北海道大学工学部研究報告
第113号（昭和58年）

Bulletin of the Faculty of Engineering,
Hokkaido University, No. 113(1983)

Air Leakage Calculations for NBS Administration Building U. S. A.

Kiyoshi OCHIFUJI* and Tamami KUSUDA**

(Received September 30, 1982)

Abstract

A comprehensive computer program for the prediction of air flow and air pressure in a building was applied to the 11 story administration building of the National Bureau of Standards, Washington D. C., U. S. A. Natural air leakage rates under various climatic conditions for several ventilation system operations were obtained. The major factors that controlled the air leakage such as outdoor temperature, wind speed, envelope porosity, air-conditioning system operation have been studied with respect to the total air leakage, floor by floor air leakage and room by room air leakage.

1. Introduction

Although it has been recognized that building energy consumption for heating and cooling is strongly affected by the air leakage through the building envelope, the calculation methodology for determining air leakage has not been well established. This is particularly true for large non-residential buildings. The reason is that analytical simulation of air leakage based upon the pressure balance equations is highly complicated, because the multiroom air flow problem must be solved.

Concurrently a comprehensive computer program has been developed to solve a set of non-linear flow pressure equations among many rooms as affected by the wind characteristic and the temperature difference between the inside and outside air. Recently, this computer program was applied to calculate the air leakage in the 11 story office building of the National Bureau of Standards U. S. A. This report describes the technique of the air flow pressure simulation, modeling of a complex office building and the results of the simulation calculations.

2. Fundamentals of Air Leakage Calculation

The basic equation that governs air leakage of the building is a simple pressure equation such as follows :

$$F = C \triangle P^{x} \quad (1)$$

where F = mass flow rate of air

C = flow coefficient

* Division of Industrial Environment, Department of Sanitary Engineering

** Building Thermal Service System Division, Center for Building Technology, National Engineering Laboratory, National Bureau of Standards, U. S. Commerce.

$\triangle P$ = pressure difference between indoor air and outside air

x = pressure exponent which takes a value between 0.5 and 1. Value of x is equal to 1 for the flow through small cracks. $x=0.5$ when the flow is through large openings such as doors.

In this equation the most difficult parameter is the value of C which is a function of the net area and the shape of the air passage. In real buildings, the openings are usually considered to be cracks around the windows and doors but recent papers by Tamura and by Hunt reveal that the air leakage around the windows and doors constitutes only about 30%–40% of total air leakage indicating that there are many other and unidentifiable openings distributed throughout the building envelope. While equation 1 describes the flow through one particular type of opening, the more general equation that describes the total air leakage into space k from a multitude of surrounding spaces can be expressed as follows :

$$\sum_{i=1}^{N_k} F_{ik}=\sum_{i=1}^{N_k} \pm C_{ik}|P_i-P_k|^x=0 \qquad (2)$$

for $k=1, 2, \cdots\cdots N$ (total number of rooms in the building)

In equation (2) F_{ik} represents the air exchange between space i and space k and C_{ik} represents the flow coefficient of a wall that separates space i and space k. P_i is the pressure of space i and P_k is the pressure of space k. Where i would vary from 1 to N_k which represents the total number of spaces that surround space k.

All the spaces in the building can be described by similar equations such as Equation 2. In order to solve the total building air leakage, all the flow coefficients of the building envelope as well as the interior partition walls, floors, and ceilings that separate one space from the others must be available. At the same time, the pressure exponent value x must be available for the different type of openings. Useable values of the opening parameters were established from the work of Tamura[1] and Sander[2]. These simultaneous sets of flow equations will be solved in terms of pressures for all the spaces in the building. Since the flow equation is non-linear, a special type of mathematical technique is necessary. Commonly adopted techniques are the Newton-Raphson and Brown-Conte methods. At times, however, a successive iteration technique is also used. Regardless of which technique is used, it requires a large amount of computer time. Although attempts have been made in the past to simplify the computation to obtain an approximate solution by assuming $x=1$, such simplifications lead to large errors and should not be used.

