THE AIRTIGHTNESS OF OFFICE-BUILDING ENVELOPES

A.K. Persily, Ph.D.
ASHRAE Associate Member

R.A. Grot, Ph.D.

ABSTRACT

Although airtightness, infiltration, and ventilation are important considerations in large office buildings, these issues have been studied less in office buildings than in residential buildings. Several features of office buildings make their air exchange characteristics different from homes. These features include curtain wall design and construction, mechanical ventilation systems, specific occupancy patterns, large volumes and building heights, and low surface to volume ratios. The recent development of measuring procedures and computer simulation programs for large buildings has enabled the study of air leakage in large buildings and the effects of air exchange on energy use and indoor air quality.

This paper discusses the airtightness of building envelopes in modern office buildings and the relationship between envelope airtightness and air exchange rates. Results of whole building pressurization measurements and tracer gas measurements of air exchange rates in several office buildings are discussed, along with the relationship between these measurement results. A multizone computer simulation program developed at the National Bureau of Standards is applied to two office buildings to examine this relationship further. The results of the simulations reveal the importance of envelope airtightness, floor-to-floor coupling, and mechanical ventilation to the air change rates in these two buildings.

INTRODUCTION

While there has been much research on the airtightness of single-family residential buildings, the issues of envelope airtightness, infiltration, and ventilation in large buildings have received comparatively little attention until recently. As in homes, airtightness studies of large buildings have included whole building and component pressurization testing [Persily and Grot 1984; Tamura and Shaw 1976], tracer gas measurement of ventilation and infiltration rates [Grot and Persily 1984; Hunt and Treado 1979; Persily and Grot 1985], and computer modeling of building airflows [Shaw and Tamura 1977; Tamura and Wilson 1967b; Walton 1983 and 1984]. Much of the research done in homes has examined the relationship between envelope airtightness, as measured by whole building pressurization testing, and naturally induced air exchange rates. The relationship between airtightness and air exchange is also of interest in large buildings, but there are several factors unique to large buildings that affect this relationship. In this paper, the relationship between envelope airtightness and rates of infiltration and ventilation are discussed for large, modern office buildings.

Modern office buildings differ from homes in several important respects with regard to airtightness and air movement. First, office buildings have mechanical ventilation systems to bring in outside air, exhaust interior air, and distribute conditioned air. Air exchange in homes is generally due to uncontrolled airflow through openings in the building envelope and natural ventilation through open windows. Air distribution in homes is accomplished by

Andrew K. Persily is a mechanical engineer and Richard A. Grot is a group leader at the Center for Building Technology at the National Bureau of Standards

natural convection, except when forced air distribution systems are in operation. In addition, there is generally little resistance to airflow between the separate floors of a home. The airflow resistance between office building floors is more complex, being strongly affected by the existence of vertical shafts within the building, such as stair and elevator shafts. Office buildings also have lower surface to volume ratios than homes, as well as different envelope designs. These factors tend to make the relationship between building envelope airtightness and air exchange rates more complex in large office buildings than in homes.

The recent development and application of techniques for measuring airtightness and air exchange in large buildings has enabled the study of large building infiltration issues. Multicell models of building airflow have been developed and are also useful for analyzing office building air exchange [Etheridge and Alexander 1980; de Gids 1977; Irving 1979; Jackman 1970; Larsen 1977; Sander 1974; Walton 1983 and 1984]. In this paper, past measurements of envelope airtightness and air exchange rates are presented in order to discuss the relationship between their values. Previous computer modeling of air leakage in large office buildings is also discussed. A multizone, computer simulation program developed at the National Bureau of Standards (NBS) is used to investigate the importance of several variables associated with office building air exchange. The modeling results are related to air exchange measurements in two office buildings.

WHOLE BUILDING PRESSURIZATION AND TRACER GAS MEASUREMENTS

Compared to the large number of homes that have been pressure tested, only a small number of office buildings have been subjected to whole building pressurization tests. These measurements involve forcing air into or out of the building interior to maintain a specific pressure difference between inside and outside. The airflow rates Q necessary to maintain the pressure differences Δp are measured and the data are fitted to a curve of the form

$$Q = C \Delta p^n, \tag{1}$$

where C and n are constants referred to as the flow coefficient and flow exponent respectively. To obtain a measure of a building's envelope airtightness, one evaluates Equation 1 at a particular reference pressure difference.

The results of whole building pressurization measurements on several modern office buildings are presented in Table 1. The first seven buildings are federal office buildings tested previously by NBS [Persily and Grot 1984], while the eighth building is a private office building tested more recently by NBS. In order to account for differences in building size, the airflow rate required to maintain an inside-outside pressure difference of 0.1 in H_2O (25 Pa) is divided by the building volume to yield air changes per hour and by the building exterior surface area to yield cfm/ft^2 (m^3/h·m^2). Air changes per hour at 0.1 in H_2O (25 Pa) are related to the actual air exchange rate of the building, while the airflow rate per unit surface area is a measure of construction quality. The results in air changes per hour are quite low compared to those measured in most U.S. homes; however, the surface to volume ratios of these buildings are about one-third the values for homes. In units of airflow rate per unit surface area these buildings are as leaky as typical U.S. homes, in spite of the fact that very different envelope construction techniques are used in homes and office buildings.

The NRC buildings in Table 1 are Canadian office buildings studied by the National Research Council (NRC) of Canada and the results are given only in units of airflow rate per unit wall area [Tamura and Shaw 1976a]. The normalization of the NRC data does not include the building roof area, but for the tall buildings involved in their study, the inclusion of the roof is only a small correction. It is interesting to note that the NRC buildings, built roughly ten years earlier than the buildings studied by NBS, are quite similar in airtightness to the NBS results.

The NBS studies also included tracer gas decay measurements of infiltration and ventilation [Grot and Persily 1984]. Infiltration refers to measurements made with the air handlers operating in order to mix the tracer gas but with no intentional outside air intake, i.e., the intake and exhaust dampers were in their closed position. The fan operation during the decay tests may affect the results due to air leakage induced by local pressurization and depressurization within the building, or through leakage across the closed intake and exhaust dampers. In several buildings these dampers have been sealed with polyethylene film, and the infiltration rates were no different than those measured without the dampers sealed. The ventilation rates are measured under occupied conditions with the air handlers operating normally and the system bringing in outside air as the control system dictates. These infiltration and ventilation rates are associated with a measurement error of about 10%.

In this paper, infiltration and ventilation rates for two office buildings are discussed in detail. The two buildings, located in Pittsfield, MA and Columbia, SC, are described in Table 2. The measured infiltration rates of these buildings are plotted against the inside-outside temperature difference in Figures 3 and 4. The data are summarized in Table 3. The values in the first row of Table 3 are the average, measured infiltration rates for each building for inside-outside temperature differences from 36 to 54 F (20 to 30 ^{o}C) and wind speeds from 0 to 4.5 mph (0 to 2 m/s). The standard deviations of these measured infiltration rates are given in parentheses. The second row is the slope of infiltration against temperature difference, based on least squares linear regression of the data. The Pittsfield building exhibits little dependence of infiltration on temperature difference, in fact the slope is slightly negative. The Columbia infiltration data exhibit a positive correlation with temperature difference. These measured temperature difference slopes are subject to large uncertainties, as indicated by the estimated variance of their slopes given in the table. Neither building's data revealed an effect of wind speed or direction on the infiltration rate. The last row of the table contains the average measured ventilation rate for each building for temperature differences between 36 and 54 F (20 and 30 ^{o}C). These are the ventilation rates with the air handling system operating at its minimum outside air intake setting.

