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WINTER INFILTRATION THROUGH SWINGING-DOOR ENTRANCES IN MULTI-STORY BUILDINGS

By T. C. Min*, Auburn, Ala.

This paper is the result of research carried out by the American Society of Heating and Air-Conditioning Engineers at its Research Laboratory located at 7218 Euclid Avenue, Clevland 3, Ohio.

Air infiltration through entrances has been recognized as an important consideration in estimating heating and air-conditioning loads, especially for tall commercial buildings, in which chimney effects are large and heavy traffic prevails. Data presently available on infiltration[1-4] are limited, and the effects of vestibules, fresh air and exhaust fans, traffic rate, and human obstruction have not been fully evaluated. At the ASHAE Research Laboratory, work on entrance infiltration has been in progress since January 1956, under the guidance of the Technical Advisory Committee on Heating and Air-Conditioning Loads**. The purpose of the investigation is to provide basic information on air infiltration through entrances of commercial-type multi-story buildings. In this paper, the infiltration through various types of swinging-door entrances under winter heating conditions is reported. Infiltration through swinging-door entrances under summer cooling conditions is being studied, and a project on infiltration through revolving-door entrances is being planned.

Method of Approach

Entrance infiltration is caused by a pressure differential across the entrance, resulting from chimney effect, supply and/or exhaust fan operation, and wind pressure. For a given pressure differential, the volume of infiltration air passing

* Former Research Engineer, ASHAE Research Laboratory, Cleveland, and now Associate Professor, Mechanical Engineering Department, Alabama Polytechnic Institute. Member of ASHAE.

Exponent numerals refer to References.

** *Personnel*: H. T. Gilkey†, *chairman*; P. H. Yeomans†, *vice chairman*; P. R. Achenbach; R. T. Baum; C. W. Coblentz†; Paul Gayman; R. A. Gonzalez; W. S. Harris†; J. N. Livermore; C. O. Mackey; G. R. Munger; I. A. Naman; T. F. Rockwell; A. M. Simpson†; J. P. Stewart; D. B. Turkington†; A. G. Wilson†; W. R. Yeary. (†Indicates a member of Subcommittee on Infiltration).

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side-swinging door. Two identical panels were made of each arrangement, so that each could be tested as a single bank or vestibule type of entrance. In each entrance model, not only the doors, but the jambs, thresholds, and other details were constructed to scale.

All tests were made under steady conditions with doors set at various angular positions. For each combination of door positions, air flow was determined for at least 3 pressure differentials across the model entrance. Wet- and dry-bulb temperatures were measured by thermometers located in the metering duct.

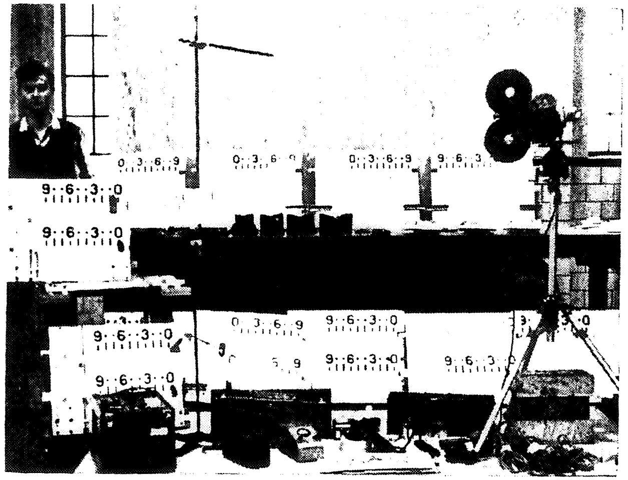

FIG. 2—EQUIPMENT USED IN FIELD TESTS OF BUILDING ENTRANCES

Phase 3: Studies on the correlation of door position and traffic rate were conducted in 7 buildings in the downtown area of Cleveland during November and December 1956, and January 1957. One of the entrances studied had power-operated doors, one set of which swung in, and the other set of which swung out. The other 6 buildings had manually operated doors which swung out.

Indicators, shown in Fig. 2 with other field test equipment, were built to show the position of the entrance doors to be studied. Fig. 3 shows the indicators for both the inner and outer banks of vestibule doors, mounted over the inner doors. Indicators were connected to the doors by a system of cords and pulleys, and were calibrated in place before the start of a test.

A 16 mm movie camera operating at a speed of 8 frames per second was used to take pictures similar to Fig. 3, showing the indicators and the people passing through the doors. At this operating speed, the 400-ft films used would last for 30 min continuous operation. The camera was actually operated intermittently for periods of 4 or 5 min each, at various times throughout the day, so that data could be obtained for various traffic patterns.

After the films were developed, the pictures were analyzed with the aid of a time-motion-study projector. Pictures could be advanced, one frame at a time, and a counter indicated the number of the frame being studied.

TEST RESULTS

Pressure Differential Across an Entrance: It was found from an analysis of the field test data that the pressure differential across a building entrance was related to the building height, and the difference between the indoor and outdoor air temperatures. It was also evident that the differential could be increased or decreased appreciably by the operation of exhaust or fresh air supply fans.

To correlate the pressure differential across an entrance with building height, temperature differential, and blower action, the observed pressure differential for

FIG. 3—ENTRANCE SHOWING DOOR INDICATORS AND TRAFFIC

each test was expressed as a percentage of the theoretical natural draft for the conditions of the test. This ratio is hereinafter referred to as a *draft-factor*.

The theoretical draft which is produced solely by the stack height and the difference in the densities of the cold outside and the warm inside air may be calculated by Equation 1.

$$\Delta P_{\text{theo.}} = 0.1924\ (\rho_o - \rho_i)\ H \quad \quad (1)$$

The theoretical draft in buildings, heated to 75 F, of any height, and for any inside-outside temperature difference, may be determined from Fig. 4. The figure is based on air densities taken from Reference 5.

In Fig. 5, the observed pressure differentials resulting from chimney action only have been plotted against the theoretical drafts obtained from Fig. 4. A straight line drawn through the points for conventional buildings has a slope of 0.7, thus indicating a *natural draft factor*, f_N, of 0.7. One of the buildings tested was of metal curtain wall construction and had windows which were tightly sealed by inflated gaskets. This building had a draft factor of 0.3 as shown by the lower curve