3. Computational Method

National Bureau of Standards, under contract to Integrated Systems, Inc., recently developed a comprehensive computer program called ISIS. This program uses an iterative technique and is capable of handling not only the air leakage among the building envelope and interior partitions but also can obtain the pressure balance associated with the complex building HVAC system. Air and pressure performance of the ventilation fan system is incorporated in the total air flow equation so that space by space pressure distribution under the pressurized condition as well as the non-pressurized condition can be solved. The majority of commercial buildings are provided with outdoor air intake fans as well as indoor air exhaust fans. In normal design prcatice, the outdoor air intake rate is usually higher than the indoor exhaust rate. This tends to create an indoor pressure of the building which is higher than the outside air. Under this condition, the building will have no uncontrolled air infiltration through the exterior envelope. The difference between the intake air and the exhaust air would exfiltrate through the cracks of the exterior envelope. The degree of pressurization is then dependent on the tightness of the exterior envelope. Even when the building is pressurized, however, some portion of the building may not have sufficient pressurization to overcome the strong wind pressure because of the uneven nature of pressure distribution in the building caused by the inadequate ventilation system design.

The general sequence of the calculation is then, first, to solve the pressure flow equation for the air conditioning systems and ducts where the pressure values are highest, followed by the shafts and finally by the rooms. The calculations are repeated until the pressures for all the nodal points become stationary.

The ISIS program was applied to the 11 story high rise of the office building of the National Bureau of Standards. The details of the calculations are given in the following chapters.

4. Building Characteristics

The NBS administration building is located in the outskirts of Washington, D. C. and has 11 stories and 1 penthouse. Schematics of the building are shown in Figures 1−2. While Figure 1 is a plan view of the floors 2−11, Figure 2 represents elevation. The building has no windows in the east and west walls. South and north facing walls have a large number of windows that are usually sealed. They can be opened, however, during window cleaning operations. Visual observation indicated that the cracks around the windows are relatively large reaching as much as 1/16th of an inch.

The first floor of the building contains the entrance hallways, whereas the second floor is the mezzanine and contains mechanical equipment. Floors 2 − 11 are standard office spaces consisting of many small modules, elevator shafts, staircases, and a central corridor and two bathrooms.

In order to simplify the calculation, it is assumed that each floor is divided into 4

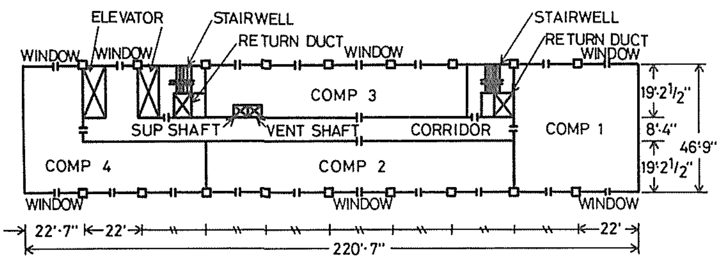

Figure 1. Plan view of floors 2 through 11 of the NBS Administration Building

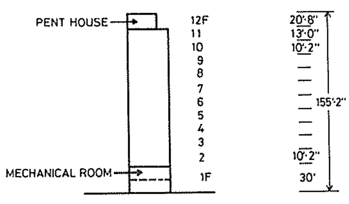

Figure 2. Elevation of the NBS Administration Building

Table 1. Opening area around windows

Room	Direction	Crack Width				
		0.008 ft	0.005 ft	0.003 ft	0.001 ft	0.003 ft
		2.4 mm	1.5 mm	0.9 mm	0.3 mm	0.1 mm
Comp. 1	South Wall	(1.30%) 0.85ft²	(0.20%) 0.85ft²	(0.12%) 0.51ft²	(0.06%) 0.17ft²	(0.04%) 0.05ft²
	North Wall	(0.32) 1.36	(0.20) 0.85	(0.12) 0.51	(0.04) 0.17	(0.01) 0.05
Comp. 2	North Wall	(0.32) 3.25	(0.20) 2.20	(0.12) 1.32	(0.04) 0.44 (0.35)	(0.01) (0.13)
Comp. 3	South Wall	(.04) 3.52	(0.25) 2.20	(0.15) 1.32	(0.05) 0.44 (0.36)	(0.213) 0.13
Comp. 4	North Wall	(0.32) 2.08	(0.02) 1.30	(0.12) 0.78	(0.04) 0.26	(0.01) 0.08
	South Wall	(0.32) 0.72	(0.20) 0.45	(0.12) 0.27	(0.04) 0.09	(0.01) 0.03
Comp. 5 (Corridor)	South Wall	(0.32) 0.32	(0.02) 0.20	(0.12) 0.12	(0.04) 0.04	(0.01) 0.01
Comp. 1	South	0.72	0.45	0.27	0.09	0.03
	North	3.52	0.85	0.51	0.17	0.05

compartments, as shown Figure 1. In many instances, the air leakage rate of the building will be expressed in terms of air change per hour. It is assumed that the volume used for such computation is 91, 394 cubic feet for the standard floors that exclude stairwells, elevator shafts, and ventilation shafts. The total building volume is 1,238,131 cubic feet excluding the mezzanine and penthouse.