Whole building pressurization is a relatively quick means of evaluating a building's airtightness, compared to conducting tracer gas measurements of air exchange rates over a range of weather conditions. Pressurization provides a single value to characterize a building's airtightness that is useful for comparison to other buildings or to airtightness standards. However, it is the actual air exchange rates of a building, along with other factors, that determine its energy consumption and indoor air quality, and it is therefore desirable to relate pressurization test results to a building's infiltration and ventilation rates. While much work on the pressurization-infiltration relationship has been done for homes, only a relatively small amount has been done in large buildings. For large buildings it is desirable to predict both the air infiltration rates induced by the weather and the ventilation rates with the air handling system operating and bringing in outside air to satisfy the building's outside air requirements.

PHYSICAL MODELS OF LARGE BUILDINGS

In order to relate envelope airtightness to air exchange rates in large buildings, it is necessary to employ physical models of the building that incorporate the important features of these buildings. One such feature is the airflow resistance between floors. Research at the NRC of Canada [Tamura and Wilson 1967a and 1967b] revealed the importance of building height and airflow resistance between floors in determining the infiltration rate of a building induced by inside-outside temperature differences. Figure 1 is a schematic of a multistory building that contains an open, vertical shaft extending through the entire building height. Such a shaft can represent a stair, return air, or an elevator shaft, with potentially several of each existing in any given building. There are airflow paths between each floor and the outside A_e, directly between floors A_f, and from each floor to the vertical shaft A_s. The values of A_e, A_f, and A_s may vary among floors and shafts, and there may be additional openings at the tops of shafts. Tamura and Wilson [1967b] made analytical calculations to demonstrate the effect of the ratios A_f/A_e and A_s/A_e, and the building height, on the vertical distribution of inside-outside pressure differences. They found that for values of A_s/A_e greater than or equal to 2.0, the building behaves quite similarly to a single zone in terms of the stack or chimney effect. Openings in the floors, represented by A_f, are less effective in providing vertical communication between floors and become even less effective as the building height increases.

In order to develop a physical model of an office building, one must have values of the exterior envelope leakage areas, the leakage areas between floors, and the leakage areas from each floor to the various vertical shafts within the building. The leakage areas of the exterior walls can be obtained by the whole building pressurization tests discussed earlier, though the net leakage area from these tests must be distributed among the floors and the sides of the building. As a first approximation, one may assume that the leakage is uniformly distributed over the exterior surface. If additional detail on the leakage distribution is available, this will improve the model. The leakage areas associated with openings between the various interior spaces can be more difficult to obtain. Measurements made by researchers at the NRC of Canada [Tamura and Shaw 1976b] provide data for the leakage associated with elevator shaft walls, elevator doors, openings at the top of elevator shafts, stair shaft walls, and stair shaft doors. They also have obtained data on leakage areas between floors [Tamura and Shaw 1978], as well as the exterior wall leakage data referred to earlier [Tamura and Shaw 1976a]. These data, along with on-site measurements of leakage areas in a building, can be used in a model of the air exchange between the interior zones of a building and the outside.

Developing a model of a large building also requires consideration of any existing return air shafts through which interior air flows back to the air handling system, either to be exhausted to the outside or recirculated by the supply system. Several such return shafts may exist in any given building and extend over almost the entire building height. These shafts connect to each floor through large return air grilles that open into ceiling return plenums. These plenums are separated from the occupied space by suspended ceilings that contain return air inlets and other openings. The return air system generally provides a great deal of floor-to-floor communication when the air handling system is off, due to the large leakage areas associated with the suspended ceilings and the large return air grilles connecting the ceiling plenums to the return air shafts.

The leakage areas from the plenums to the shafts can be determined from visual inspection or from the building plans. The leakage areas associated with suspended ceilings are more difficult to determine, since they include more than just the return air openings. Based on a recommendation for average return inlet velocities of 800 fpm (4 m/s) [ASHRAE 1985], an assumed room air change rate of 4.0 per hour, and a 13 ft (4 m) ceiling, one obtains a ratio of return inlet opening area to suspended ceiling area of 0.1%. There are additional openings in the suspended ceiling including those associated with light fixtures and the ceiling tile grid. Thus, the ceiling leakage ratio can be larger than 0.1%. Rather than the percent of open area in the suspended ceiling, designers often consider the pressure difference across the suspended ceiling when the air handling system is operating. The maximum design pressure difference is typically between 0.02 and 0.05 in H_2O (5.0 and 12.5 Pa). Pressure differences from about 0.001 to 0.01 in H_2O (0.25 to 2.5 Pa) are considered to be more typical. By running a computer simulation of the building model and examining the calculated pressure differences across the suspended ceiling, one can determine if one's assumption for the percentage of open area is reasonable. A measurement of the pressure difference across the suspended ceiling will provide a value for comparison to the computer predictions.

Finally, an office building model needs to consider mechanical ventilation, and therefore the supply and return airflow rates must be input to the model. When measured values of these airflow rates are not available, one can use the design specifications of the building's mechanical equipment. These specifications of the supply and return airflow rates are generally on the order of 4.0 air changes per hour, with lower airflow rates occuring at times in variable air volume systems. Air handler operation may be modeled as an airflow into the occupied space and an airflow out of the return air system. To model intentional outside air intake, one increases the supply airflow rate relative to the return airflow rate by an appropriate amount. A common rule of thumb for minimum outside air intake levels is that the supply airflow rate should be 10% larger than the return airflow rate, corresponding to a ventilation rate of about 0.4 air changes per hour. The net building air exchange rate under these conditions will be larger than 0.4 due to uncontrolled air leakage through the building envelope. The amount of additional envelope leakage depends on the envelope airtightness, the airflow resistance between floors, the building height, and the leakage area of the suspended ceiling. The effect of these factors on air leakage associated with air handler operation is discussed below. The effect of air handler operation on inside-outside pressure differences, and building air exchange, also depends on the balancing of the supply and return airflow rates. The actual ratio of these two airflow rates can be quite different from the design value, leading to additional envelope air leakage. This ratio can also vary among the floors of a building, leading to complex and perhaps undesirable pressure differences and airflow patterns within a building.

Based on a combination of measurements, visual inspection of a building and its plans, and data from the literature, one can develop a physical model of a building. A computer simulation of the internal air movement and air exchange with the outdoors can then be applied to this model of a building. Such a simulation requires interior and exterior temperatures, the wind speed and direction, and a relation between the wind and the pressure on the building's exterior surface. This latter relation is probably the most uncertain aspect of such a simluation.

Tamura and Wilson [1967a and 1967b] conducted such simulations, as well as measurements of pressure differences across exterior walls and interior partitions, in tall office buildings. Both the simulations and measurements revealed that when the air handlers are off, ventilation shafts constitute a significant mechanism for airflow between floors. Their pressure difference measurements in three tall buildings revealed that the stack pressures were very close to those expected in a structure with no airflow resistance between the floors. Tamura and Wilson also examined the effect of building air handler operation on stack pressures. Neglecting the suspended ceiling, they modeled the effect of various pressurization strategies for controlling the magnitude of the pressure difference at ground level entrances. In measurements of the three tall buildings mentioned earlier, they found a higher resistance to airflow between floors with the air handling system on, presumably because the return shaft no longer served as a connection between floors. They also noted considerable variation in the effects of ventilation system operation on the inside-outside pressure differences among the buildings and among the floors of the same building. This variation is due to differing imbalances of the supply and return airflow for the individual floors of a building.