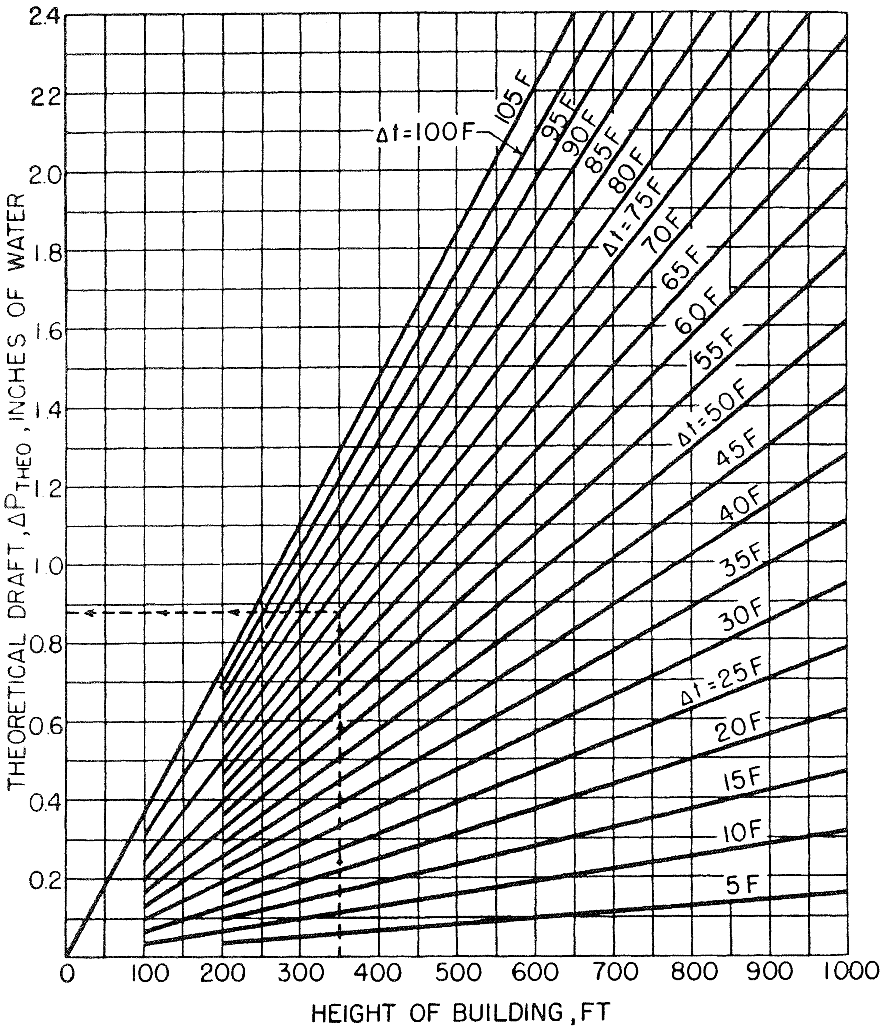

FIG. 4—THEORETICAL DRAFT IN TALL BUILDINGS DUE TO CHIMNEY EFFECT (BASED ON AVERAGE INSIDE AIR AT 75 F, 50 PERCENT RH, STANDARD ATMOSPHERIC PRESSURE 29.921 IN. HG)

of Fig. 5. However, since only one building of this type was tested, it is not known if this lower factor would be typical for other buildings of similar construction.

The operation of exhaust or fresh air supply fans tends to increase or decrease the pressure differential across a building entrance caused by natural draft. Corrections for the natural draft factor, for various rates of air exhaust or supply, are given in Fig. 6. The corrected factors, or the *forced draft factors*, are also given in the figure.

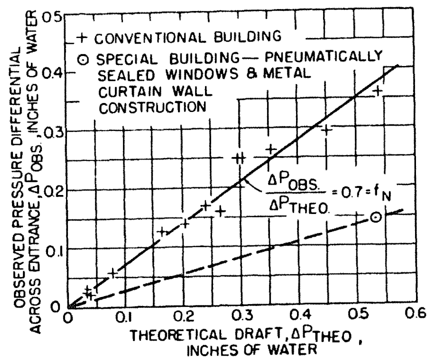

FIG. 5—NATURAL DRAFT FACTOR FOR BUILDING ENTRANCES

Wind velocity was found to have a negligible effect on the pressure differential in the congested business areas where the field tests were conducted. Although some tests were made on rather windy days when wind velocities of 20 mph were being recorded by the U. S. Weather Bureau, wind velocities measured windwardly at the curb line in front of the entrance were not more than 6 mph, and the maximum velocity normal to the entrance was only about 2 mph, which is equivalent to a pressure differential of less than 0.002 in. of water. The wind direction past the building entrance was found to be quite erratic.

No attempt was made to investigate the effect of vertical openings. However, the presence of large escalator openings in two of the buildings tested did not seem

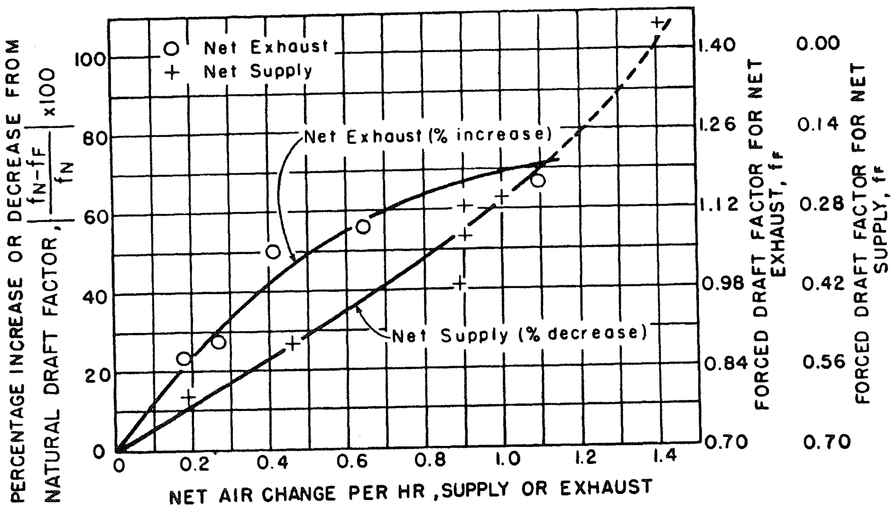

FIG. 6—EFFECT OF BLOWER ACTION UPON PRESSURE DIFFERENTIAL

to cause any significant difference in the draft factors. It was also surprising to the investigators to find that the pressure differential remained essentially constant regardless of variations in the rate of traffic through the entrances. No effect of *elevator pumping* was observed.

Both the inside and outside air temperatures were found to be reasonably constant over the entire height of the buildings. The maximum variation observed was of the order of 5 F.

Flow Coefficients for Door Openings: As previously indicated, the feasibility of scale model tests was demonstrated by the comparison of data obtained with models

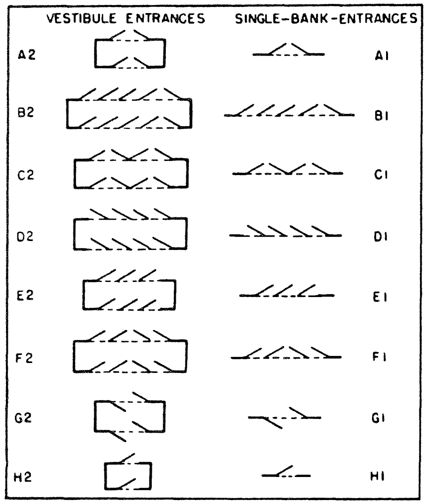

FIG. 7—TYPES OF ENTRANCES FOR WHICH FLOW COEFFICIENTS WERE CALCULATED

at two different scales, with the results of tests on a full scale door. A discussion of the theory of model testing appears in Appendix A.

