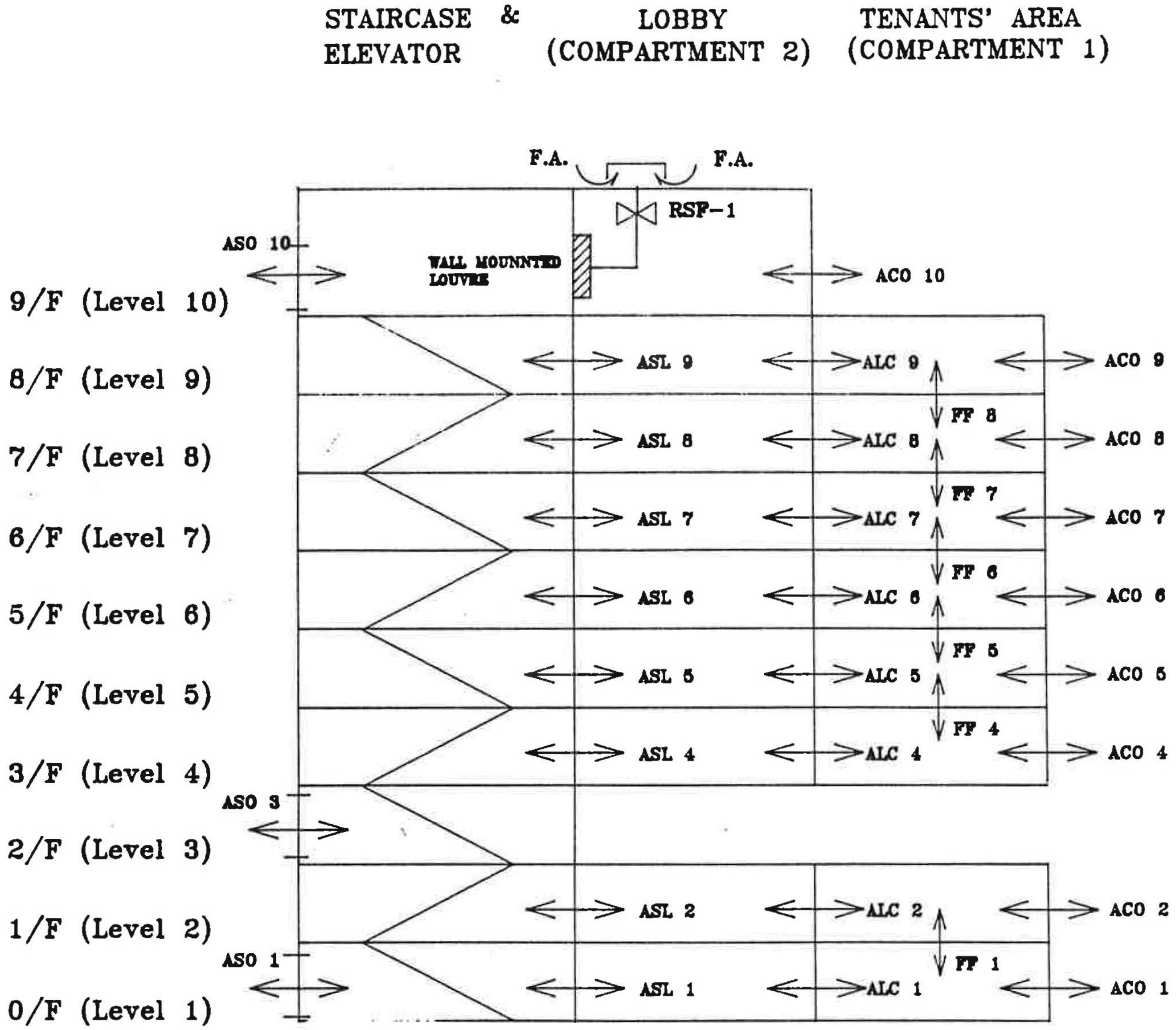


Figure 7b *Measured door opening force for door between lobby and tenant area*



LEGEND

ASO	FLOW AREA BETWEEN STAIRCASE AND OUTDOOR
ASL	FLOW AREA BETWEEN STAIRCASE AND LOBBY
ALC	FLOW AREA BETWEEN LOBBY AND COMPARTMENT
ACO	FLOW AREA BETWEEN COMPARTMENT AND OUTSIDE
AFF	FLOW AREA BETWEEN FLOORS
<—>	FLOW PATH