When considering the characteristics of air flow passage, one must remember that the method for estimating it is highly critical in air leakage calculation. In this analyses, it is assumed that all the envelope air leakage takes place around the window cracks and the width of the window cracks are used as control parameters. Table 1 shows the total open area of the air passage for each compartment as a function of the assumed window crack width. For example, the crack width of 0.001 ft. means that each window has an opening of 0.3 milimeters around its parameter. Table 2 shows the crack width and the air leakage passage of the doors for the elevator shafts and the stairwells.

Table 2. Opening areas around the doors

Floor	Doors		Crack Width	
			0.04ft (12.0mm)	0.01ft (0.30mm)
1 F	Corridor		0.5feet²	0.5teet²
≀ 11 F	Stairwell	1	0.88	0.22
		2	0.88	0.22
	Elevator		1.92	0.48
1F	Outdoor		1.76	0.44
12F	Outdoor		0.88	0.22

* Date used for the natural ventilation

5. Ventilation System

The building has an induction re-heat system in which the high pressure primary air is processed in the central air conditioning unit located in the mezzanine. There are a total of 4 air-conditioning units that supply the processed air into the perimeter zones of the building. These 4 air conditioning units are responsible for the supply of air to the 4 compartments.

The return air from all the compartments is brought into the corridor and brought back to the mechanine room in the mezzanine. Outdoor air intake in accomplished in the mezzanine and the exhaust is accomplished by the ventilation outlet and the air leakage through the cracks in the building envelope, thus each of the standard floors is pressurized. Total building ventilation based upon these figures corresponds to 0.9 air change per hour. Although there are many vertical air supply ducts to the perimeter induction units, it is assumed for the sake of simplified computation that each compartment has only 1 vertical duct having its cross-portion area which is equal to the sum of the total cross-section area of all the ducts.

6. Air Leakage Calculation for NBS Administration Building

The calcultions were performed with several combinations of indoor outdoor temperature difference, wind speed and HVAC system operation for different envelope porosity.

Indoor temperature : 68°F

Outdoor temperature : 0°F and 68°F

wind speed : 0, 9 and 18 mph

The wind speed was assumed constant with respect to the height of the building with directions from north or south. The wind pressure constants were estimated as .75 at the windward side and −.5 at the leeward side.

HVAC system : off

on, no pressurization (balance)

on, pressurization

"no pressurization" implies that the outdoor intake rate is equal to the exhaust air rate.

"pressurization" implies that the system is operated under designed conditions.

Envelope porosity : 0.04%, .12%, .20%, and .32% (North wall)

These data correspond to the equivalent window crack width of 0.3, 0.9, 1.5, and 2.4 millimeters respectively.

7. Discussion on Building Air Change

In this analyses the "standard floor" calculations were done for the floors 4, 7 and 10. The results of the calculation are shown in the Table 3 and indicate that the air change data are dependent upon the operations of HVAC system, crack width, temperature difference and wind data.

If attentions are given to No's 1, 2, 3 and 5 (Where the crack width is 0.9mm), the hourly air change is 0.05 for the total building due to the temperature difference, 0.33 due to the wind effect and 0.38 under the combined effect of temperature and wind. The reason why the temperature draft effect is so small is that the envelope opening area is very small between the floors as compared to the vertical envelope. For example, the vertical surface opening of the standard floor is 4.83 ft^2 as compared to the horizontal surface opening of 0.92 ft^2 .

The air change data for the standard floor is slightly larger than that for the total building. This is because the total building includes the volume of the first floor which has a large ceiling height, stairwells, elevator shafts and the ventilation shaft.

Table 3. Conditions used for the simulation of NBS Administration Building air leakage.