For doors of given dimensions, arrangement, and direction and angle of opening, the flow coefficient, C_F, was found to be the same regardless of the scale of the model used, or the pressure differential applied across the model entrance. The flow coefficient may be defined by Equation 2.

$$C_F = q_n/4005\ NA\sqrt{\Delta P} \qquad (2)$$

About 300 tests were made in the Laboratory on a 1/6 scale model of a 4-door single-bank entrance (type F1 in Fig. 7) to determine the flow coefficients for various door positions. Test data obtained on the performance of adjacent doors of various arrangements (opposite-swinging, parallel-swinging, one swinging in and the other out) were used to compute the coefficients for the various types of en-

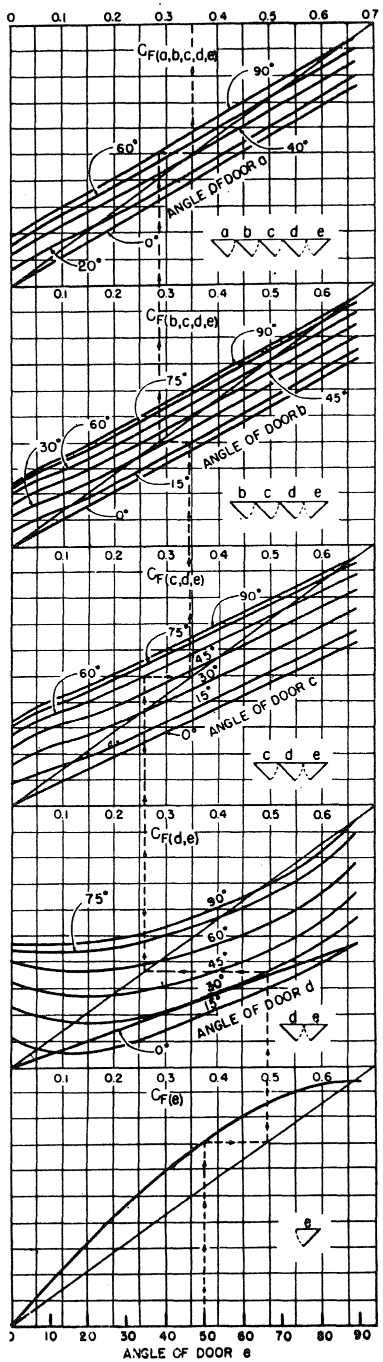

FIG. 8—CHART FOR DETERMINING FLOW COEFFICIENTS FOR TYPE B1 ENTRANCE

trances shown in Fig. 7. The effect of adjacent doors, either parallel- or opposite-swinging, are shown in Figs. B-1 and B-2 of Appendix B.

Fig. 8 is a graph constructed for determining the flow coefficients for a 5-door entrance (type B-1 of Fig. 7) for any combination of door positions. It is composed of 5 sets of curves. The first set, at the bottom of the figure, shows the performance of door "e" as a single door. The second set of curves, when entered at the point indicated by the "e" curves, gives the coefficient for the combined performance of doors "e" and "d". Similarly, the scale at the top of each successive set of curves indicates the combined coefficient for the door represented by the curves, in com-

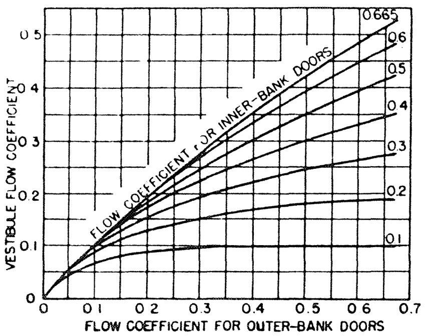

FIG. 9—FLOW COEFFICIENTS FOR VESTIBULE ENTRANCES

bination with all preceding doors. Fig. 8 is typical of a number of graphs constructed for various entrance arrangements.

To determine the performance of a vestibule-type entrance, tests were made on a ⅙ scale model of a type F2 entrance having a vestibule depth of 8 ft in prototype. It was at first thought that the relative locations of the open doors in the inner and outer banks, as well as the numerous combinations of positions of the doors in each bank, might be important variables in the study. However, it was found that the coefficient for the vestibule could be predicted from the coefficients for the inner and outer banks, regardless of the positions of the individual doors in each bank. For example, any combination of door positions in the 2 banks which gave individual bank coefficients of 0.3 and 0.4 would produce a vestibule coefficient of 0.225. Flow coefficients for vestibule entrances may be determined from Fig. 9, if the coefficient for each bank of doors is known.

A few tests were made with vestibules 4 ft and 16 ft deep in prototype. The results of these tests indicated that the depth of the vestibule had no significant effect on the infiltration through a building entrance. Tests were also made with a marquee at several heights above the entrance, but no significant effects were found.

The flow coefficients as determined from Figs 8 and 9 are for doors at the indicated positions but unobstructed by people passing through them. The effect of human obstruction was studied by placing a scaled model of human figure at various positions in a door opening. The results of these tests are given in Appendix

C. Other tests, in which 3 human figures were placed at various positions in an open doorway indicated that the entire effect observed was created by the one figure which created the maximum obstruction.

Since the reduction of infiltration due to human obstruction depends upon the length of time the opening is obstructed, further discussion on the subject will be given with the results of the traffic analysis.

A few tests were made to determine the infiltration through a full scale door crack 34½ in. long and adjustable in width up to ½ in. The results are given in Fig. 10.

Analysis of Traffic and Evaluation of Entrance Coefficients: In the field studies made to correlate traffic and door position, seven 400-ft films or a total of over

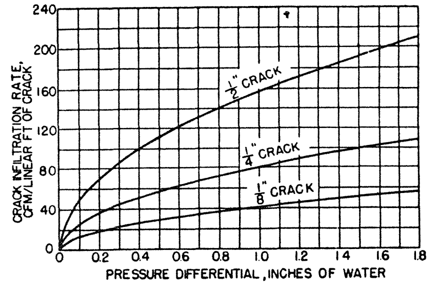

FIG. 10—INFILTRATION THROUGH DOOR CRACKS

100,000 frames were taken at a speed of 8 frames per second. These pictures showed traffic at various rates passing through vestibule-type entrances having various door arrangements and vestibule depths. It was found that good accuracy could be obtained by the analysis of every eighth frame (1 picture per second), and the results presented are therefore based on the examination of approximately 12,500 frames.

The analysis was made by projecting every eighth frame onto a screen, and noting the indicated position of each door in both the inner and outer banks. For each combination of door positions, the flow coefficient for each bank of doors was determined from a chart similar to Fig. 8, constructed for the particular entrance being studied. The traffic rates through the doors for certain selected sequences were also determined from the pictures.

From the data obtained from the pictures, *entrance coefficients* were calculated for the various entrances tested. An entrance coefficient may be defined as the flow coefficient corresponding to a given traffic rate through a given entrance.

Entrance coefficients for a single-bank entrance were determined by averaging the flow coefficients for the outer bank of vestibule entrance doors. A plot of these entrance coefficients *vs.* traffic rate is shown by the upper curve of Fig. 11. The flow coefficients for the outer bank of doors were used because it was felt that the outer bank more nearly represented the performance of single bank doors. In every building tested, the outer doors closed more rapidly than the inner doors, probably due in part to the adjustment of the door closers, and in part to the greater pressure differential acting on the outer doors. Field tests had indicated that most of the pressure differential across a vestibule-type entrance occurred at the outer set of doors. Coefficients based on the inner doors would have been about 10 percent higher than those shown in Fig. 11.

Flow coefficients for vestibule-type entrances were determined from the separate flow coefficients for the inner and outer banks of doors by means of Fig. 9. The vestibule entrance coefficients shown by the upper curve of Fig. 12 were determined by averaging the vestibule flow coefficients for given traffic rates. An example of the determination of entrance coefficients is given in Appendix D.