PREDICTING INFILTRATION IN LARGE BUILDINGS

There are several techniques for relating envelope airtightness to actual infiltration and ventilation rates in office buildings, including the following: direct correlations between measured values of airtightness and measured air exchange rates; simple empirical relations between airtightness, air exchange rates and weather conditions; physical models that treat the building as a single zone; and computer simulations employing detailed physical models that consider the factors outlined in the previous section. Examples of these relations are discussed below with reference to the results of the NBS measurements discussed earlier. The latter two techniques are discussed in detail.

The first approach to predicting infiltration rates from pressurization test results is a direct comparison between the two quantities, as shown in Figure 2. Figure 2 is a plot of measured infiltration rates in eight buildings studied by NBS, averaged over specific weather conditions, versus the specific airflow rate at 0.1 in H_2O (25 Pa) from the building pressurization tests. Both quantities are in units of air changes per hour. The scatter in this plot is similar in magnitude to that observed for homes. The correlation in Figure 2 does not include the dependence of infiltration on weather conditions and does not allow one to consider the effects of air handler operation on infiltration rates.

These airtightness and infiltration data were also analyzed using empirical expressions that include the inside-outside temperature difference ΔT and the wind speed u [Grot and Persily 1984]. A variety of relationships between infiltration I, the airflow rate at 0.1 in H_2O (25 Pa) from the pressurization tests Q_p, ΔT, and u were considered. These relationships were of the following general form,

$$I = Q_p \; (\; C_1 u^x + C_2 \Delta T + C_3 u^x \Delta T \;)^m \qquad (2)$$

C_1, C_2, and C_3 are empirical constants obtained by least squares linear regression of the measured data. In some cases C_3 was set equal to zero. The wind exponent x was set equal to either 1.0 or 2.0, and the flow exponent m was assumed to be either 1.0, 0.65, or 0.5. The data obtained by NBS for the first 7 buildings in Table 1 were fitted to six different empirical expressions. The correlations obtained with these empirical expressions are stronger than those in Figure 2, but these equations do not allow for consideration of the physical characteristics of the building or of mechanical ventilation.

The following two approaches to predicting large building air exchange are based on a more physical basis. The first of these approaches treats the building as a single zone and employs simple expressions for calculating infiltration rates. Alternately, one employs a multizone model of a building and computes air exchange rates by directly solving the mass balance equation for the individual zones.

The Shaw-Tamura model [1977] is an example of a calculation method that models the building as a single zone. It has separate predictive equations for wind- and stack-induced infiltration, which were developed from computer studies of a model building and wind tunnel tests of a model of a 40-story building. Both the wind and stack expressions utilize the constants C and n of Equation 1, which may be obtained from whole building pressurization tests, to characterize the building envelope airtightness. The wind expression uses a single wind pressure coefficient for the windward wall and a correction factor to account for wind directions other than normal to the longest building wall. The stack expression requires two inputs; the ratio of the neutral pressure level to the building height and the thermal draft coefficient. The thermal draft coefficient characterizes the extent of resistance to vertical airflow within the building. It can vary from a value of 0.0, corresponding to no communication between floors, to a value of 1.0, corresponding to a totally open interior. While there is no straightforward technique for determining the appropriate value of the thermal draft coeffícent for a building, Shaw and Tamura suggest a value of 0.80 for office buildings. Based on the values of the inside and outside air temperatures, and the wind speed and direction, one evaluates the wind-and stack-induced infiltration rates. These two infiltration rates are combined to yield the net infiltration rate using a separate expression. The Shaw-Tamura model can predict weather induced infiltration, but it does not allow one to include mechanical ventilation. Other single-zone approaches exist, and they all require the user to input several parameters that characterize the building. These parameters are difficult to determine for any given building and have significant effects on the predicted infiltration rates.

Walton's [1983 and 1984] mass balance algorithm allows one to model the building as several individual zones, which exchange air with each other and with the outdoors. A simultaneous solution of the mass balances in all the zones, based on a slightly modified Newton's method, is used to calculate all interzone airflows and the air exchange rate between each zone and the outdoors. For each opening between zones or to the outside, the user must input the leakage area A, the flow exponent n, and the discharge coefficient C_D. These parameters are used to calculate the airflow q through the opening according to

$$q = C_D\, A\, \sqrt{2/\rho}\, (\Delta p)^n \tag{3}$$

Δp is the pressure difference across the opening and ρ is the air density. The zones of a building may include occupied spaces on individual floors, plenum spaces on the same floors, stair shafts, elevator shafts, and return air shafts. One must characterize the openings of these zones to each other and to the outside using the parameters in Equation 3. Using the leakage data described earlier and the results of building pressurization tests, one develops a fairly detailed model of a building. The algorithm also allows for the imposition of supply and/or exhaust airflows on any given zone. This algorithm can be run on a personal computer and requires only a small amount of time to determine a solution, even for very complex representations of a building. For example, a 40-zone model with about 500 openings requires less than a minute to obtain a solution for each case of weather conditions. A listing of the program is given in Walton [1983]. Other multizone, mass balance approaches exist, and they all require a complete description of all the openings in the building model. Such multizone computer simulation programs are useful for studying contaminant migration within buildings and evaluating smoke control systems, along with other important issues in large building air movement and air exchange.

Several calculation methods, of both the single zone and multizone types, are available. The single-zone approaches involve simple expressions that provide quick, and in some cases, sufficiently accurate results. Current microprocessors have made the time advantage of single-zone approaches over complete mass balance algorithms almost negligible. The multizone algorithms are practical to employ, allow more realistic physical models of a building, provide detailed information in the results, and enable the parametric study of the numerous factors that affect large building air exchange.

AIR EXCHANGE MODELING RESULTS

Both the Shaw-Tamura model and Walton's mass balance algorithm were applied to the Pittsfield and Columbia buildings, described in Table 2. The Pittsfield building has a separate air handler for each floor, thus there is no return air shaft connecting the two floors. The Columbia building has five separate return air shafts that run from the second and third floor to various higher floors. The Columbia building is modeled with vents at the top of the elevator shafts, while the Pittsfield building model includes no such vents.

Shaw-Tamura Predictions

Infiltration rates for the two buildings were predicted first with the single-zone, Shaw-Tamura approach described earlier [Shaw and Tamura 1977]. In these calculations the neutral pressure level was assumed to be one-half of the building height and the thermal draft coefficient was set at 0.8 for both buildings. The flow exponent n was set equal to 0.65 and the value of the flow coefficient C was based on the 0.1 in H_2O (25 Pa) airflow rate from the pressurization tests. The predicted infiltration rates for the Columbia building are plotted in Figure 5. These results are representative of all the infiltration predictions made as part of this study. For large values of the wind speed, the effect of temperature difference on infiltration is weak at low values of ΔT. The larger the wind speed, the higher the temperature difference at which the temperature effect manifests itself. The temperature difference slope approaches the same constant value for large ΔT, regardless of the wind speed. As expected, the wind speed effect is stronger for the lower wind speeds at the smaller values of ΔT. The predicted infiltration rates for all buildings will be similar to those shown in Figure 5 with significant variation in the slopes and in the values of u and ΔT at which there are transitions between wind-dominated infiltration and stack-dominated infiltration.

