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Some Induced-Pressure Measurements in a High-Rise Office Building

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ABSTRACT: Induced-pressure measurements were made in the tower of an eleven-story office building using a fan of 7.55-m^3/s capacity. The fan was used to depressurize the entire tower as well as a single floor. Sulfur hexafluoride (SF_6) tracer gas was used to trace air movements from floor to floor during single-floor depressurization.

Average flow coefficients of approximately 5×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ for the tower and 7×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ for the single floor were estimated from single point measurements. The effect of opening and closing office doors also was determined.

By simultaneous solution of flow equations for the whole tower and a single floor, it was estimated that about 80 to 90% of the airflow during depressurization of a single floor came from floors above and below. From SF_6 tracer gas measurements, it was estimated that about 50% of the flow could be traced to the floor below.

The pressure difference measurements upon which the previous estimates are based were in the 3- to 10-Pa range. Uncertainties in the estimates of flow coefficients and airflow from above and below are discussed in the text. The results essentially are descriptive, but they suggest an experimental approach to the determination of flow coefficients for modeling through the wall and for floor-to-floor components of airflow in building ventilation.

KEY WORDS: ventilation—large buildings, induced-pressure tests in buildings, air movements in buildings, sulfur hexafluoride tracer measurements, infiltration

Fan-induced pressure tests have become a common method of assessing the tightness of homes. Air is blown in or drawn out of a building at several measured rates, and induced indoor-outdoor pressure differences are measured. There are published descriptions of the method [*1,2*], and there is also an

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ASTM standard, Method for Determining Air Leakage Rate by Fan Pressurization Test (E 779-81).

Induced-pressure measurements have been scaled up for use in large buildings, although the logistical problems become much greater than with single-family residences and increase with the increasing size of the building. If a building has a central, forced ventilation system, it may be possible to use the building's own ventilating fans [3]. However, it is sometimes difficult to obtain an accurate measure of flow rate, particularly when there are a number of fans, each supplying a different zone, or when a building may not have a central, forced ventilation system. An alternate procedure, where possible, is to use a high-capacity fan which may be moved from building to building. Shaw describes such a fan, with a maximum capacity of 24 m^3/s, which is used to depressurize supermarkets [4] and schools [5]. It operates from its own trailer and draws air from the building through a long 0.9-m-diameter duct.

The present report describes exploratory tests in which a fan with 7.55-m^3/s capacity was used to depressurize the tower of an eleven-story office building. This fan had about one third the capacity of the one used by Shaw but was much larger than those normally used for single-family residences. The building, having an envelope area of nearly 7000 m^3, was larger than the schools with envelope areas from about 1100 to 2100 m^2 [5] or the supermarkets with areas from about 700 to 3500 m^2 [4]. Thus the present measurements were a test of equipment as well as of the building. The fan was of a size to enable it to be moved through doors inside the building. Use was made of this fact to depressurize a single floor and to compare floor-to-floor flow resistance with that of the exterior envelope. Sulfur hexafluoride (SF_6) tracer-gas measurements were used to trace air movement from floor to floor during single-floor fan operation.

Air exchange rate measurements of the building were previously reported [6]. The present report is a preliminary work to measure the flow resistance of internal and external elements of the building structure and to aid in analysis of air movement through the building envelope and within the building.

Apparatus

The 7.55-m^3/s axial fan and the accessories that were used to depressurize the whole tower of the building and a single floor are shown in Fig. 1. The fan motor was 3740 W (5 hp) and was driven by a 7000-w, 230-v single-phase, gasoline generator (also shown in Fig. 1). The starting winding connections of the fan motor were modified to permit manual operation in order to accommodate the starting load. Flow rates were measured with a Pitot-static flow monitoring assembly with a built-in flow straightener that was mounted approximately one fan diameter, or 0.77 m, upstream from the fan (also shown in Fig. 1).