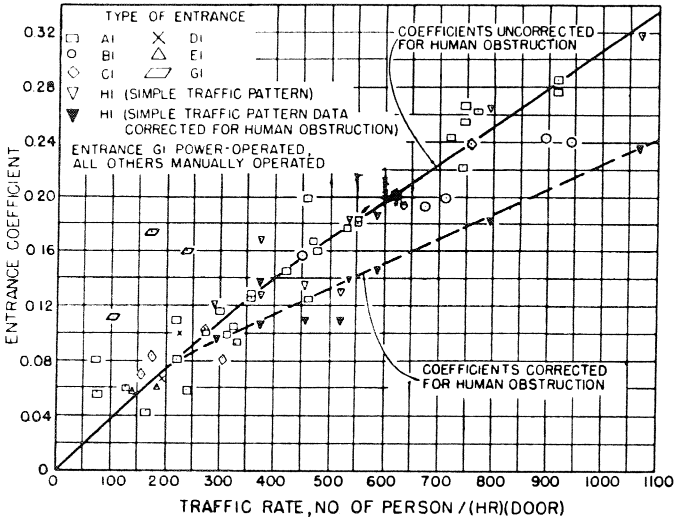

Fig. 11—Entrance Coefficients for Single-Bank Entrances

To study the effect of human obstruction upon infiltration, it was decided to analyze only those sequences showing a simple traffic pattern of 1, 2, 3, or 4 people entering or leaving one door (or one set of doors in the case of the vestibule entrance) at about the same time. Each analysis started with the frame before the first person entered through the outer door (or departed through the inner door), and continued until the last person had completed the passage through the doors, and the doors were closed. The angles of door opening, as well as the position of each person relative to the doors, were noted; and the effects of the obstruction were determined and can be seen from Fig. C-1 of Appendix C. The lower curves of Figs. 11 and 12 were plotted on the assumption that the ratio of the corrected to the uncorrected entrance coefficients, as found for the simple traffic patterns studied, would hold for the more complex patterns. As shown in the figures, the effect of human obstruction is negligible at low traffic rates, and increases to approximately 25 percent with 1,000 persons per hour passing through each door.

The solid curves in Figs. 11 and 12 were drawn to represent the average coefficients for all of the entrances tested. A close inspection of the figures reveals that the

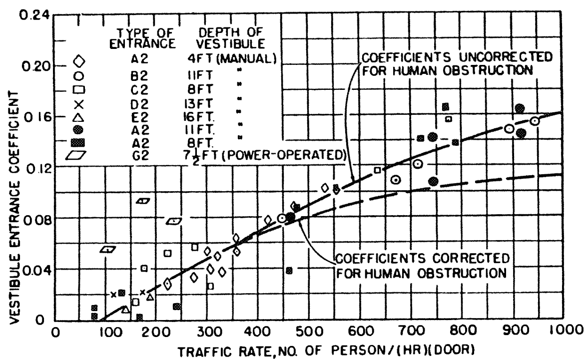

Fig. 12—Entrance Coefficients for Vestibule Entrances

solid curves also represent a reasonably good average for each of the entrances tested except those having power-operated doors, G1 and G2. It is therefore recommended that the entrance coefficient for any entrance having manually operated doors be determined from the curves of Figs. 11 and 12, regardless of door size or arrangement. The use of the broken curves, giving values corrected for human obstruction, is recommended for practical application.

The curves of Fig. 13 show the relationship between the effective (actual) pressure differential across an entrance, the entrance coefficient, and the infiltration

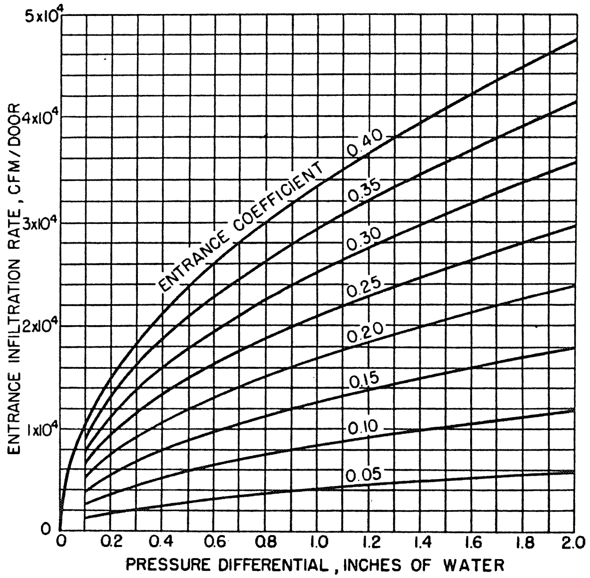

Fig. 13—Entrance Infiltration Rates for Various Pressure Differentials and Traffic Rates

rate per door. It should be noted that the infiltration rates shown in this figure are based on a 3- x 7-ft door. Infiltration through doors of other sizes will be proportioned to the door areas.

Discussion

As indicated in Figs. 11 and 12, the entrance coefficients for the one set of power-operated doors tested were much higher than for manually operated doors. This is to be expected, since the power-operated door opens a full 90 deg each time a person passes through it, and remains open longer than the average manually-operated door. The increase in infiltration through power-operated doors will probably vary widely, depending upon the adjustment of the operating mechanism. It is also apparent that the effect of human obstruction will be less with power-operated than with manually-operated doors.

The data on infiltration through door cracks will be applicable only to entrances through which the traffic rate is very low.

Illustrative Example: Given: A conventional building 350 ft high has a net cubage of 4,200,000 cu ft. Fresh air fans supply outside air at the rate of 80,000 cfm, and exhaust fans discharge 50,000 cfm. The building has a vestibule-type entrance having four 3- x 7-ft doors and the inside temperature is maintained at 75 F. Find: Infiltration rate through the entrance at a time when the outside temperature is zero F, and the traffic rate is 2,000 persons per hour.

Solution: From Fig. 4, the theoretical draft for a 350-ft building height and a 75 F inside-outside temperature differential is 0.88 in. of water.

The net air supply rate is 80,000 − 50,000 = 30,000 cfm. This is 30,000 × 60/4,200,000 or 0.43 air changes per hour. From Fig. 6, the draft factor for a conventional building, corrected for an air supply rate of 0.43 air changes per hour is 0.525, and the effective pressure differential is 0.88 × 0.525 = 0.462 in. of water.

The traffic rate per door is 2000/4 = 500 persons per hour. From Fig. 12, the vestibule entrance coefficient corrected for the effect of human obstruction is 0.08.

From Fig. 13, for an effective pressure differential of 0.46, and an entrance coefficient of 0.08, the infiltration rate per door is 4,500 cfm. Infiltration through the 4-door entrance = 4 × 4,500 = 18,000 cfm.

Conclusions

1. A procedure and the necessary data for the calculation of infiltration through entrances of tall buildings are presented in the paper. An approximate general equation for the calculation of infiltration are also given in Appendix E.

2. The most important variables determining the infiltration rate through building entrances are (*a*) building height, (*b*) indoor-outdoor temperature difference, (*c*) the quantity of air supplied and/or exhausted, (*d*) traffic rate, and (*e*) type of building entrance.

3. The infiltration through a vestibule-type entrance varies from about 50 to 60 percent of that for a single bank entrance, depending upon the traffic rate.

4. Wind velocity is not an important factor in determining entrance infiltration.

5. Entrance infiltration is not appreciably affected by the depth of the vestibule or the presence of a marquee.

6. It is only during periods of very low traffic rate that the infiltration through cracks around the doors becomes an appreciable part of the total infiltration. During periods of normal or high traffic rates, infiltration through door cracks may be neglected without serious error.

7. The approximate entrance infiltration in a 30-story building at a temperature differential of 75 F is as follows:

For single-bank door entrances—900 cu ft per person per passage.

For vestibule-type entrances—550 cu ft per person per passage.

A net air supply of 1/2 air change per hour, and a traffic rate of 500 persons per (hour) (door), were assumed in arriving at these values.