Air Change/hr

Number No.	HAVC Operation	Opening Area	Outdoor Temp.	Wind Speed	1~11F	4F	7F	10F
1	......	(0.12%) 0.9mm	0°F	0mil/h	0.05	0.07	0.04	0.09
2	......	(0.12%) 0.9	68	18	0.33	0.42	0.42	0.42
3	......	(0.12%) 0.9	0	18	0.38	0.52	0.48	0.51
4	......	(0.04%) 0.3	0	18	0.16	0.22	0.20	0.22
5	On Balance	(0.12%) 0.9	0	18	0.41	0.59	0.52	0.58
6	On Balance	(0.20%) 0.9	0	18	0.62	0.93	0.85	0.87
7	On Balance	(0.32%) 2.4	0	9	0.98	1.37	1.29	1.36
8	On Balance	(0.12%) 0.9	0	18	0.20	0.33	0.26	0.39
9	On Pressure	(0.04%) 0.3	32	18	0.71			

Assumed indoor temperature−68°F
Figures shown in the parenthesis are porosity %

Figure 3 depicts the air change with respect to the building envelope porosity under the outdoor temperature of 0°F and wind speed of 18 mph. Also included in Figure 3 are air change values for compartments 1 and 2 of the fourth floor, as well as that of the total fourth floor. Air change values of compartment No. 1 appeared to represent the total air change of the fourth floor, yet it is very much different to that of the total building.

Figure 3 is extremely important for the measurement of the large building air leakage using the tracer gas technique. For the tracer gas air leakage measurement it is assumed that the concentration of the tracer gas, the time decay rate of which is measured is uniform throughout the building. In the case of the large building, tracer gas must be fed into all the building spaces by a central air handling unit, thus ensuring the uniformity of the concentration throughout the building. It is customary to monitor the concentration decay of the return air into the central air handling unit. When the central air handling system is not available, air leakage must be measured at several typical areas in the building that represent the total building. Because of the air exchange among the spaces in the building, the air

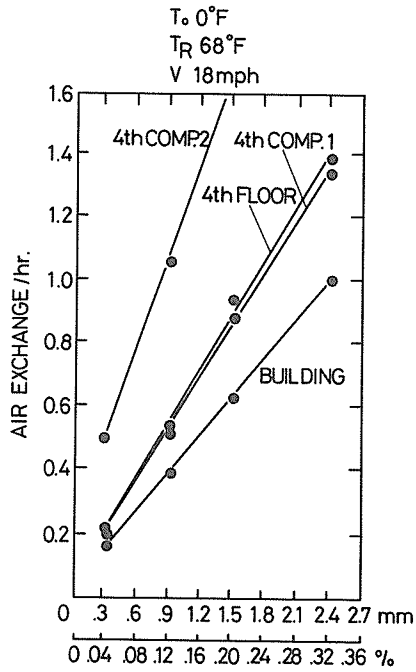

Figure 3. Relationship between the air change per hour data and building envelope porosity under 18 mph wind condition

change value measured at a selected space will be expected to be different from that of the total building. If the data such as Figure 3 is available, it is possible to relate the localized air leakage measurement into a total building air leakage.

8. Floor by Floor Air Flow and Pressure Distribution

Floor by floor air flow for the envelope porosity of 0.12% has been obtained and is shown in Figure 4 for the stack effect of ventilation without wind. A similar figure for the wind pressure ventilation without stack pressure is given in Figure 5, while Figure 6 depicts the air leakage due to the combined stack and wind pressure.

Figure 4 shows that there exists a neutral pressure zone somewhere between floor 6 and 7 under a no wind condition. Except for the bottom and top floors, the air leakage varies somewhat linearly with respect to differential pressure between indoors and outdoors. Also, as mentioned previously, in Figure 5, the wind pressure is considered uniform along the building height. Thus, all the floors are under a uniform differential pressure. Figure 6, representing the combined stack and wind pressure effect, indicates the wind effect on leakage overshadows the temperature difference effect. Most of the air entering at the windward side of the building flows right through the floor to the leeward side.

Figure 7 and 8 summarize the studies conducted herein, and show clearly the relationships between the stack pressure and wind pressure effects. These two pressure effects are basically additives.