The Shaw-Tamura predictions for the two buildings are summarized in Table 4. The wind slope is the average slope of infiltration versus wind speed between 4.5 and 22.0 mph (2 and 10 m/s) at a temperature difference of 9 F (5 $^{\circ}C$). The temperature difference slopes are calculated for each of the two wind speeds shown for temperature differences from 18 to 54 F (10 to 30 $^{\circ}C$). The table also shows the predicted infiltration rate for a temperature difference of 45 F (25 $^{\circ}C$) and zero wind speed. Comparing the data in Tables 3 and 4, we see that the predicted infiltration rates are lower than the measured rates. The model predicts a significant dependence of infiltration on wind speed that was not observed in either of the two buildings. The lack of an observed wind dependence may be due in part to the existence of only limited infiltration measurements at elevated wind speeds. Also, during the infiltration measurements, the wind speed was measured about 20 ft (6 m) above the building roof, which is not representative of ambient wind conditions. The model assumes that the wind speed input is a freestream value under identical terrain conditions as the building's. Thus, the relation between the wind speeds used in the predictions and the measured wind speeds is not clear and may explain in part the lack of an observed dependence of infiltration on wind speed. The predicted temperature difference slopes in Table 4 are close to the measured values in Table 3 for Columbia, but not for Pittsfield.

Mass Balance Predictions - Pittsfield

The air exchange rates for the two buildings were predicted using the mass balance algorithm of Walton [1983 and 1984]. Since this algorithm allows a more complete and realistic model of the building than a single zone approach, the rates were predicted for several different cases allowing a parametric study of several factors related to large building air exchange.

A schematic of the Pittsfield building is given in Figure 6 and depicts the physical model used for the building. The figure includes both an overhead view and a side view of the Pittsfield building. This building has three vertical shafts that extend the entire building height, i.e., two stair shafts and an elevator shaft, as shown in the figure. Each floor is divided horizontally into the occupied space and the plenum space as shown in the side view. There are doors from each of the three vertical shafts into the office space, and there is shaft wall leakage from each shaft to both the office space and the plenum space. Openings in the suspended ceiling are depicted as return inlets, although there are other openings as well. The office and plenum spaces are assumed to be totally open on each floor, i.e., there are no significant obstructions to airflow within these spaces. The interior opening leakage areas are based on the data of Tamura and Shaw [1976b]. The exterior wall leakage areas are based on the results of the whole building pressurization test, and this leakage is assumed to be evenly distributed over the building envelope with six openings per wall. Two of the exterior wall openings are located in the plenum spaces. In the calculations there are seven zones and 39 openings between the zones and the outside. All openings are assumed to have a flow exponent n of 0.65 and the leakage areas are based on a pressure difference of 0.1 in H_2O (25 Pa).

The Pittsfield air exchange rates were predicted for several different cases. The predictions were made first with the building treated as a single zone, i.e., with no interior obstructions to airflow and no mechanical ventilation. All other cases were analyzed for three different modes of air handler operation. The rates were calculated with the air handlers off, with an airflow equivalent to 4.0 air changes per hour into the occupied space and 4.0 air changes per hour out of the return plenums, and with 4.4 air changes per hour (10% oversupply) into the occupied space and 4.0 out of the return plenums. The second case corresponds to the conditions under which the tracer gas measurements of infiltration were conducted. The third case corresponds to the building being ventilated with a minimum amount of outside air intake. The air handling system and the ductwork were not modeled explicitly. In the Pittsfield building, the supply and return airflows were simply imposed on the occupied space and plenum space of each floor respectively.

The opening areas between the vertical shafts and the building interior were based on the data of Tamura and Shaw [1976b]. Their data cover a wide range of values for the leakage of stair and elevator doors and shaft walls. Leakage values in the middle of their range of measurements were used in the so-called "nominal" predictions shown in Table 5. The air exchange rates were also predicted for leakage values that are at the low and high ends of Tamura and Shaw's measurements, although these predictions are not shown. The nominal value of the leakage area of the suspended ceiling was assumed to be 0.2%, twice the value based on ASHRAE's [1985] recommendation for return inlet velocities in order to account for additional ceiling leakage sites. The percent ceiling leakage refers to the opening area in the suspended ceiling as a percent of the total ceiling, or floor, area. The air change rates were also predicted for ceiling leakage values of 0.1% and 0.3% of the ceiling area. In addition, the air change rates were calculated for cases in which the envelope tightness was set equal to one-half of the measured value and in which the envelope was made 50% leakier than measured. In all, 22 different cases were run for 36 different weather conditions. The temperature differences in the predictions ranged from 9 to 54 F (5 to 30 °C) in 9 F (5 °C) increments. The wind speeds ranged from 0 to 22.4 mph (0 to 10 m/s) in 4.5 mph (2 m/s) increments.

The results of the Pittsfield predictions for the nominal cases are summarized in Table 5. The first column is the slope of the predicted air exchange rate versus wind speed, calculated at a temperature difference of 9 F (5 °C) and for wind speeds from 4.5 to 22.4 mph (2 to 10 m/s). The next two columns are temperature difference slopes calculated at the two wind speeds shown for temperature differences from 18 to 54 F (10 to 30 °C). The fourth column is the predicted infiltration rate for a temperature difference of 45 F (25 °C) and zero wind speed. The last column is the predicted pressure difference across the suspended ceiling. Its value is not given for cases in which the air handlers are not operating because in these cases it is very small. In the following discussion for Pittsfield, as well as the subsequent discussion for the Columbia building, the wind speed slope is not examined since there is no measured value for comparison. Also, its value is extremely sensitive to one's assumptions regarding the relation between wind speed and the pressure induced on the building's exterior surface.

The first case listed in Table 5 models the building as a single zone with no interior obstructions to airflow. The temperature difference slope is greater than that predicted using the Shaw-Tamura approach (Table 4), and the slope decreases less rapidly with wind speed than the Shaw-Tamura predictions. Both predicted slopes are larger than the measured value of -0.0029. The predicted infiltration rate of 0.17 is closer to the measured value of 0.26 than the Shaw-Tamura prediction (0.08). The predictions for the three nominal cases model the building as seven zones and include the three subcases of air handlers (fans) off, balanced ventilation at four air changes per hour, and 10% oversupply. Predictions with the fans off are similar to the single zone case, except that both the temperature difference slopes and the predicted infiltration rate at 45 F (25 °C) temperature difference are smaller, presumably due to the airflow resistance between floors.

When the air handlers are turned on in the balanced ventilation mode, the temperature difference dependence of the Pittsfield air exchange rates is reduced significantly, in fact, it is almost eliminated. This is because the supply airflow pressurizes the occupied space below the suspended ceiling and the return airflow depressurizes the plenum space. These system pressures tend to counteract the stack effect, which is relatively weak in this 2-story building. Since the fan operation works against the natural stack effect, the infiltration rate at a temperature difference of 45 F (25 °C) is also reduced. The predicted pressure drop across the ceiling is 0.017 in H_2O (4.3 Pa), which is just below the range of design maximums of 0.02 to 0.05 in H_2O (5 to 12.5 Pa). Whether this predicted pressure difference is unrealistically high is not clear without on-site measurements. For the 10% oversupply case, the predicted air exchange rate listed includes only the envelope infiltration in addition to the 10% oversupply (0.37 exchanges per hour), which equals zero in Table 5. The 10% oversupply corresponds to 0.37 air changes per hour instead of 0.4 because of differences in the volumes of the ventilated space and the whole building. For higher values of wind speed, this additional infiltration becomes significant. The net air exchange rate for the 10% oversupply case is equal to 0.37 exchanges per hour, which is very close to the measured value of 0.38 in Table 3. The value in Table 5 is based on assumed, not measured, values of the airflow rate through the ventilation system and the percent of outside air intake.