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Nomenclature

A = area of a door, square feet.
C_F = flow coefficient, dimensionless.
f_F = forced draft factor, dimensionless.
f_N = natural draft factor, dimensionless.
H = building height, feet.
N = number of doors per bank.
ΔP = pressure differential across the entrance, inches of water.
$\Delta P_{obs.}$ = observed pressure differential, inches of water.
$\Delta P_{theo.}$ = theoretical pressure differential, inches of water.
q_n = air flow through entrance, cubic feet per minute.
ρ_i = density of inside air, pounds per cubic foot.
ρ_o = density of outside air, pounds per cubic foot.

APPENDIX A

Preliminary Investigation on Model Entrance Tests

Before the model tests could be of any value, investigation was made to determine how a geometrical, kinematic, and dynamic similarity could be established between the prototype and the model, so that the phenomena of the prototype could be reproduced in the model, and the information obtained from the model could be used to predict the performance of the prototype.

From the knowledge of the physical situation, it was assumed that the controlling factors for the air volume flow through the door entrance would be ΔP, D, ρ, g, and μ, and that the air volume flow q might be expressed by the equation:

$$q = \phi(\Delta P, D, \rho, g, g_c, \mu) \quad \text{(A-1)}$$

where

q = air infiltration, cubic feet per minute
ϕ = any function
ΔP = pressure differential, pounds_f per sq ft
D = characteristic dimension, feet
ρ = air density, pounds_f per cubic foot
g = acceleration due to gravity, feet per minute (minute)
g_c = conversion factor, $\frac{(\text{lb}_m)(\text{ft})}{(\text{lb}_f)(\text{min})(\text{min})}$
μ = air viscosity, $\frac{\text{lb}_m}{(\text{ft})(\text{min})}$

By the use of the dimensional analysis, Equation A-1 becomes:

$$\frac{q/D^2}{\sqrt{2g_c \frac{\Delta P}{\rho}}} = a_1 \left(\frac{D\rho \sqrt{2g_c \frac{\Delta P}{\rho}}}{\mu}\right)^{a_2} \left(\frac{\Delta P g_c}{D\rho g}\right)^{a_3} \quad \text{(A-2)}$$

where

a_1 = experimental constant
a_2 = experimental exponent
a_3 = experimental exponent

Since D^2 may be replaced by any convenient dimension of area such as the area of a door A, Equation A-2 may be written as

$$\frac{q}{A\sqrt{2g_c \frac{\Delta P}{\rho}}} = C_F = a_1 \left(\frac{D\rho \sqrt{2g_c \frac{\Delta P}{\rho}}}{\mu}\right)^{a_2} \left(\frac{\Delta P g_c}{D\rho g}\right)^{a_3} \quad \text{(A-3)}$$

where

C_F = flow coefficient

or

$$N_{Eu} = a_1(N_{Re})^{a_2}(N_{Fr})^{a_3} \quad \text{(A-4)}$$

where

$$N_{Eu} = \frac{q}{A\sqrt{2g_c \frac{\Delta P}{\rho}}} = \text{Euler Number}$$

$$N_{Re} = \frac{D\rho}{\mu}\sqrt{2g_c \frac{\Delta P}{\rho}} = \text{Reynolds Number*}$$

$$N_{Fr} = \frac{\Delta P g_c}{D\rho g} = \text{Froude Number*}$$

* *Fluid Mechanics for Hydraulic Engineers*, by Hunter Rouse (McGraw-Hill Book Company, Inc., New York, First Edition, 1938, p. 303).

As dimensional analysis can serve only as a yardstick to reveal the possible parametric groups which may govern the characteristics of the flow, the final answer must rely on the test results, first to determine the effect of the Reynolds and the Froude Numbers on the Euler Number, and then to determine the experimental constants a_1, a_2, and a_3.

If experiments showed that both the Reynolds and Froude Numbers were important, the flow coefficient would have to be split into two parts†, one to be a function of the Reynolds Number, and the other the Froude Number.

Experiments were run in the wind tunnel with a ¼ scale single-door entrance as prototype and ⅙ scale single-door entrance as the ⅔ scale model, both at the fully open position. By proper choice of the size of doors and selection of the pressure differentials, either the Reynolds Number or the Froude Number was held constant, and the Euler Number, in either case, was found to be the same. This pointed out that both the

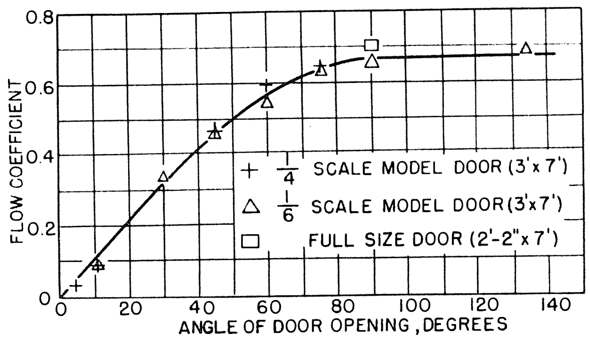

FIG. A-1—FLOW COEFFICIENTS FOR A 3- × 7-FT DOOR AT VARIOUS ANGLES OF OPENING

Reynolds and Froude Numbers were unimportant, and that the Euler Number, or the flow coefficient, depended only upon the geometry of the boundary, *i.e.*, for a given geometrical orientation, the average velocity was proportional to the square root of the pressure differential, and the proportionality constant was the same for both the prototype and model regardless of the pressure differential and the size of the scale model. In other words, the experimental exponents a_2 and a_3 in Equation A-4 were zero, and the value of a_1 remained the same for a given boundary orientation.

The fact that the Euler Number remained constant for a given boundary condition indicated that the Reynolds and Froude Numbers were sufficiently large ($N_{Re} > 10^5$, $N_{Fr} > 2$) that the viscous and gravity forces were negligible in comparison to the inertia and pressure forces*.

Existing data** show that the Euler Number or flow coefficient for a circular orifice is constant at a Reynolds Number of 1 x 10^5 and higher. The literature also shows that, for a flow with free surface, the Euler Number is constant for a Froude Number of 2 and greater. In the case where the flow is not free but guided by a horizontal plane, such as in a door entrance with floor simulation, the gravity force is not important, and

† *Fluid Mechanics*, by Russell A. Dodge and Milton J. Thompson (McGraw-Hill Book Company, Inc., New York, First Edition, 1937, p. 436).
* *Fluid Mechanics for Hydraulic Engineers*, by Hunter Rouse (McGraw-Hill Book Company, Inc., New York, First Edition, 1938, pp. 303, 304).
** *Elementary Mechanics of Fluid* by Hunter Rouse (John Wiley & Sons, Inc., New York, 1946, pp. 168, 105, 93, 95).

the flow coefficient is independent of the Froude Number and depends only upon the boundary proportions and orientations. This is also found to be true for a sluice gate††.

Since the wind tunnel tests were run at room temperature, the properties of air were essentially constant. Only the pressure differential ΔP and scale of the model D were varied. For a single-door entrance of ⅙ scale at a pressure differential even as low as 0.02 in. water, the corresponding Reynolds and Froude Numbers were 4 x 10^5 and 2 respectively. The pressure differentials used in all 700 tests ranged from 0.05 to 0.98 with most tests made around 0.5 in. water, which was the practical range encountered in the field tests. The Reynolds and Froude Numbers were therefore greater than their critical values in all tests.