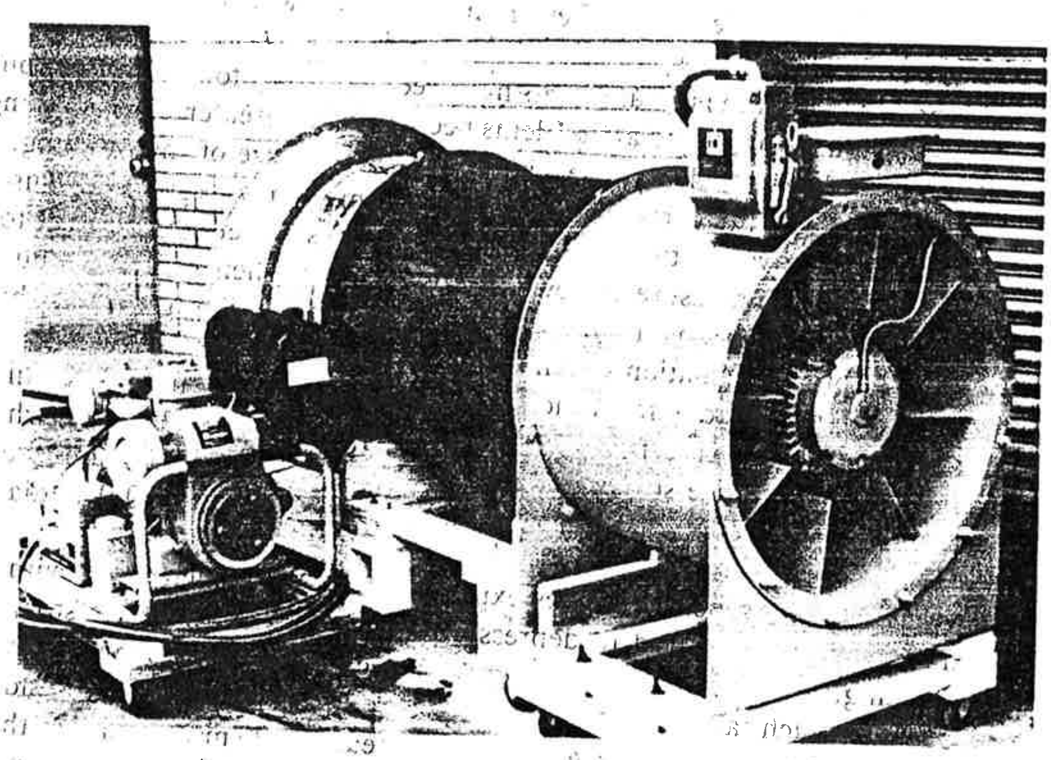

FIG. 1—*The 7.55-m³/s axial fan, flow-measuring assembly, and 7000-w generator used in induced-pressure tests.*

A gas chromatograph with an electron capture detector was used for the SF_6 tracer gas measurements. It was incorporated in a semiautomated air-sampling system that was a compact modification of the apparatus described previously [7].

Building Description

Measurements were made in the tower of the Administration Building of the National Bureau of Standards. The tower, comprising Floors 2 through 11, is separated from the rest of the building by a mezzanine that contains most of the mechanical equipment for the building. The tower has its own ventilation system. A diagrammatic representation of the building is shown in Fig. 2. Dimensions of some of the important structural elements of the tower are given in Table 1.

Whole-Building Depressurization

The fan was placed at the first-floor level, where it drew air from the tower through a closed stairwell and vented it into a courtyard. This position is designated in Fig. 3 as Fan Location 1. Pathways of air egress were opened to facilitate depressurization, while air intake pathways were sealed or re-