The effects of a tighter or leakier building envelope and the effects of varying the suspended ceiling leakage area in the Pittsfield building are shown in the predictions given in Table 6. The tight envelope case corresponds to envelope leakage areas equal to one-half of the measured values, and the leaky case corresponds to 1.5 times the measured leakage area. The tight envelope cases show that as the envelope is tightened, the air exchange rates and the weather dependence of these rates are reduced. These results reveal that it is easier to control ventilation in a tight building than in a leaky one. The leaky envelope predictions exhibit larger infiltration rates and a stronger weather dependence. The predicted infiltration rates are seen to be approximately linear with exterior envelope leakage area.

By tightening the suspended ceiling to 0.1%, the temperature difference slope is reduced relative to the nominal case, in fact it becomes negative as was measured. When the suspended ceiling leakage is 0.1%, the air exchange is dominated by the ventilation system pressurizing the occupied space and depressurizing the ceiling plenum. In this two-story building, the stack pressures are weak enough that the ventilation system induced pressures overpower the stack effect. As the temperature difference increases, the stack pressures compete with the ventilation system pressures, reducing the net pressure difference across the building envelope and the air exchange rate. Thus, the slope of infiltration versus temperature difference is negative. The predicted infiltration rate for the tight ceiling is also closer to the measured value. The pressure difference across the ceiling for this case is 0.045 in H_2O (11.3 Pa), which is quite large. Decreasing the ceiling leakage also increases the infiltration rate associated with the 10% oversupply case. Increasing the suspended ceiling leakage to 0.3% decreases the predicted infiltration rate slightly and increases the temperature difference slope for the balanced ventilation case relative to ceiling leakage of 0.2%. As the ceiling leakage increases, the infiltration moves from system pressure domination to stack pressure domination. In the 0.1% case, the infiltration is essentially system dominated. As the ceiling leakage increases towards 0.3%, the stack pressure counteracts the system pressure and the infiltration rate is reduced. As the ceiling leakage is increased further, the infiltration rate approaches the value obtained when the fans are off.

The Pittsfield mass balance predictions show that reasonable assumptions regarding interior leakage areas lead to predicted infiltration rates and temperature dependences that are close to the measured values. We also see that in a two-story building in which stack pressures are relatively weak, the system induced pressures have a significant effect on building air exchange. The pressure difference across the building envelope and the predicted infiltration are seen to depend strongly on the suspended ceiling leakage area when the air handlers are operating.

Mass Balance Predictions - Columbia

A schematic of the physical model used for the Columbia building is shown in Figure 7. This overhead view of a typical floor shows the ten separate vertical shafts in this building. There are three elevator shafts, all extending from the first to the fifteenth floor. Two of these shafts have three doors on each floor. There are two stair shafts that also run from the first to the fifteenth floor. The main return shaft, located within the central core of the building, extends from the second to the fifteenth floor and has two openings to the suspended ceiling plenum on each floor. There are also four smaller return shafts located in each corner of the building. Two of them run from the second to the fourteenth floor, while the other two start at the third floor. There are three exterior wall openings on each face of each floor, with one of the openings located in the ceiling plenum. In Columbia, the return shafts were modeled as separate zones with the total return airflow for each shaft imposed on that shaft. The supply airflows were imposed on the occupied space of each floor. In Columbia the pressure drop through the return shafts was not modelled, but the stack effect was included in these shafts. The computer program is being expanded to include more complex and realistic representations of mechanical ventilation systems including duct losses and fan curves. The building model is otherwise similar to the Pittsfield building model, except that in Columbia there are vents at the top of the each elevator shaft. The Columbia model contains 40 separate zones and about 500 openings.

Table 7 shows the results of the nominal mass balance algorithm predictions for Columbia. The first case models the building as a single, open zone with no interior obstructions to airflow. As in the case of Pittsfield, the multiple zone cases are analyzed with the air handlers off, a balanced ventilation rate of 4 air changes per hour, and 10% oversupply. The exchange rates were also predicted with the measured envelope tightness reduced by 50% and with two alternate values of the ceiling leakage, as shown in Table 8.

The single zone-case in Table 7 predicts the measured infiltration rate (0.34) at a temperature difference of 45 F (25 °C) better than the Shaw-Tamura model (0.16). The temperature difference slopes are larger than measured. The nominal case with fans off yields predictions that are very close to the single zone case. This is probably true because the Columbia building has significant means of airflow communication between floors, e.g., two elevator shafts with multiple doors and five return air shafts. When the air handlers are operated, the return air shafts no longer serve as a means of communication between floors, and the predicted infiltration rates and the temperature difference slopes are reduced slightly. We do not see the elimination of the temperature difference dependence in this building, when the air handlers are operating, that was predicted in Pittsfield. This is true because in this 15-story building the stack induced pressures are much larger than those in the two-story Pittsfield building. The plenum space depressurization and the occupied space pressurization caused by fan operation are not strong enough to counteract the stack effect. The 10% oversupply predictions show a strong temperature dependence that was not observed in the measured data. We see much larger values of the envelope air leakage under 10% oversupply in Columbia than in Pittsfield, presumably due to the large stack pressures in this tall building. The predicted infiltration rate (0.24) plus the intentional outside air intake rate (0.38) equals 0.62 exchanges per hour, which is exactly equal to the average measured ventilation rate in Table 3. Again, these predictions are based on ventilation system airflow rates and oversupply fractions from the building's mechanical equipment specifications, not on measured values of these quantities.

Considering the predictions in Table 8, we see that when the exterior envelope leakage is reduced by 50%, the weather dependence is reduced for all cases of air handler operation by about one-third. The predicted infiltration rates are reduced on the order of 50%. Tightening the suspended ceiling reduces the temperature dependence somewhat, but does not have the large effect predicted in Pittsfield. Again, this is because the combination of building height and the large amount of floor-to-floor communication cause a strong stack effect in the Columbia building. These factors may explain the success of the Shaw-Tamura model in predicting the temperature difference slope. Increasing the ceiling leakage area has almost no effect on the predictions, presumably because the building is already in a stack dominated regime in which the system pressures have no significant effect.

CONCLUSION

Using multizone models of large buildings to study their air exchange characteristics has revealed several interesting factors in large building air exchange. The importance of floor to floor airflow communication, either directly or via vertical shafts, has been shown to be quite important in large building air exchange. There are many pathways for such communication, particularly return air shafts, and the existence of such pathways can cause a building's air exchange characteristics to closely approximate those of a single, open zone. It does not require unusual numbers or sizes of shafts or openings to create these conditions.