Figure 8 *Idealized airflow network of site*

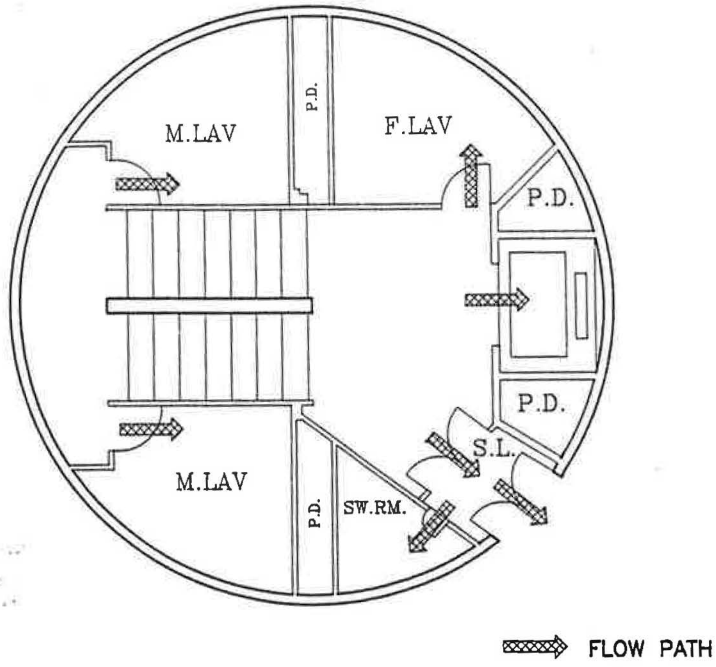
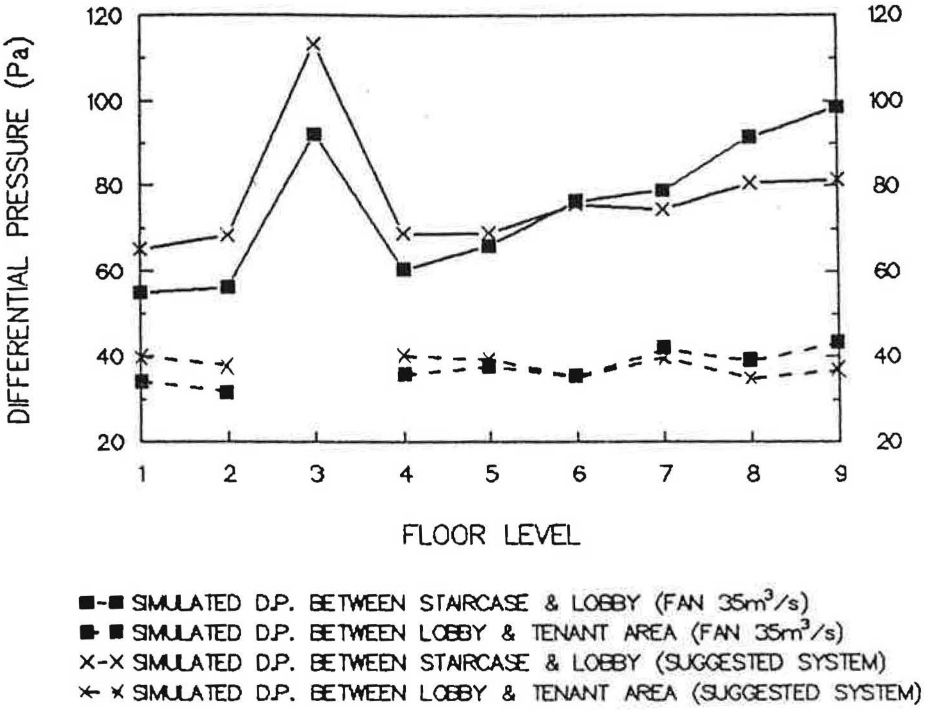