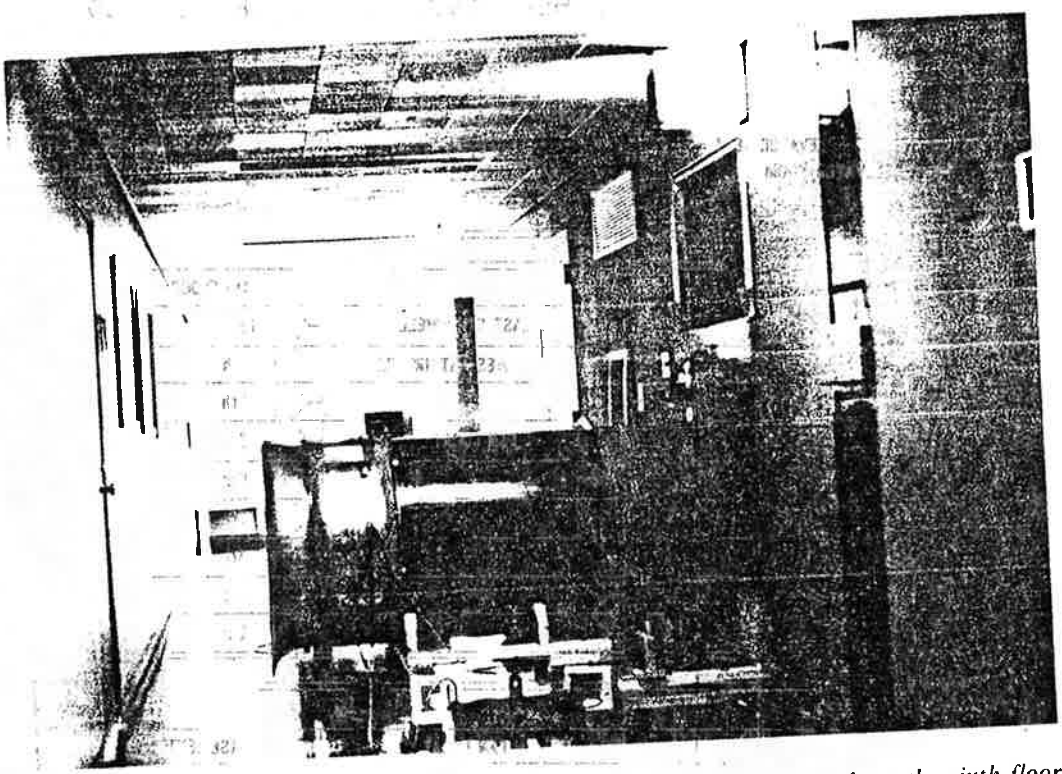

FIG. 2—*Fan and flow-measuring apparatus in position for drawing air from the sixth floor and ejecting it into the stairwell.*

TABLE 1—*Dimensions of the tower of the National Bureau of Standards Administration Building.*

Number of floors	10
Floor-to-floor distance	3.1 m
Floor area per floor	890 m²
Outside wall area per floor	500 m²
Total envelope area including top and bottom surfaces	6 780 m²
Total volume	28 000 m³

stricted. For example, doors in the west stairwell where the fan was located were opened, while doors in the east stairwell and on the first floor and in the basement of the west stairwell were closed and covered around the edges with thin plastic films. Plastic sheets were sealed over the stairwell, toilet, and elevator vents, as well as over ventilation grilles in the stairwells.

Unsealed plastic sheets were placed in the air handling units to restrict inflow of outdoor air. These sheets did not provide complete seals but covered the open areas. Smoke tests during fan operation showed no airflow around the borders of contact, which indicates that the main leakages were elsewhere in the building.

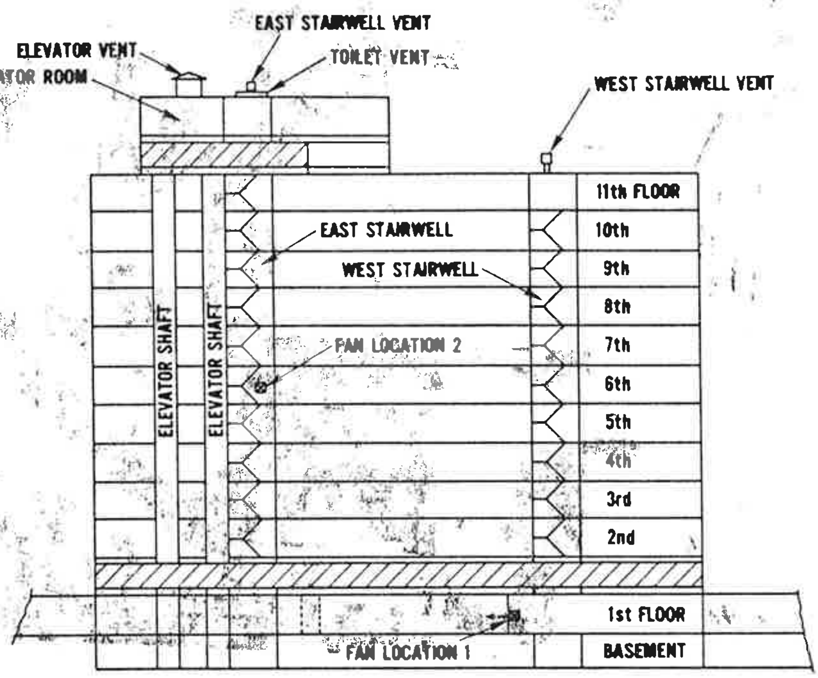

FIG. 3—*Vertical section through building along an east-west axis.*

The fan was then turned on, and indoor-outdoor pressure differences were measured between the north side of the building and the hall at the second and eleventh floor levels with a Magnehelic[2] gage. Measurements also were made with a capacitance gage as a calibration check. The fan was turned off, and the cycle was repeated. The average pressure difference due to the fan was 3 Pa. This difference is smaller than commonly observed fluctuations due to wind. Thus, a single fan of this size did not deliver enough air to develop a curve of flow rate versus inside-outside pressure difference for this building. Nevertheless, measurements were performed when wind activity was low enough to permit stable and repeatable measurements and, for descriptive purposes, to permit some rounded estimates of the tightness and flow characteristics of the building to be made.