Two buildings with very different characteristics were studied in detail. The Pittsfield building has only two stories and has minimal communication between floors. The Columbia building has 15 stories and has significant means of communication between the floors. Thus, the Pittsfield building is much less susceptible to the stack effect than the Columbia building. When the floor space is modeled as an occupied zone and a ceiling plenum space, the operation of the air handlers tends to counteract the stack effect. In the Pittsfield building the stack effect is weak enough for the fan operation to practically eliminate the dependence of infiltration on temperature difference. In the Columbia building, the stack effect is too strong for this to occur. For both buildings, the algorithm's predictions were quite close to the measured data.

These predictions of the multi-zone, mass balance algorithm have shown the value of this technique for studying large building envelope leakage and air movement. The ability to run the program on a micro-computer has enabled parametric analyses that have revealed several interesting effects. The predictions revealed a greater dependence of air change rates on weather in leaky buildings than in buildings with tight envelopes. The importance of mechanical ventilation and suspended ceiling leakage on air change rates has also been shown. In addition, the predicted air exchange rates were found to be linear with envelope airtightness.

REFERENCES

ASHRAE. 1985. ASHRAE handbook - 1985 Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1981. ASTM E 779-81, "Standard practice for measuring air leakage by the fan-pressurization method." American Society for Testing and Materials.

Etheridge, D.W., and Alexander, D.K. 1980. "The British Gas multi-cell model for calculating ventilation." ASHRAE Transactions, Vol.86, Part 2.

de Gids, W.F. 1977. "Calculation method for the natural ventilation of buildings." TNO Research Institute for Environmental Hygiene, Delft, Netherlands.

Grot, R.A., and Persily, A.K. 1984. "Air infiltration and ventilation measurements in large office buildings." ASTM Symposium on Measured Air Leakage Performance of Buildings, Philadelphia.

Hunt, C.M., and Treado, S.J. 1981. "Air exchange measurements in a high-rise office building," in proceedings of DOE/ASHRAE Conference, Thermal Performance of Exterior Envelopes of Buildings ASHRAE SP 28.

Irving, S.J. 1979. "The computer simulation of smoke movement during building fires." Fire Prevention Science and Technology, Vol.22.

Jackman, P.J. 1970. "A study of natural ventilation of tall office buildings." Institute of Heating and Ventilating Engineers, Vol.38.

Larsen, B.T. 1977. "Energy consumption of residential buildings. The computer program ENCORE. Part 1: User's manual and Part 2: Documentation." Norwegian Building Research Institute.

Persily, A.K., and Grot, R.A. 1984. "Pressurization testing of federal buildings." ASTM Symposium on Measured Air Leakage Performance of Buildings, Philadelphia.

Persily, A.K, and Grot, R.A. 1985. "Ventilation measurements in large office buildings." ASHRAE Transactions, Vol.91, Part 2.

Sander, D.M. 1974. "Fortran IV program to calculate air infiltration in buildings." Computer Program No.37, National Research Council of Canada, Division of Building Research.

Shaw, C.Y., and Tamura, G.T. 1977. "The calculation of air infiltration rates caused by wind and stack action for tall buildings." ASHRAE Transactions, Vol.83, Part 2.

Tamura, G.T., and Shaw, C.Y. 1976a. "Studies of exterior wall air tightness and air infiltration of tall buildings." ASHRAE Transactions, Vol.82, Part 1.

Tamura, G.T., and Shaw, C.Y. 1976b. "Air leakage data for the design of elevator and stair shaft pressurization systems." ASHRAE Transactions, Vol.82, Part 2.

Tamura, G.T., and Shaw, C.Y. 1978. "Experimental studies of mechanical venting for smoke control in tall office buildings." ASHRAE Transactions, Vol.86, Part 1.

Tamura, G.T. and Wilson, A.G. 1967a. "Pressure differences caused by chimney effect three high buildings." ASHRAE Transactions, Vol.73, Part 2.

Tamura, G.T. and Wilson, A.G. 1967b. "Building pressures caused by chimney action and mechanical ventilation," ASHRAE Transactions, Vol.73, Part 2.

Walton, G.N. 1984a. "A computer algorithm for estimating infiltration and inter-room air flows." NBSIR 83-2635, National Bureau of Standards.

Walton, G.N. 1984b. "A computer algorithm for predicting infiltration and interroom airflows." ASHRAE Transactions, Vol.90, Part 1.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of George N. Walton in conducting the mass balance computer simulations. This research was supported by the U.S. Department of Energy through an interagency agreement with the National Bureau of Standards.

TABLE 1
Whole Building Pressurization Test Results

Building	Year of Construction	Specific Airflow Rate at 0.1 in H_2O (25 Pa)		
		ach*	cfm/ft^2	($m^3/h \cdot m^2$)
Anchorage	1979	0.88	0.37	(6.7)
Ann Arbor	1977	0.86	0.23	(4.1)
Columbia	1979	0.67	0.33	(6.0)
Huron	1977	0.45	0.10	(1.9)
Norfolk	1979	1.36	0.40	(7.2)
Pittsfield	1978	1.07	0.19	(3.5)
Springfield	1982	1.00	0.51	(9.2)
Plainsboro-1	1984	1.35	0.44	(8.1)
NRC-A	1970		0.60	(11.0)
NRC-B	1964		0.30	(5.5)
NRC-C	1970		0.25	(4.6)
NRC-D	1971		0.33	(6.0)
NRC-E	1968		0.10	(3.5)
NRC-F	1973		0.19	(3.5)
NRC-G	1974		0.27	(4.9)
NRC-H	1974		0.13	(2.4)

* ach refers to air changes per hour.

TABLE 2
Building Descriptions

	Pittsfield	Columbia
Number of Stories	2	15
Volume: ft^3	3.0×10^5	3.0×10^6
(m^3)	(8.5×10^3)	(1.6×10^5)
Floor Area: ft^2	2.0×10^4	2.2×10^5
(m^2)	(1.9×10^3)	(2.1×10^4)
Number of Stair Shafts	2	2
Number of Elevator Shafts	1	3
Number of Return Air Shafts	0	5

TABLE 3
Air Exchange Measurement Results

	Pittsfield	Columbia
Average Measured Infiltration Rate (ach*) ΔT: 36 to 54 F (20 to 30 °C u: 0 to 4.5 mph (0 to 2 m/s)	0.26 (0.09)**	0.34 (0.10)
Slope of Infiltration with Respect to Temperature Difference		
ach/F	-0.0016	0.0026
(ach/°C)	(-0.0029)	(0.0047)
Estmated Variance in the Slope of Infiltration with Respect to Temperature Difference		
ach/F	0.0006	0.0007
(ach/°C)	(0.0011)	(0.0013)
Average Measured Ventilation Rate (ach) ΔT: 36 to 54 F (20 to 30 °C)	0.38	0.62

* ach refers to air changes per hour.
** Standard deviation of the measured infiltration rate.

TABLE 4
Shaw-Tamura Predictions

	Pittsfield	Columbia
Wind Speed Slope		
ach*/mph	0.103	0.056
(ach/(m/s))	(0.046)	(0.025)
Temperature Difference Slope ach/F (ach/°C)		
0 mph (0 m/s)	0.0013 (0.0023)	0.0028 (0.0050)
8.9 mph (4 m/s)	0.0002 (0.0004)	0.0024 (0.0043)
Infiltration Rate at ΔT = 45 F (25 °C) u = 0 mph (0 m/s)	0.08	0.16

* ach refers to air changes per hour.