The flow coefficient for both ¼ scale and ⅙ scale single-door entrances was found to be about 0.665 for the fully open position. A check test was made in a corridor by

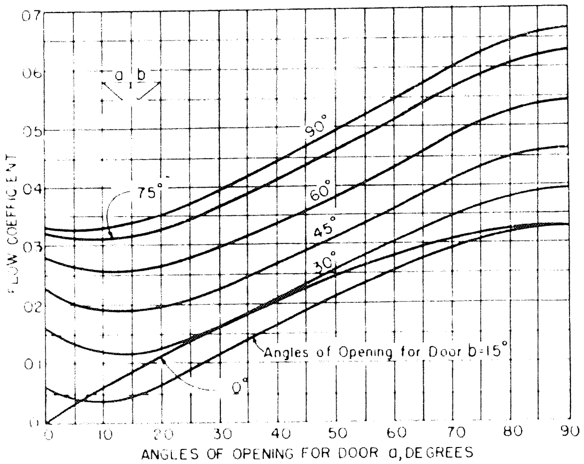

Fig. B-1—Flow Coefficients for Opposite-Swinging-Door Entrance

using 2 large exhaust fans as the suction source and measuring the average velocity and pressure differential across a full-size single-door entrance connecting the corridor and a room. With the pressure differential of 0.034 in. water and an average velocity of 520 fpm, the flow coefficient was found to be 0.7 which agrees well with the model test value of 0.665.

Tests were run on both ¼ and ⅙ scale models at different angles of opening, and the results showed that the flow coefficients[1] remained the same for both scales at the same angles of opening. This is shown in Fig. A-1.

APPENDIX B

Effect of the Direction of Swing of Adjacent Doors on the Flow Coefficient

The effect of the direction of swing of adjacent doors was investigated so that the flow coefficient for various types of entrances (Fig. 7) could be evaluated. Fig. B-1

†† *Elementary Fluid Mechanics* by John K. Vennard (John Wiley & Sons, Inc., New York, Third Edition, 1954, p. 305).

[1] The flow coefficients for a door at various angles of opening were based on the full area of the door, as defined in Equation 2, instead of the actual area of the opening of the door.

shows the flow coefficients for a pair of opposite swinging doors, and Fig. B-2 shows the coefficients for a single door as influenced by an adjacent parallel-swinging door.

Tests indicated that, for an opposite-swinging-door entrance with one door swinging out and the other in, the flow coefficient was essentially the same as for a parallel-swinging-door entrance with both doors swinging out.

APPENDIX C

Effect of Human Obstruction

To evaluate the reduction of air infiltration through an entrance due to the obstruction of people passing through, tests were run in the wind tunnel with scaled figures of

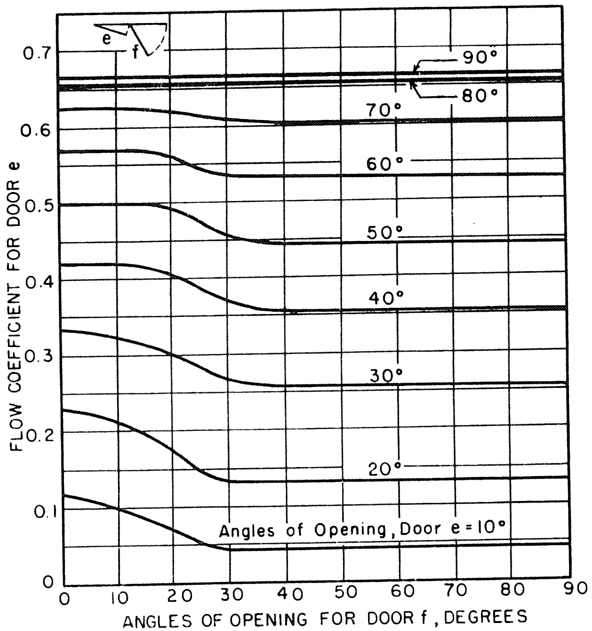

Fig. B-2—Flow Coefficients for Door e Showing Influence of Adjacent Door f

persons standing at the model single-bank-door entrance. The results are shown in Fig. C-1.

For vestibule entrances, corrections for human obstruction may be computed by the use of Figs. 8, C-1, and Fig. 9. For instance, at a single-door vestibule entrance with one subject standing at the threshold of the outer door and the other at the threshold of the inner door, and both inner and outer doors at fully open position, the flow coefficients for inner door and outer door with correction for human obstruction are $0.665 \times 0.67 = 0.45$ (Figs. 8 and C-1 for position 4 curve at 90 degrees). The vestibule coefficient is 0.31 (from Fig. 9) which agrees well with the test value of 0.33.

APPENDIX D

Sample Calculation of Entrance Coefficient

The entrance coefficient for each sequence of frames analyzed was determined by averaging the flow coefficients for the sequence.

Table D-1 is a sample of the data developed by analyzing a sequence of pictures.

By dividing the totals for the sequence by the number of frames in the sequence, 266, the following results are obtained.

$$\text{Single-bank entrance coefficient} = \frac{51.704}{266} = 0.194$$

$$\text{Vestibule-entrance coefficient} = \frac{28.412}{266} = 0.107$$

APPENDIX E

APPROXIMATE GENERAL EQUATION FOR THE CALCULATION OF INFILTRATION

Entrance infiltration is primarily affected by the indoor-outdoor temperature difference, the height of the building, the quantity of air supplied and/or exhausted, and the traffic rate. A correlation of these variables may be approximated by the equation:

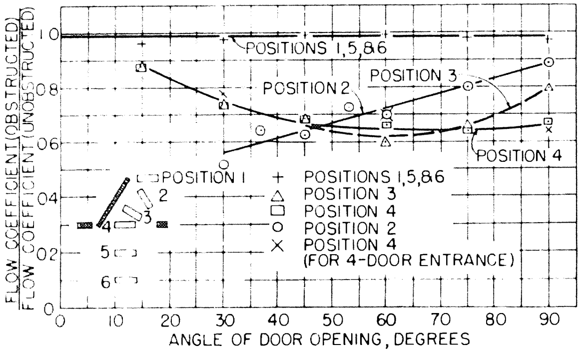

FIG. C-1—EFFECT OF HUMAN OBSTRUCTION ON FLOW COEFFICIENTS

$$q' = k_1(M + k_2)\left[\frac{H}{T_o}(\Delta t)(1 + k_3 N^{k_4})\right]^{\frac{1}{2}} \quad . \; . \; . \; . \; . \quad \text{(E-1)}$$

where

q' = entrance infiltration corrected for human obstruction, based on inside design temperature of 75 F, cubic feet per minute per door
M = traffic rate, number of persons per (hr)(door)(limited to 200 to 1,000)
H = building height, feet
T_o = Absolute outside air temperature, Rankine degrees
N = net air changes per hour, (exhaust or supply) (limited to 0 to 1.1)
k_1 = constant, 1.1 for vestibule entrance; 1.6 for single-bank-door entrance
k_2 = constant, 125 for vestibule entrance; 216 for single-bank-door entrance
k_3 = constant, −0.6 for net supply air; +0.7 for net exhaust air
k_4 = exponent, 0.9 for net supply air; 0.6 for net exhaust air
Δt = indoor-outdoor temperature difference, Fahrenheit degrees

DISCUSSION

H. T. GILKEY, Cleveland, Ohio (WRITTEN): Having been associated with the Technical Advisory Committee on Heating and Air Conditioning Loads during the period of

TABLE D-1—ANALYSIS OF A TYPE B ENTRANCE WITH A TRAFFIC RATE OF 674 PERSONS PER (HR)(DOOR)