An empirical equation commonly used to represent flow as a function of pressure difference is

$$Q = kA(\Delta p)^{\eta} \tag{1}$$

where

Q = airflow rate, m^3/s,
A = area over which flow is distributed, m^2,

[2]Proprietary names are used to more accurately describe experiments. This does not comprise an endorsement of the product by the National Bureau of Standards.

Δp = indoor-outdoor pressure difference, Pa,
k = average flow coefficient of the flow area, $m^3/m^2 \cdot s \cdot Pa^n$, and
n = flow exponent.

Average flow coefficient treats the flow resistance as if it were homogeneously distributed over the entire envelope area. According to Eq 1, the average flow coefficient of the envelope of the Administration Building tower is 5×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$, using the envelope area from Table 1 and assuming a flow exponent of 0.65, a commonly used approximation [*3-6,8-10*].

In a computational analysis of air infiltration in tall buildings, Shaw and Tamura [*8*] used an estimate of 0.93×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ as an average flow coefficient for walls of average tightness. If this value is substituted in Eq 1, it predicts that a fan delivery rate of 7.55 m^3/s would produce a pressure difference of nearly 46 Pa in a structure with the dimensions of the Administration Building tower. A modern single-family residence of good construction, but with no special provisions for building tightness such as plastic films in the walls, was observed by the author to have an average flow coefficient of 1.33×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$. This coefficient would correspond to a pressure drop in the Administration Building tower of 26 Pa. Finally, a value of 1.5×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ has been calculated using data obtained by Shaw [*9*] for a five-story apartment building. This would correspond to a pressure drop across the tower envelope of about 21 Pa. Thus, the envelope of the Administration Building tower was loose compared to these other structures, but the previous examples are cited to point out that a fan capacity of 7.55 m^3/s might be sufficient to develop flow-pressure relationships for some buildings of the size of the Administration Building tower.

On the other hand, in measurements of schools, Shaw and Jones [*5*] estimated average flow coefficients to be 3.0×10^{-4}, 5.0×10^{-4}, and 7.0×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ for buildings of tight, average, and loose construction, respectively. Corresponding estimates for supermarkets [*4*] were 2.7×10^{-4}, 9.6×10^{-4}, and 16.5×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$. These latter values are more in line with the estimated coefficient of the Administration Building tower.

Shaw's supermarket study also presented data in which Eq 1 was applicable to pressures as low as 3.5 Pa. Tamura [*10*] developed an air infiltration model in which the average flow coefficient in Eq 1 serves as the measure of tightness. He applied it to houses and obtained satisfactory agreement with infiltration rates obtained by the tracer-gas dilution method.

However, the laws governing flow through building surfaces are an area of active research. Work by Sherman, Grimsrud, and Sonderegger [*11*] present evidence that Eq 1 is not applicable over the entire pressure range of interest in air infiltration. At high and very low pressures, for example, flow rates are reported proportional to the square root of the pressure as in orifice flow. Modera, Sherman, and Grimsrud [*12*] developed an infiltration model which uses effective leakage area instead of the average flow coefficient as the tightness parameter. They define flow at low pressures by

$$Q = L\sqrt{\frac{2}{\rho}\Delta p} \tag{2}$$

where

Q = air flow rate, m^3/s,
L = effective leakage area, m^2,
ρ = density of air, kg/m^3, and
Δp = indoor-outdoor pressure difference.

At pressures in the range of 10 to 60 Pa, flow is defined by

$$Q = K\Delta p^n \tag{3}$$

where

Q = air flow rate, m^3/s,
Δp = indoor-outdoor pressure difference,
n = flow exponent, and
K = a graphically determined constant.

Equation 3 has a form similar to Eq 1, where K has the same dimensions as kA. Since, according to the model, the relationship between Q and p changes between 0 and 60 Pa, a more generalized definition of L is

$$L = K\sqrt{\frac{\rho}{2}}(\Delta p_r)^{n-1/2} \tag{4}$$

where

L = effective leakage area, m^2,
K = graphically determined constant,
ρ = density of air, kg/m^3,
n = flow exponent appropriate to the pressure, and
Δp_r = pressure difference at an arbitrarily selected reference pressure, selected by the authors at 4 Pa.