TABLE 5
Nominal Mass Balance Predictions - Pittsfield

	Wind Speed Slope ach*/mph (ach/(m/s))	Temperature Difference Slope ach/F (ach/°C)		Infiltration Rate ach	Predicted Pressure Difference across Ceiling in H_2O (Pa)
		0.0 mph (0 m/s)	8.9 mph (4 m/s)	ΔT = 45 F (25 °C)	
Single Zone	0.024 (0.053)	0.0029 (0.0053)	0.0016 (0.0028)	0.17	---
<u>Nominal</u> Fans Off	0.030 (0.067)	0.0022 (0.0040)	0.0011 (0.0020)	0.13	---
Balanced Ventilation	0.027 (0.060)	0.0004 (0.0007)	0.0002 (0.0004)	0.10	0.017 (4.3)
10% Oversupply	0.030 (0.067)	0.0000 (0.0000)	0.0004 (0.0007)	0.00**	0.018 (4.5)

The nominal conditions correspond to the measured envelope airtightness, shaft leakage in the middle range of Tamura and Shaw's [1976b] data, and ceiling leakage equal to 0.2% of the ceiling area.

* ach refers to air changes per hour.
** Envelope infiltration in addition to the 10% oversupply, which equals 0.37 ach.

TABLE 6
Envelope Airtightness and Ceiling Leakage Effects on Mass Balance Predictions - Pittsfield

	Wind Speed Slope ach*/mph (ach/(m/s))	Temperature Difference Slope ach/F (ach/°C)		Infiltration Rate ach	Pressure Difference across Ceiling in H_2O (Pa)
		0.0 mph (0 m/s)	8.9 mph (4 m/s)	ΔT = 45 F (25 °C)	
<u>Tight Envelope</u>					
Fans Off	0.015 (0.033)	0.0011 (0.0020)	0.0007 (0.0012)	0.07	---
Balanced Ventilation	0.013 (0.030)	0.0002 (0.0004)	0.0001 (0.0002)	0.05	0.017 (4.3)
10% Oversupply	0.013 (0.030)	0.0000 (0.0000)	0.0001 (0.0002)	0.00**	0.018 (4.5)
<u>Leaky Envelope</u>					
Fans Off	0.045 (0.101)	0.0032 (0.0057)	0.0014 (0.0026)	0.19	---
Balanced Ventilation	0.041 (0.091)	0.0007 (0.0012)	0.0003 (0.0006)	0.15	0.017 (4.3)
10% Oversupply	0.045 (0.101)	-0.0014 (-0.0025)	0.0006 (0.0010)	0.01**	0.018 (4.5)
<u>0.1% Ceiling</u>					
Balanced Ventilation	0.024 (0.054)	-0.0004 (-0.0007)	-0.0003 (-0.0005)	0.18	0.045 (11.3)
10% Oversupply	0.023 (0.052)	-0.0008 (-0.0014)	0.0002 (0.0003)	0.11**	0.048 (12.0)
<u>0.3% Ceiling</u>					
Balanced Ventilation	0.029 (0.064)	0.0010 (0.0018)	0.0008 (0.0015)	0.09	0.0095 (2.4)
10% Oversupply	0.030 (0.068)	0.0000 (0.0000)	0.0003 (0.0005)	0.00**	0.0099 (2.5)

* ach refers to air changes per hour.
** Envelope infiltration in addition to the 10% oversupply, which equals 0.37 ach.

TABLE 7
Nominal Mass Balance Predictions - Columbia

	Wind Speed Slope ach*/mph (ach/(m/s))	Temperature Difference Slope ach/F (ach/°C)		Infiltration Rate ach	Predicted Pressure Difference across Ceiling in H_2O (Pa)
		0.0 mph (0 m/s)	8.9 mph (4 m/s)	ΔT = 45 F (25 °C)	
Single Zone	0.025 (0.055)	0.0083 (0.015)	0.0072 (0.013)	0.47	---
<u>Nominal</u>					
Fans Off	0.025 (0.056)	0.0078 (0.014)	0.0067 (0.012)	0.45	---
Balanced Ventilation	0.025 (0.055)	0.0072 (0.013)	0.0067 (0.012)	0.42	0.014 (3.5)
10% Oversupply	0.029 (0.065)	0.0067 (0.012)	0.0054 (0.0097)	0.24**	0.015 (3.7)

The nominal conditions correspond to the measured envelope airtightness, shaft leakage in the middle range of Tamura and Shaw's [1976b] data, and ceiling leakage equal to 0.2% of the ceiling area.

* ach refers to air changes per hour.
** Envelope infiltration in addition to the 10% oversupply, which equals 0.38 ach.

TABLE 8
Envelope Airtightness and Ceiling Leakage Effects on Mass Balance Predicitons - Columbia

	Wind Speed Slope ach*/mph (ach/(m/s))	Temperature Difference Slope ach/F (ach/°C)		Infiltration Rate ach	Predicted Pressure Difference across Ceiling in H_2O (Pa)
		0.0 mph (0 m/s)	8.9 mph (4 m/s)	ΔT = 45 F (25 °C)	
Tight Envelope					
Fans Off	0.013 (0.029)	0.0048 (0.0087)	0.0044 (0.0079)	0.28	---
Balanced Ventilation	0.013 (0.028)	0.0047 (0.0085)	0.0043 (0.0078)	0.28	0.014 (3.5)
10% Oversupply	0.015 (0.033)	0.0039 (0.0071)	0.0033 (0.0059)	0.11**	0.015 (3.7)
0.1% Ceiling					
Balanced Ventilation	0.024 (0.053)	0.0067 (0.012)	0.0061 (0.011)	0.43	0.038 (9.4)
10% Oversupply	0.026 (0.059)	0.0061 (0.011)	0.0049 (0.0089)	0.24**	0.038 (9.4)
0.3% Ceiling					
Balanced Ventilation	0.025 (0.056)	0.0072 (0.013)	0.0067 (0.012)	0.43	0.008 (2.0)
10% Oversupply	0.029 (0.065)	0.0072 (0.013)	0.0054 (0.0098)	0.24**	0.008 (2.0)

* ach refers to air changes per hour.
** Envelope infiltration in addition to the 10% oversupply, which equals 0.38 ach.