Frame No.	Bank	Angles of Doors[a]					Flow Coefficients	
		A	B	C	D	E	Single Bank	Vestibule
3137	outer	18	0	30	84	40	0.244	0.167
	inner	65	48	0	36	0	0.276	
3145	outer	8	0	20	65	14	0.150	0.131
	inner	68	64	0	30	0	0.295	
3153	outer	2	0	10	16	5	0.047	0.047
	inner	66	59	0	30	20	0.276	
3161	outer	4	0	0	10	0	0.044	0.044
	inner	44	60	0	22	61	0.292	
3169	outer	4	0	0	20	0	0.054	0.054
	inner	17	58	0	22	90	0.279	
3177	outer	4	0	0	48	36	0.116	0.122
	inner	9	32	0	30	76	0.210	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4609	outer	38	50	0	8	0	0.179	0.137
	inner	50	0	4	40	74	0.259	
4617	outer	25	60	0	4	0	0.174	0.133
	inner	64	0	0	20	76	0.249	
4625	outer	54	54	0	0	0	0.210	0.142
	inner	56	0	0	4	74	0.232	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
5241	outer	2	0	0	0	26	0.060	0.060
	inner	45	15	0	38	0	0.194	
5249	outer	2	0	0	0	10	0.034	0.033
	inner	20	10	0	38	0	0.133	
5257	outer	2	0	0	0	4	0.015	0.015
	inner	10	5	0	38	0	0.107	
5265	outer	2	0	0	0	4	0.015	0.015
	inner	6	0	0	40	0	0.095	
	Total of coefficients for outer bank						51.704	
	Total of coefficients for vestibule entrance							28.412

[a] See Fig. 8 for door designations.

the investigation reported in this paper, perhaps I am in a better position than some to express my appreciation to Mr. Min and the staff of the Research Laboratory for the information presented. Quite frankly, several members of the TAC were initially skeptical that information of practical value could come from such an investigation. I think that the committee was somewhat overwhelmed by the number of factors which might affect entrance infiltration. Many, but not all of those, are listed in the paper. It is true that some of these variables were found to be of negligible importance during the course of the investigation, but this fact detracts in no way from the skill and ingenuity exhibited in conducting the investigation, and in analyzing and interpreting the data.

It should be pointed out that a great many types of structures are grouped within the classification of *conventional buildings* shown in Fig. 5. This classification includes buildings of curtain-wall construction, as well as of masonry construction. The paper specifically mentions that one of the buildings tested was of metal curtain-wall construction and had windows which were tightly sealed by inflated gaskets; this building had a much lower draft factor than did the other buildings investigated. Obviously, not all metal curtain-wall buildings are as tightly sealed against air leakage as was this one, and the lower natural draft factor was probably due to the tightly sealed windows rather than to the curtain-wall construction as such.

The report states that the pressure differential across the building entrance remained essentially constant regardless of variations in the rate of traffic through the entrances. One wonders if this situation was observed only during the day, when there would always be at least light traffic, or was it also observed in the evening at an essentially zero-traffic condition?

Obviously, the entryway is not a building's only source of air leakage. There is some question, I think, as to whether the entryway represents the major source of infiltration in buildings such as those studied, or if it is merely a source of substantial air leakage. Unfortunately, this question is not resolved by the observation *that the pressure differential remained essentially constant regardless of variations in the rate of traffic through the entrances.* It is wondered, therefore, for the building sited in the illustrative example, if there are means of estimating the proportion of total air leakage which the 18,000 cfm entrance leakage represents.

It is unfortunate that the appendices could not be published with the paper in the Journal, for without them complete analysis of the paper is impossible. Furthermore, these appendices explain techniques of investigation and analysis which will prove valuable to other investigators.

R. A. Parsons, Lansing, Mich., (Written): The information provided by this paper should be helpful in determining infiltration rates through swinging type doors at street level entrances to large buildings. It is applicable to large buildings in congested areas during business hours. This data is necessary for computing the capacity of equipment needed to properly temper outside air as it enters such buildings.

Additional information would be useful if it were applicable to isolated buildings which do not have the benefit of surrounding buildings to minimize the effect of wind. Included might be such items as:

(1) Effectiveness of an *air curtain* in reducing infiltration. It has been stated that this type of installation seals entrances hermetically even against heavy winds, without producing a draft.

(2) The effect of exhausting air at entrances (pressurizing). Minimum volumes and velocities of exhaust air necessary to eliminate infiltration at various wind velocities could be determined.

D. R. Bahnfleth, Urbana, Illinois (Written): The author has presented useful infiltration data in a form which is easily understood and easily applied. Many of the variables that influence infiltration through entrances have been studied and their relative importance established. However, it does seem that the omission of resistance to air flow between floors and through the building envelope should be given some consideration as an important variable. The *draft-factor*, which is the ratio of observed pressure difference at entrance level to theoretical pressure difference for a stack of the same height as the building, is a function of the resistance to air flow between floors and the resistance to air flow through the building envelope. A high draft-factor, which is indicative of a high pressure differential at entrance level, implies low resistance and a low draft-factor high resistance. Thus, if a structure is extremely tight above the level of the entrance, the pressure differential and entrance infiltration would be small.

To illustrate the effect of the resistance to air flow on infiltration consider the extreme case of an air-tight structure of 500-ft height that has a swinging door entrance. At an indoor-outdoor temperature difference of 75 F the theoretical pressure difference from Fig. 4 would be 1.25 in. water. The *draft-factor* would be nearly zero, and infiltration through the entrance would be negligible. From the results it is apparent that in conventional construction today the flow resistance between floors and the flow resistance of the envelope is very small, and no significant differences in draft-factor could be measured. The draft-factor of 0.7 places the neutral zone for infiltration at about 0.7 of the height, which is in agreement with earlier studies of heat loss in multi-story buildings. However, as new construction materials and new construction methods are introduced, the conventional building may have a greater resistance to flow and lower entrance infiltration rates. This is suggested by the results from the one test conducted on a presumably tighter-than-average building.

It should also be noted that the reduction of entrance infiltration can only be accomplished by (1) selecting the proper type of entrance, (2) controlling the net amount of ventilation air supplied to the structure, and (3) reducing the pressure differential across the entrance by increasing the resistance to flow of the building envelope, as such things as traffic rate, height and temperature difference cannot be controlled. Thus, if minimum entrance infiltration is desirable some attention must be given to the tightness of other components of the structure.

For the reasons mentioned, it would seem that the resistance of the building interior and envelope to air flow should be considered as one of the important variables determining entrance infiltration, and it would seem advisable to extend the present investigation, if possible, to evaluate draft factors for newer types of structures.

C. M. Humphreys, Cleveland, Ohio: In his discussion Mr. Gilkey stated that some of the members of the Technical Advisory Committee doubted if the many variables associated with the problem of entrance infiltration could be resolved. These misgivings were also shared by some at the Laboratory. Mr. Min is to be commended for the work which he did, and particularly for his perseverance and resourcefulness in the analysis of the data.

As Mr. Min has stated, tests were made on buildings in both Cleveland and Pittsburgh. It is pleasant to take this opportunity to thank the owners, managers and engineers of these various buildings. In every case they offered their complete cooperation. Without this cooperation the project could not have been completed.

A. G. Wilson, Ottawa, Canada: I would like to add my commendation to Mr. Min and his colleagues at the ASHAE Laboratory for an excellent piece of work and one which I am sure will be regarded as highly significant. Having looked at the infiltration chapter of The Guide recently, I realize how little information there is of the type that is presented in this paper. This information will be directly useable I am sure by the consulting engineer.

As has already been implied by some of the discussers the paper suggests further work that might be carried out, as is often the case. One of the subjects that has been discussed is the matter of the pressure differences across the entrances and the extent to which they approach the theoretical draft of the building. This is one aspect of the work which I think might usefully be extended to include pressure differences across the exterior walls of buildings at various heights. I believe this would provide much needed information on pressure differences leading to infiltration into spaces at other levels in the building.