Since the present data are based on a single point, the flow exponent, n, in Eq 1, is an assumed value which is considered representative of a number of buildings at intermediate pressures. If Eq 2 is taken as the governing equation, a pressure difference of 3 Pa at a flow rate of 7.55 m^3/s corresponds to an effective leakage area of approximately 3.4 m^2. The data are unsuitable to permit full application of Eqs 2, 3, and 4.

Single-Floor Depressurization

The fan was moved to the sixth floor (Fan Location 2 in Fig. 3), and air was drawn from the hallway and ejected into the stairwell. All doors to the outdoors at the top and bottom of the stairwell were opened to minimize back pressure. Figure 2 is a picture of the fan in position, and Fig. 4 is a diagram of the floor plan showing the location of the fan. The pressure drop on the sixth floor produced by the fan was measured between the hall and the west, or nonfan, stairwell.

It was noted that 15 office doors which opened into the hall could be opened at this floor level. When they were open, the fan-induced pressure change was 5 Pa. This is only slightly greater than the value obtained during whole-building depressurization, which suggests very low resistance to airflow between floors. When all doors were closed, an induced pressure of 10 Pa was observed.

The area of the envelope of a single floor is 2280 m^2 (Table 1). If flow is averaged over this area, it is equivalent to a flow coefficient of 12×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ with doors open and 7×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ with doors closed.

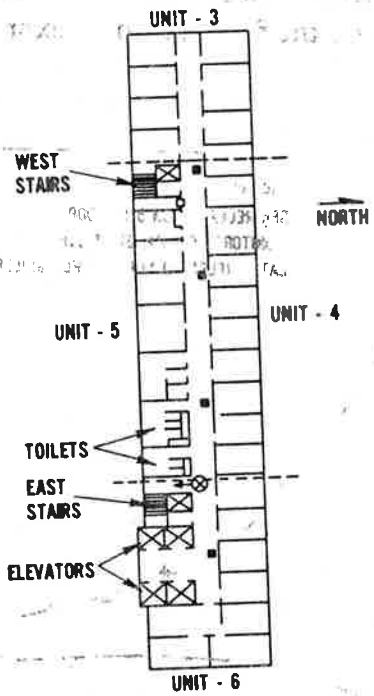

FIG. 4—*Typical floor plan showing location of the fan on the sixth floor and the location-sampling points: ⊗ = fan location (sixth floor); □ = location differential pressure gage; ■ = network sampling points (fifth, sixth, and seventh floors).*

Fan-Tracer Measurements

To trace air movement between floors during fan operation, SF_6 tracer gas concentration was monitored as a function of time on the fifth, sixth, and seventh floors. Sampling networks were used to sample on each floor, with sampling points distributed at floor level at locations indicated in Fig. 4. Each network integrated the flow from the four sampling locations on each floor.

The fifth floor was seeded by distributing 100 mL of SF_6 over several locations, and the fan was turned on. The concentration of tracer gas on the fifth and sixth floors is plotted as a function of time in Fig. 5. No tracer gas was detected on the seventh floor. After an elapsed time of 75 to 80 min, 100 mL of SF_6 was released near the window grilles on the fourth floor. The amount of tracer gas reaching the fifth and sixth floors from the fourth floor caused only a small transient increase in the concentration. This small effect suggests that most of the upward movement of air to the fan came from the floor immediately below.

Analysis of Air Movement Between Floors

To analyze air movement between floors, consider the concentration of tracer gas on the fan floor to be expressed by the relationship