When the air leakage rate of a highrise building is to be determined the floor by floor distribution of air flow and pressure are available. The minimum requirement for estimat-

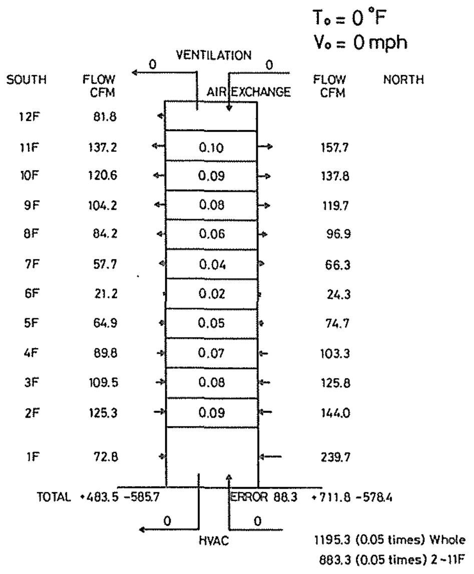

Figure 4. Floor by floor air flow and air change per hour under stack effect.

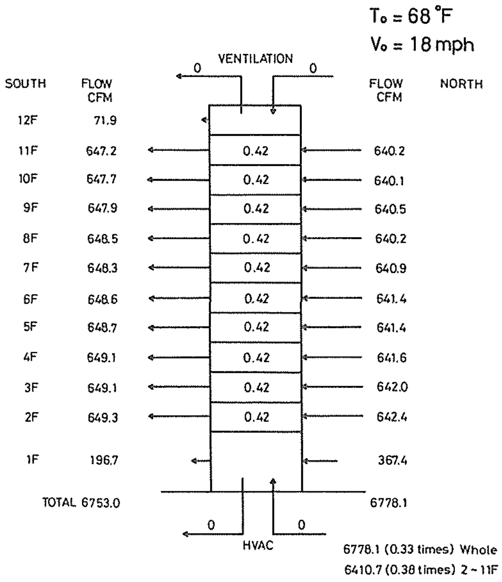

Figure 5. Floor by floor air flow and air change per hour under wind effect.

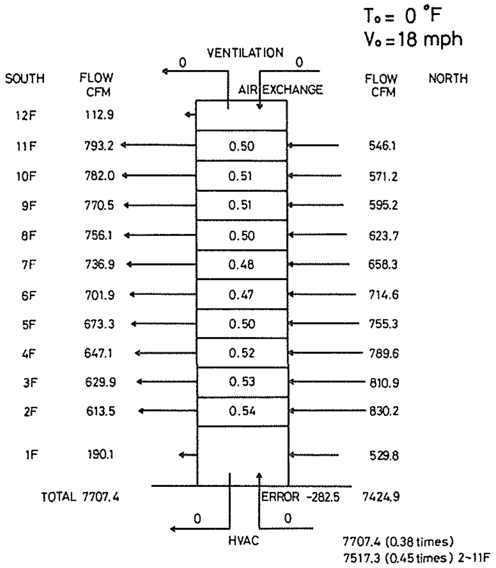

Figure 6. Floor by floor air flow and air change per hour under combined effects of stack and wind pressures

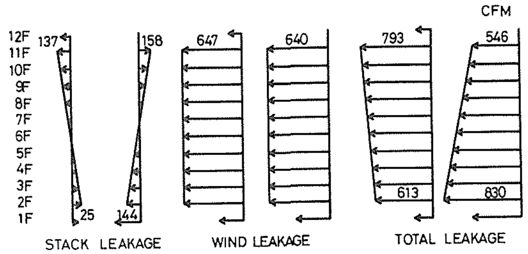

Figure 7. Summary of air flow calculations.

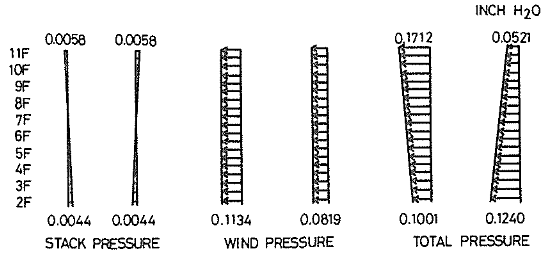

Figure 8. Summary of differential pressure calculations.

ing the floor by floor flow and pressure distribution is to determine them at least at the upper floor, middle floor and lower floor.