Finally, I would like to ask Mr. Min, to what extent he thinks the entrance flow coefficients obtained might be applicable to the determination of infiltration through entrances in the summer time in air-conditioned buildings.

W. R. RATAI, Milwaukee, Wis.: Fig. 8 is a chart for determining flow coefficients for type B-1 entrance. The angles, I presume, were measured by test or observed from test or from frames. Is any more work going to be done on any type of entrance such as plotting the coefficient for various types of entrances so one can determine the entrance which gives the lowest coefficient? As a previous discusser brought out, there are actually only two ways of decreasing or combatting infiltration. One is changing the entrance and the other is by increasing the net supply of air.

The second question is this. In any of these buildings was there any attempt at building up a positive pressure in the building by static-pressure-regulating the exhaust and supply fans?

Other questions I have are in regard to elevators. What type of elevators were there? How many were there? Did they have sealed doors?

Another question is in regard to the type of building—whether of masonry construction, 8-in. blocks or 4-in. brick or plaster, or what was the type of building construction.

Also in the equation, an area is shown. Is that area based on the total area of the door opening or is it based on the angular area, when the door is opened at a certain percentage angle?

E. C. MILES†, Pittsburgh, Penna.: I want to ask why the tightness of the building is not indicated as one of the important factors affecting the amount of infiltration, since it would appear that if a building were tight enough there wouldn't be any infiltration—no matter how tall, or how much updraft there might be.

AUTHOR'S CLOSURE: In answering Mr. Gilkey and Mr. Wilson's questions, it must first be said that it is most fortunate that this project has such a fine group on the Technical Advisory Committee who are not only able and experienced but also active and helpful. Several of the members are pioneers in the field of infiltration. This work represents, indeed, a joint effort.

As pointed out by Mr. Gilkey, this paper does not include information as to the proportion of the infiltration from other parts of the building. There are many problems in air infiltration. The paper, as its title implies, deals only with winter infiltration through swinging-door entrances in multi-story buildings. The investigation of many other problems such as infiltration at various levels of the building, infiltration through revolving-door entrances, entrance exfiltration under summer cooling conditions, and infiltration through various modern types of windows, is either being planned or being considered by the Technical Advisory Committee on Heating and Air-Conditioning Loads.

Mr. Wilson asks to what extent the entrance coefficients obtained under winter heating conditions might be applicable to summer cooling conditions. In the *wind tunnel* with scale-model entrances, it was found that flow coefficients for swinging-door entrances under summer cooling conditions are essentially the same as those under winter heating conditions. This was mentioned in the progress report to the Director of Research, ASHAE Research Laboratory, for the month of August, 1957. It should be noted, however, that whether the assumed complete reversed condition would exist awaits experimental verification. To be more specific, it means that the entrance coefficients shown in Figs. 11 and 12 in the text can be applicable to both winter heating and summer cooling conditions, but the natural draft factor and forced draft factors

† Pittsburgh Plate Glass Company.

shown in Figs. 5 and 6 may be applicable in one but not in other conditions. This was mentioned in research on infiltration in residences done at the University of Illinois†. In other words, infiltration through entrances of summer air-conditioned tall buildings may not be evaluated by the data presented in this paper.

All are aware of the fact that the leakage of the cooled air is more costly than that of the warmed air, and it is desirable that further work under summer cooling conditions be encouraged and carried out. Also, in order to better understand the characteristics of infiltration, information on pressure differences across exterior walls of buildings at various levels is greatly needed.

In regard to Mr. Parsons' discussion concerning the effectiveness of the *air curtain* in reducing infiltration, the author is inclined to think that the air curtain would be applicable only to low buildings wherein the pressure differentials existing across the entrances are small. In order to overcome big pressure differentials and high velocity of infiltration air in tall buildings, *air jet* should be provided instead of air curtain. This obviously would be objectionable to passers-by. Mr. Parsons also suggested that more work should be done on the effect of wind upon the pressure differential in isolated buildings. Observations so far have shown that wind velocity at the street level is small‡*. In one of the field tests on a building located at the bank of a river, the observed pressure differentials across the entrance at street level showed little difference with appreciable wind and with relatively no wind. Mr. Parsons also is interested in knowing about the effect of pressurizing the building in eliminating infiltration at the entrance. The effect of blower action on the pressure difference is shown in Fig. 6 of the text.

The author agrees with Professor Bahnfleth that at least 3 things could be done to control the entrance infiltration, *i.e.*,

1. sealing the entrance by using proper type of entrance doors provided it is economically and environmentally feasible;
2. reducing the pressure differential across the entrance by pressurizing the structure with ventilation air; and
3. reducing the pressure differential across the entrance by sealing or tightening other parts of the building envelope.

The author also feels that additional field tests on draft factors for newer types of structures (presumably tighter than average buildings) are very desirable and should be encouraged.

The author appreciates the remark made by Mr. Miles that tightness of the building is also an important factor affecting the entrance infiltration. It is correct that there should be no infiltration across entrances in buildings no matter how tall they are so long as their envelopes are *100% tight or sealproof*. The paper showed that a great many conventional buildings tested, which apparently are not 100% tight, have a natural draft factor of 0.7. It also is mentioned that a presumably tighter-than-average building has a lower draft factor, but data are far from enough for quantitative correlation. In acknowledging his discussion, I would like to add to the second conclusion of the paper that the most important variables determining the infiltration rate through building entrances are (a) building height (b) indoor-outdoor temperature difference (c) the quantity of air supplied and/or exhausted (d) traffic rate (e) type of building entrance and (f) tightness of building envelope. I believe that Mr. Miles would agree that until information on the criteria of tightness of building envelope and on the draft factors for buildings with various degrees of tightness is available, the last factor is only a qualitative statement, not quantitative.

† ASHAE RESEARCH REPORT No. 1615—Measurement of Infiltration in Two Residences, Part II—Comparison of Variables Affecting Infiltration, by D. R. Bahnfleth, T. D. Moseley and W. S. Harris (ASHAE TRANSACTIONS, Vol. 63, 1957, p. 455).

‡ ASHAE RESEARCH REPORT No. 1615—Measurement of Infiltration in Two Residences, Part II—Comparison of Variables Affecting Infiltration, by D. R. Bahnfleth, T. D. Moseley and W. S. Harris (ASHAE TRANSACTIONS, Vol 63, 1957, p. 460, 467, 475, 476).

* Heat Requirements of Snow Melting Systems, by W. P. Chapman and Samuel Katunich (ASHAE TRANSACTIONS, Vol. 62, 1956, p. 370, 371).

Regarding Mr. Ratai's inquiry about the flow coefficients, only those of the typical arrangements as shown in Fig. 7 of the text were calculated. Actually, with the aid of Figs. A-1, B-1, and B-2 in the Appendix, the flow coefficients of entrances with any door arrangement can be determined. However, this would not be necessary, as Figs. 11 and 12 show that the entrance coefficients for manually-operated single-bank and vestibule entrances of various arrangements do not differ appreciably for a given traffic rate, no matter how different are the traffic patterns. His other questions are concerned with the basis of the infiltration rates and construction details of the buildings. Infiltration rates shown in Fig. 13 was based on a 3- x 7-ft door area, *i.e.*, 21 sq. ft. No attempt was made to survey the construction details of the buildings in this investigation.

In closing, the author wishes to thank each of the discussers for his interest and remarks. These remarks significantly increase the value of the paper. The author is indebted to Alabama Polytechnic Institute for making this presentation possible and especially to Professor P. J. Potter for his encouragement.