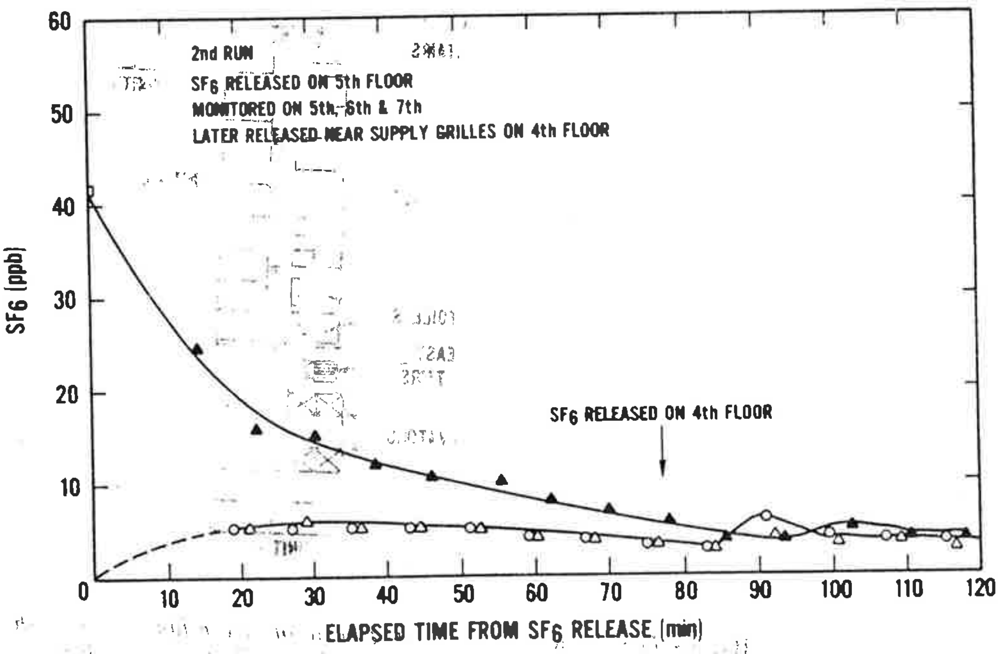

FIG. 5—*SF_6 concentration on fifth and sixth floors after release on the fifth floor:* ▲ = *fifth floor hall network (SF_6 release floor):* ○ = *sixth floor hall (single point near fan):* △ = *sixth floor hall network:* □ = *Initial concentration of fifth floor (based on volume of SF_6 released and volume of space).*

$$c_j = \frac{g}{\dot{v}_j}(1 - e^{-I_j t}) \tag{5}$$

where

c_j = concentration of tracer gas at the jth (fan) floor,
g = rate at which tracer gas enters the jth floor,
I_j = air exchange rate of the jth floor, h^{-1},
$\dot{v}_j$ = volume rate at which air enters and leaves the jth floor, and
t = elapsed time.

However

$$g = c_i \dot{v}_{ij} \tag{6}$$

where

c_i = concentration of tracer gas on the ith floor where it was released, and
$\dot{v}_{ij}$ = volume rate at which air passes from ith floor to jth floor.

Substituting Eq 6 in Eq 5

$$\frac{c_j}{c_i} = \frac{\dot{v}_{ij}}{\dot{v}_j}(1 - e^{-I_j t}) \tag{7}$$

Thus the fraction of total air flow entering and leaving the jth floor which comes from the ith floor, $\dot{v}_{ij}/\dot{v}_j$ approaches c_j/c_i with increasing time. The foregoing analysis is idealized and assumes perfect mixing of tracer gas on both floors.

In Fig. 6, c_j/c_i is plotted against time and levels off somewhere near 0.5.

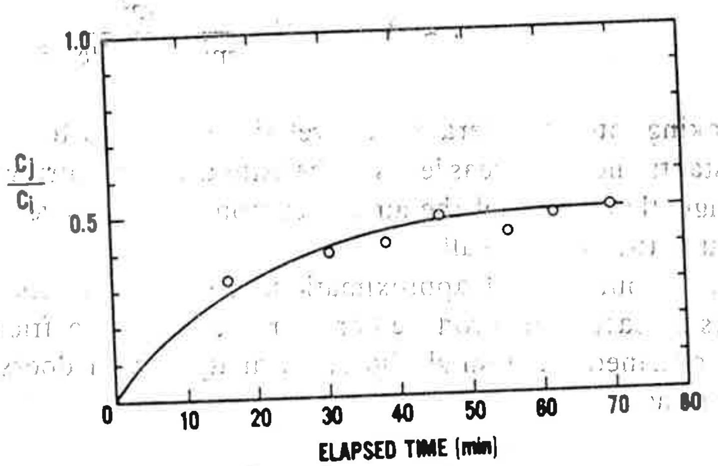

FIG. 6—*Ratio of tracer gas concentrations on the fan floor to that on the source floor,* c_j/c_i *plotted as a function of time.*

According to this analysis, about half of the air reaching the fan floor came from the floor below. Because of structural similarities from floor to floor, a comparable volume of air also should come from the floor immediately above.