Figure 9 *Flow path in typical floor*



NOTE : LEVEL 3 IS EXIT TO OUTSIDE

Figure 10 *All doors closed*

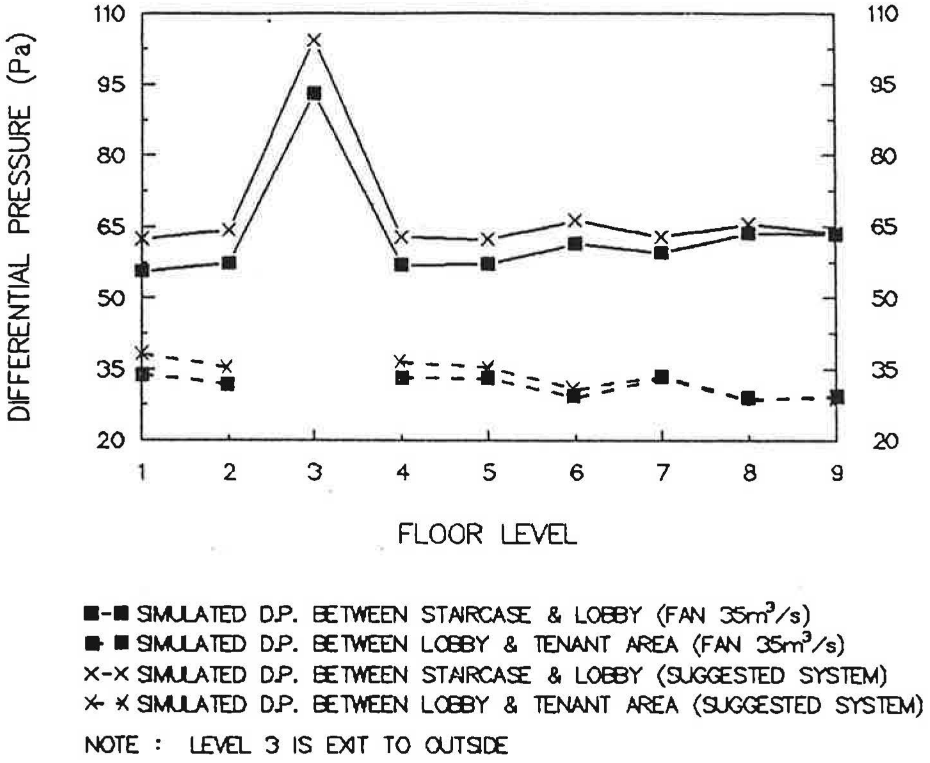


***Figure 11** Level 10 exit door open*