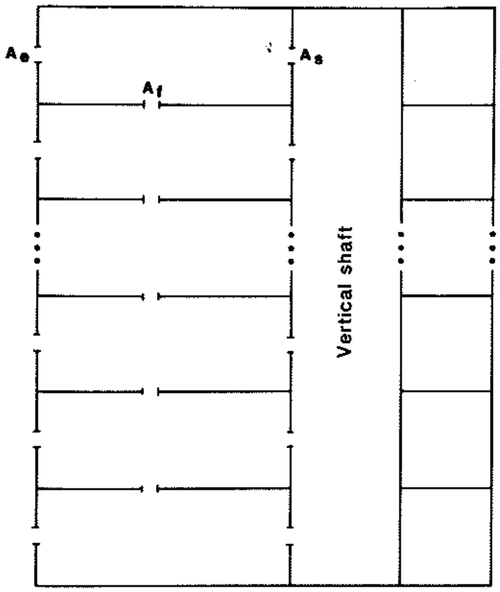

Figure 1. General model of multistory building

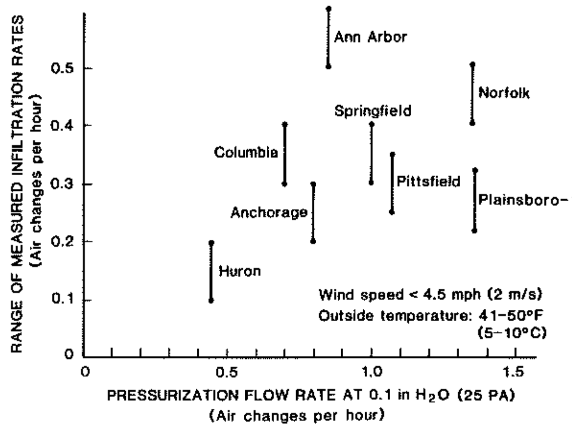

Figure 2. Measured infiltration rates vs. pressurization test results

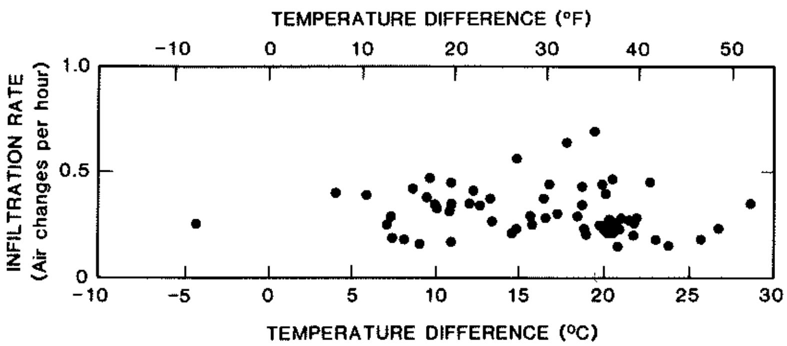

Figure 3. Measured infiltration data, Pittsfield

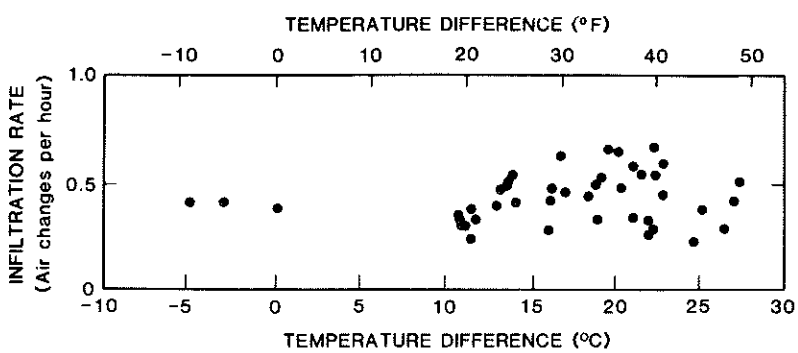

Figure 4. Measured infiltration data, Columbia

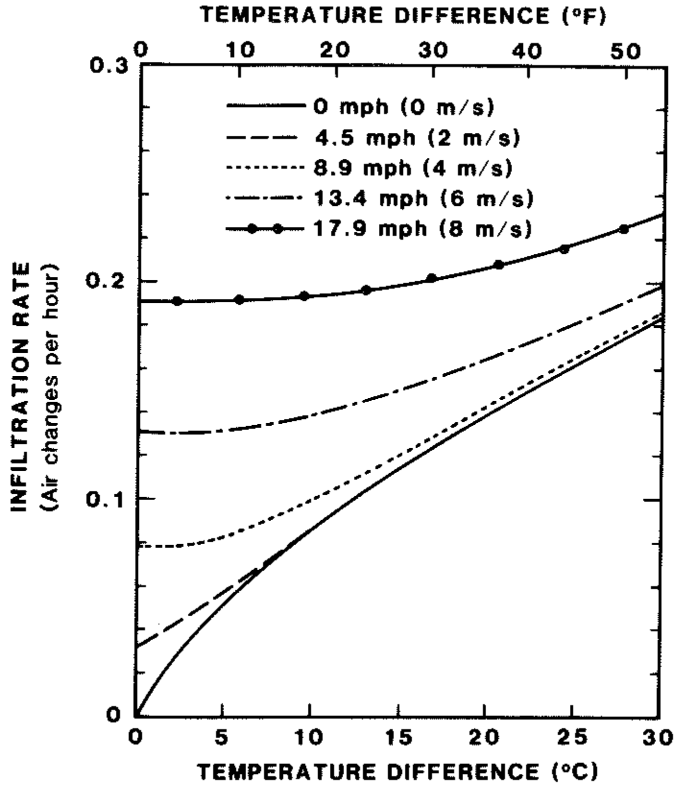

Figure 5. Predictions of the Shaw-Tamura model for the Columbia building

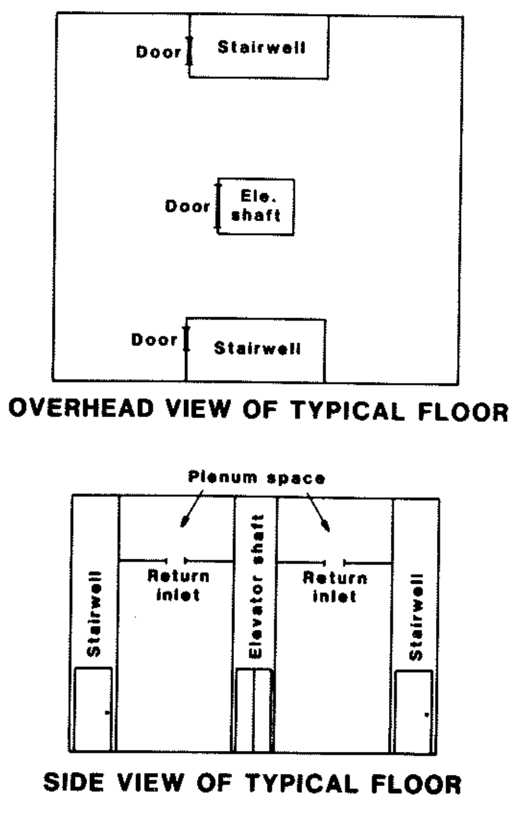

Figure 6. Schematic of Pittsfield building

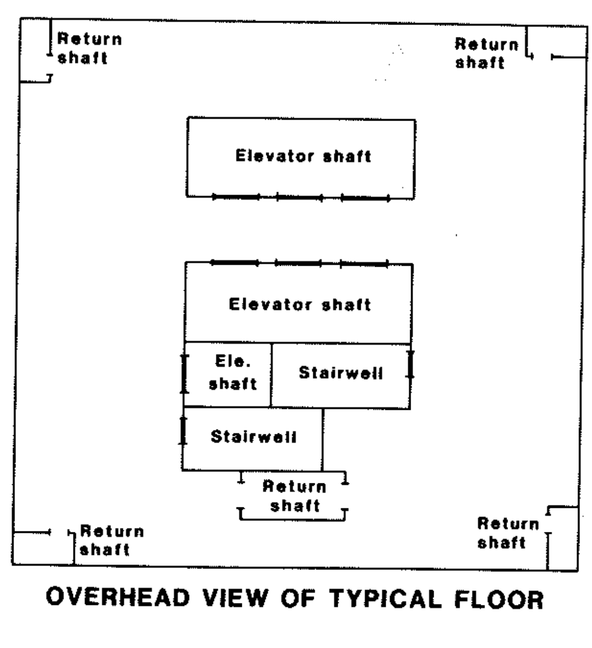

Figure 7. Schematic of Columbia building