It is also possible to make an independent analysis of floor-to-floor air movement from the fan depressurization data. The outside wall represents about 23% of the exterior surface of a single floor (Table 1). The total airflow is the sum of floor-to-floor and outside wall flows. If it is hypothesized that k, the average flow coefficient of a single floor, is a weighted average of coefficients for floor-to-floor and outside wall flow, then

$$k \approx 0.23\, k_w + 0.77\, k_f \tag{8a}$$

where k_w and k_f are the flow coefficients averaged over the outside wall area and the areas between floors, respectively. When office doors are closed, this corresponds to

$$7 \times 10^{-4} \approx 0.23\, k_w + 0.77\, k_f \tag{8b}$$

Similarly, the area between the tower and the lower floors represents about 12% of the tower envelope area. Thus, for the tower

$$5 \times 10^{-4} \approx 0.88\, k_w + 0.12\, k_f \tag{9}$$

Solving Eqs 8b and 9 simultaneously leads to the empirical values

$$k_w \approx 5 \times 10^{-4} \frac{\mathrm{m}^3}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{Pa}^{0.65}}$$

$$k_f \approx 8 \times 10^{-4} \frac{\mathrm{m}^3}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{Pa}^{0.65}}$$

Taking into consideration the relative floor area together with these flow constants and wall areas leads to the estimate that, during depressurization of a single floor, 84% of the air comes from floors above and below and 16% through the outside wall.

If, for purposes of approximation, it is assumed that opening 15 office doors on each floor produced an increase in flow coefficient proportional to that obtained for a single floor, an analysis with doors open leads to the equations

$$12 \times 10^{-4} \approx 0.23k_w + 0.77k_f \tag{10}$$

$$12/7 \times 5 \times 10^{-4} \approx 0.88k_w + 0.12k_f \tag{11}$$

and

$$k_w \approx 8 \times 10^{-4} \frac{m^3}{m^2 \cdot s \cdot Pa^{0.65}}$$

$$k_f \approx 13 \times 10^{-4} \frac{m^3}{m^2 \cdot s \cdot Pa^{0.65}}$$

and 84% of the air is calculated to come from the floors above and below.

In this analysis, airflow from above and below are treated as equal. This assumes no structural dissimilarities between the two floor interfaces. Thus, 42% of the total flow is calculated to come from each direction with office doors closed or open.

The assumption of equal flow from above and below disregards any possible stack effect. The stack pressure at 31 m, the height of the tower, would be about 1.2 Pa for an inside-outside temperature difference of 1 K at an average temperature of 299 K (26°C). The average pressure difference across a single floor would be one tenth of this or 0.12 Pa. If the average flow coefficient between floors is 13×10^{-4} $m^3/m^2 \cdot s \cdot Pa^{0.65}$ and the floor area 890 m^2, according to Eq 1, the flow rate at 0.12 Pa would be 0.3 m^3/s per degree inside-outside temperature difference. This is 4% of the total flow of 7.55 m^3/s. If flow due to fan and stack effect are additive, equal flow from above and below would not exist. On the other hand, if flow is fan-dominated, analogous to the loss of stack effect in building infiltration at moderate-to-high wind speeds [*13*], there would be no stack effect. At the time these measurements were made, the temperature in the west (nonfan) stairwell was 0.5°C lower than the outside temperature of 26°C. Thus the stack effect, if any, would have been small and negative.

Measurement Uncertainties

The foregoing analyses, based on single point measurements, do not permit experimental determination of the flow exponent, n, nor do they provide an estimate of the repeatability of k, the flow coefficient, or F, the combined fraction of air coming from above and below. However, it is possible to determine the sensitivity of k and F to differences in n by repeating the calculation at more than one assigned value of n. The values $n = 0.55$ and $n = 0.65$ have been selected for the purpose.

It also is possible to estimate a range of k and F values corresponding to a given uncertainty in the pressure measurement. For Magnehelic gage measurements, a value of ±2.7 Pa is selected. This number is based upon several separate measurements of Q as a function of Δp in a room in the same building. The data were fitted to Eq 1, and 2.7 Pa was the pooled standard deviation [14] between the measured Δp and the values from the equation. A pooled standard deviation is used instead of a simple standard deviation because five sets of measurements were made, each with different leakage pathways sealed. The whole-tower measurements, on the other hand, were simultaneously made with a Magnehelic gage and a variable capacitance gage, and both gave the same result. For computational purposes an uncertainty of ± 1 Pa is selected.

Table 2 summarizes the values of k calculated with $n = 0.55$ and $n = 0.65$ and also the range of values corresponding to the specified pressure uncertainties. The ranges of k values are rather broad, particularly in the doors-open condition. It also should be noted that the effect pressure uncertainty is unsymmetrical. A negative differential pressure displacement has a larger effect than an equal positive displacement.