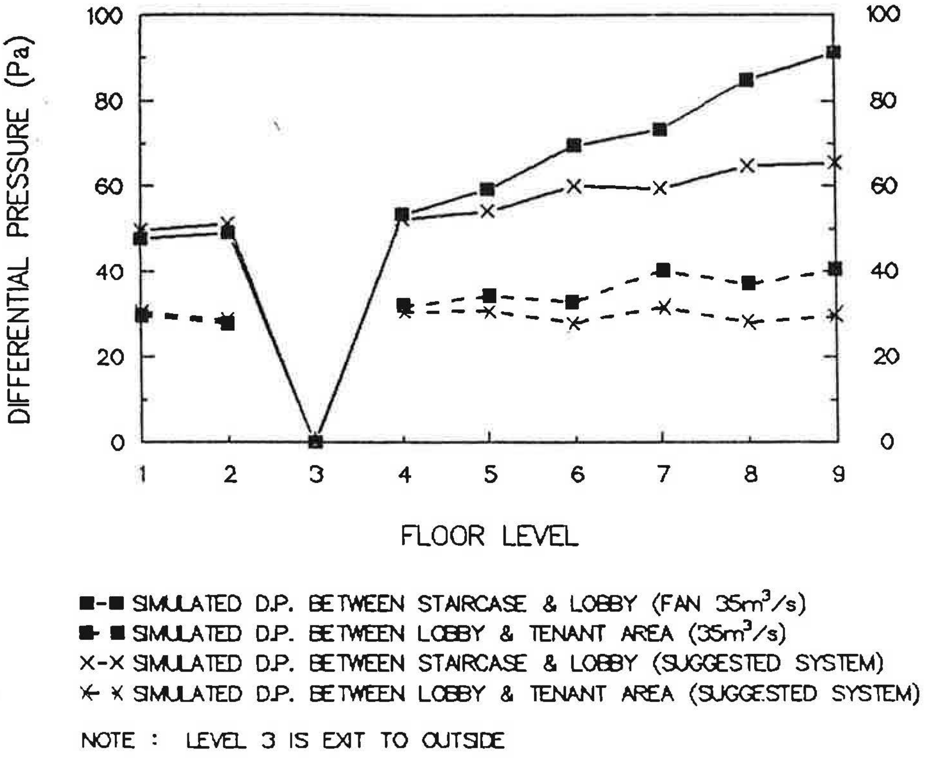
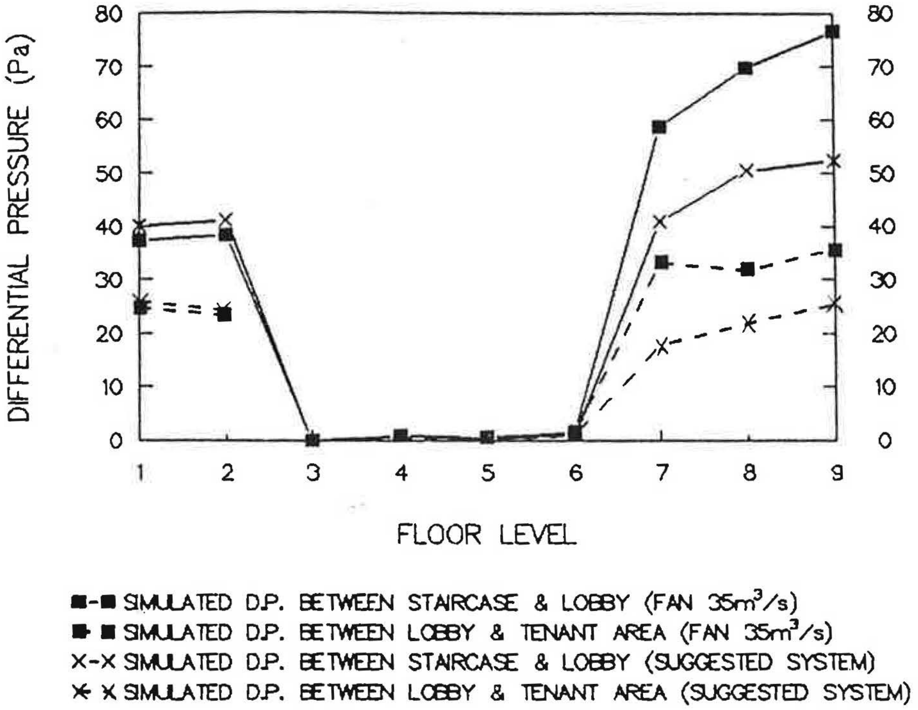


***Figure 12** Level 3 door open*



NOTE : LEVEL 3 IS EXIT TO OUTSIDE

***Figure 13** Levels 3, 4, 5, and 6 doors open*