9. Room Air Change

Although previous discussions have been directed toward the total building air leakage and floor by floor air leakage, this section deals with individual room air leakage. As mentioned in the previous section, room by room air leakage data for the building with no central air distribution system is extremely important for the estimation of the total building air leakage. Figure 9 depicts room by room air flow and air change rate of standard floors under the combined stack and wind pressure conditions for envelope porosity of 0.12%. The room air flow patterns are strongly affected by the wind pressure as in the case for the floor by floor air leakage. The in/out flow rates, however, vary from floor to floor. Because of the temperature difference or stack effect, the outflow rate at the upper floor is larger than the inflow rate. The reverse is true at the lower floor. The air flow direction of the stairwells and the elevator shafts are reversed because of the stack effect. The air change of a room depends upon the height of the floor, orientation of the room, and the porosity of the room envelope. Even on the same floor, it will vary as much as 200% depending upon the location of the room. The room by room air change data agrees fairly well with the floor by floor data especially for compartment 1 and 4. This is because these compartments have exposed windows both on the windward and leeward sides. The compartments 2 and 3, however, have windows on only one side and show a very high airchange rate. The reason why the air change rates for these two compartments are twice as high as that of compart-

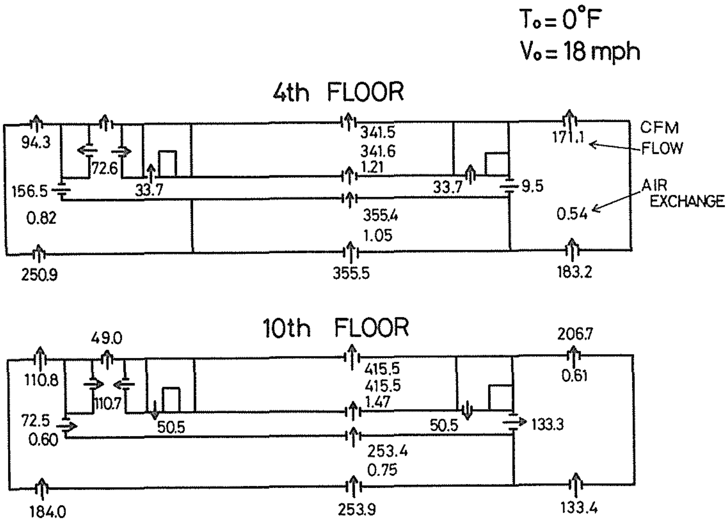

Figure 9. Air flow through compartments under combined wind and stack pressure effects envelope porocity 0.12%.

ment 1 becames clear. For the air leakage measurement, compartment 1 should be chosen. If compartments such as 2 or 3 are chosen for air leakage measurement, air change values should be corrected on the basis of the inter-room air flow pattern and room volume.

10. Summary

The air leakage analysis computer program developed by Integrated Systems, Inc. U. S. A. for a large building with many rooms has been examined and corrected. The corrected computer program was then used to estimate the air leakage rate of the 11-story NBS Administration Building. The major factors that controlled the air leakage such as outdoor temperature, wind speed, envelope porosity, air-conditioning system operation have been studied with respect to the total air leakage, floor by floor air leakage, and room by room air leakage. As to the air leakage characteristics of the NBS building, the following conclusions can be drawn :

1. The wind pressure effect is much higher than the stack pressure effect indicating the opening areas between the floors are much smaller than those of the building envelope.
2. If we assume the porosity of the envelope to be .12%, the air change of the total building is 0.05 with the temperature difference of 68°F, 0.33 with the wind velocity of 18 mph, and 0.38 under combined conditions. If it is assumed that the envelope porosity is 0.04%, the combined air leakage becomes 0.16 air change per hour.
3. Air change rate is proportional to the envelope porosity.
4. Floor by floor air flow distribution and the differential pressure distribution are both approximately linear.
5. The room by room air change is strongly affected by the room location and the room envelope and could vary as much as 200% from each other.

The following guidelines could be given for the air leakage measurement

1. Air leakage measurement should be obtained from at least 3 different floors covering the lower floors, the middle floors, and the upper floors except when neutral zone is above or below the total building.
2. On a given floor, rooms having windows at both windward and leeward sides should be chosen. Rooms having windows at any one side tend to show higher air change value than the total floor.
3. Further investigations based upon actual measurements and the calculations similar to this report are needed for the establishment of air leakage measurement guidelines.

Reference

1) Tamura, G. T., and Shaw , C. Y., "Air Leakage Data for the Design of Elevator and Stair Shaft Pressurization Systems", ASHRAE Meeting, Feburary 1977, Chicago, Illinois.
2) Sander, D. M., and Tamura, G. T., "A FORTRAN IV Program to Simulate Air Movement in Multi-Story Buildings", National Research Council of Canada, Ottawa, DBR Computer Program No. 35, March 1973.