The calculation of F involves the simultaneous solution of two equations such as Eqs 8*b* and 9, each with a large range in the value of k. The corresponding ranges of F have been calculated and are given in Table 3. This calculation represents a "worst case." That is, if the k value for the whole tower is at the upper end of the range in Table 2, the value for the single floor is at the lower end, and vice versa.

The results in Table 3 indicate that there is no magnification of errors in

TABLE 2—*Effect of specified uncertainties in* p *and* n *on the calculated average flow coefficients (average flow coefficients* 10^{-4} $m^3/m^2 \cdot s \cdot Pa^n$*).*

		$n = 0.55$		$n = 0.65$	
	p	k	Range	k	Range
Whole tower	Pa	...	...	...	...
Doors closed	3 ± 1	6	5 to 8	5	5 to 7
Doors open	...[a]	10	7 to 15	9	7 to 15
Single floor	...	...	...	...	...
Doors closed	10 ± 2.7	9	8 to 11	7	6 to 9
Doors open	5 ± 2.7	14	11 to 21	12	9 to 19

[a] Whole tower range of k with doors closed multiplied by $(10 \pm 2.7/5 \pm 2.7)^n$ to estimate range with doors open; $k_{\text{doors open}} = k_{\text{doors closed}} \times 12/7$.

TABLE 3—*Effect of specified uncertainties in* p *and* n *on* F, *the fraction of air flowing from above and below during fan operation.*

	$n = 0.55$		$n = 0.65$	
	F_1	Range	F	Range
Doors closed	0.87	0.77 to 0.92	0.84	0.74 to 0.89
Doors open	0.85	0.68 to 0.96	0.84	0.59 to 0.94

the calculation of F. In fact, there is partial cancellation. Also, the range of F is unsymmetrical with respect to the values calculated from measured data. The best estimate is probably between 0.8 and 0.9, which corresponds to about 40 to 45% flow from above or below. This estimate compares with about 50% from below by SF_6 tracer gas measurements. These results are essentially descriptive, but they suggest an experimental approach to the determination of flow coefficients for modeling horizontal and vertical components of airflow in building ventilation.

Summary and Conclusions

Exploratory depressurization measurements were made in the tower of an eleven-story office building using a 7.55-m³/s fan. Some of the salient observations and conclusions from these measurements are:

1. The fan developed pressures in the 3- to 10-Pa range. It is estimated that about 60 to 70 m³/s would be required to develop a pressure difference of 50 Pa in the whole tower.
2. Under wind conditions sufficiently calm to permit stable pressure readings, a fan-induced pressure difference of 3 Pa was obtained. Assuming a flow equation of the form

$$Q = kA(\Delta p)^{0.65}$$

an average flow coefficient of 5×10^{-4} m³/m² · s · Pa$^{0.65}$ was calculated.
3. A single floor of the building also was depressurized, and the opening and closing of office doors was found to influence the induced pressure. A value of 10 Pa was obtained with all office doors closed and 5 Pa with 15 doors open. These values correspond to flow coefficients of 7×10^{-4} m³/m² · s · Pa$^{0.65}$ and 12×10^{-4} m³/m² · s · Pa$^{0.65}$, respectively, when averaged over the envelope area of a single floor.
4. Flow to the fan was treated as the sum of the fraction of air passing through the wall, $f_w k_w$, and the fraction coming from floors above and below, $f_f k_f$, and is expressed by the equation

$$k \approx f_w k_w + f_f k_f$$

Simultaneous solution of flow equations for the whole tower and single floor lead to estimates of k_w and k_f, which permit calculation of F, the fraction of air coming from the floors above and below, by the relationship

$$F \approx \frac{f_f k_f}{f_f k_f + f_w k_w}$$

F was estimated to be about 80 to 90% of the total flow, or about 40 to 45% from above or below.

5. It was estimated from SF_6 tracer measurements that about half of the air reaching the fan during depressurization of a single floor could be traced to the floor below.

6. Ranges of uncertainty in flow coefficients and the combined fraction of air from above and below are given in the text. The results of the foregoing analyses are essentially descriptive, but they suggest an experimental approach to the determination of flow coefficients for lateral and vertical air movements in modeling building ventilation.

Conversion of SI to English units

1. Pa × 0.004015 = in water (H_2O).
2. $m^3/s \times 2118.9 = ft^3/min$.
3. $m/s \times 196.85 = ft/min$.
4. $m^3/m^2 \cdot s \cdot Pa^n \times 196.85(0.004015)^n = ft^3/ft^2 \cdot min \cdot (in\ H_2O)^n$, where n is the flow exponent.

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